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Toward sustainable landscape irrigation using a novel design for water collection systems that use atmospheric moisture condensation

Zaid A. O. Aldeek

Department of Architecture, Hijjawi Faculty for Engineering Technology, Yarmouk University, Jordan
E-mail: zaid.d@yu.edu.jo

ZAOA, 0000-0001-7205-599X

ABSTRACT

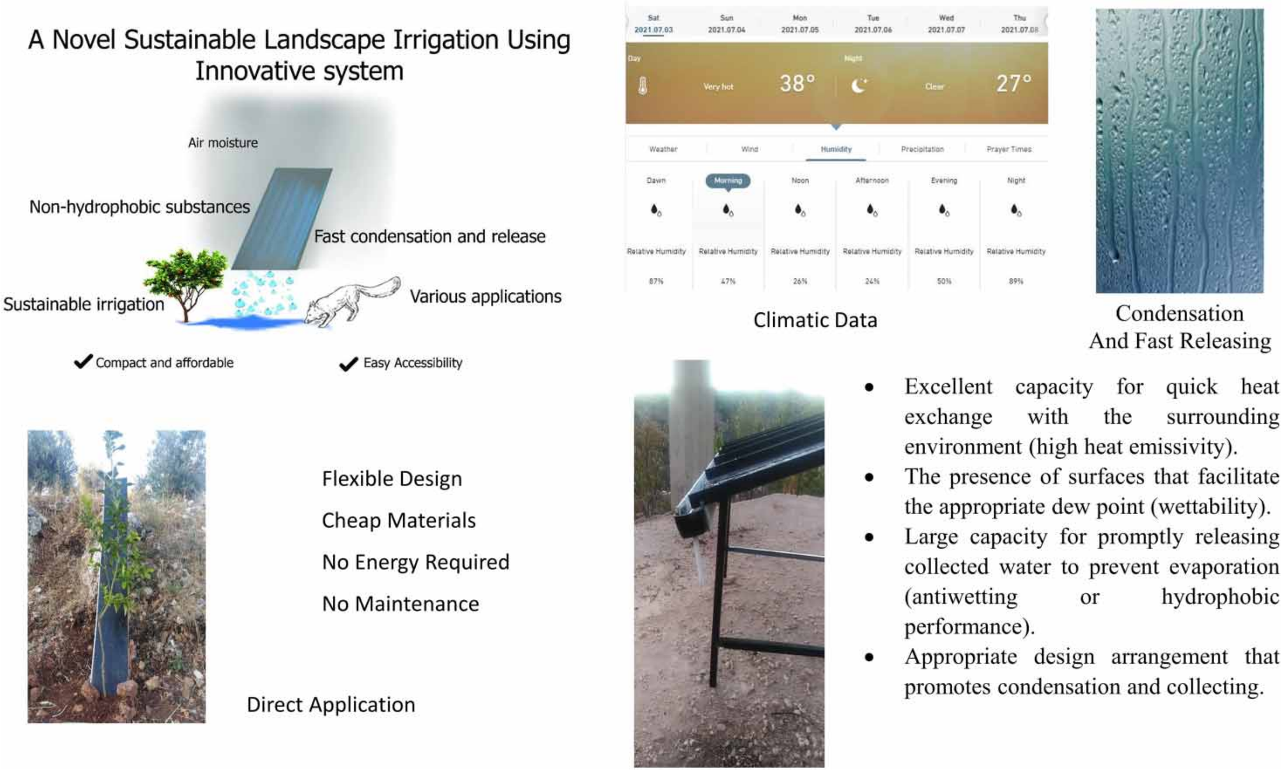
This paper introduces a novel design that uses high-emissivity materials with no hydrophobic surfaces to increase the speed of condensation and the dropping-off process in water collection systems from atmospheric moisture. The design incorporates simple and low-cost technology that takes advantage of advanced material properties to enable sustainable irrigation in regions characterized by water resource scarcity, generally favoring greening. The concept is based on the application of universal physics principles such as dew point, wetting and antiwetting, and material emissivity coefficients. The innovative collection system design and experimentation confirm the feasibility of collecting water from the air in various semi-arid regions with a low number of rainy days. The first novel aspect of the collection system design is the rapid increase in condensation and the use of materials with a high capacity to release collected water to address unwanted evaporation. The second novel feature is that the volume is reduced, and the system is flexible and inexpensive, allowing it to be distributed across a specific landscape. Reduced construction costs and ease of use demonstrate the real possibility of its use in developing and poor countries to first increase vegetation diffusion and then contribute to sustainable agriculture and green architecture.

Key words: antiwetting, atmospheric humidity condensation, innovative condensation collection systems, super wettability, sustainable landscape irrigation, wettability

HIGHLIGHTS

- Valorization of an alternative resource such as water vapor in the atmosphere.
- Simple methods that can be used with low costs in a simple way.
- The vast choice of materials that could be used allows for the usage of recycled materials.
- The launch of a zero-carbon-footprint technology is completely passive.
- Allowing for cost savings and ensuring that vegetation survives in a self-sustaining condition.

GRAPHICAL ABSTRACT



- Excellent capacity for quick heat exchange with the surrounding environment (high heat emissivity).
- The presence of surfaces that facilitate the appropriate dew point (wettability).
- Large capacity for promptly releasing collected water to prevent evaporation (antiwetting or hydrophobic performance).
- Appropriate design arrangement that promotes condensation and collecting.

LIST OF ABBREVIATIONS

SLIPS	slippery liquid-infused surfaces
FWC	film-wise condensation
DWC	dropwise condensation
PVC	polyvinyl chloride
CL	centiliter
ε	emissivity coefficient
Temp.	temperature

1. BACKGROUND

Water scarcity is one of the most pressing issues confronting the world's countries, particularly in light of global warming and low precipitation levels, making the ability to harvest water through rainwater collection and the development of water condensers that transform fog and water vapor suspended in the atmosphere important. Indeed, many efforts have been made in the field of water harvesting, particularly in countries where water is scarce, such as some Middle Eastern and African countries where land degradation caused by a lack of policies that encourage vegetation growth and a lack of studies to employ alternative water resources will result in total desertification in these semi-arid arias (Tzanakakis *et al.* 2020). The main issue is determining how to implement a type of irrigation that will ensure and aid in the survival of trees and vegetation. In Jordan, traditional agriculture, before the introduction of modern methods, people had the awareness to leave the natural stones in camps to benefit from natural moisture condensation to mitigate temperature and to have spontaneous irrigation of their summer cultivations. In particular, for cultivations such as tomato, people used to make small towers of little stones near their vegetation as a form of mini-irrigation and also to shade the vital land.

The ongoing degradation of prospective agricultural regions and landscapes in semi-arid countries such as Jordan requires us to investigate how to enhance sustainable systems that are less expensive and easier to build in order to allow for actual implementation and growth of the systems. These systems should be used in a variety of modalities, including urban landscape irrigation, microscale agricultural activities, and tree irrigation in drought-prone areas. In the following sections of this study, we will explore the inadequacy of previously implemented systems based on the principle of harvesting water from air humidity, particularly in semi-arid environments. Despite their effectiveness in a variety of situations, these methods are incompatible with the particular characteristics of semi-arid climates. Their usefulness is often based on strategies such as humidity absorption in hot-humid areas, followed by water release, or harnessing the heat generated by wind friction across water-iced meshes in frigid alpine regions. When used in semi-arid areas, these devices have a severe drawback: the captured water evaporates quickly. These prior techniques are rendered ineffectual for specific semi-arid climatic situations due to this restriction.

Water vapor could be condensed from the atmosphere and converted into drops of water to meet the demands of irrigation and daily human use. Many experiments and studies have been conducted on this topic by various authors and organizations, resulting in a consolidated literature that encourages research in this field. The goal of this paper is to introduce innovative elements that will enable a wide distribution of condensation collection systems while lowering costs and increasing capacity. According to the United Nations, water is the most important issue affecting long-term socioeconomic development; it is the central element that connects society and the environment (United Nations 2018).

To improve the new design of water collection systems, this research integrates the technical development of materials with existing testing and associated literature. The innovative aspect is connected to the changeable and reduced dimensions, the lower costs, and the use of cutting-edge materials to address the underlying physical principles governing condensation. Basic science shows that the presence of water vapor, a decrease in temperature, and the presence of surfaces with a certain ability to attract condensation are three requirements that must all be met simultaneously for the dew point of water vapor to occur in an environment (wettability) (Giancarlo 2007). The wettability of a solid surface is a macroscopic representation of the interaction between the liquid and the substrate solid material (Wang *et al.* 2016). In vegetation, humidity adsorption is governed by other processes, and there is a substantial difference between the processes of condensation and adsorption in organic and non-organic systems. The comparison in this paper is finalized to demonstrate the validity of the proposed system in terms of the quantity of atmospheric water vapor that could be used. Wang *et al.* (2016) indicated that an important application of interfacial materials with special wettability for vapor condensation is the atmospheric water collected from fog or dew in areas where fresh water is scarce.

1.1. Scientific aspects of high-emissivity materials and non-hydrophobic surfaces in atmospheric water collection

Water collection from atmospheric moisture, also known as atmospheric water harvesting, is a viable solution to water scarcity, especially in semi-arid and arid environments. This notion is based on the condensation principle, which is a basic process in which water vapor in the air is turned to liquid water. The objective for this technique is to optimize the efficiency of the condensation process by leveraging unique material features, Tu & Hwang (2020).

High-emissivity materials are critical in this regard. Emissivity is the capacity of a material to emit energy as thermal radiation. A material with a high emissivity may emit more thermal energy, which cools the material surface quicker than its surroundings, especially at night. Because the chilled surface provides a desirable site for water vapor in the air to convert into liquid form, this cooling action promotes condensation. Not only should the surface encourage condensation, but it should also allow water droplets to slide off fast for effective water collecting. This is when the hydrophobicity, or water-repelling quality, comes into play. Hydrophobic surfaces are frequently used in traditional water-collecting technologies to enhance droplet shedding; however, these surfaces might be detrimental since they can obstruct condensation. As a result, our new design employs non-hydrophobic (or hydrophilic) surfaces that, in addition to drawing water for condensation, have the necessary structure or texture to allow water droplets to glide off and gather easily, therefore reducing evaporation losses (Trosseille *et al.* 2022).

As a result, the careful selection and combination of high-emissivity materials and non-hydrophobic surfaces is the fundamental scientific premise underlying our suggested atmospheric water collecting system. The goal is to speed up the condensation and droplet deposition processes for effective atmospheric moisture harvesting, resulting in a long-term solution for irrigation and greening water-scarce areas.

The suggested system requires minimal maintenance and is intended to be passive, leaving no carbon footprint. Jordan and other semi-arid countries are using strategies that focus on categorizing natural types of plants scattered within difficult climatic zones and utilizing them in greening recovery efforts. The use of vegetation types that persist in harsh climates is the first step in combating desertification in a sustainable manner, and it is based on observations about the natural characteristics of some suitable vegetation types that have demonstrated a high capacity to persist under very harsh conditions. The adoption of this type of plant (in conjunction with sustainable irrigation systems) could provide numerous benefits, including delaying desertification and stabilizing the landscape, allowing some towns to implement sustainable urban greening (National Research Council 2010). The low cost and simple maintenance requirements of the suggested methodology support its implementation in underdeveloped nations to address environmental policies that actively contribute to mitigating global warming and desertification processes.

1.2. Literature review

The Warka Arca project, established by Arturo Vittori and his colleagues, is the most well-known endeavor linked to building systems to capture water from the air. This project included the creation of the Warka Water Tower, a water harvesting machine whose main function is to harvest water from the atmosphere by absorbing it on a mesh surface in order to give a community with 100 L of water per day. The tower is primarily made of a polyester mesh supported by a bamboo frame that captures moisture in the air and condenses it into water droplets that fall into a reservoir at the base of the structure. A cloth canopy can also be utilized to shade the area around the tower, offering people the opportunity to stay cool (see Figure 1). The efficiency of this network is limited, and it results in the loss of collected water by evaporation or movement by flowing air. Numerous researchers have attempted to increase the efficiency of the net and to further develop its components. Wind velocity, liquid fog water volume, droplet size distribution, and net properties all influence efficiency (Warka Water Inc. 2017). The water tower features a triangular mesh structure made of readily available natural materials that may be simply constructed by the residents themselves. The tower is a 9-mtall building composed of a particular fabric, textile polyethylene, that can absorb water from the air through condensation. The structure weighs only 60 kg and is made up of five modules that can be constructed from bottom to top by four persons without the use of scaffolding; however, due to its light weight, the system must be secured to the ground. Warka Water is capable of collecting up to 100 L of drinking water every day. The system is completely passive (requires no energy) and operates by trapping moisture delivered by wind and absorbing it from the surrounding environment (Warka Water Inc. 2017). The Arca Warka system requires communal installation at its peak, as well as a structure with some resistance to wind solicitations, which relays its capillary diffusion. On the other hand, it encouraged us to create a simpler and less expensive alternative.

Researchers in various countries have devised projects and devices for harvesting water from air humidity, which exploit the universal concept of condensation. Dehumidifiers used as water extraction devices and deployed throughout Bahrain attest to the economics of this form of water collection when compared to other nonconventional approaches (Dahman *et al.* 2017). Once engaged, these systems enable water vapor condensation among electric devices that collect water and reduce air temperature, demonstrating the significance of this type of research for particular countries.

The many forms of collection systems proposed by Jarimi *et al.* (2020) are distinguished by their large dimensions and a number of issues linked to the use of mesh and the degradation of collection system components (see Table 1). The

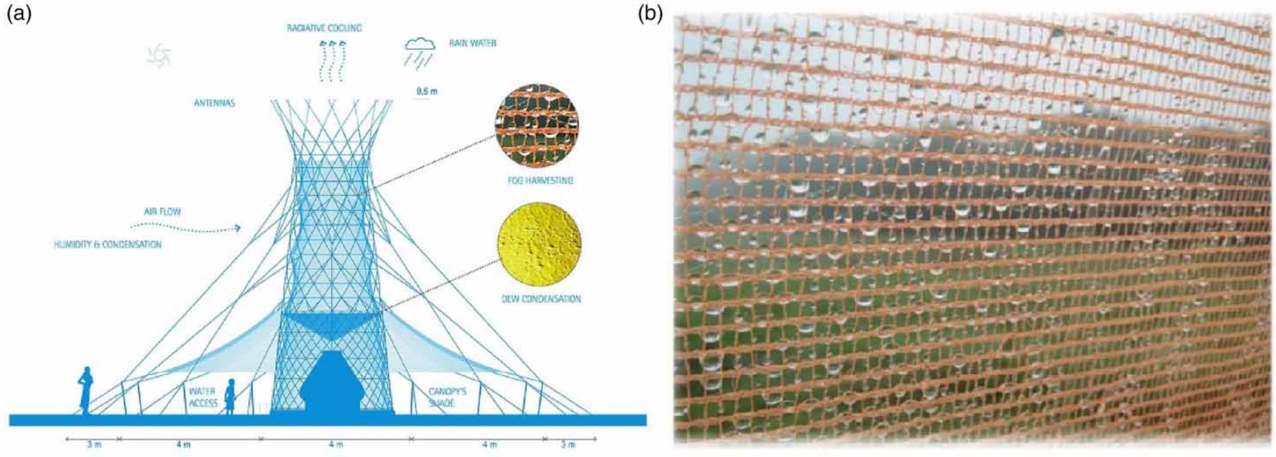


Figure 1 | (a) The Warka Water Tower. (b) Detailed image of relative mesh. *Source:* Warka Water Inc. (2017).

Table 1 | Selected fog collector design

Selected fog collector design

Type	Size/design	Application	Advantage ratio	Capacity (L/day)	Country
Warka Arca	Circular tower with a radius of 5 m and a height of 13 m	Limited scale	Benefits from the high level of air humidity by absorption	100–500	Ethiopia and Central Africa
Electrical condensers	Different dimensions	Limited scale	Requires a power supply and maintenance	20–200	Oman
Eiffel Collector	4 × 8 × 0.3 m metal frame, two separated layers	Large-scale experiment	Advantageous for places with no unique wind direction	2,650 during the peak fog season	Peru
Harp Collector	2 × 4 × 0.3 m metal frame, 2,256 m of 1.5 mm thick rubber string vertically installed	Large-scale experiment	Advantageous for places with unique wind direction	200 during the peak season	Peru
Diagonal harp collector	2 × 4 × 0.3 m metal frame, 1,520 m of 1.5 mm thick string	Large-scale experiment	Advantageous for places with unique wind direction	94 during the peak season	Peru

Source: Elaboration data from Jarimi *et al.* (2020).

importance of passive systems and the necessity to expand their capabilities is demonstrated by a comparison of several types of traditional passive devices (i.e., devices that do not utilize energy) versus those constructed with an active mode. Active systems are now unviable due to their high prices and technical problems associated with production and installation. None of the devices investigated or provided in current research for arid and semi-arid zones address the necessity of our task. The targeted design of this paper is focused on the utilization of micro applications that allow for large-scale use (Aldeek 2020a, 2020b).

Domen *et al.* (2014) describe the Eiffel Collector as a vertical mesh supported in vertical mode to contrast wind appropriate for directional winds. The mesh design could be single or double, and the grid dimensions are configurable to optimize droplet caption. There is no discernible difference between this and the Arca Warka collection design; however, it may perform better in high mountains where wind velocity is higher and temperatures are lower. Textile polyethylene is not the only material used in mesh fabrication; metal grids of various designs are also employed to provide the proper cutting angle. The amount of water collected depends on the mesh diameters and is critical on high mountains.

Harp collectors, as described by Jarimi *et al.* (2020), are extremely similar to previous collectors, with the key difference being the relative lowered dimensions and some mesh realization approaches. All of the preceding varieties are passive and ideal for some zones more than others, but not for arid and semi-arid zones.

The use of innovative paints and materials may aid in the development of novel collecting systems with improved water vapor absorbance and condensation performance. In architecture, engineering, and biomedical studies, advanced materials and paints are used to prevent many issues, such as moisture in walls, to provide internal healthy environments, perform self-cleaning, form viral or bacterial agglomerations, and release disinfecting substances (Rădulescu *et al.* 2016).

1.3. Study relevance

As indicated in the literature review, the technology presented in this study is relevant to many research sectors and has the potential to be a useful instrument for harvesting and collecting water in countries with limited water resources. The challenge in this paper is to transform traditional collection systems into novel water collection systems that permit capillary diffusion, reduce costs and volume, and enable simple management. The significance of developing this type of technology is its contribution on many sectors, including providing potable water in areas where water sources are exposed to high levels of pollution or diffuse infections, contributing to micro agricultural systems in remote regions, incentivizing limits to desertification in many semi-arid regions, providing sustainable micro water resources for sylvatic small animals and insects, and contributing to climate change efforts. For many years, the focus has been on megaprojects in developing nations as a vehicle for sustainable development, ignoring the fact that sustainable development must involve broad distribution and capillary production in remote places. As a result of the loss of agricultural resources, there is ongoing internal and foreign migration.

Micro projects that use new technology and are simple to understand and implement serve as the foundation for recovery strategies in a variety of industries (Aldeek 2020a, 2020b). Based on this idea and concept, the suggested innovative water collecting system design employs a basic approach mixed with advanced materials to offer portable devices that can be simply managed. We concentrated on the major elements that regulate the condensation and water-droplet generation process, as indicated in subsequent sections of this paper. The materials utilized in the building of our innovative water collection system must meet the following:

- Excellent capacity for quick heat exchange with the surrounding environment (high heat emissivity).
- The presence of surfaces that facilitate the appropriate dew point (wettability).
- Large capacity for promptly releasing collected water to prevent evaporation (antiwetting or hydrophobic performance).
- Appropriate design arrangement that promotes condensation and collecting.

2. METHODS

We intend to investigate the potential application of techniques that use air humidity to deliver water for diverse purposes, with a focus on semi-arid climatic situations. To do this, we will collect data and observations connected to semi-arid zones, allowing us to formulate a hypothesis requiring the introduction of a new type of device due to the different condensation principles. To begin, we will examine outcomes from past experiments that used air humidity for water supply in various circumstances. We can assess the potential practicality of using such technologies in semi-arid regions by utilizing the data from these tests. This study will shed light on the concepts underpinning the condensation process and how they differ in semi-arid environments.

Following that, we will perform experiments and observations in semi-arid areas to validate our idea. These tests will determine whether it is possible to capture the condensed moisture produced by natural condensation in these places. We will concentrate on considerable daily temperature fluctuations and the availability of appropriate humidity, as these conditions are conducive to water collecting. We can evaluate the best design and materials for our devices by watching numerous nights and seasons. We have already seen large amounts of water covering grasses, boulders, and other solid things during nights of condensation in our excursions to semi-arid zones. It is worth noting, however, that these water accumulations dissipate within a few minutes of condensation. This discovery emphasizes the importance of efficient collection methods capable of capturing and storing condensed water before it evaporates.

Finally, our research aims to look at the feasibility of using air humidity to supply water in semi-arid areas. We hope to develop a novel design for devices that can successfully harness the unique principles of condensation in these specific climatic conditions by analyzing prior experiences, performing experiments, and making observations. Finally, we want to create novel technologies that can supply a sustainable water source in semi-arid areas.

This work proposes to leverage the physical features of materials in a simple technique of collecting water from air humidity that is low in cost and has the potential for large diffusion. For this purpose, we examined contemporary approaches utilized in many parts of the world with the goal of identifying the best way for arid and semi-arid zones. The research is separated into several sections, beginning with bibliographic research and relevant material. Data gathering linked to geographic and climatic elements of the targeted zones validated the initial concept that it is possible to exploit condensation of air humidity in semi-desert zones for sustainable greening and desertification mitigation. The proposed system might supply little water to the targeted vegetation on several nights of the year. As a result, flora can thrive in harsh climatic circumstances. The design of the revolutionary collector ensures its construction and function without any intervention after installation, while lower prices and ease of implementation ensure widespread adoption. Finally, the prototype building and tests demonstrated a variety of suitable materials and forms of the final model and how they may be used. The validity of the suggested system within predefined objects was proved through tests. In this study, we used conclusions based on the following methodologies:

- Data elaboration: The data obtained contain information about the weather in the experimentation zone, such as wet days, the number of days with condensation avenue, and whether or not the proposed system can be replicated. The information is gathered from official statistics as well as national and international reports. Other information is gathered directly.
- Prior experiences: The goal of this section is to demonstrate the legitimacy and importance of extracting water from this novel source. We highlighted the numerous efforts made in this regard to develop this industry, with significant outcomes.

- Experiments: The primary goal of these tests is to provide evidence on the functionality of the suggested design.

The methods used are heavily reliant on experimentation and practical confirmation. This method entails testing a variety of materials, surfaces, and panel configurations used to condense air humidity, as discussed in the following sections. The major test site is at Rihaba, Jordan, at an elevation of 860 m above sea level, with longitude 35.7877385 and latitude 32.4328263. During the summer, the relative humidity ranges between 30 and 95%. The temperature fluctuates greatly during the day, from a comfortable 12 °C at night to a sweltering 39 °C during the day, and annual rainfall occurs mostly over the course of 20–30 days according to the Jordanian Meteorological Department.

3. WORKING PRINCIPLES OF THE PROPOSED NOVEL WATER COLLECTION SYSTEM FROM ATMOSPHERIC HUMIDITY CONDENSATION

Before getting into the particular design details of the proposed system, its functioning principles must be clarified. The primary goal of this device is to capture spontaneous morning dew, which occurs regularly in semi-arid zones for several nights before it evaporates. Timing is an important aspect in the overall operation of the system for two reasons. To begin, perfect dew-forming circumstances generally occur late at night or early in the morning. Second, if dew is not used properly, its evaporation duration is extremely short.

The final prototype of this gadget is made out of metal panels, which are notable for their strong emissivity. This property enables them to effectively dissipate heat through radiation. These panels are also painted and coated with nano-ceramic material to improve surface wettability. This modification facilitates the quick release of dew-collected water, which will be discussed more in the next section.

4. NOVEL WATER COLLECTION SYSTEM

The surface properties of the proposed collection system must reflect the above-mentioned performances. The proposed water collection system model is made up of three major components: a collection surface area responsible for condensing droplets carried in the air or fog as moisture, a water collection system, and a distribution system.

4.1. Novel design of water collection systems from atmospheric humidity condensation

The most important aspect of the suggested system design that must be addressed is the change in materials utilized in traditional nets. Environmental conditions can be classified into three types: high mountains (generally characterized by low temperatures and diffuse wind and fog), hot-humid zones (characterized by high levels of saturation (high humidity and temperature), and arid and semi-arid zones (characterized by summer-night dew formation caused by the high daily temperature difference). These factors suggest that zones have low precipitation amounts for a variety of reasons. Conventional elements employed in hot-humid zones are incapable of immediately converting humid air from a gas to a liquid. As illustrated in Figure 1, traditional materials must first absorb moisture from the atmosphere, implying that they can only function at sufficiently high saturation levels. This procedure takes a long time, and evaporation lowers the capacity of the net to gather water. Conventional elements utilized in high mountains are developed for unique geographical conditions and will not work in semi-arid or desert zones.

As illustrated in Figure 2, this new system intended for semi-arid and arid zones takes advantage of the properties of the materials employed. When temperatures drop, a solid surface has a significant ability to draw moisture from the environment.

Figure 2 | (a) The water drops condense against a high-heat-emissivity solid surface, (b) proposed use of elements of the solid surface, (c) proposed use of elements of the solid surface in combination with the traditional net (*Source:* Author).

This capability is based on dew point-related physical considerations. A solid surface, such as anodized aluminum or other suitable metal elements (see Table 2), rapidly loses heat in relation to the environment, satisfying the first criterion, while smooth surfaces, in general, satisfy the second principle, i.e., the dew point condition. Since they hinder heat transport, high thermodynamic structures such as rough surfaces act as an energy barrier for the nucleation of super hydrophobic surfaces. Slippery liquid-infused surfaces (SLIPS) could provide a solution to the high water sliding ability and surface smoothness of the liquid layer (Tsuchiya *et al.* 2017).

The parameters listed above must be met in the creation of our innovative system. Figure 2 depicts the development concept. The addition of metallic parts improves the amount of water gathered because, like in traditional nets, the amount of water collected verifies the dew point. Because the elements lower the amount of time a water droplet persists on the collection system surface area, adding these metallic elements provides a hydrophobic capacity that reduces evaporation of the collected water on the net. The metal surface design and the introduction of a hydrophobic element through the use of substances such as nano-ceramics, liquid ceramics, or other appropriate paints are the most novel aspects of the system. These materials have the advantage of not interacting with water and hence do not modify the properties of the painted materials; their job is simply to accelerate the droplet fall after condensation.

The materials used in the novel design of this water collection system reflect its desired performance, and the system parts that aid in achieving this performance can be summarized as follows: its high absorption and wettability capacity, its high capacity to lose heat in a manner that favors rapid condensation, its capacity to rapidly release the accumulated water, and the design configuration of the proposed system. Gravity does not help a horizontal surface release condensation quickly, and a particularly smooth surface does not address the surface tension of water droplets. The capacity of the chosen material for building the suggested system is determined by its wettability, availability, and durability.

4.2. Wetting phenomena and thermal radiation capacity

Wettability and super wettability happen when a water drop falls on a surface; ‘superwetting’ happens when the droplets form a sphere or completely wet the surface. Antiwetting and super-antiwetting relate to the surface ability to discharge water droplets created during the condensation process (Durand *et al.* 2011). While exploring heat transfer and humidity applications in general, wetting and antiwetting are very relevant. These concepts secure the unique system operation in this environment. The materials we chose have a high capacity to dissipate heat through radiation, which ensures high wettability (heat emissivity) of the system. The wetting process is linked to the thermal radiation capacity (Durand *et al.* 2011), which is based on the Stefan–Boltzmann law, and this capacity is compared to heat radiation from an ideal ‘black body’ with an emissivity coefficient $(\varepsilon) = 1$. The emissivity coefficient (ε) for various common materials is shown in Table 2. When the ambient temperature changes, the emissivity coefficient (ε) of some materials changes (Analytical Testing Solutions Ltd 2020).

Table 2 shows the emissivity of some materials at 26.85 °C. Emissivity is the ability of some materials to dissipate heat, resulting in a temperature lower than the surrounding environment. This property determines the possibility of condensation on the surface under consideration. Surface behaviors may alter at low temperatures ranging from 0 to 26 °C. To further understand this aspect, we conducted laboratory tests that involved exposing different materials to 0 °C and an outdoor

Table 2 | Thermal radiation capacity-emissivity coefficient (ε)

Thermal radiation capacity-emissivity coefficient (ε)

Material	Emissivity coefficient	Material	Emissivity coefficient
Alumina, flame sprayed	0.80	Polyvinyl chloride (PVC)	0.91–0.93
Aluminum, commercial sheet	0.09	Plastics	0.90–0.97
Aluminum, anodized	0.77	Wood, pine	0.95
Asphalt	0.93	Wrought iron	0.96
Black body	1.00	Black epoxy paint	0.89
Black lacquer on iron	0.83	Glass smooth	0.92–0.94
Paper	0.93	Black silicone paint	0.93
Clay	0.91	Oil paints, all colors	0.92–0.96

Source: Analytical Testing Solutions Ltd (2020).

temperature of 26 °C using the same method and period of exposure. We discovered that materials that attain equilibrium with the surrounding environment sooner produce better results than other materials because they have the maximum level of heat exchange at low temperatures when measured at progressive time intervals (see Table 3).

4.3. Hydrophobic phenomena

There are currently several industrial applications of super hydrophobic substances, particularly in the field of paint production, such as anti-fog coatings, antifreeze surfaces, oil and water separation, and antibacterial surfaces, which are used in the medical and industrial fields to prevent bacterial accumulation and improve performance against metal and device corrosion (Darband *et al.* 2020). The ability of an antiwetting surface to avoid water collection is referred to as hydrophobic phenomenon. The lotus effect, where water droplets on a lotus surface exhibit contact angles of around 147° (cutting angle) generated by the surface arrangement, has been seen in nature (see Figure 3(a)) (Latthe *et al.* 2014).

The lotus effect explains the behavior of highly hydrophobic surfaces with a water contact angle of more than 150° and a low sliding angle, and an angle of less than 10° has sparked significant study interest in terms of potential anti-icing qualities. Anti-adhesive coatings, self-cleaning compounds, antifouling materials, and anticorrosion chemicals are used in daily life,

Table 3 | Thermal radiation capacity at low temperatures based on laboratory tests on materials with an area of 5 × 5 cm^2 and a thickness of 2 mm

Material	Temp. after 1 min	Temp. after 10 min	Temp. after 20 min	Temp. after 60 min	Material	Temp. after 1 min	Temp. after 10 min	Temp. after 20 min	Temp. after 60 min
Smooth glass	0	7	15	26	PVC	0	7	14	25
Untreated aluminum	0	3	10	20	Plastic	0	7	14	25
Anodized aluminum	0	6	13	24	Wood	0	6	14	25
Iron	0	7	15	25	Oil-painted surface	0	7	14	25
Asphalt	0	7	15	26	Porcelain	0	7	15	25
Smooth glass	0	7	15	26	Paper	0	7	14	25

Source: Author.

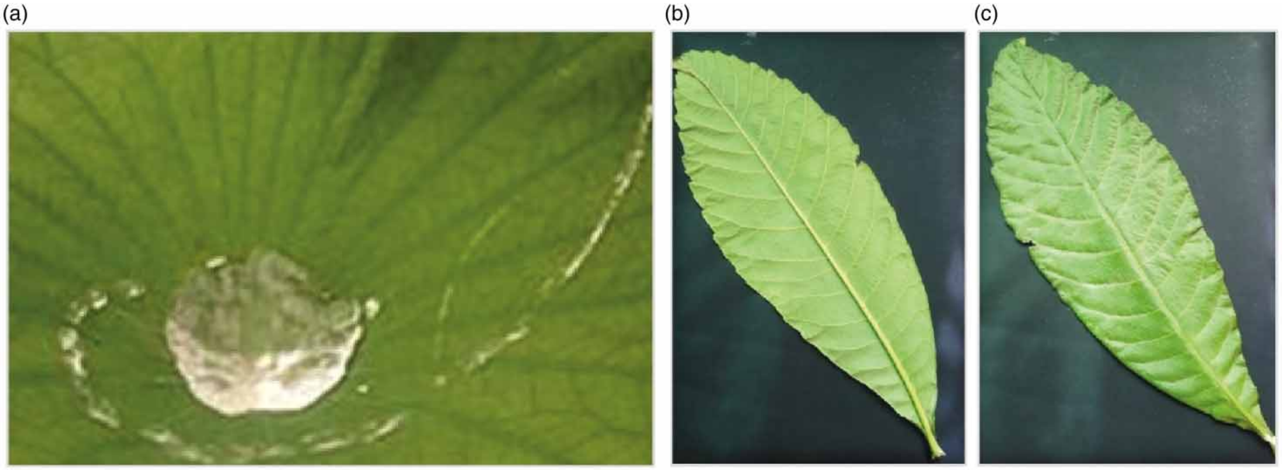


Figure 3 | (a) The behavior of a water droplet on the lotus leaf surface. (b) Typical rough leaf surface and (c) smooth leaf surface (*Source:* Author).

agriculture, and many industrial operations (Yu *et al.* 2020). Highly hydrophobic paints and other commercial applications, such as the usage of nano-ceramics on surfaces, mimic the lotus effect and can be easily included in the suggested system.

5. DISCUSSION

The proposed prototype considers the challenges of directly extracting water from the air. Table 4 shows the key difficulty in determining the dew point in connection to specific variables such as specific temperature, specific relative humidity level, and unique surfaces. At night, several varieties of vegetation are effective at absorbing moisture from the air. Such vegetation handle the aforementioned issues by continuously lowering the leaf temperature produced by their architecture and directly absorbing the moisture in the air (see Figure 3(a)). In general, as seen in Figure 3(b) and 3(c), a leaf has two surfaces: the upper surface, which is smooth and encourages condensation, and the lower surface, which is rough and maximizes dew absorption from the nearby air. Water absorption in plants is a complex process that benefits from air moisture in the form of condensation or humidity saturated with air. While working with harsh and desert plants, the level of complexity rises. In arid and semi-arid zones, atmospheric water is the primary water source for plants; however, how trees receive atmospheric water in these habitats is unknown precisely. Desert plants develop techniques to exploit all feasible water supplies in order to live in a harsh climate (Gong *et al.* 2019). Air humidity accounts for 28–66% of the water intake in the coastal prairie ecosystem (and 74% of the water required by vegetation to develop and survive in zones) (Corbin *et al.* 2005).

5.1. The concept of absorption of condensation in vegetation as inspiration model

Vapor condensation mechanisms were critical in both natural and artificial systems. Understanding these processes could aid in the design of a water supply system at several layers, such as desalination and the use of air humidity to generate drinkable water. The significance of these processes is in maintaining a high level of energy balance. Condensate morphology is generated in two modes: film-wise condensation (FWC), when the condensing surface is hydrophilic, and dropwise condensation (DWC), when the condensate forms a liquid film over the wetted condenser surface. In DWC, the condensate is formed as droplets on the surface, while the FWC is a continuous liquid film with major heat transfer resistance offering higher heat transfer and resulting in a more efficient method of condensation. It is possible to improve the condensation heat transfer ratio by using super hydrophilic surfaces, promoting droplet and water condensation, and incentivizing droplets to leave surfaces using anti-adhesive paints, as in our prototype, to increase the heat transfer ratio caused by efficient removal of droplets from the condenser surface (Wang *et al.* 2016).

Bennett (1878) explained that gardeners universally assume that developing plants can absorb water through their leaves, both in the liquid and gaseous form, in addition to using suction through the roots. Sachs claims that when land plants wither on a hot day and revive again in the evening, it is due to reduced transpiration with the decrease of temperature and the increase of moisture in the evening air, and continued root activity; not because of absorption of aqueous vapor or dew through the leaves (Sachs & Thiselton Dyer 2011).

These two perspectives appear to differ in terms of the manner of absorption of dew and water vapor from the air, but they provide proof that dew and water vapor can be absorbed from the air and that trees cannot easily profit from the liquids collected by leaves. Indeed, when we analyze certain trees, we notice that the water collected by the leaves is canalized and sent into the tree roots. Based on both claims, we established that our innovative collecting system design should incorporate these factors in terms of the surface of the condenser sections. According to our findings, ideal materials for condenser construction include metallic strips, strips of cooked clay, and plastics. A multilayer technique is required to ensure that absorption and dew condensation occur simultaneously. The construction type of the collection system is determined by the relative humidity and daytime temperatures.

Table 4 | Water absorption–condensation material performance

Water absorption–condensation	Anodized aluminum	Ceramics	Semi cooked ceramics	Dried clay	Wood	Iron
Absorption per cubic centimeter in 30 min	0.0%	34%	50%	60%	20%	0.0%
Condensation in grams per square centimeter at 26 °C with a relative humidity of 60%	0.77	0.95	0.90	0.90	0.93	0.96

Source: Author.

Yet, based on our findings, the usage of clay could be very beneficial at various temperatures and relative humidity levels due to its strong performance in absorbing water and facilitating dew condensation. Cooked clay, and ceramics in general, have a great capacity to absorb water due to the presence of micro channels (porosity), which ensures dew and water vapor absorption. Ceramics, on the other hand, do not readily release absorbed water. Consequently, with our innovative collection method, specific paints can be employed to improve the process (see Table 4).

Table 4 demonstrates that a ceramic derivate satisfies both absorption and condensation criteria at the same time, contradicting the basic premise of employing solely metallic elements. The initial prototype was created using a framework that holds metallic strips (see Figure 4). Experiments demonstrated that the prototype in Figure 4 works effectively in the summer, when dew production and daily sensible temperature reduction occur regularly.

5.2. First prototype construction and experimentation

Initially, the collecting grid was made up mostly of intersecting metallic strips with high emissivity (radiative capacity) to lose heat through radiation and so promote the condensation process at specific temperature fluctuations. The surface of these strips has been elaborated to improve their antiwetting performance. This elaboration could be accomplished in a variety of ways, such as by employing nanoceramic paints or by drawing micro channels on the surface with a laser cutter, for example. We determined from multiple testing that the innovative collection technique operates effectively in all seasons when precipitation is scarce in semi-arid and arid zones (from March to November). It should be noted that vapor saturation and light rainfall are common in these areas. To improve our basic collection system, it has been painted in a dark hue to fulfill the intended role in all seasons.

According to the results of studies to identify which materials should be utilized in the proposed innovative system, metallic strips or panels painted with liquid ceramic, nanoceramic, nanographene, or any other oil paint might achieve the desired emissivity performance, which favors dew condensation. The prototype was coated with nanoceramics (to improve antiwettability), which is often used to protect automobiles as it is cost-effective and simple to use. Tables 2 and 3 demonstrate that a range of sustainable materials can be used. In our case, we used metal strips for the prototype framework. Numerous other materials, such as iron strips, PVC, or polymers may be more suitable and used successfully. Table 5 contrasts the unique prototype with the current models.

5.2.1. Prototype

The design of the prototype structure takes into account the operating system, the paint utilized, the nanoceramics employed, and the testing needed. The prototype includes a light iron construction (see Figure 4) that can be developed in a variety of alternative shapes that are better appropriate for specific applications. Dimensions and shapes can be changed depending on where it will be situated.

Figure 4 | First metallic prototype used in experimentation (*Source:* Author).

Table 5 | Comparison between other types of collectors and the proposed novel collector

Comparison between other types of collectors and the proposed novel collector

Type of collector	Construction method	Working method	Notes	Climatic zone application
Warka Arca	Vertical very high structure with a cotton mesh	Absorption from very high relative humidity	Dew dimensions cannot be diffused. Works only in humid regions. Cannot achieve humidity in cold seasons.	Humid and hot regions
Harp	Horizontal large dimensions: mesh realized from the finest metallic files	Resistance to wind under foggy conditions and condensation carried by wind	Target destinations limit its use to just very high mountain zones.	Very high regions exceeding 2,000 m above sea level
Eiffel	Vertical large dimensions: mesh realized from the finest metallic files	Resistance to wind under foggy conditions and condensation carried by wind	Target destinations limit its use to just very high mountain zones.	Very high regions exceeding 2,000 m above sea level
Novel Collector 01	Vertical or horizontal mixed metallic and cotton mesh	Resistance to wind under foggy conditions and condensation carried by wind	During cold seasons, it absorbs humidity from air. During hot seasons, it condenses humidity. Limited dimensions and could be constructed from different materials.	Semi-arid and arid zones
Novel Collector 02	Inclined surfaces	Conducive to dew condensations	Benefits from weak rains. During hot seasons, it condenses humidity. Limited dimensions and could be constructed from different materials.	Semi-arid and arid zones

Source: The Author.

Longitudinal metallic strips, as indicated in section 5.1, were utilized to create the wind-resistant net and to remove moisture from the air. Vertical strips were used to better utilize gravity as the water droplets dropped off, while horizontal elements were used to structure the net. The metallic strip net was erected and coated once the nanoceramic treatment was completed (see Figure 4).

5.2.2. Developed prototype construction and experimentation

The principal dew locations closest to the ground surface drove the alteration of the initial prototype into a horizontal surface that was better suited for during the experiment on July 21 in Rihaba (a region of Irbid, Jordan). The condensation process is shown in Figure 5, and the weight of the water droplets favored their aggregation near the ground. As a result, the final version of the collecting system took this into account because if not collected and settled, all condensation on the surfaces will evaporate within a few minutes.

5.3. Developed prototype construction

We discussed in section 5.1 the necessity to build different types of collection techniques that are more appropriate for the weather circumstances in the trial area. This prototype provides a major horizontal surface for collecting dew condensation. Its operation and low-cost materials distinguish it. The PVC panels (the final prototype was made of iron panels painted black and treated with nanoceramics) had a high emissivity (see Table 2).

The new collection system succeeded admirably, as seen by the documentation. The final prototype also benefited from light rainfall that spread throughout the semi-arid zones, aiding efforts to combat desertification. As previously stated, condensation capacity is determined by two factors: the high emissivity of the collecting system surface and how quickly the surface releases condensation to be used for spontaneous watering (or other uses). This component is ensured by the antiwetting capacity of the collection system surface. Figure 6 depicts the collection system function during the experiment. Figure 6(a) depicts the initial test, while Figures 6(b) and 6(c) depict the concept of the final form of the collection system. Figure 7 depicts the finished prototype. As demonstrated in Figure 8, the collection system might be simplified to a simple panel for each tree or plant, resulting in a significant cost decrease.

Figure 5 | (a) Moisture accumulation in low-level banks. (b) Condensation on metal surfaces (*Source:* Author).

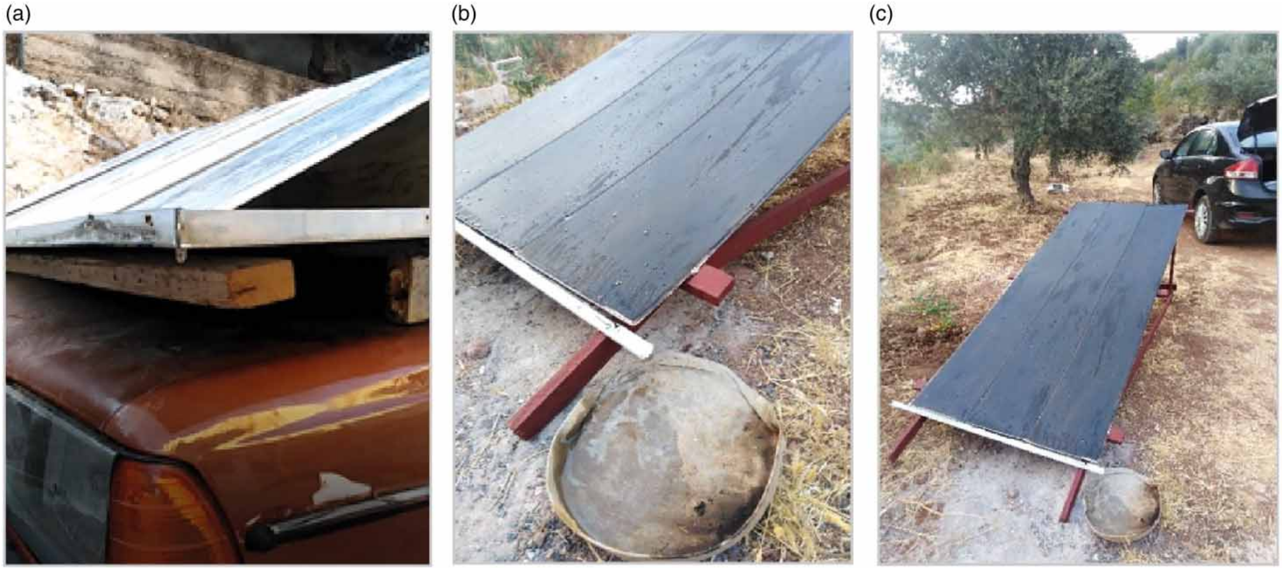


Figure 6 | First experimentations (*Source:* Author).

The prices of prototype creation vary depending on the materials used; in all situations, they would be relatively low if manufactured through an industrial process.

5.4. Tests and measurements

The tests involved determining the efficiency of the system in terms of the amount of water collected. We chose three different sites depending on climatic conditions: Yarmouk University in Irbid (Jordan), which had a hot, mild temperature; the Jordanian University of Science and Technology in Ramtha (Jordan), which had a semi-desert climate; and Rihaba (Jordan), which had a moderate climate. The experiments revealed (see Table 6) the possibility of getting from 800 to 3,000 cL (depending on

Figure 7 | Final prototype construction and testing (*Source:* Author).

Figure 8 | Sample prototype connected directly to the targeted vegetation (*Source:* Author).

Table 6 | Experimentation of the novel collector

Description of test location: Rihaba (in Jordan)

Date	Time	Max daily temperature °C	Min daily temperature in °C	Humidity level (%) at experimentation time	Min temperature to verify the dew point (as in Table 7) in °C	Water quantity harvested (per hour) in mL
10 Jul 21	0:00 am–6:00 am	32	18	90	25.1	2,000
11 Jul 21	0:00 am–6:00 am	31	21	90	25.1	1,800
12 Jul 21	0:00 am–6:00 am	31	21	85	25.1	1,800
13 Jul 21	0:00 am–6:00 am	30	20	85	25.1	1,900
14 Jul 21	0:00 am–6:00 am	29	19	80	25.1	1,600
15 Jul 21	0:00 am–6:00 am	31	21	70	25.1	1,200
16 Jul 21	0:00 am–6:00 am	32	22	65	22.7	600

Source: The Author.

the site location and degree of relative humidity) for a prototype with a 1 m^2 surface when the relative humidity was greater than 70% and the daily temperature was decreased significantly. All selected sites (many of which are in semi-arid zones) experience a significant reduction in daily temperature and, according to Climate and Average Weather in Jordan (2020), have more than 10 nights per month with relative humidity levels above 80%, which are ideal conditions for the operation of this novel collection system. The studies showed that it is possible to collect 800 to 3,000 mL of water overnight, ensuring the sustainability of connected trees and vegetation. Figure 7 depicts the installation of a simple collector version, while Table 7 illustrates the collector surface temperatures in proportion to the degree of humidity required to initiate condensation.

5.5. Prototype costs analysis

The materials used to build experimental prototypes are both inexpensive and widely available. The major materials utilized in these tests are lightweight iron panels that are either painted or made of PVC. These panels are inexpensive, with prices ranging from 10 US dollars per square meter for iron to 5 US dollars per square meter for PVC. These expenses may be reduced more as industrial output increases. The near-zero connection between implementation costs and water output is a notable characteristic of this technology. This is largely because recyclable materials may be used, and the entire procedure is fully passive, needing no energy use.

6. PERSPECTIVES

This project arose from the need to offer a sustainable method of collecting water from alternate sources that might be used in semi-arid and desert zones. We concluded from the data obtained and specialized studies on climatology that dew banks with significant amounts of water brought up are present in these places for many days of the year. According to Jordan's climate and meteorological service records, the presence of verified conditions for condensation of air humidity varies from 7 to 12 days per month from March to November. Media also shows that rainfall occurs in 8 days per month from September to March. In both cases seen, the low quantity of water does not produce any impact on vegetation and trees because the above-mentioned resources evaporate in a short time.

This is a problem in many other geographical areas across the world. These water resources have little economic efficiency to warrant costly investments, thus they are squandered. Any intervention designed to collect this water resource must be low-cost, simple to implement, widely distributed, and require no maintenance. The use of air humidity and condensation is not limited to the dry and semi-arid zones, but can be used in all zones characterized by high relative humidity for a variety of purposes, including irrigation of roof gardens and green walls, and drinking water for people and animals. It can be used to supply water for bees and wild animals in continuous mode by beekeepers and in national parks.

The proposed system can be used in self-organization by final private users due to its low cost and simplicity of design. Users of the suggested system might be private individuals, as shown previously, or public entities, such as national parks,

Table 7 | Dew point index

Dew point index between surfaces and environment temperatures

		Relative humidity (%)									
Surface temperature (°C)		**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**
Environmental temperature (°C)	30	18.4	20.0	21.4	22.7	23.9	25.1	26.2	27.2	28.2	29.1
	29	17.5	19.0	20.4	21.7	23.0	24.1	25.2	26.2	27.2	28.1
	28	16.6	18.1	18.1	19.5	20.8	22.0	23.2	24.3	25.2	26.2
	27	15.7	17.2	18.6	18.9	20.1	21.2	23.3	24.2	25.2	26.1
	26	14.8	16.3	17.6	18.0	19.1	20.3	21.3	23.3	24.2	25.1
	25	13.9	15.3	16.7	17.0	18.2	19.3	19.4	22.3	23.2	24.1
	24	12.9	14.4	15.8	16.1	17.2	18.3	19.4	21.3	22.3	23.2
	23	12.0	13.5	14.8	15.1	16.3	17.4	18.4	20.3	21.3	22.2
	22	11.1	12.5	13.9	14.2	15.3	16.4	17.4	19.4	20.3	21.2
	21	10.2	11.6	12.9	13.2	14.4	15.4	16.5	18.4	19.3	20.0
	20	9.3	10.7	12.0	12.3	13.4	14.5	15.5	17.4	18.3	19.2
	19	8.3	9.8	11.1	11.3	12.5	13.5	14.5	16.4	17.3	18.2

Source: Author elaboration on third information.

and all parties responsible for public greening and desertification. The suggested technology's manufacturing and industrialization allow for the production of stamped panels with acceptable design and materials at very low costs.

Finally, the suggested system is sustainable in every way: it does not require maintenance once placed, operates autonomously every time the condensation conditions are evaluated, and does not require an artificial energy supply. These characteristics are critical because they ensure the survival of trees and vegetation planted in desertification projects, where the main issue is that these trees and vegetation do not survive in the first years due to the current climatic circumstances.

7. CONCLUSIONS

This study culminates in several key findings:

- The valorization of atmospheric water vapor as a universal alternative resource. Its ubiquitous presence around the globe offers a technology platform with broad applications across numerous sectors.
- The inception of a straightforward method that can either serve as a cost-effective and performance-enhanced industrial product or as a simple solution for farmers in areas where industrial products are challenging to procure. This paves the way for many under-resourced regions to capitalize on their own resources.
- The feasibility of using a wide array of materials, including recyclable ones, provides ample flexibility in terms of resource selection.
- The introduction of a zero-carbon-footprint technology. The proposed system operates passively, necessitating no artificial energy.
- The provision of cost savings and the assurance of vegetation survival in self-sustaining conditions requiring minimal maintenance. The components or entire models of this system can be reused in subsequent or future projects.
- The relationship between costs of realization and produced water is near zero. The construction of the proposed irrigation system does not need any specific professional preparation and is available for all.

Our innovative collection system blends technological advancements with traditional features, enhancing efficiency and diffusion rates while curbing costs – a crucial aspect when collaborating with resource-constrained developing countries. The entire system can be locally manufactured and does not demand intricate construction techniques. With no carbon impact, no energy requirement, and all operations guided by natural physical principles, this technology can provide benefits to numerous sectors, including sustainable agriculture, urban landscape greening, roof and vertical gardens. Most importantly, it accomplishes our primary objective of combating desertification and making a positive impact on climate change by designing a technology that is comprehensible and constructible for anyone.

AVAILABILITY OF DATA AND MATERIAL

Data is available on demand.

AUTHORS' CONTRIBUTIONS

The author collected data, realized prototypes, conducted the experimentations, and wrote the research paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The author declare there is no conflict.

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