SYNTHETIC TREES FOR UNDERGROUND WATER EXTRACTION AND PURIFICATION

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Abstract

Synthetic trees, inspired by natural trees, have the capability of renewably extracting and filtering water using the process of transpiration. As water evaporates from nanoporous leaves, a negative pressure is generated, which exerts a hydraulic load across the tree that can be exploited for filtering and elevating water. Here, we engineer synthetic trees that are capable of underground water extraction, purification, and harvesting. Each tree is comprised of five vertical glass tubes attached at the top to a nanoporous ceramic disk. The underground extraction was accomplished by burying the bottoms of the tubes under a wetted soil, where filter elements were attached to the ends of each tube to screen out soil particles. The water was collected above-ground by using a heating element to drive evaporation from the leaf and re-condensing inside of a solar still. These results show that large-scale synthetic trees can be used for renewable water harvesting applications.

Introduction

Water covers about 70% of the planet, but less than 1% is fresh water that can be used for daily activities such as drinking, hygiene, farming, and many others. Especially in areas with harsh climate, water scarcity is a prevalent issue. Many times, a water source is present but is contaminated in some way. Synthetic trees have emerged as a possible solution to this problem, harnessing transpiration to power flow against gravity from a reservoir of liquid or moist soil.

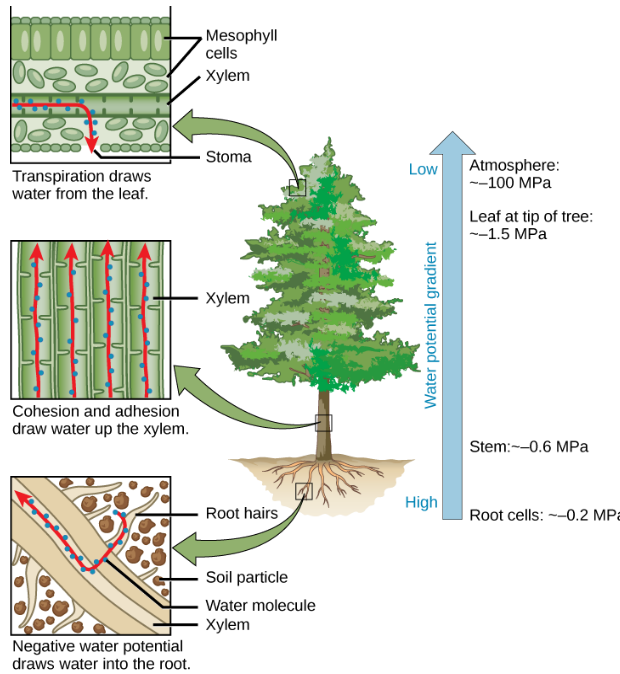

Figure 1. Diagram of transpiration process in natural trees. The water potential gradient from low to high pressure causes the tension in the xylem, which draws water from the roots until it is evaporated through the leaves. Adapted from Lumen.[1]

Transpiration is a process in which water is drawn up the plant or tree and evaporated through the leaves.[1] There is a natural gradient in water saturation between the soil and the atmosphere. The air stands in a subsaturated state, creating tension and pulling the flow of water up through the xylem conduits.[2] This tension within the column of liquid water drives the process. The hydraulic load typically requires anywhere between 10-60 atm of suction to spur the ascent of water based on the species of plant and its surrounding climate.[2]

Inspired by the effective and pumpless transport of water in natural plants, synthetic trees reproduce the transpiration process with engineered materials. The basic components of a synthetic tree include a nanoporous ‘leaf,’ tubing or channels that connect on one end to the nanoporous media, and a reservoir that acts as a water supply.[3] The nanoporous media allows water to pass through it and evaporate into the atmosphere, creating the water-air interface that mimics the stomata in plants. The tubing demonstrates the role of the xylem, acting as a conduit for the water to pass from the root to the leaf. The reservoir is the store from which the water is drawn. The reservoir can be altered to various media as long as there is water for the tree to use. For these experiments, we used moist soil rather than the traditional liquid water.

To date, synthetic trees have either been attached to bulk water reservoirs[4] or micro-well reservoirs[5] bonded to the conduits. It has not yet been shown to extract water from soil, despite this being the dominant mode of water extraction for most natural plants. Additionally, most current synthetic tree models simply evaporate the water from the tree into the environment without any means of collection. To go beyond fundamental curiosities, synthetic trees need to re-condense and collect the water for use. Here, we demonstrate for the first time that we can renewably extract and elevate water from moist soil, analogous to natural trees. Further, we re-condense the transpired vapor in a solar still, for above-ground water harvesting. In essence, we have created a renewable “well” and pump that extracts water from under-ground for above-ground use.

Design Methods

Fabrication of Synthetic Tree

The synthetic tree was comprised of a ceramic disk, glass tubes, and filter caps. The leaf was fabricated by drilling five holes of 6.73 mm diameter and 3.5 mm depth into a nanoporous ceramic disk. The nanoporous disk had a pore radius of r_p = 80 nm, diameter of D = 54 mm (cross-sectional area of A = 22.9 cm^2), and thickness of t = 7 mm. Five glass tubes, each exhibiting an inner diameter of D_i = 4.06 mm and a height of H = 30 cm were set into the recesses using a heat and water-resistant epoxy. The filter caps made up the synthetic root that enabled filtration. Each filter cap consisted of 1 micron stainless steel mesh as the filtration component sandwiched between two aluminum flanges.

Solar Still

Acrylic sheets were cut and bonded together to create a 30 cm x 16 cm x 18 cm right triangular prism shaped solar still. A hinged door was included as part of the bottom face in order to insert the leaf. A hole 52 mm in diameter (i.e., just smaller than that of the leaf), was cut into the bottom face to accommodate the leaf. This hole was cut half into the hinged door and half into the base. One hole 20 mm in diameter was cut into the left face to insert the cord from the band heater. A cold plate was fastened to the top face of the solar still, encouraging the re-condensation of the evaporated water. Two tubes stemming from the chiller cycled a mixture of 75% ethylene glycol and 25% water to maintain a 10 °C temperature.

Soil Reservoir

The reservoir was created by weighing the amount of soil necessary to fill the container

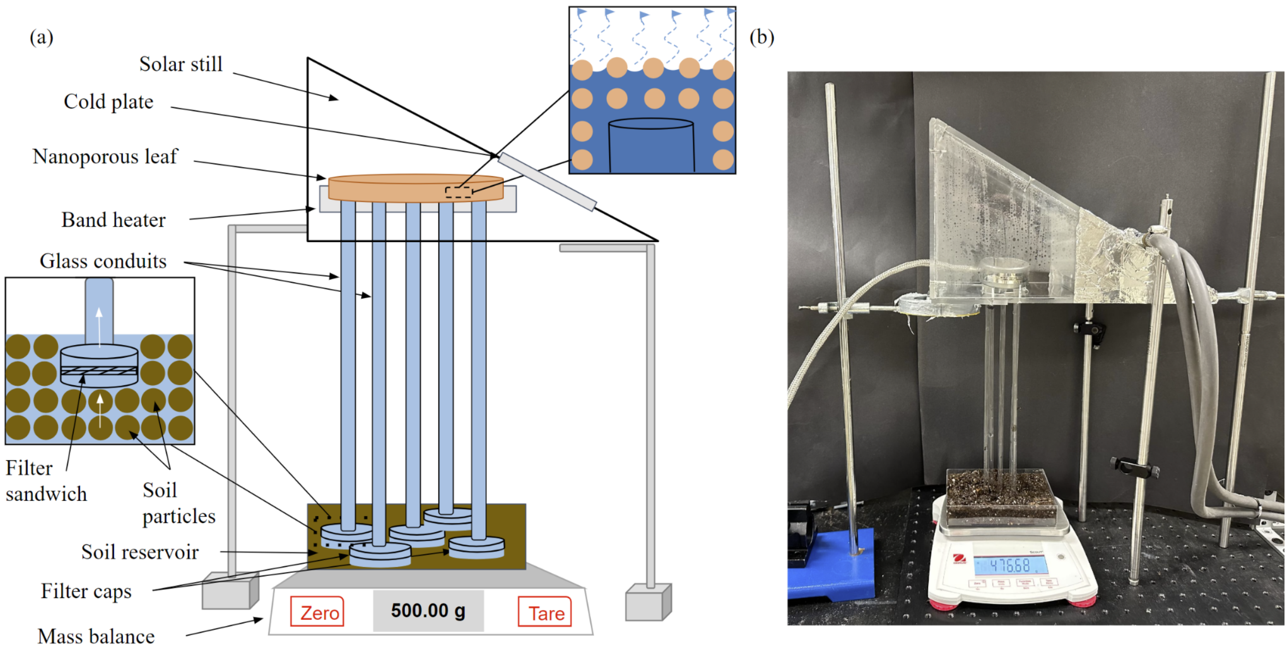

Figure 2. Transpiration powered water extraction and harvesting. **(a)** Diagram and **(b)** photograph of the experimental set up with the roots of the synthetic tree submerged in a soil reservoir and the nanoporous leaf contained in a solar still. The inset in the bottom left of the diagram shows the relative construction and purpose of the synthetic roots, filtering out soil particles from the reservoir. The inset in the top right illustrates how evaporating water from between the nanopores in the leaf creates concave menisci, generating a negative Laplace pressure that causes tension through the conduits.

and using the calculated soil porosity to determine the volume of water needed. Soil porosity, Φ, was determined using:

$$\Phi = \frac{Vp}{Vb} \quad (1)$$

Where Vp is the volume of void space and Vb is the bulk volume of the soil. The trials that have been conducted thus far have used a fully wetted soil.

<u>Experimental Procedure</u>

In preparation for each trial, the tree was boiled and then left to settle for several hours. A pot containing 40 L of distilled water was boiled on an industrial hot plate heated to 260°C for 3h. The synthetic tree was then fully submerged in the boiling pot for at least 1h before cooling overnight. Boiling the tubes ensured that they were filled with degassed water, removing any traces of air in the tree that could have affected the trials. After settling and while still submerged, the filter caps were attached to the bottom of the tubes. The tree was then moved to the experimental setup with the bottom of the tubes constantly submerged in a water reservoir. The band heater was secured around the circumference of the leaf, such that there was constant contact between the heater and leaf. Then, the leaf was inserted into the solar still through the hinged door. The chiller was set to maintain the cold plate at 10 °C and the power supply to the band heater was set to 41.15 V and 0.489 A. Each trial was allowed to proceed for 90 minutes before conclusion.

The transpiration rate as well as the mass of water collected were measured to show the effectiveness of the synthetic tree for water harvesting purposes. A control trial was conducted with the leaf exposed to ambient air to show proof of concept. To date, two complete trials have been performed for the experiment where the leaf was enclosed in the solar still and the reservoir contained fully wetted soil. The mass balance recorded the decrease in the mass of the reservoir at 1 min intervals over the course of each 90 minute trial, which is equivalent to the transpiration mass flow rate. After each trial, the collection tray within the solar still was removed and its mass was recorded.

Results and Future Work

The transpiration rate measured in each experiment is evaporation-limited; it can only be as fast as the evaporation rate from the nanopores. In order to increase the transpiration rate, a band heater was applied to the leaf. The increase in temperature made a visible difference in the amount of mass lost. Figure 3 shows both the amount of transpired and collected water for each trial, where the average transpiration rate of both trials was 2.18×10^{-3} kg/m^2·s across the cross-sectional area of the leaf.

The collection rate of the transpired water was much less than the evaporation rate due to a hole in the solar still located at the entrance site of the synthetic tree. This hole allowed a significant amount of the evaporated water to escape into the surrounding environment rather than condensing in the solar still.

Figure 3. Graph of the transpired and collected mass from the synthetic tree over the course of 90 minute experiments. Trial 1 transpired 30.17 g and collected 4.12 g, and trial 2 transpired 23.86 g and collected 4.18 g of water.

This problem is being addressed for future trials by creating and using a 3D printed plug that fits around the glass tubes and sits over the hole in the solar still. This is expected to drastically increase the collection rate, as the vapor would not be able to escape into the surroundings.

With the addition of the plug, 68.7% of transpired water was collected in the first trial run. This confirmed the hypothesis that better sealing the solar still solved the issue of low vapor-to-liquid conversion efficiency. I hope to show a further increase in collection to 75% as trials are conducted in the future. Referencing the calculated transpiration rate from the initial trials, the goal is to harvest 141.66 kg/m^2·day. Figure 4 shows the first trial conducted with this plug and the dramatic difference in collection from the initial trials, an increase from approximately 15% to 69% collection.

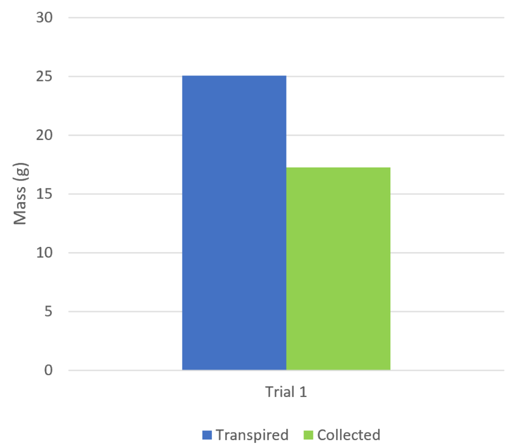

Figure 4. Graph of the transpired and collected mass from the synthetic tree over the course of 90 minute experiments with the addition of the 3D printed plug. Trial 1 transpired 25.08 g and collected 17.24 g of water.

In addition to increasing the collection rate of vapor, I intend to complete trials varying the substrate and saturation of the soil. The current trials have used a fully wetted, natural soil. Future trials will include water-trapping hydrogel beads with no interstitial water, and silica beads, mimicking a synthetic soil.

Here, we have shown the ability of synthetic trees to renewably extract and harvest water. The future trials as well as the ongoing adjustments to current procedures will demonstrate the effectiveness of such tactics and increase the yield of harvested water.

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