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Better understanding of solar water evaporation systems using a biosourced foam and its modelling

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1 **BETTER UNDERSTANDING OF SOLAR WATER**
2 **EVAPORATION SYSTEMS USING A BIOSOURCED**
3 **FOAM AND ITS MODELLING**

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20 **ABSTRACT**

21 A two-dimensional axisymmetric finite element model of a solar evaporator based on a tannin foam
22 has been developed using COMSOL Multiphysics. This model includes a set of boundary
23 conditions and mass transfer within the porous structure. Experiments were conducted to validate
24 the model as the parameters changed over time. Using the model, the effects of light absorption at
25 the surface, water diffusion inside the material, and the thickness of the material and the insulating
26 wall were investigated. We showed that a 38% decrease in evaporation rate was observed when
27 water diffusion does not allow sufficient transport of water to the surface. In addition, an increase
28 in light absorption from 0.8 to 0.9 increases the evaporation performance by 12% and insulation of
29 the exterior does not yield significant changes. A final section of the article focuses on the temporal
30 evolution of water evaporation in several locations around the world. We concluded that hot and
31 dry climates have the highest evaporation potential. Among the cities studied, the highest
32 theoretical evaporation for this biosourced foam was predicted for Dubai, 5342 kg.m⁻², followed
33 by Cairo, 4723 kg.m⁻².

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37 **Keywords:** Simulation; Biosourced material; Solar energy; Solar evaporation; Porous media; Heat
38 and mass transfers

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Nomenclature

a	[-]	Water activity
c_p	[J K ⁻¹ kg ⁻¹]	Heat capacity
D	[m ² s ⁻¹]	Coefficient of diffusion of water inside the material
E	[-]	Emissivity of the material and of the side of the beaker
h_c	[W m ⁻² K ⁻¹]	Heat transfer coefficients
h_v	[kJ.kg ⁻¹]	Enthalpy of vaporisation
H_R	[-]	Relative humidity
k	[m.s ⁻¹]	Convective mass exchange coefficient
M	[kg mol ⁻¹]	Molar mass of water
P	[Pa]	Pressure
$P_{s,0}$	[W.m ⁻²]	Average solar illumination
R	[J mol ⁻¹ K ⁻¹]	Universal gas constant
T	[K]	Temperature
T_{ref}	[K]	Reference temperature

Special characters

ε	[-]	Volume fraction
λ	[W m ⁻¹ K ⁻¹]	Thermal conductivity
φ	[-]	Porosity
ρ	[kg m ⁻³]	Density
η	[-]	Efficiency
σ	[W m ⁻² K ⁻⁴]	Stefan-Boltzmann constant
τ_o	[-]	Tortuosity

Subscripts

a	Ambient
b	Bottom
i	Component i
m	Material
s	Side
sat	Saturation
v	Vaporisation
w	Water
0	Reference

46 **1 INTRODUCTION**

47 Due to global warming, increasing world population and river pollution, drinking water resources
48 will become scarcer in the coming years. By 2050, 3.9 billion people, or more than 40% of the
49 world's population, will be living in watersheds under severe water stress [1]. To solve this
50 problem, in addition to reducing consumption, several complementary approaches could be
51 developed, including storage and/or recovery and treatment of water unsuitable for consumption.

52 One of the water purification strategies is direct evaporation by a passive evaporation system, using
53 solar energy to recover salty and/or polluted water. Indeed, some materials called photothermal,
54 once placed on the surface of water, have the ability to absorb solar energy and accelerate its
55 evaporation, thus transforming between 80 % and 90 % of the solar energy received into water
56 vapour [2]. Water evaporation systems improve evaporation compared to a system without
57 materials and therefore have attracted much attention and a wide variety of materials have been
58 developed [3].

59 Heat transfer is the driving force of the evaporation phenomenon and its study is the key to optimize
60 performance of the evaporation process [4–6]. A water evaporation system consists of a material
61 that has high absorption of light radiation to allow maximum utilisation of the incoming energy. In
62 the literature, three configurations have been proposed. The first configuration consists of an
63 absorbing material placed at the bottom of the water [7,8]. In the second configuration, the material
64 is dispersed in the water as a powder, giving a black tint to the bulk water [2,9]. In the last and most
65 efficient configuration, the material is placed on top of the bulk water. In this case, after absorption
66 of sunlight, the heat must remain at the top of the material, where evaporation occurs, to increase
67 the surface temperature and thus the vapour pressure. To keep the heat at the evaporative surface,
68 thermal insulation is placed between the bulk water and the evaporative material [10]. In this case,

69 thin materials such as cotton or other water transport media can be used to transfer the bulk water
70 to the evaporation interface [11]. Therefore, the thin material is placed on an insulating layer to
71 allow it to float and increase the evaporation rate [12,13]. Alternatively, some materials such as
72 wood show good insulating and water transport properties, and they can be placed in direct contact
73 with bulk water. By using India ink to enhance the sunlight absorption of basswood, a production
74 of $1.6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ under 1 sun illumination was achieved [14]. Another example achieved $1.5 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$
75 under 1 sun illumination with a flame-treated coconut [15]. 3D structures have also been used
76 to increase the exchange area with reported values higher than $10 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ [16,17]. Although
77 numerical simulations have been implemented for solar evaporation systems [18–20], they have
78 been limited to verifying certain aspects of their design, such as temperature distribution, airflow
79 velocity, water diffusion or geometry.

80 Most of the studies reported in the open literature focus on the development of materials from a
81 chemical or structural point of view without addressing the impact of material properties on the
82 overall performance. In order to understand the phenomena undergone and to optimise these
83 systems, a two-dimensional axisymmetric model of a tannin-based foam solar evaporator was
84 developed in a previous study [21], including a set of boundary conditions and water transport in
85 the porous medium. The latter study helped to validate the previously recommended conditions for
86 measuring evaporation performance [22], namely an air temperature of about $25 \text{ }^\circ\text{C}$ and a relative
87 humidity of less than 60 %.

88 The present study utilises the previously used tannin foam with an optimised configuration. In our
89 previous study [21], the foam was placed directly on top of liquid water, whereas here the foam is
90 placed on top of an insulator to limit the downward heat loss and increase the surface temperature
91 of the foam. The previous model has been modified accordingly and is used to study specific
92 material properties, such as sunlight absorption, water transport and thickness of the porous

93 structure and the insulating wall. In a first step, the validation of the model against the experimental
94 data is performed with a cyclic evolution of lighting conditions to simulate the day and night phases
95 and, in a second step, a parametric study is performed on the material properties and the geometry
96 of the system. Finally, a temporal study of evaporation during a summer day for the city of Paris is
97 performed. This is followed by the determination of water evaporation over a full year and the
98 study of the impact of latitude, temperature and relative humidity for several cities around the world
99 using our tannin-derived foam.

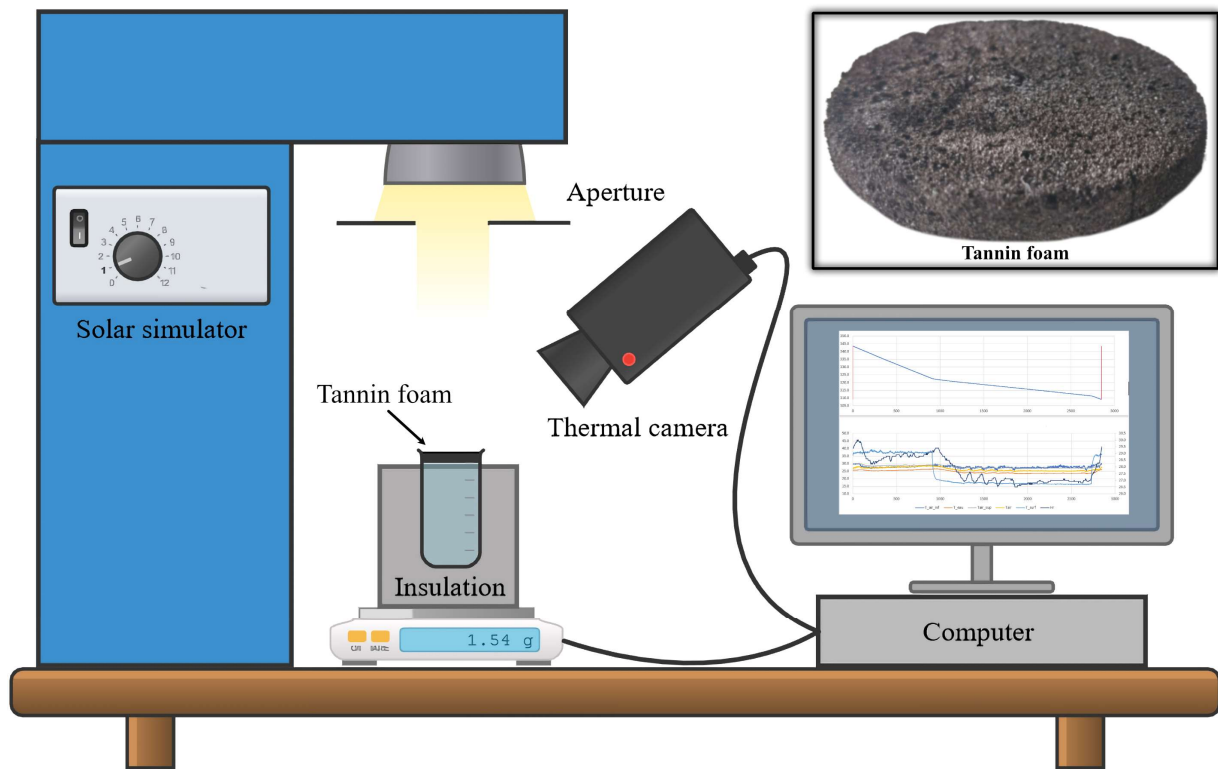
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101 **2 MATERIALS AND METHODS**

102 **2.1 EVAPORATION MATERIAL**

103 The tannin used to produce the foam was extracted from the bark of the mimosa tree (*Acacia*
104 *Mearnsii*) using an industrial process, and the synthesis of the foam from this tannin is described
105 elsewhere [23,24]. The foam was then cut to the appropriate size (58 mm diameter and 2 mm thick)
106 and can be seen in **Figure 1**.

107



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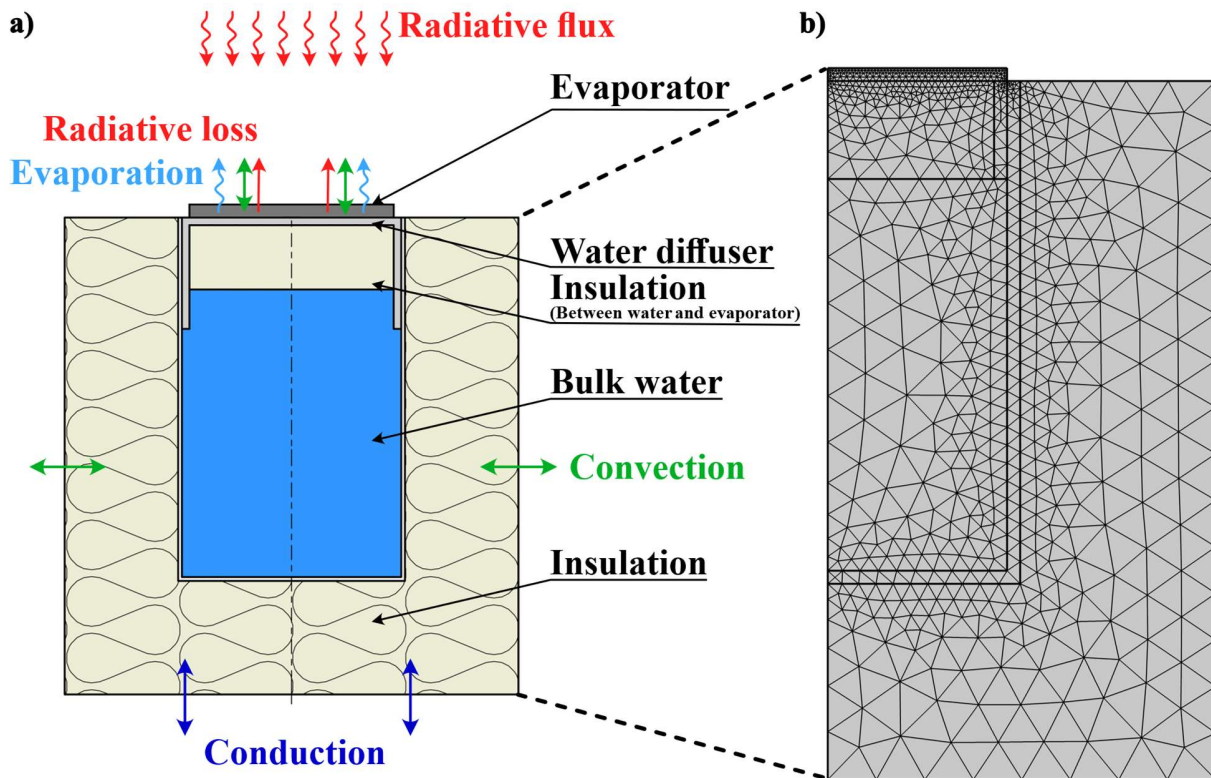
109 **Figure 1.** Experimental setup with a photo of the tannin foam in the upper right frame.

110

111 2.2 EXPERIMENTAL PROTOCOL AND MEASUREMENT METHODS

112 The experiments were conducted using a solar light simulator (SOLAR LIGHT LS-1000) to
 113 illuminate a beaker (60 mm diameter) filled with distilled water: see **Figure 1**. The tannin foam
 114 was on a cotton layer wrapped around a polystyrene foam for insulation between the evaporation
 115 and water surfaces. The system was placed on a Sartorius ENTRIS balance accurate to the
 116 milligram to monitor the overall mass of the system and thus the evaporation rate. In addition, a
 117 thermal camera (OPTRIS PI) pointing to the top of the beaker was used to measure the surface
 118 temperature. Ambient temperature and humidity conditions were also monitored during the
 119 experiment using a sensor placed in the room. The solar simulator was first calibrated to deliver

120 1000 W.m⁻² of solar light and the beaker was wrapped with the insulation layer and filled with
 121 water and, the evaporation system was placed on its surface. It was then positioned on the balance
 122 to record the evolution of the water mass over two six-hour cycles (**Figure 2a**), during which the
 123 sunlight was switched on for the first three hours and off for the last three hours. The evolution of
 124 the mass over time was used to calculate the evaporation rate and to compare the experimental
 125 results to those predicted by the numerical model. The evolution of heat and mass could thus be
 126 followed with the variation of the solar concentration.



127
 128 **Figure 2.** a) Types of heat exchange at the boundaries of the water evaporation system and b)
 129 mesh used for the numerical simulation.

130 The overall system efficiency was calculated using Eq.1.

131
$$\eta = \frac{\dot{m}[h_v + c_{p,v}(T - T_{ref})]}{P_s}$$
 Eq. 1

132 with h_v the vaporisation enthalpy (kJ.kg^{-1}), $c_{p,v}$ the thermal capacity of water vapour ($\text{J.kg}^{-1}.\text{K}^{-1}$), T_{ref} the reference temperature (273.15 K), P_s (W.m^{-2}) the sunlight power on earth per unit area
133 and \dot{m} ($\text{kg.m}^{-2}.\text{h}^{-1}$) the evaporation rate, calculated as follows :

$$135 \quad \dot{m} = \frac{1}{S_i} \int_0^{S_e} F_m dS \quad \text{Eq. 2}$$

136 with S_i (m^2) the projected area that is irradiated by sunlight, S_e (m^2) the evaporation surface and
137 F_m the boundary mass flux calculated later in Eq.10.

138 In the literature, a typical result is an evaporation rate coupled with an efficiency, for a given
139 solar energy concentration. Theoretically, an efficiency of 100 %, knowing that the enthalpy of
140 evaporation of water is 2450 kJ.kg^{-1} (at standard temperature and pressure), gives an evaporation
141 rate \dot{m} of $1.47 \text{ kg.m}^{-2}.\text{h}^{-1}$ for a received solar energy of 1 sun. This represents the theoretical
142 evaporation limit for these conditions, if the material were perfect. It should be noted, however,
143 that this does not take into account the thermal exchanges with the exterior.

144 **2.3 PHYSICAL AND NUMERICAL MODEL**

145 COMSOL 6.0 was used to build a 2D axisymmetric model of the system. Rectangles were used to
146 model the bulk material and water (red and blue in **Figure 2**, respectively). Heat transfers occur in
147 the overall geometry while mass transfers occur only in evaporative material. Boundary conditions
148 at the surface include solar illumination, air convection and water evaporation. Air convection
149 occurs at the sides and conduction occurs at the bottom. All input parameters used for the system
150 simulation are gathered in **Table 1**.

151 **2.3.1 General equations for the evaporative material**

152 The mass transfer was described by the diffusion of water into the material. A transient equation
 153 was used to allow the material to dry out and thus reduce surface evaporation when it is no longer
 154 saturated. This equation was obtained by maintaining liquid water inside the material (Eq. 3).

$$155 \quad \rho_w \frac{\partial \varepsilon_l}{\partial t} + \vec{\nabla} \cdot (\vec{m}_w + \vec{m}_v) = - \frac{\partial(\varepsilon_g \rho_v)}{\partial t} \quad \text{Eq. 3}$$

156 where ε_l is the liquid volume fraction, ε_g is the gas fraction, ρ_w is the density of liquid water (kg.m⁻³)
 157 ³, ρ_v is the density of vapour (kg.m⁻³) and \dot{m}_w and \dot{m}_v are the mass fluxes of water and vapour
 158 (kg.m⁻².s⁻¹), such as :

$$159 \quad \vec{m}_w = -\rho_w D_w \vec{\nabla} \varepsilon_l \quad \text{Eq. 4}$$

$$160 \quad \vec{m}_v = -\rho_g \frac{D_v \varepsilon_g}{\tau_o \varphi} \vec{\nabla} \frac{\rho_v}{\rho_g} \quad \text{Eq. 5}$$

161 where ρ_g is the density of gas defined as a mixing of dry air and vapour at atmospheric pressure
 162 (kg.m⁻³), D_w (m².s⁻¹) is the diffusion coefficient of water in the material, D_v (m².s⁻¹) is the diffusion
 163 coefficient of vapour in the air, φ (dimensionless) is the porosity of the material and τ_o
 164 (dimensionless) the tortuosity of the material.

165 The heat and mass transfer that occurs during the evaporation process was simulated using two
 166 state variables, the temperature, T , and the volume fraction of liquid in the pores, ε_l , with the energy
 167 and mass conservation equations (Eq. 3 and Eq. 6, respectively). The energy associated with mass
 168 transfer was assumed to be negligible due to the very slow kinetics of this phenomenon.

$$169 \quad \rho_m c_{p,m} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\lambda_m \vec{\nabla} T + \vec{m}_w c_{p,w} (T - T_{ref}) + \vec{m}_v [c_{p,v} (T - T_{ref}) + h_v])$$

$$170 \quad = - \frac{\partial(\varepsilon_g \rho_v)}{\partial t} h_v \quad \text{Eq. 6}$$

171 where ρ_m is the density of the material (kg.m^{-3}), $c_{p,m}$ is the thermal capacity of the material ($\text{J.kg}^{-1}.$
172 K^{-1}), λ_m is the thermal conductivity of the material ($\text{W.m}^{-1}.\text{K}^{-1}$), $c_{p,w}$ is the thermal capacity of
173 water ($\text{J.kg}^{-1}.\text{K}^{-1}$), T_{ref} is the reference temperature (273.15 K), $c_{p,v}$ is the thermal capacity of the
174 vapour ($\text{J.kg}^{-1}.\text{K}^{-1}$), h_v is the vaporisation enthalpy (kJ.kg^{-1}) and ρ_v is the density of the vapour
175 (kg.m^{-3})

176 2.3.2 General equations for bulk water, beaker and insulation

177 In the other parts of the system, the beaker, the bulk water and the outer insulation as well as the
178 insulation between the water and the material, there is only heat transfer:

$$179 \rho_i c_i \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\lambda_i \vec{\nabla} T) = 0 \quad \text{Eq. 7}$$

180 where ρ_i is the density (kg.m^{-3}), $c_{p,i}$ is the thermal capacity ($\text{J.kg}^{-1}.\text{K}^{-1}$) and λ_i is the thermal
181 conductivity ($\text{W.m}^{-1}.\text{K}^{-1}$) of the component i (water, beaker or insulation).

182 2.3.3 Boundary conditions

183 At the surface boundary (Eq. 8), the heat exchange takes into account air convection, sunlight
184 radiation and heat loss due to water evaporation. The latter involves the energy required for
185 evaporation (enthalpy of vaporisation of water, h_v in J.kg^{-1}) multiplied by the evaporation rate \dot{m}
186 in $\text{kg.m}^{-2}.\text{h}^{-1}$.

$$187 -\vec{n} \cdot (-\lambda_m \vec{\nabla} T) = h_c (T_a - T) + F_m [c_{p,v} (T - T_{ref}) + h_v] + P_s + E_m \sigma (T_a^4 - T^4) \quad \text{Eq. 8}$$

188 with λ_m ($\text{W.m}^{-1}.\text{K}^{-1}$) the thermal conductivity of the material, h_c ($\text{W.m}^{-2}.\text{K}^{-1}$) the convection
189 coefficient at the surface, T_a (K) the air temperature, E_m (dimensionless) the emissivity of the
190 material and σ ($5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$) the Stefan-Boltzmann constant. $-\vec{n}$ represents the unit vector
191 normal to the boundary.

192 At the upper surface, water evaporation was described by the following equation:

193 $-\vec{n} \cdot (\vec{m}_w + \vec{m}_v) = F_m$ Eq. 9

194 Finally, F_m was deduced from the difference between the water concentration at the material
195 surface and the air and was calculated as follows [25]:

196 $F_m = -k_m \frac{M}{R} \left(\frac{P_w^{v,sat}}{T} a_w - H_R \frac{P_a^{v,sat}}{T_a} \right)$ Eq. 10

197 where M (18×10^{-3} kg.mol⁻¹) is the molar mass of water, R (8.314 J.mol⁻¹.K⁻¹) is the universal gas
198 constant, $P_w^{v,sat}$ (Pa) and $P_a^{v,sat}$ (Pa) are the water vapour pressures at the local temperature, T (K),
199 and at the air temperature, T_a (K), respectively, a_w (dimensionless) is the water activity, H_R (%) is
200 the relative humidity and k_m (m.s⁻¹) is the convective mass exchange coefficient, calculated using
201 the Colburn analogy [26]:

202 $k_m = \frac{h_c}{1000}$ Eq. 11

203 Besides, $P_w^{v,sat}$ and $P_a^{v,sat}$ were calculated from the Clapeyron formula as follows:

204 $P_x^{v,sat} = P_0 \exp \left(\frac{h_v}{R} M \left(\frac{1}{T_0} - \frac{1}{T} \right) \right)$ Eq. 12

205 where P_0 is the reference pressure, 1 atm, and T_0 is the boiling point of water, 373.15 K.

206 The heat exchange between the air and the insulation takes place by convection and radiation:

207 $-\vec{n} \cdot (-\lambda_i \vec{\nabla} T) = h_{c,s}(T_a - T) + E_s \sigma (T_a^4 - T^4)$ Eq. 13

208 where λ_i is either λ_w , λ_b or λ_{im} depending on the location, $h_{c,s}$ (W.m⁻².K⁻¹) is the convection
209 coefficient on the side and E_s (dimensionless) is the emissivity of the beaker side.

210 At the interface between the balance and the bottom of the insulation, only a convective heat flow
211 was assumed:

212 $-\vec{n} \cdot (-\lambda_b \vec{\nabla} T) = h_{c,b}(T_a - T)$ Eq. 14

213 where $h_{c,b}$ (W.m⁻².K⁻¹) is the convection coefficient at the bottom of the beaker.

214 At the interface between the water and the material, as the material was considered saturated, the
 215 liquid fraction was set equal to the porosity, and thermal continuity was assumed.

$$216 \quad \epsilon_l = \varphi \quad \text{Eq. 15}$$

217 where φ is the porosity of the material.

218 The calculated variables, T and ϵ_l , were obtained by using the commercial software COMSOL
 219 Multiphysics 6.0. A mesh consisting of 1517 elements was used (**Figure 2b**) to model the entire
 220 system (beaker, insulation foams, water and evaporation material). The evaporating surface area
 221 was divided into smaller elements to have a better accuracy, and 59 elements were used for this
 222 purpose. The rest of the mesh was created automatically by the software, depending on the physics
 223 involved. An internal parametric study on the number of mesh elements was performed. The mesh
 224 presented here offers the most interesting compromise between simulation time and calculation
 225 accuracy. Using a desktop computer with two Xeon Silver 4214R CPUs (24 cores) combined with
 226 256 GB of RAM, the model was computed in 48 seconds.

227 Table 1. Input parameters used in the simulation.

Symbols	Definitions	Units	Values
$\lambda_w, \lambda_s, \lambda_a,$ λ_{im}, λ_b	Thermal conductivities of water, skeleton of the evaporation material, air, insulating material and beaker	$\text{W m}^{-1} \text{K}^{-1}$	0.6, 0.32, 0.0262, 0.043, 1.38
φ	Porosity of the evaporation material	-	0.955
$c_{p,w}, c_{p,v}, c_{p,s},$ $c_{p,im}, c_{p,b}$	Heat capacities of water, vapour, evaporation material, insulating material and beaker	$\text{J K}^{-1} \text{kg}^{-1}$	4180, 1890, 1800, 871, 703
D_w	Coefficient of diffusion of water inside the material	$\text{m}^2 \text{s}^{-1}$	10^{-8}
D_v	Coefficient of diffusion of vapour in the air	$\text{m}^2 \text{s}^{-1}$	2.82×10^{-5}
ρ_w, ρ_s, ρ_i	Density of water, skeleton density of the evaporation material and bulk density of the insulating material	kg m^{-3}	1000, 1550, 30
σ	Stefan-Boltzmann constant	$\text{W m}^{-2} \text{K}^{-4}$	5.67×10^{-8}

R	Universal gas constant	$\text{J mol}^{-1} \text{K}^{-1}$	8.314
M	Molar mass of water	kg mol^{-1}	0.01801
P_0	Standard pressure	Pa	101325
T_0	Boiling point of water	K	373.15
T_a	Air temperature	K	293.15
T_{ref}	Reference temperature	K	273.15
$h_c, h_{c,b}$	Heat transfer coefficients at the surface and the bottom	$\text{W m}^{-2} \text{K}^{-1}$	10, 1
E_m	Emissivity of the material	-	1
H_r	Relative humidity	-	0.5
τ_o	Tortuosity	-	1.3

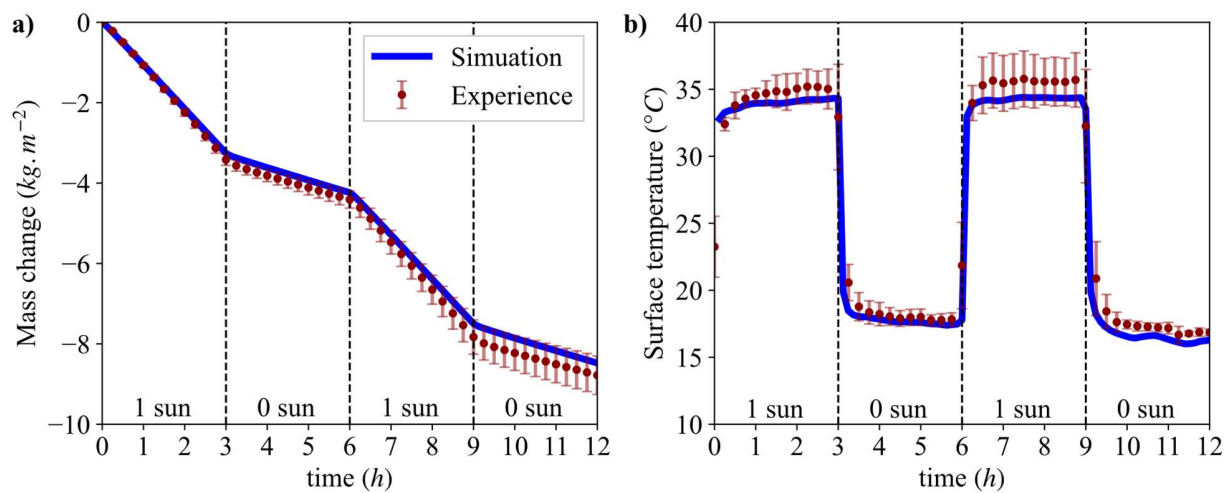
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229 3 RESULTS AND DISCUSSION

230 3.1 MODEL VALIDATION

231 In order to validate the model, experiments were conducted and the ambient conditions of these
 232 experiments (T_a and H_r) were set as parameters in the simulation. **Figure 3** shows the simulated
 233 and experimental results of the temperature, measured at the evaporation surface, as well as the
 234 simulated and experimental evolution of the water mass of over time.

235 During the first phase of illumination, the evaporation rate is $1.17 \text{ kg.m}^{-2}.\text{h}^{-1}$ and the average surface
 236 temperature reaches 35°C after the three-hour period. During the second period, when the sunlight
 237 is switched off, the evaporation rate is $0.34 \text{ kg.m}^{-2}.\text{h}^{-1}$ and the average surface temperature after
 238 three hours is about 18°C . Overall, the cycles are well visible and the simulation fits for the
 239 evolution of the water mass well. The calculated surface temperature shows a slight difference,
 240 which is due to temperature variations. We can therefore validate the model and conclude that it
 241 can be used to simulate the behaviour of the evaporation system over time.



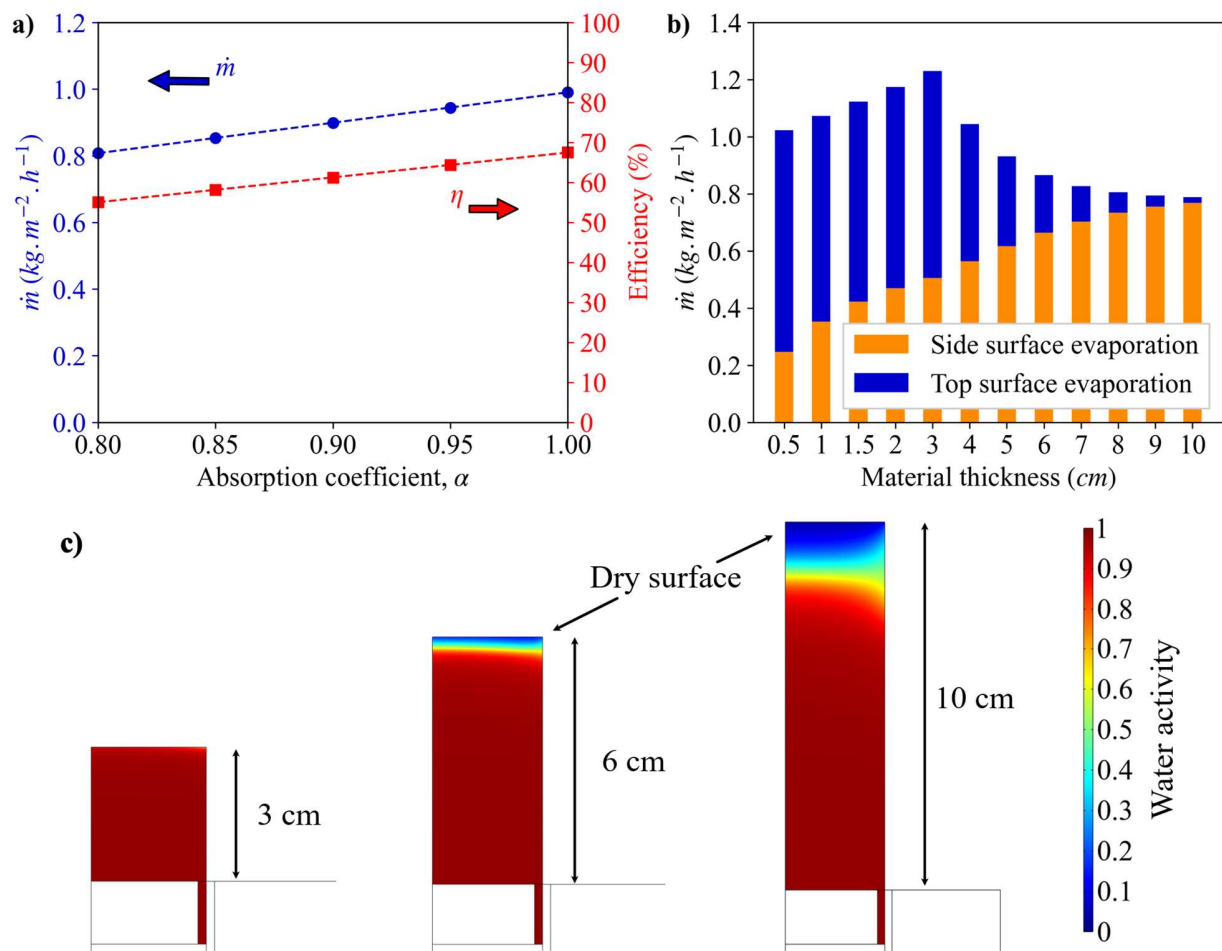
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 243 **Figure 3.** (a) Experimental (red dots) and simulated (blue line) mass changes, and (b)
 244 experimental (red dots) and simulated (blue lines) surface temperature for a 12h experiment with
 245 alternating periods of sunlight and darkness of 3 hours each.

246 3.2 PARAMETRIC STUDY

247 3.2.1 Solar flux absorption coefficient

248 One parameter that can vary depending on the type of material is the absorption of sunlight by its
 249 surface. Typically, materials achieve absorption values above 95% for maximum solar energy
 250 utilisation [2,27,28]. A parametric study was conducted to investigate the impact of this parameter
 251 on performance.

252 **Figure 4a** shows the evaporation rate and efficiency as a function of surface absorption of sunlight.
 253 A gain of 0.1 in sunlight absorption results directly in a gain of $0.1 \text{ kg.m}^{-2}.\text{h}^{-1}$ in evaporation rate
 254 and 5% in efficiency. This represents a loss of evaporation performance of 11%, which means that
 255 the improvement in surface absorption makes sense.



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261 3.2.2 Thickness of the porous structure

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Figure 4. (a) Simulated evaporation rate and efficiency for different solar flux absorption coefficients; and (b) simulated top and lateral evaporation rates for different values of porous structure thickness. (c) Simulated maps of water activity in the foam for three different heights (3 cm, 6 cm and 10 cm).

Some types of materials allow for different thicknesses to be chosen during manufacture. Wood, for instance, can be set to a certain thickness [29], while a lotus leaf has a fixed thickness [11,30]. For a material with a controlled thickness (wood, foam etc.), there is an optimal value for its use as an evaporation material. **Figure 4b** shows the simulated evaporation rate and efficiency as a

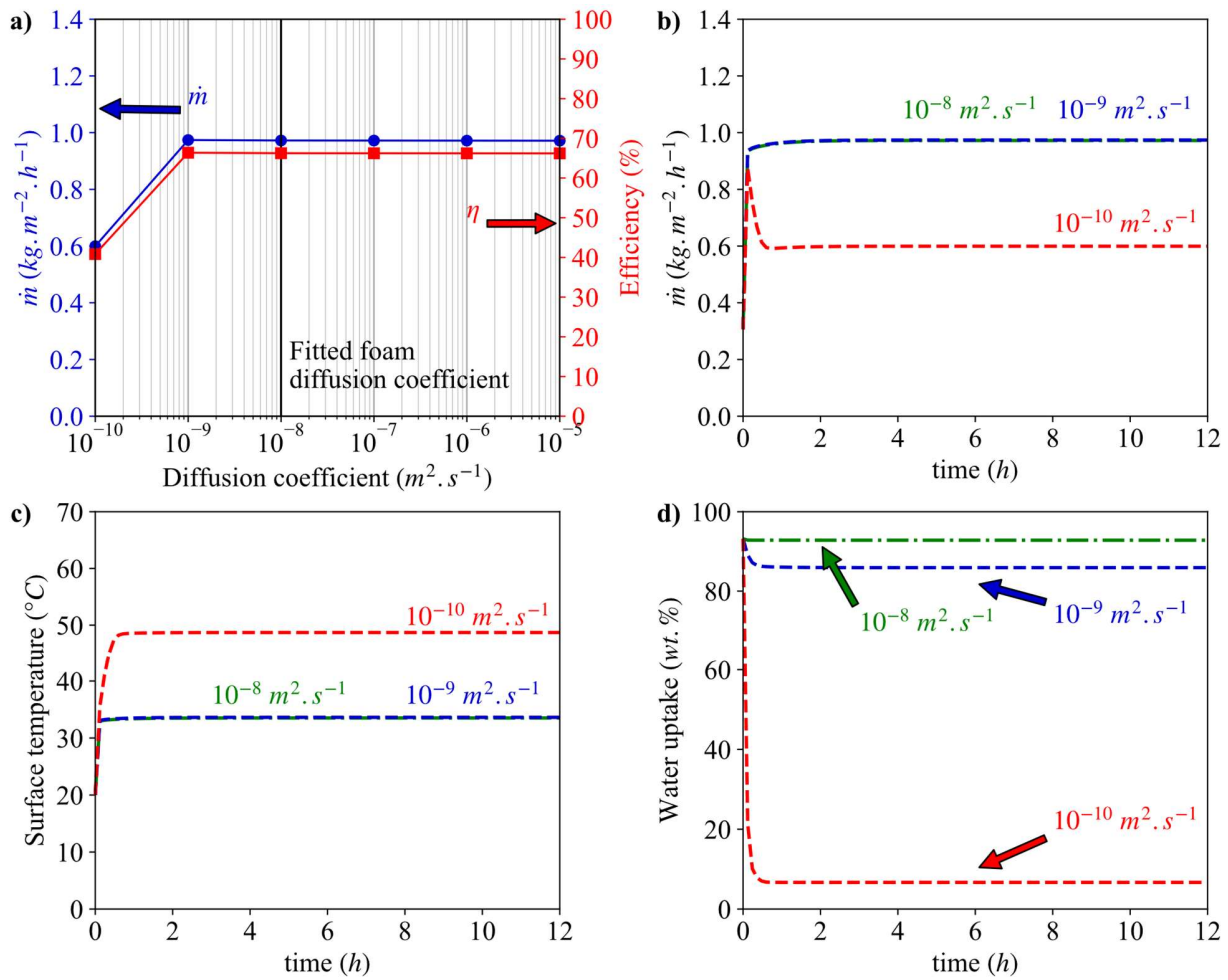
266 function of thickness, from half a centimetre to several centimetres. Overall, the evaporation rate
267 increases with the material thickness, but a local maximum can be seen at 3 cm. This is due to the
268 fact that, with increasing material height, water transport starts to be a limiting factor. In addition,
269 the thicker the foam, the higher the evaporation area. Thus, until water transport becomes a limiting
270 factor, the evaporation rate increases. For thicknesses greater than 3 cm, water transport is limited,
271 so that only lateral evaporation increases until a maximum is reached and water can no longer
272 progress through the foam. However, this does not increase the overall evaporation rate since the
273 evaporation rate at the surface decreases with thickness This is clearly visible in **Figure 4c** for the
274 6 cm and 10 cm cases. The water activity at the surface is low, meaning that the surface is dry. For
275 3 cm, the water activity is still close to 1, so evaporation is still possible. The increase in evaporation
276 with thickness up to a certain point correlates with recent studies that have been conducted to
277 harness the maximum transportability of water [16].

278 **3.2.3 Diffusion coefficient of liquid water**

279 Diffusion within the evaporative material is essential, because even if energy management at the
280 surface is effective, insufficient water will prevent evaporation from occurring, as it has been
281 shown in 3.2.2. To simulate the unavailability of water at the surface, a parametric study of the
282 water diffusion coefficient within the porous structure was conducted.

283 **Figure 5a** shows the results of the evaporation rate and efficiency as a function of the diffusion
284 coefficient. Little change is visible when water transport is sufficient (above 10^{-9} m.s⁻¹). However,
285 below this value of diffusion coefficient, the evaporation rate is strongly impacted by the limited
286 water transport, decreasing from 1.0 kg.m⁻².h⁻¹ to 0.6 kg.m⁻².h⁻¹ for a diffusion coefficient of 10^{-9}
287 m.s⁻¹ and 10^{-10} m.s⁻¹, respectively. This phenomenon can be explained by the fact that, with a low
288 diffusion coefficient, the water does not reach the surface (**Figure 5d**), resulting in a decrease in

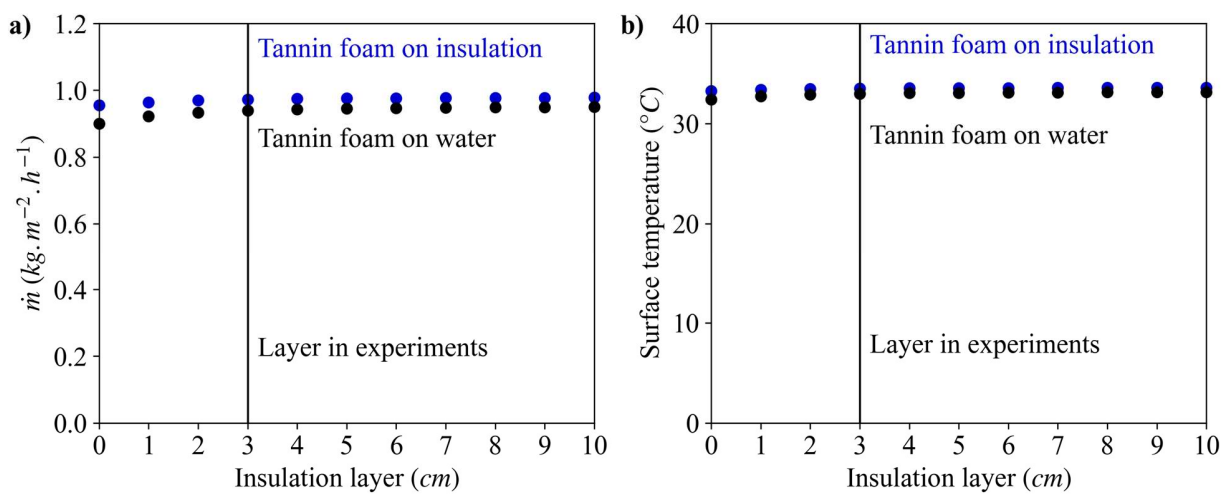
289 evaporated flux (**Figure 5b**) and an increase in surface temperature (**Figure 5c**). After 2 hours, the
 290 surface of the foam is completely dry for a diffusion coefficient of less than $10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$, while the
 291 water uptake stabilises at 86%, which still allows water to reach the surface, for a coefficient of 10^{-9}
 292 $\text{m}^2 \cdot \text{s}^{-1}$.



293
 294 **Figure 5. (a)** Simulated evaporation rate and efficiency for different values of water diffusion
 295 coefficient; and (b) transient evolution of evaporation rate; (c), surface temperature; and (d) water
 296 uptake for different values of the water diffusion coefficient.

297 **3.2.4 Thickness of the insulating wall**

298 Since external conditions affect evaporation performance [21], it may be worthwhile to add a layer
299 of insulating foam to focus on studying the performance of the material at the surface where
300 evaporation occurs. **Figure 6a** shows the performance of the system as a function of the thickness
301 of the insulating foam, with a thermal conductivity of $0.043 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, around the beaker. The
302 evaporation rate increases until it stabilises at about $1.04 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, which represents a 4% increase
303 compared to the system without thermal insulation. This is due to the fact that energy is no longer
304 lost through the sides of the material, which increases the surface temperature and thus the
305 evaporation rate (**Figure 6b**). However the increase is minimal compared to a previous study [21],
306 because an additional insulating layer is used between the water and the evaporating material.
307 Exchanges through the side of the beaker are carried out with already insulated bulk water.



308
309 **Figure 6.** (a) Evaporation rate and efficiency; and (b) surface temperature as a function of the
310 thickness of the insulation around the beaker (0 cm is the case without insulation, and the vertical
311 line represents the case for a 3 cm insulating layer, used in the experiment).

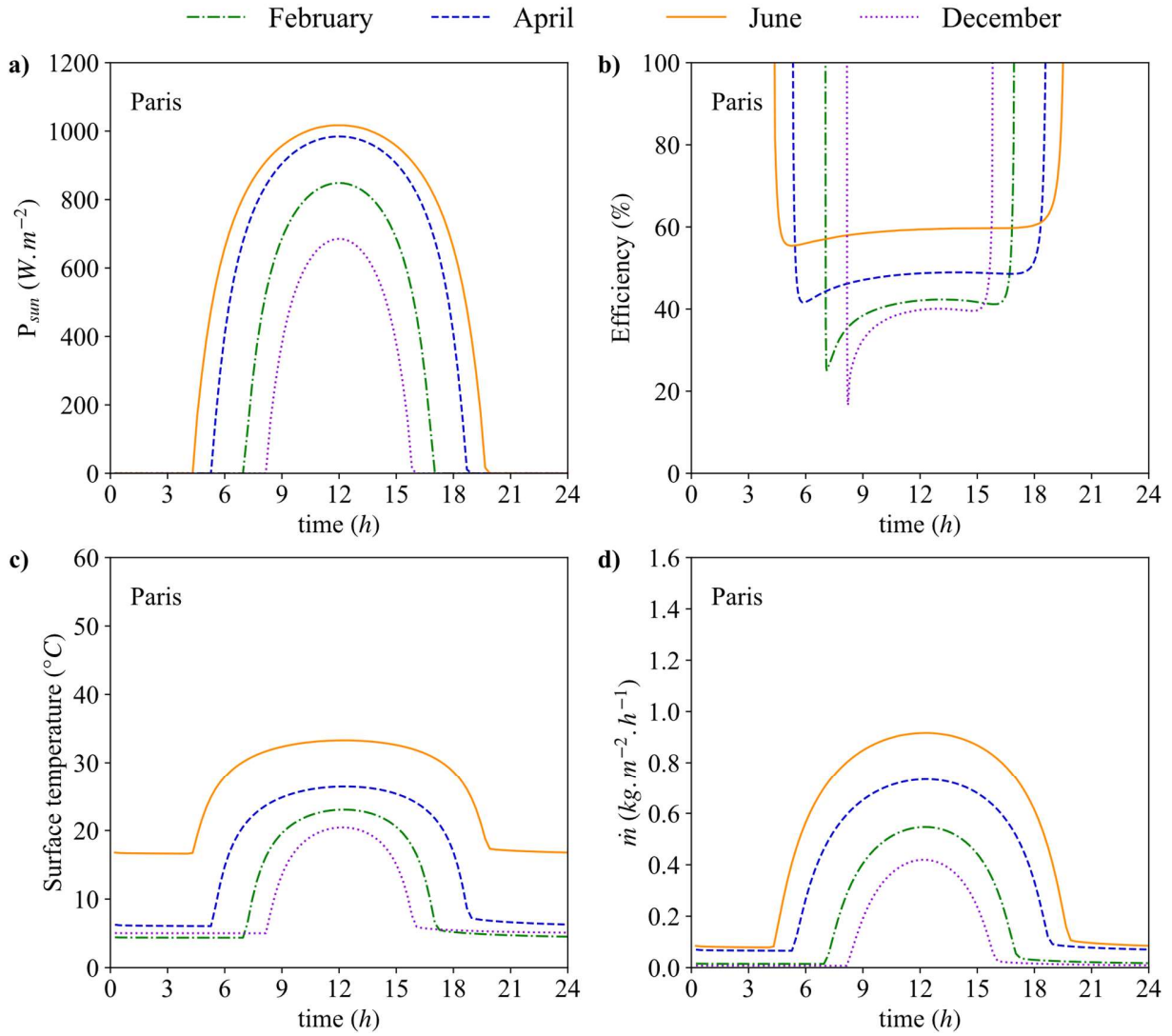
312 **3.3 Water evaporation potential**

313 In the literature, experimental measurements are performed in a controlled environment with
314 constant simulated solar radiation, or outdoors in a chamber (or under a bell jar or in a solar still)
315 subjected to solar radiation that varies throughout the day. This section proposes to simulate the
316 behaviour of the evaporator illuminated by real solar radiation and to estimate the potential water
317 evaporation of this system if it were located in large cities in the northern hemisphere.

318 **3.3.1 Temporal evolution in Paris**

319 **Figure 7** shows the evolution of solar radiation, efficiency, surface temperature and evaporation
320 rate for four 21st of the month, from winter to summer solstice. Sunshine data from Paris (France
321 – Latitude 48°51'12") were used [31] as well as air temperature and humidity data throughout 2021
322 [32]. As expected, the evaporation rate increases with solar radiation. It should be noted that a
323 phase shift is observed between the solar radiation and the evaporated flux. Indeed, the maximum
324 evaporation does not occur at the time when the solar flux is the most important, the maximum is
325 at 13h for evaporation while the solar flux is maximum at 12h. It should be noted that solar time is
326 considered here, i.e., for which the sun is at its zenith at noon. Considering the calculation of the
327 efficiency (Eq. 1), the value calculated at the beginning and end of the day is inconsistent because
328 it implies a sunshine close to 0. Nevertheless, an overall increase in efficiency is observable during
329 the day and is maximal in the afternoon (**Figure 7b**). The increase in efficiency at the beginning
330 and end of the day can be explained by Eq. 1, which shows a decreasing illumination until it reaches
331 zero, thus mathematically increasing the efficiency value. This phenomenon and the observed
332 phase shift are due to the temperature at the evaporation surface increasing with the concentration
333 of solar radiation (**Figure 7a**) and the thermal energy stored in the material (**Figure 7c**), which

334 enhances evaporation (Eq. 10 and Eq. 12). The total potential evaporation on a summer day (21st
 335 June) is 12 L per m² of the present tannin foam.



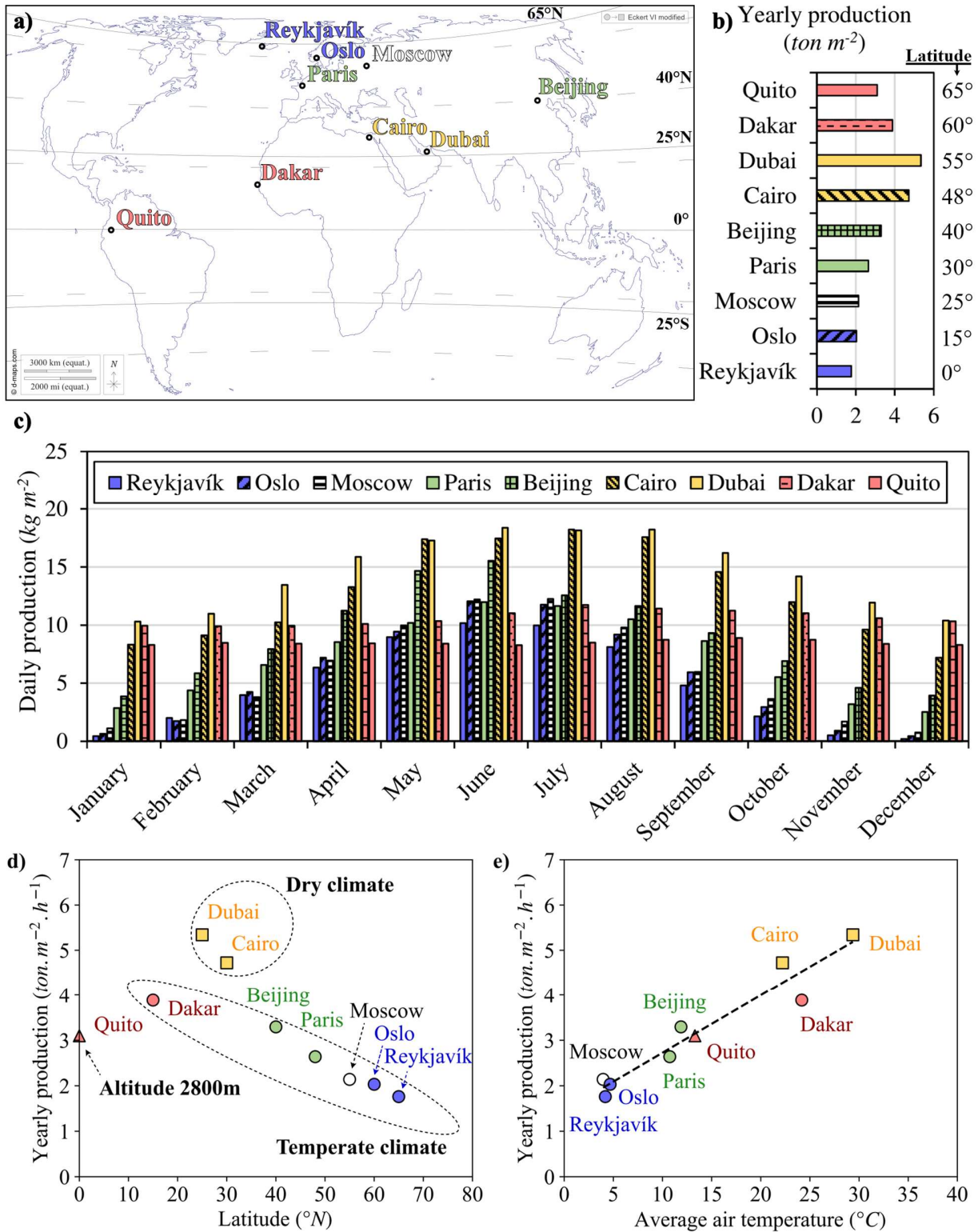
336
 337 **Figure 7.** (a) Simulated hourly evolution of solar radiation; (b) efficiency; (c) surface temperature
 338 and (d) evaporation rate in Paris (France – Latitude 48°51'12"). Four 21st of the month were
 339 selected over the year: December, February, April, June.

340 3.3.2 Annual potential water evaporation for different locations on earth

341 **Figure 8** shows the annual and monthly evaporation per unit area simulated for different locations
342 on the planet. In these calculations, direct radiation is changed as well as local air temperature and
343 humidity, taken throughout the year [32]. The monthly calculation was made for a typical day
344 corresponding to the 21st of the month in order to take into account the summer and winter solstices.
345 The annual calculation was performed by summing the evaporated quantities of all months of the
346 year, the monthly value being considered constant. The monthly results show significant variations
347 with the latitude of the city studied. Indeed, cities located near the poles show almost no
348 evaporation during winter and evaporation close to other latitudes during the summer, since the
349 sun shines almost all day in Reykjavik in summer time, for example (**Figure 9a**). On the contrary,
350 cities located near the equator offer similar evaporation performance all year round, about 8.5 kg.m^{-2}
351 ² for Quito from December to June, which is due to the constant illumination throughout the year
352 (**Figure 9g**). Indeed, between the northernmost capital city, Reykjavík, and a city located on the
353 equator, Quito, there is a 76% increase in annual evaporation. However, evaporation is not only
354 related to latitude, as local ambient conditions, relative humidity and temperature also have a
355 significant impact on evaporation, as has been shown previously [21]. Dubai, for instance, is
356 located 25° north of Quito and has a 72% higher annual evaporation, which is due to the fact that
357 the local air is much drier and the average temperature is higher throughout the year, as shown in
358 **Figure 9e** and **Figure 9h**.

359 In **Figure 8b**, we can observe that the simulated annual freshwater production increases at low
360 latitudes with an arid climate, with the highest theoretical evaporation located in Dubai with 5342
361 kg.m^{-2} , followed by Cairo with 4723 kg.m^{-2} . For the other cities selected, Beijing, Paris or Moscow,
362 evaporation decreases with latitude. **Figure 8d** shows that the annual amount of water produced is

363 not directly linear with latitude, as warmer climates have higher evaporation values compared to
364 the trend observed for other cities as a function of latitude. This Figure shows that there can be a
365 dispersion in the amount of water recovered for the same latitude. **Figure 8e** shows that the main
366 factor impacting on the amount of water produced is temperature with a linear trend with the annual
367 average temperature and therefore with the climate.

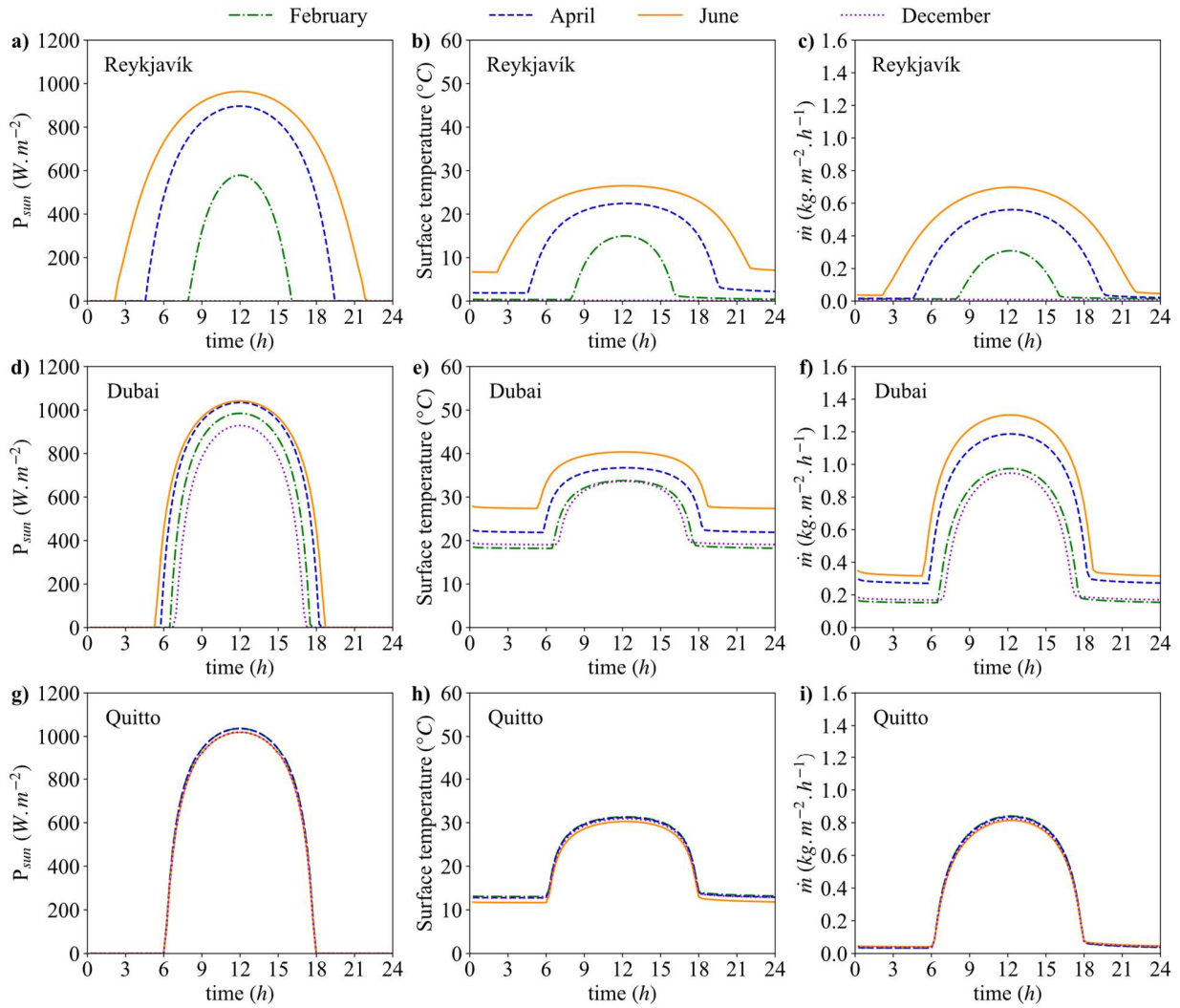


368

369 **Figure 8.** (a) Map [33] of locations used to estimate simulated (b) yearly and (c) monthly

370 evaporation per unit area over the planet (air temperature and relative humidity are set to local

371 values throughout the year [32]); simulated annual water production as a function of (d) latitude
 372 and climate: Dry climate, Dubai and Cairo, \square ; High altitude climate, Quito, \triangle , and Temperate
 373 Climate, all others \circ (colours as in a); and of (e) the average air temperature the for the cities
 374 studied.



375
 376 **Figure 9.** Simulated evolution of: (a), (d) and (g) solar radiation; (b), (e) and (h) surface
 377 temperature; and (c), (f) and (i) evaporation rate in Reykjavik (top), Dubai (middle) and Quito
 378 (bottom).
 379

380 **4 Conclusions**

381 Using a two-dimensional axisymmetric model that was validated for temperature and water mass
382 changes as a function of time, several phenomena were explored. These included the effect of three
383 material properties: water diffusion coefficient, material thickness and surface light absorption
384 coefficient. Foam thickness, diffusion coefficient and light absorption have been shown to be key
385 factors. By increasing the area available for evaporation, thickness directly increases the
386 performance until the material can no longer diffuse water. The diffusion coefficient allows for the
387 presence of liquid water, because if it is too low, not enough water can be transported to the surface,
388 and light absorption improves energy consumption and therefore performance. The study of the
389 thickness of insulation around the measuring system shows that evaporation is no longer improved
390 above a certain thickness and that the presence of insulation between the bulk water and the
391 evaporation surface decreases the usefulness of the added insulating layer around the beaker.

392 A typical summer day in Paris was also evaluated, and we show that the theoretical potential
393 amount of water evaporated would be 12 L per m² of foam area, using the (non-optimised) rigid
394 foam used here to validate the model. The simulated evolution of the evaporation rate at different
395 locations of the planet shows that latitude has a significant impact on the performance in winter.
396 Ambient temperature and humidity conditions also play a major role in evaporation performance.
397 Dubai, for instance, is located 25° north of Quito and has 72% higher annual evaporation, which is
398 due to the fact that the local air is much drier and the average temperature is higher throughout the
399 year.

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405 REFERENCES

- 406 [1] C. Chen, Y. Kuang, L. Hu, Challenges and Opportunities for Solar Evaporation, *Joule*. 3
407 (2019) 683–718. <https://doi.org/10.1016/j.joule.2018.12.023>.
- 408 [2] P. Zhang, Q. Liao, H. Yao, Y. Huang, H. Cheng, L. Qu, Direct solar steam generation system
409 for clean water production, *Energy Storage Materials*. 18 (2019) 429–446.
410 <https://doi.org/10.1016/j.ensm.2018.10.006>.
- 411 [3] F. Zhao, Y. Guo, X. Zhou, W. Shi, G. Yu, Materials for solar-powered water evaporation, *Nat*
412 *Rev Mater.* (2020) 1–14. <https://doi.org/10.1038/s41578-020-0182-4>.
- 413 [4] S. Meng, X.-J. Zha, C. Wu, X. Zhao, M.-B. Yang, W. Yang, Interfacial Radiation-Absorbing
414 Hydrogel Film for Efficient Thermal Utilization on Solar Evaporator Surfaces, *Nano Lett.* 21
415 (2021) 10516–10524. <https://doi.org/10.1021/acs.nanolett.1c04066>.
- 416 [5] Hierarchically structured evaporator with integrated water supply and evaporation layers to
417 retard salt accumulation - ScienceDirect, (n.d.). [https://www-sciencedirect-com.bases-](https://www-sciencedirect-com.bases-doc.univ-lorraine.fr/science/article/pii/S0017931021015453?dgcid=rss_sd_all)
418 [doc.univ-lorraine.fr/science/article/pii/S0017931021015453?dgcid=rss_sd_all](https://www-sciencedirect-com.bases-doc.univ-lorraine.fr/science/article/pii/S0017931021015453?dgcid=rss_sd_all) (accessed
419 March 28, 2022).
- 420 [6] Md.N.A.S. Ivan, A.M. Saleque, S. Ahmed, P.K. Cheng, J. Qiao, T.I. Alam, Y.H. Tsang,
421 Waste Egg Tray and Toner-Derived Highly Efficient 3D Solar Evaporator for Freshwater
422 Generation, *ACS Appl. Mater. Interfaces*. 14 (2022) 7936–7948.
423 <https://doi.org/10.1021/acsami.1c22215>.
- 424 [7] V.K. Dwivedi, G.N. Tiwari, Experimental validation of thermal model of a double slope
425 active solar still under natural circulation mode, *Desalination*. 250 (2010) 49–55.
426 <https://doi.org/10.1016/j.desal.2009.06.060>.
- 427 [8] J.T. Mahdi, B.E. Smith, A.O. Sharif, An experimental wick-type solar still system: Design
428 and construction, *Desalination*. 267 (2011) 233–238.
429 <https://doi.org/10.1016/j.desal.2010.09.032>.
- 430 [9] S.K. Hota, G. Diaz, Activated carbon dispersion as absorber for solar water evaporation: A
431 parametric analysis, *Solar Energy*. 184 (2019) 40–51.
432 <https://doi.org/10.1016/j.solener.2019.03.080>.
- 433 [10] H. Li, S. Wang, Z. Yan, X. Niu, X. Sun, W. Hong, Harvesting conductive heat loss of
434 interfacial solar evaporator for thermoelectric power generation, *Applied Thermal*
435 *Engineering*. 208 (2022) 118279. <https://doi.org/10.1016/j.applthermaleng.2022.118279>.
- 436 [11] Y. Liao, J. Chen, D. Zhang, X. Wang, B. Yuan, P. Deng, F. Li, H. Zhang, Lotus leaf as solar
437 water evaporation devices, *Materials Letters*. 240 (2019) 92–95.
438 <https://doi.org/10.1016/j.matlet.2018.12.133>.
- 439 [12] N. Xu, X. Hu, W. Xu, X. Li, L. Zhou, S. Zhu, J. Zhu, Mushrooms as Efficient Solar Steam-
440 Generation Devices, *Advanced Materials*. 29 (2017) 1606762.
441 <https://doi.org/10.1002/adma.201606762>.
- 442 [13] X. Li, W. Xu, M. Tang, L. Zhou, B. Zhu, S. Zhu, J. Zhu, Graphene oxide-based efficient and
443 scalable solar desalination under one sun with a confined 2D water path, *PNAS*. 113 (2016)
444 13953–13958. <https://doi.org/10.1073/pnas.1613031113>.

- 445 [14] X.-F. Zhang, Z. Wang, L. Song, Y. Feng, J. Yao, Chinese ink enabled wood evaporator for
446 continuous water desalination, *Desalination*. 496 (2020) 114727.
447 <https://doi.org/10.1016/j.desal.2020.114727>.
- 448 [15] J. Li, X. Zhou, G. Chen, F. Wang, J. Mao, Y. Long, H. Sun, Z. Zhu, W. Liang, A. Li,
449 Evaporation efficiency monitoring device based on biomass photothermal material for salt-
450 resistant solar-driven interfacial evaporation, *Solar Energy Materials and Solar Cells*. 222
451 (2021) 110941. <https://doi.org/10.1016/j.solmat.2020.110941>.
- 452 [16] C.T.K. Finnerty, A.K. Menon, K.M. Conway, D. Lee, M. Nelson, J.J. Urban, D. Sedlak, B.
453 Mi, Interfacial Solar Evaporation by a 3D Graphene Oxide Stalk for Highly Concentrated
454 Brine Treatment, *Environ. Sci. Technol.* 55 (2021) 15435–15445.
455 <https://doi.org/10.1021/acs.est.1c04010>.
- 456 [17] Y. Xu, J. Xu, J. Zhang, X. Li, B. Fu, C. Song, W. Shang, P. Tao, T. Deng, All-in-one polymer
457 sponge composite 3D evaporators for simultaneous high-flux solar-thermal desalination and
458 electricity generation, *Nano Energy*. 93 (2022) 106882.
459 <https://doi.org/10.1016/j.nanoen.2021.106882>.
- 460 [18] Y. Wang, X. Wu, P. Wu, J. Zhao, X. Yang, G. Owens, H. Xu, Enhancing solar steam
461 generation using a highly thermally conductive evaporator support, *Science Bulletin*. 66
462 (2021) 2479–2488. <https://doi.org/10.1016/j.scib.2021.09.018>.
- 463 [19] F. Zhao, X. Zhou, Y. Shi, X. Qian, M. Alexander, X. Zhao, S. Mendez, R. Yang, L. Qu, G.
464 Yu, Highly efficient solar vapour generation via hierarchically nanostructured gels, *Nature*
465 *Nanotech.* 13 (2018) 489–495. <https://doi.org/10.1038/s41565-018-0097-z>.
- 466 [20] A.K. Menon, I. Haechler, S. Kaur, S. Lubner, R.S. Prasher, Enhanced solar evaporation using
467 a photo-thermal umbrella for wastewater management, *Nat Sustain.* 3 (2020) 144–151.
468 <https://doi.org/10.1038/s41893-019-0445-5>.
- 469 [21] R. Fillet, V. Nicolas, V. Fierro, A. Celzard, Modelling heat and mass transfer in solar
470 evaporation systems, *International Journal of Heat and Mass Transfer*. 181 (2021) 121852.
471 <https://doi.org/10.1016/j.ijheatmasstransfer.2021.121852>.
- 472 [22] X. Li, G. Ni, T. Cooper, N. Xu, J. Li, L. Zhou, X. Hu, B. Zhu, P. Yao, J. Zhu, Measuring
473 Conversion Efficiency of Solar Vapor Generation, *Joule*. 3 (2019) 1798–1803.
474 <https://doi.org/10.1016/j.joule.2019.06.009>.
- 475 [23] G. Tondi, V. Fierro, A. Pizzi, A. Celzard, Tannin-based carbon foams, *Carbon*. 47 (2009)
476 1480–1492. <https://doi.org/10.1016/j.carbon.2009.01.041>.
- 477 [24] Z. Marie, V. Nicolas, A. Celzard, V. Fierro, First approach for modelling the physical foaming
478 of tannin-based thermoset foams, *International Journal of Thermal Sciences*. 149 (2020)
479 106212. <https://doi.org/10.1016/j.ijthermalsci.2019.106212>.
- 480 [25] V. Nicolas, F. Vanin, D. Grenier, T. Lucas, C. Doursat, D. Flick, Modeling bread baking with
481 focus on overall deformation and local porosity evolution, *AIChE Journal*. 62 (2016) 3847–
482 3863. <https://doi.org/10.1002/aic.15301>.
- 483 [26] Y. CENGEL, *Heat Transfer a practical approach*, Second Edition, 2002.
- 484 [27] C. Du, C. Huang, A floating vapor condensation structure in a heat-localized solar evaporation
485 system for facile solar desalination, *Applied Thermal Engineering*. 201 (2022) 117834.
486 <https://doi.org/10.1016/j.applthermaleng.2021.117834>.
- 487 [28] Biomimetic Hybridization of Janus-like Graphene Oxide into Hierarchical Porous Hydrogels
488 for Improved Mechanical Properties and Efficient Solar Desalination Devices | *ACS Nano*,
489 (n.d.). <https://pubs-acscs-org.bases-doc.univ-lorraine.fr/doi/10.1021/acsnano.1c07391>
490 (accessed January 18, 2022).

- 491 [29] Z. Yu, S. Cheng, C. Li, Y. Sun, B. Li, Enhancing efficiency of carbonized wood based solar
492 steam generator for wastewater treatment by optimizing the thickness, *Solar Energy*. 193
493 (2019) 434–441. <https://doi.org/10.1016/j.solener.2019.09.080>.
- 494 [30] J. Fang, J. Liu, J. Gu, Q. Liu, W. Zhang, H. Su, D. Zhang, Hierarchical Porous Carbonized
495 Lotus Seedpods for Highly Efficient Solar Steam Generation, *Chem. Mater.* 30 (2018) 6217–
496 6221. <https://doi.org/10.1021/acs.chemmater.8b01702>.
- 497 [31] C.B.Honsberg, S.G.Bowden, Photovoltaics Education Website, (2019).
498 <https://www.pveducation.org/>.
- 499 [32] Global Modeling and Assimilation Office (GMAO), MERRA-2 tavg1_2d_slv_Nx: 2d,1-
500 Hourly,Time-Averaged,Single-Level,Assimilation,Single-Level Diagnostics V5.12.4,
501 Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES
502 DISC), Accessed 06/12/2021 DOI:10.5067/VJAFPLI1CSIV, (2015).
- 503 [33] d-maps, Planisphere World (Europe Africa), (2022). <https://d-maps.com/index.php?lang=en>.
- 504