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A review of natural materials for solar evaporation

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23 **Abstract**

24 One way to harvest solar energy is to produce steam from liquid water. Steam can be used
25 to provide freshwater even in a harsh environment, with extreme temperature and low
26 groundwater supplies. It can also be extracted from polluted soil or water, purifying the water
27 in the process at the same time. Water evaporation systems are energy effective, with
28 efficiencies ranging from 60% to over 90%. Furthermore, they can be cost-effective and have
29 a low environmental impact, using the right materials. In this article, we will review natural
30 materials, mainly of biological origin, proposed for solar evaporation, from wood and plants
31 to algae and other atypical biomass such as fungi or wastes such as pomelo peels, through gels
32 and foams, raw or charred. Their evaporation effectiveness will be presented and discussed, as
33 well as their energy efficiency. This timely review suggests the suitability of natural materials
34 for this application and reports on the progress that has already been achieved, as well as on
35 the advances that remain to be made to improve the performance of these low cost, low
36 environmental impact but high performance systems.

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41 **Keywords:** Natural materials; Steam generation; Water treatment; Low-energy-consumption;

42 Solar energy

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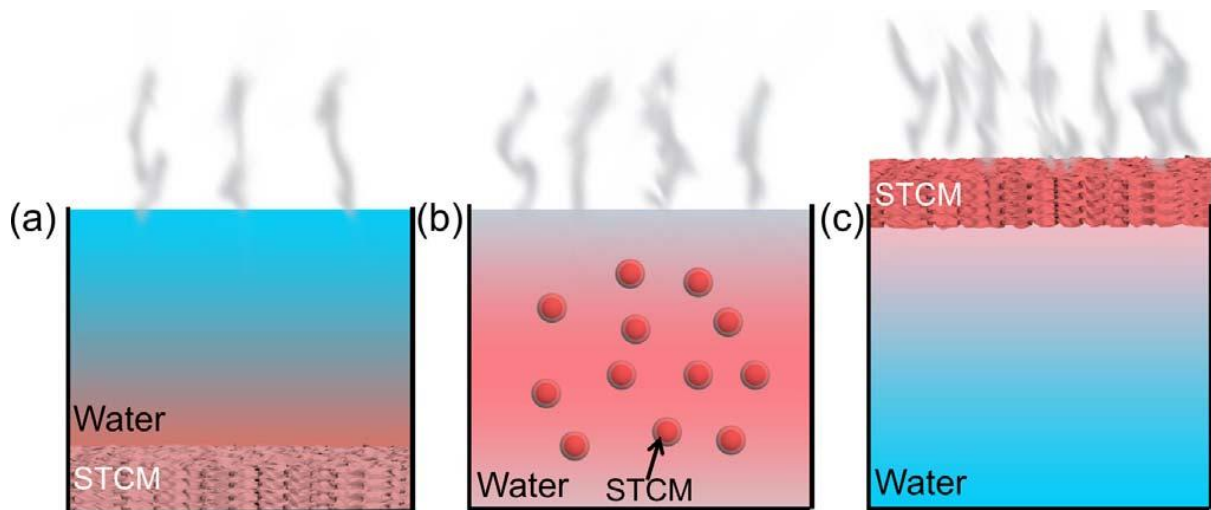
44 **1. Introduction**

45 Energy is an essential part of human life and development, whether it is used for industrial
46 purposes, transport or basic needs such as the provision of food and water. Among the many
47 ways of harvesting energy, the use of renewable energy has been the subject of research and
48 industrial efforts. Solar energy is a promising renewable energy because the amount that hits
49 planet earth every hour is higher than what is consumed by human activities over an entire
50 year [1]. Electricity can be generated using photovoltaic panels, but the efficiency of these
51 systems is low and the cells are expensive. Hence, recent research has focused on the use of
52 heat generated by solar flux [2,3]. It is mainly used to heat water that can be applied to
53 heating systems or to generate clean water from seawater or polluted water. Besides, the water
54 can also be used with heat engines to generate electricity [4].

55 In this paper, the process of water evaporation discussed here consists of exposing a certain
56 amount of water to solar radiation. Unlike boiling at 100°C under normal pressure conditions,
57 evaporation can occur at any temperature. Evaporation is a slow endothermic process that
58 takes place at the surface of water, so several criteria can accentuate the phenomena: the
59 radiative heat absorbed by the surface, the evaporation area of the water or a humid material,
60 the ambient humidity and the amount of heat transferred by convection. An example of this
61 process is the drying of laundry. To allow the laundry to dry quickly, it is essential to hang it
62 stretched, in a room with low ambient humidity or outdoors, exposed to the sun. If the laundry
63 is not stretched or is hung in a cellar, it will take much longer to dry.

64 Several types of systems exist and use a variety of materials. Some of these water
65 evaporation systems (WESs) were first fixed under the surface of water (see Erreur ! Source
66 du renvoi introuvable.(a)). In these conditions, sunlight passes through the water and is
67 converted into heat at the surface of a solar thermal conversion material (STCM), which
68 gradually increases the temperature of bulk water. The disadvantage of this method is that it

69 behaves poorly under real circumstances, losing heat in the bulk of water and reflecting the
70 light back to the environment [2,3]. Another type of WES uses particles with high
71 photothermal properties and dispersed in water to achieve the same goal as the former system
72 (see Erreur ! Source du renvoi introuvable.(b)), but with the same disadvantages. Therefore, a
73 third type of WES, in which the STCM is placed on the surface of the water, using foam or a
74 porous structure to float (see Erreur ! Source du renvoi introuvable.(c)), is more suitable for
75 solar evaporation. By using surface treatment processes, such as carbonisation or coatings to
76 allow high radiation heat transfer, these systems can achieve high energy efficiency (over
77 90%) and high evaporation rates. It is interesting to note that, with this kind of WES, only a
78 small area (typically less than one square meter) is normally enough to generate the amount of
79 water necessary for the average human requirement, which is approximatively 2.5 L per day.
80 In the following, all the examples of WESs and STCMs that will be discussed will refer to the
81 case (c) shown in **Fig. 1**.



83 **Fig. 1.** (a) Different configurations of WESs, based on a solar thermal conversion material
84 (STCM) either: (a) attached to the bottom; (b) dispersed in water; or (c) floating above the
85 water. Reproduced from [2]. Copyright (2019), with permission from Elsevier.

86 To optimise the performance of STCMs, three main factors must be taken into account [2]:
87 having a high solar absorbance, optimising the transport of water to the surface, and limiting
88 thermal losses. To achieve high absorbance, treatment at the interface between the material

89 and the air is often performed. It is possible to use metallic nanoparticles [5,6], nanostructured
 90 semiconductors [7,8], or dark materials based on carbon [9,10] or on polymers [11,12].

91 Once the absorbance at the material surface is optimised, it is necessary to provide a
 92 constant flow of liquid water while retaining heat at the surface. The method used to improve
 93 the transport of liquid water to the surface is to use the capillary phenomenon of porous
 94 materials [13–15] and/or to use hydrophilic materials [16,17].

95 Finally, in order to design an efficient STCM, it is necessary to limit thermal losses. At the
 96 interface between the STCM and the air, the heat flux received by the absorber material
 97 consists of a thermal equilibrium depending on the solar flux received, the losses by
 98 convection and radiation, and the energy lost by the phase change of water (from liquid to
 99 vapour). Thus, this heat transfer can be written as follows:

$$100 \quad \phi_t = \phi_{sun} + \phi_{conv;t} + \phi_{rad;t} + \phi_{l \rightarrow v} \quad (1)$$

$$101 \quad \phi_t = \phi_{sun} + h_{c;t} (T_{inf;t} - T) + \varepsilon \sigma (T_{inf;t}^4 - T^4) + m_{tot}^* h_v \quad (2)$$

102 where ϕ_t is the total heat flux (W m^{-2}), ϕ_{sun} is the heat flux received from the sun (W m^{-2}),
 103 $\phi_{conv;t}$ is the convective heat flux (W m^{-2}) exchanged with the ambient temperature ($T_{inf;t}$ in
 104 $^{\circ}\text{C}$), $h_{c;t}$ is the convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$), $\phi_{rad;t}$ is the radiative heat flux
 105 (W m^{-2}) exchanged with the ambient temperature ($T_{inf;t}$ in $^{\circ}\text{C}$), ε is the emissivity of the
 106 material, σ is the Stefan-Boltzmann constant ($\text{kg s}^{-3} \text{K}^{-4}$), $\phi_{l \rightarrow v}$ is the heat flux due to the
 107 phase change of liquid water to vapour depending on the total vapour flux m_{tot}^* ($\text{kg m}^{-2} \text{s}^{-1}$), h_v
 108 is the sum of the enthalpy of vaporisation and the sensible heat (J kg^{-1}), and t is an index
 109 referring to the top of the absorber material.

110 At the bottom, there is heat transfer at the interface between the material and water. There
 111 are three main transfers: conduction, radiation and convection. The general heat transfer to the
 112 bottom of the water tank can then be written as follows:

$$113 \quad \phi_b = \phi_{conv;b} + \phi_{rad;b} \quad (3)$$

$$114 \quad \phi_b = h_{c;b} (T_{inf;t} - T) + \varepsilon \sigma (T_{inf;t}^4 - T^4) \quad (4)$$

$\phi_{conv;b}$ $\phi_{rad;b}$

115 where ϕ_b is the total heat flux (W m^{-2}), $\phi_{conv;b}$ is the convective heat flux (W m^{-2}) exchanged
 116 with the bulk water ($T_{inf;t}$ in $^{\circ}\text{C}$), $h_{c;b}$ is the convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$),
 117 $\phi_{rad;b}$ is the radiative heat flux (W m^{-2}) exchanged with the bulk water ($T_{inf;t}$ in $^{\circ}\text{C}$), and b is an
 118 index referring to the bulk water.

119 At the top of the STCM, it is quite difficult to imagine a reduction in convection losses
 120 because they are directly related to vapour transfer. Indeed, the vapour is mainly transported
 121 by convection outwards. On the contrary, it is possible to limit radiation losses by applying a
 122 3D radiation shield in the form of a cylinder at the top of the STCM [18]. Heat losses at the
 123 bottom are reduced by the use of thermal insulation (carbon foam or low-density wood, for
 124 instance) [19] or by designing an air volume inside the system [20].

125 There are already several review articles concerning this type of systems [2,3,5,21,22], but
 126 these former reviews mainly report on the strategies used to improve WESs in a very general
 127 way, in particular through the design of steam-to-liquid water conversion systems based on all
 128 types of materials without restriction, and discuss their potential applications. In this very
 129 general case, the materials used can be synthetic or natural (biological or mineral). Thus, as
 130 explained above, absorbers can be composed of metallic nanoparticles, nanostructured
 131 semiconductors or dark materials based on carbon or polymers, the latter two leaving many
 132 possibilities for the use of biological materials.

133 Insulating materials to limit heat transfer to water can be made from polyurethane foam
134 [23], porous carbon [10], expanded polystyrene [9,14,18,24–28] or natural materials such as
135 wood [19,29,30] and its derivatives [31], or even simply air [20]. Concerning the transport of
136 liquid water, bio-based materials are often suggested. In general, WESs are made of several
137 materials, whether bio-based or not, and bio-based materials do not necessarily result in lower
138 performance compared to their synthetic counterparts.

139 This paper will cover the variety of WESs that use natural materials, the vast majority of
140 them bio-based, and explain how their particular characteristics can benefit solar evaporation.
141 Many natural structures found in nature, especially biologic species, can indeed be a source of
142 inspiration and studies have already been inspired by features present in nature. First, it will
143 be explained how the performance of a given WES can be measured, and the different
144 quantities and notations required will be defined. These will be referred to throughout the
145 following when comparing the efficiency of the systems with each other. Then, the main
146 strategies to improve the evaporation rate will be explained and linked to the specific
147 characteristics of different materials. Finally, evaporation rates and other results obtained
148 using bio-based and other natural materials will be presented, as well as prototypes existing to
149 date.

150

151 **2. General information on solar water evaporation**

152 ***2.1. Measurement process and definitions***

153 Solar water evaporation measurements are usually conducted using a solar light simulator,
154 most often with a xenon lamp that simulates the sunlight spectrum very well. In a typical
155 experiment, a container filled with water and including the evaporation device according to its
156 design, is then placed under the lamp and on an electronic balance. The illumination is set to a
157 chosen value, which is usually a multiple of 1 sun (e.g. 1, 3 or 10 suns). 1 sun represents an

158 irradiation with a power density of 1 kW m⁻², i.e., the average photonic energy flux through
159 the atmosphere at an altitude close to sea level. Although the simulator can be set to several
160 output powers, in real conditions, optical devices or lenses can be used to achieve a power
161 density higher than 1 kW m⁻². The balance, ideally coupled to a continuous data logging
162 system, then measures any water loss over the period under consideration. From this loss, the
163 evaporation rate (ER) can be calculated with the common unit found in the literature: kg m⁻²
164 h⁻¹.

165 In order to quantify the performance of WESs, almost all of the work reviewed on this
166 topic reports efficiency values, most often calculated using the following equation:

$$167 \quad \eta = \frac{\dot{m}h_v}{C_{opt}P_0} \quad (5)$$

168 where η is the efficiency (dimensionless, but more often expressed in %), \dot{m} is the net
169 evaporation rate (i.e., the evaporation rate only due to light) in kg m⁻² h⁻¹, h_v is the sum of the
170 enthalpy of vaporisation and sensible heat (J kg⁻¹), C_{opt} is the optical concentration of the
171 solar flux, and P_0 is the power density of the solar flux, usually reported in sun number
172 (equivalent to 1 kW m⁻²). To compare the capacity of water evaporation systems, it is
173 preferable to use the evaporation rate rather than the efficiency, as the latter can be calculated
174 in different ways so that, in some cases, systems with comparable efficiencies may have
175 significantly different ERs from each other [32,33].

176 Indeed, depending on the system used to test the material and on the experimental
177 conditions, the energy balance is likely to change from one test to another [34]. As one study
178 [35] pointed out, if the temperature of the system is lower than the temperature of the
179 environment, heat transfer occurs from the environment to the system, adding energy to it.
180 This energy is not taken into account when using Equation (5), and most publications do not
181 mention it. Moreover, if the vessel containing the water to be evaporated is not insulated, the

182 diffuse radiation increases the evaporation rate without being taken into account in the
183 efficiency calculation, resulting in a higher efficiency value. For instance, it has been reported
184 that the efficiency of a wood-polydopamine system increased from 87% when exposed to 1
185 sun to 135% when exposed to 3.5 sun [36]. In general, Equation (5) is used in many reviews
186 but has limitations, as the efficiency can never be greater than 100%.

187 ***2.2. Main characteristics of water evaporation systems***

188 Exposing bulk water to solar radiation allows the water to extract energy from sunlight,
189 even if part of this energy is lost in the process. Part of the light is indeed reflected back to the
190 environment, resulting in less energy being gained by the system. Moreover, the system will
191 have a different temperature than the environment, which will allow heat transfer from one to
192 the other, usually from the WES, resulting in energy losses.

193 The first way by which studies have tried to remedy these losses has been to adjust the
194 amount of solar energy absorbed and transferred to the water. The ideal situation is therefore
195 when most of the energy is absorbed and nothing is returned to the environment. This can be
196 achieved by using a surface with a high absorbance over the entire solar spectrum, either by
197 being dark (such as carbon) or by having special semiconducting or plasmonic properties
198 (such as titanium-based compounds and metallic nanoparticles, respectively), which results in
199 high photothermal properties. Another source of losses in WESs is the heat that is given to
200 bulk water (i.e., not retained on the surface) and then returned to the environment by thermal
201 conduction. To minimise this, most devices use materials with low thermal conductivity. A
202 material with low thermal conductivity means that less energy will be lost in contact with bulk
203 water and, since evaporation is a superficial phenomenon, the WES has the advantage of
204 retaining as much heat as possible at the surface. However, this is only possible if the water

205 has actually reached the surface where evaporation takes place. Therefore, water transport is
206 another characteristic to be taken into account when designing evaporation systems.

207 Bio-based materials are especially well suited for water transport because this is precisely
208 the function of most of them in nature. The sapwood for example, through its vessels or
209 tracheids, is used to supply sap from the bottom of the tree to the top. Similarly, rice straws
210 have a spiral geometry that allows an upward capillarity effect [37]. In general, many natural
211 materials are both porous and hydrophilic. These characteristics allow them to combine a
212 character of thermal insulation (given the very low thermal conductivity of air, 0.026 W m^{-1}
213 K^{-1} at room temperature) with a capacity to transport water within them. It is therefore not
214 surprising that this type of material has been suggested as the core of devices for solar WESs,
215 and the following section reports many examples of this type of materials, which are now
216 detailed and discussed. Unless otherwise stated, the data reported below in terms of
217 evaporation rate and efficiency were obtained under a solar irradiation equivalent to 1 sun.
218 When the photonic energy was higher, the evaporation rate corresponding to 1 sun was
219 calculated assuming proportionality. More details are given below.

220

221 **3. Review of natural materials for solar evaporation**

222 In the following, materials reported as efficient cores for solar water evaporation systems
223 have been classified according to their origin and, to some extent but not completely,
224 according to their structure. As with any classification, it is not completely satisfactory, as
225 there are always materials that do not fall into any category, and which should be listed in an
226 "other natural materials" subsection. But any other classification of materials, whether based
227 on their structure, nature or function, always leads to the same imperfections. We have
228 therefore chosen to present them by major types of natural resources, mainly plant resources,
229 with special emphasis on the treatments carried out. Indeed, depending on whether the

230 biomass is used in its raw state or after carbonisation, giving what is called a biochar, the
231 resulting materials are very different. They will nevertheless appear in the same sections, as
232 they come from the same raw material.

233 *3.1. Wood-based materials*

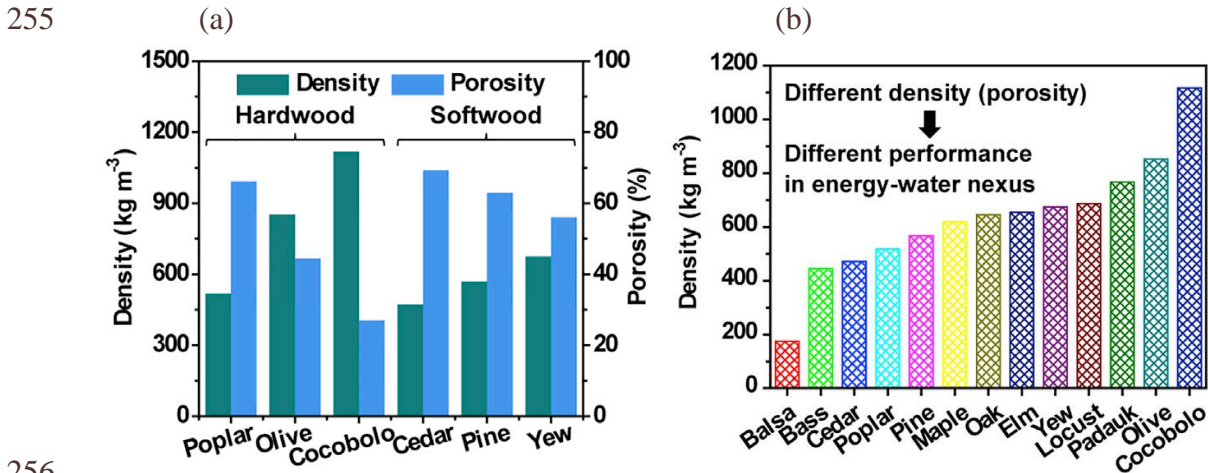
234 Wood is the structural material of trees, which also provide them with capillary capacity to
235 feed sap to the leaves. While there are more than twenty thousand species, only a handful of
236 them are actually used regularly for their mechanical properties for structural purposes or for
237 making furniture. Its solar evaporation capacities have been explored by numerous studies to
238 date.

239 *3.1.1. Main characteristics of wood*

240 Wood consists of approximately 45% cellulose, 30% hemicellulose and 25% lignin. These
241 numbers may vary whether it is hardwood or softwood, and depending on the species.
242 Cellulose is a homopolymer of glucose while hemicellulose is an amorphous heteropolymer
243 of polysaccharides. This means that wood has many hydroxyl groups, which are very
244 hydrophilic. Softwood has two main types of cells, parenchyma cells and tracheids. The latter
245 are used as mechanical support and for sap transport. Hardwood, on the other hand, has an
246 additional type of cells specially designed for this task, the vessels. Both softwood and
247 hardwood have ligneous rays that provide additional porosity from the centre of the trunk to
248 the outside.

249 Most woods have a lower density than water, which allows them to float on it. Some are
250 atypical, for instance balsa has a remarkably low density of 200 kg m^{-3} . Softwoods have an
251 average density of 400 to 500 kg m^{-3} while hardwoods have a density ranging from 600 to 800
252 kg m^{-3} (**Fig. 2**). As mentioned above, thermal insulation plays a major role in WESs. Wood

253 meets this criterion by having a thermal conductivity ranging from 0.1 to 0.5 W m⁻¹ K⁻¹
 254 depending on the species [38,39] and the direction of the fibres [40].



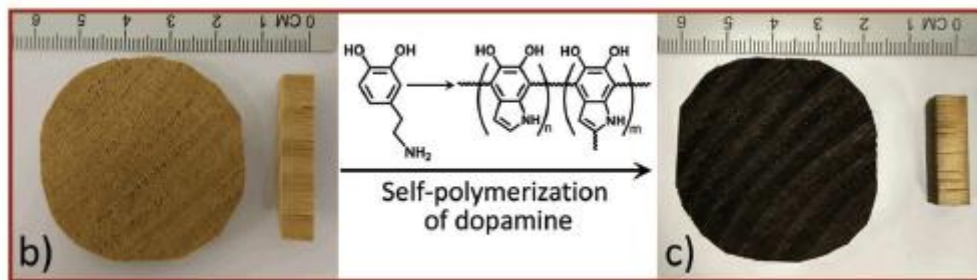
256 **Fig. 2.** (a) Density and porosity of different types of woods; (b) Density of several wood
 257 species. Reproduced from [41]. Copyright (2017), with permission from Elsevier.
 258

259 *3.1.2. Wood with coatings*

260 Naturally, wood is not a very light-absorbing material [42]. Therefore, a surface coating or
 261 process is required to achieve higher evaporation rates. Carbon-based materials such as
 262 carbon nanotubes (CNTs) [43], graphite [40] or graphene [44] have proven to be excellent
 263 light absorbers and are indeed present in many WESs, including those based on biomass.
 264 Chen’s team obtained an evaporation rate as high as 11.22 kg m⁻² h⁻¹ under an irradiation
 265 equivalent to 10 suns for an efficiency of 81%, using balsa coated with CNTs [19]. Although
 266 the proportionality may not apply strictly because systems become more efficient as light
 267 intensity increases, this result suggests that the maximum ER calculated proportionally for 1
 268 sun (MERCPI) would be 1.12 kg m⁻² h⁻¹. In the following, for system-to-system comparison
 269 purposes, the notation “MERCPI” will be used to give a maximum ER value under 1 sun,
 270 calculated from measurements under more than 1 sun.

271 In addition to carbon, metals are also found as coatings on the surface of wood products
 272 [29,45,46]. These metals are sprayed as particles in a thin, controlled layer on the surface of
 273 wood. Tannic acid – Fe³⁺ complexes were also found to present good photothermal properties,

274 without the need for high temperatures in their preparation [38]. In fact, based on the results
275 of evaporation rates, this type of coating performed better than others did, with an ER of 1.85
276 $\text{kg m}^{-2} \text{h}^{-1}$ at 90% efficiency. Another coating that has been found to perform well when
277 applied to wood is polydopamine (PDA), a polymer used by mussels to attach securely
278 underwater. It should be noted that with a solar light intensity higher than 1 sun, wood
279 products treated with PDA (**Fig. 3**) achieved an efficiency higher than 100% when calculated
280 with Equation (5). The authors suggested that enthalpy is reduced in these systems, and that
281 water evaporation is boosted by the formation of bubbles near the surface where boiling takes
282 place, and therefore does not require so much energy input [36].

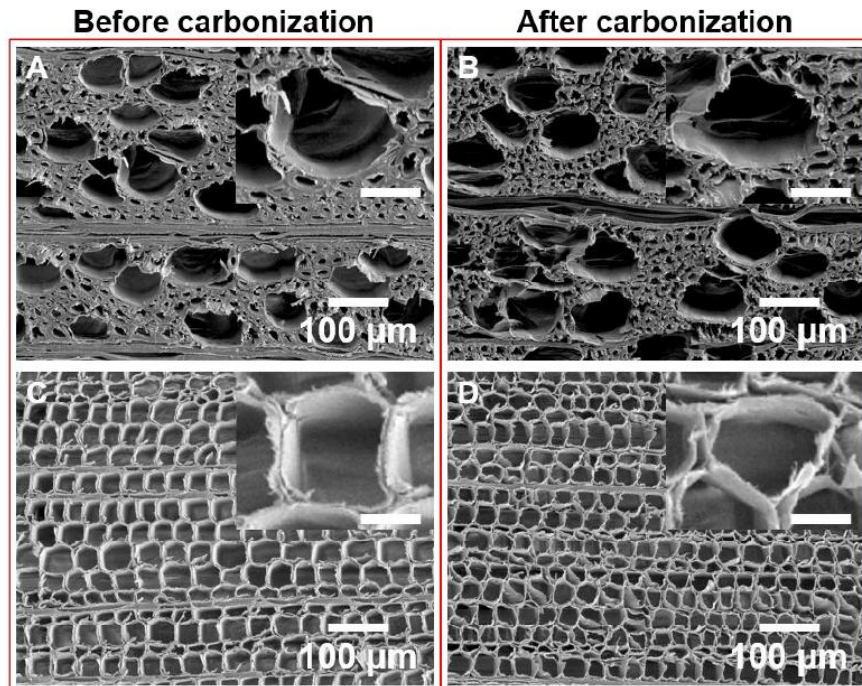


283
284 **Fig. 3.** Wood before (left) and after (right) applying a PDA coating .Reproduced with
285 permission from [36]. Copyright 2017, Wiley-VCH.

286 3.1.3. Carbonised wood

287 In addition to coatings, another way to improve the absorption of light by wood is to
288 convert it into a biochar by carbonisation, to make its surface darker and more porous. Indeed,
289 during the pyrolysis of biomass with little or no oxygen, a biochar is formed. The process is
290 highly scalable and the biochar can have a controlled pore size depending on the pyrolysis
291 temperature, time, catalyst present during the process and activation after pyrolysis [47,48].
292 As shown in **Fig. 4**, carbonisation opens and develops the natural porosity of wood, which
293 improves water transport. One way to achieve this is pyrolysis, which consists of treating the
294 wood to a temperature of around 500 °C in the absence of oxygen to prevent its combustion,
295 e.g. under nitrogen flow. This moderate temperature allows an intense darkening of the

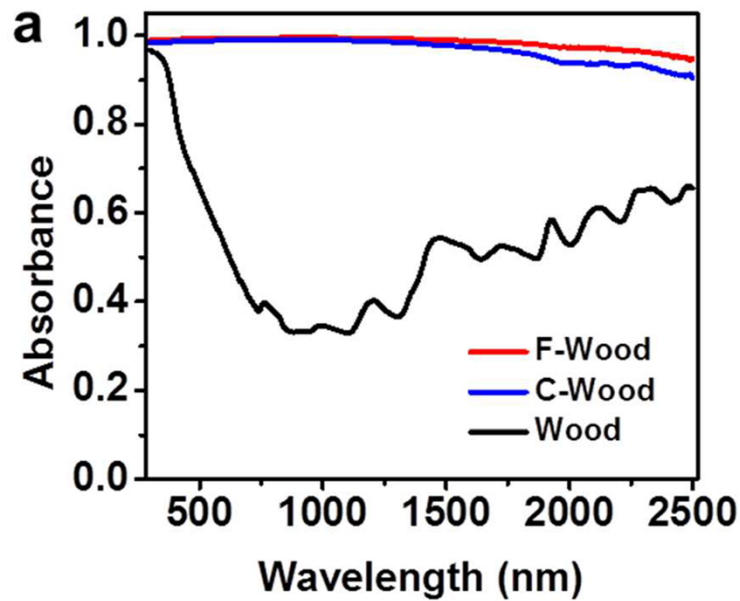
296 surface without making the material hydrophobic, which would be detrimental to the desired
297 capillary effect.



298
299 **Fig. 4.** SEM images of poplar (top) and pine (bottom) woods, before (left) and after (right)
300 carbonisation. Reproduced from [41] Copyright (2017), with permission from Elsevier.

301 This process has been used in several studies, and its effectiveness ranges from 72% to
302 90% (see Table 1 in the next section). As shown in **Fig. 5**, the absorbance of the material is
303 then much higher than that of natural wood. Another process is the use a laser to carbonise the
304 surface of wood, which has the advantage of not damaging the pores and allows better control
305 of the speed and accuracy of the process. However, with an evaporation rate of $2.52 \text{ kg m}^{-2} \text{ h}^{-1}$
306 under 3 suns (MERCPI: $0.84 \text{ kg m}^{-2} \text{ h}^{-1}$), it gave poorer results than pyrolysis ($2.88 \text{ kg m}^{-2} \text{ h}^{-1}$,
307 i.e., a MERCPI of $0.96 \text{ kg m}^{-2} \text{ h}^{-1}$) under the same test conditions [39]). The use of flames to
308 treat the wood surface can also be considered but, like laser treatment, it did not show better
309 efficacy than pyrolysis, with a water evaporation rate of $1.05 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 sun. It can be
310 noted that the combination of pyrolysis and metallic coating is possible and can induce a
311 higher evaporation rate. In fact, this is the method that has shown the best results of all the
312 tests carried out [39]. By coating the wood with gold nanoparticles before carbonising it in a

313 second step, the surface structure is less degraded, less brittle, and therefore mechanically
314 stronger and more durable.



315

316 **Fig. 5.** Absorbance of flame-treated wood (F-Wood) and carbonised wood (C-Wood)
317 compared to that of natural wood (Wood) as a function of wavelength. Reproduced with
318 permission from [42]. Copyright (2017) American Chemical Society.

319 *3.1.4. Other advantages of wood*

320 Wood is not an isotropic material and therefore behaves differently parallel and
321 perpendicular to the direction of the fibres. Some authors have shown the interest of cutting
322 wood crosswise to study its radial porosity [40]. Wood has a lower thermal conductivity in the
323 radial direction while its porosity is still high due to the connection between the inside and
324 outside of the wood via the ligneous rays and lumens. Graphite has been sprayed at the
325 surface of the wood sample to provide high photothermal properties. The result is an
326 evaporation rate of $1.20 \text{ kg m}^{-2} \text{ h}^{-1}$ for an efficiency of 80%.

327 *3.2. Annual plants and perennial plants*

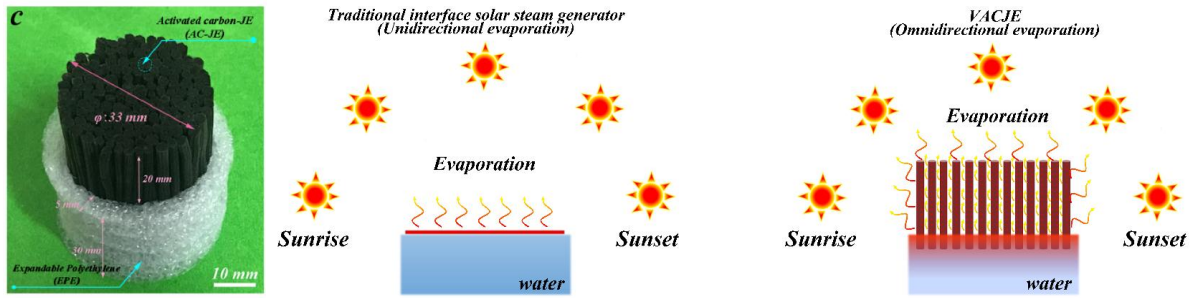
328 While wood has been well tested for the solar evaporation of water and gives good results,
329 it is already used for its mechanical properties in the building industry, for the energy it

330 produces when burned, or to make furniture. All in all, it is a material that has a proven
331 history of reliable service in many applications and which remains indispensable in the
332 industry. Therefore, the exploration of less noble materials, which are poorly valorised or
333 even considered as waste, can bring additional interest to solar evaporation. Rice straw, for
334 instance, is often left and burned on site, which is a very polluting process [49]. It is therefore
335 important to find a way to use this type of waste. The materials can also be used as such but
336 after treatment to make their surface more light-absorbent, or in the form of biochar.

337 3.2.1. *Plant stems*

338 The first way non-wood plants have been tested as an evaporation system is in the form of
339 bundles to transport water using their pipe geometry. The particular system used in the
340 example shown in **Fig. 6** is based on *Juncus effusus*, a flowering herbaceous plant from
341 China, coupled with sprayed carbon powder to give the light-absorption property and thus its
342 dark appearance. The results of water evaporation under 1 sun were $2.23 \text{ kg m}^{-2} \text{ h}^{-1}$, which is
343 higher than usual and would give an efficiency of more than 100% using the regular enthalpy
344 (equation (5)) for the energy supplied to the system. Indeed, the area used for evaporation is
345 not only the top surface area but also the sides that are higher than the expandable
346 polyethylene foam used as a float, allowing the system to favour evaporation in three
347 dimensions (**Fig. 6**). This has been proven from results obtained with different heights of 0, 10
348 and 20 mm: the 20 mm system presented the best results. However, the reason why the height is
349 important is that the structure of the *Juncus effusus* intrinsically has microscopic channels and
350 when bundled together, the pipe geometry allows macroscopic spaces between each straw.
351 These free spaces allow a higher area of solar evaporation, a longer optical path length, a
352 lower thermal conductivity and the release of water vapour in several directions. Overall, the
353 *Juncus effusus* system is very efficient [50].

354



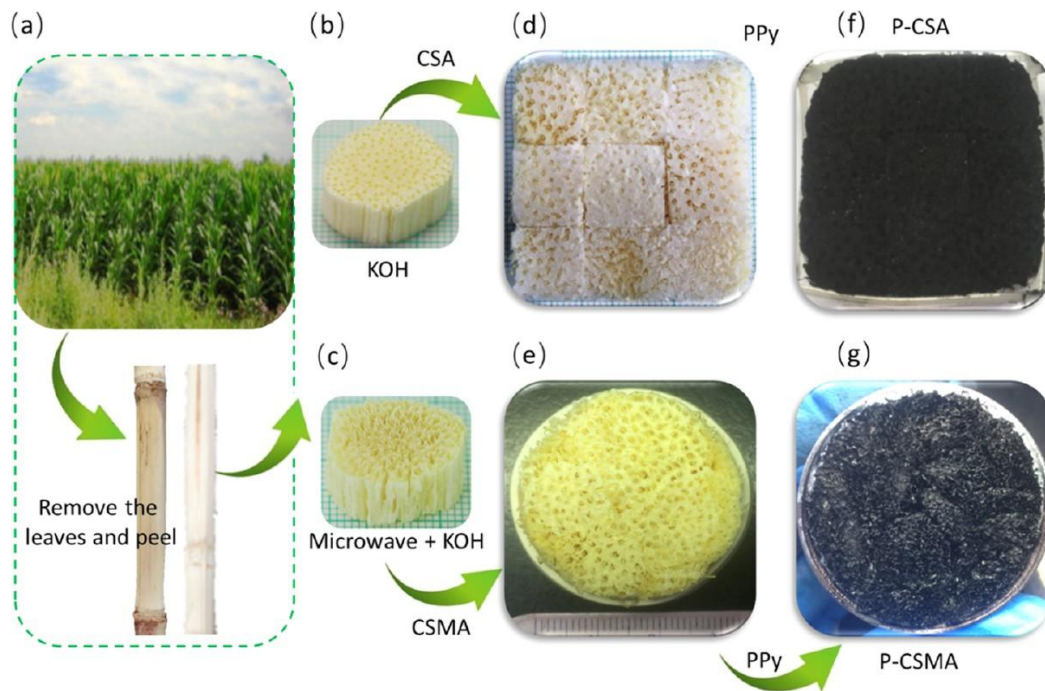
355 **Fig. 6.** Water evaporation system based on *Juncus effusus* (left) and its increased area
356 available for a better solar absorption and evaporation (right), compared to a conventional
357 interface solar steam generator (middle). Reproduced from [50]. Copyright (2020), with
358 permission from Elsevier.

359 In addition to reeds, rice straws have been investigated for the same purpose. In contrast to
360 the aforementioned system, this one used the upper leaves of the rice straw as absorbing
361 material. To do this, the leaves were ground, packed and pyrolysed to form a flat surface that
362 was then placed over the straws that serve as pipes to transport the water. While the former
363 reeds, although surface-treated to better absorb light, were used directly as absorbing material,
364 this system uses different parts of the plant to transport water and absorb light. However, this
365 system based on rice by-products obtained medium results of $1.05\text{ kg m}^{-2}\text{ h}^{-1}$ with an
366 efficiency of 66% [37].

367 3.2.2. Vegetable “foams”

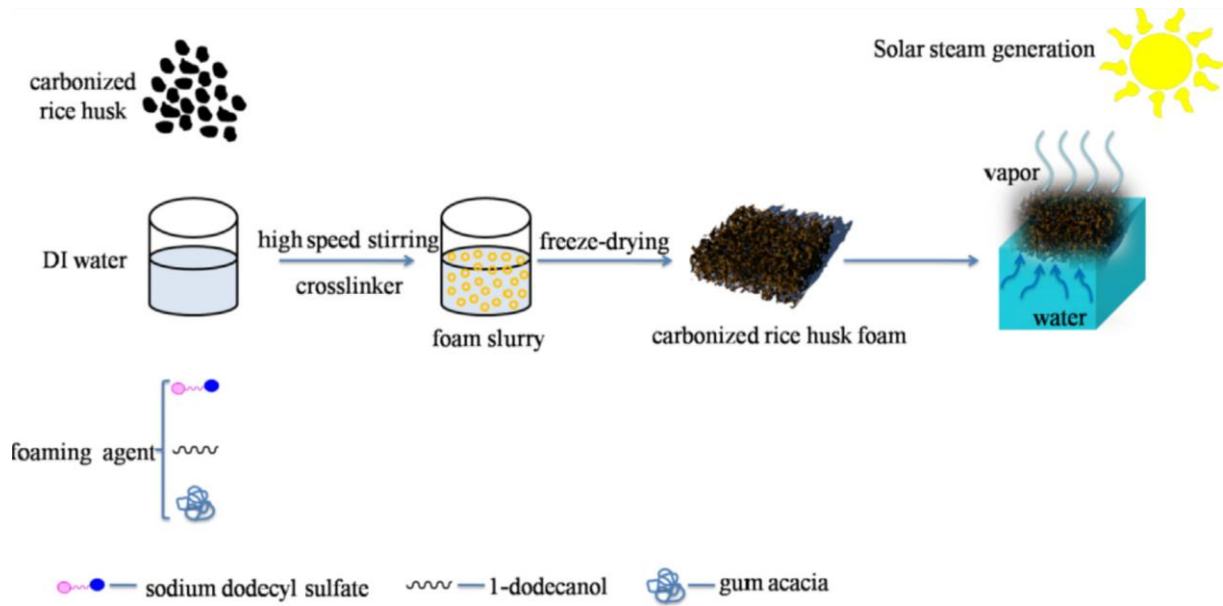
368 Another way to create a WES from straws is to make a vegetable foam-like material. Corn
369 straws have been tested in this form in [51]. The straws were first microwaved for 90 seconds,
370 then soaked in a 5 wt. % aqueous solution of KOH for 24 h. They were then washed with
371 deionised water and freeze-dried to obtain a “foam”. The treatment used to enhance light
372 absorption was a layer of polypyrrole, a polymer known to absorb radiation in the near-
373 infrared range. The resulting foam-like product is shown in **Fig. 7** and presents a remarkably
374 low thermal conductivity of $0.027\text{ W m}^{-1}\text{ K}^{-1}$, indicating its excellent insulation properties, as

375 well as a wide range of pore sizes. The evaporation rate of water on corn straw “foam” was
376 $1.77 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 sun irradiation, which represents an efficiency of 96%.



377
378 **Fig. 7.** Process of making a WES based on corn straw “foam”. Reproduced with permission
379 from [51]. Copyright (2020) American Chemical Society.

380 Foams are also an interesting technical solution for biomass waste that cannot be used
381 because of its shape, such as rice husks [52]. As shown in **Fig. 8**, rice husk was first
382 carbonised and then put in deionised water. A stirring process, which involved foaming agents
383 and binders, was then used to produce a slurry. This slurry was then shaped into the desired
384 form which, after freeze-drying, was porous and had a low thermal conductivity. To convert
385 better light energy into heat, the rice “foam” was carbonised further. The resulting
386 evaporation rate of the resultant biochar was $1.03 \text{ kg m}^{-2} \text{ h}^{-1}$ with an efficiency of 71%.

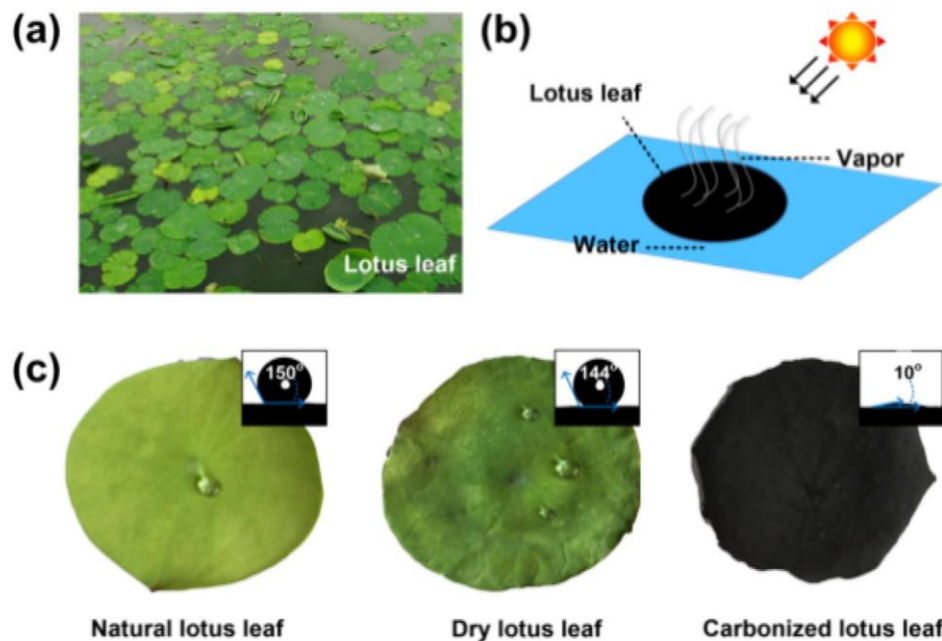


388 **Fig. 8.** Process of making a WES based on a foam-like material made of carbonised rice husk.
 389 Reproduced from [52]. Copyright (2020), with permission from Elsevier.

390 3.2.3. *Lotus*

391 Lotus is a plant for which interest has been found in solar evaporation. Two studies have
 392 used part of this plant to create a solar WES. On the one hand, the seedpod was used for its
 393 porous structure, which offers low thermal conductivity and high water absorption. Light
 394 absorption was improved by a pyrolysis process to achieve 98% to 99% over the wavelength
 395 range 250-2000 nm. In the end, when exposed to 1 sun irradiation, this system produced 1.30
 396 $\text{kg m}^{-2} \text{h}^{-1}$ with an efficiency of 87% [53].

397 On the other hand, lotus leaves were also tested [54]. Once carbonised (**Fig. 9**), their
 398 surface becomes hydrophilic and highly light-absorbent, making it a good surface to put on
 399 top of a water-transporting material. In the study, with a synthetic foam used as the transport
 400 material, the water evaporation rates doubled from $1.55 \text{ kg m}^{-2} \text{h}^{-1}$ for bulk water to 3.10 kg m^{-2}
 401 h^{-1} using the system based on carbonised lotus leaf. During the experiment, the surface
 402 temperature was indeed much higher with the lotus system. This work thus confirms the
 403 interest of lotus leaves as biomass-based absorbing material.

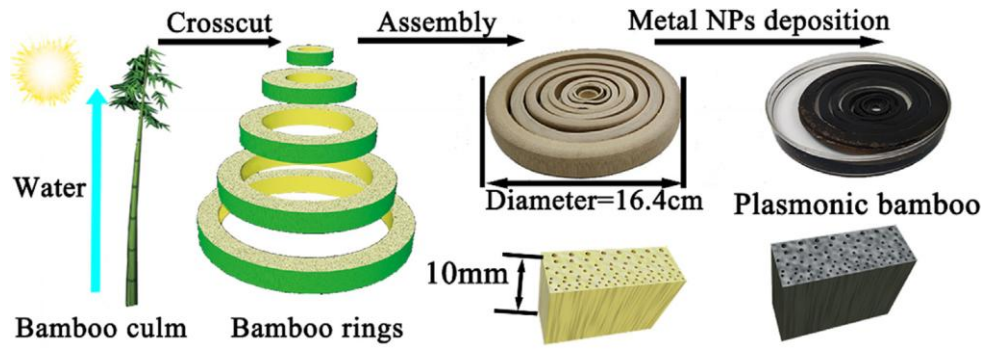


404

405 **Fig. 9.** (a) Lotus leaves found in nature, (b) process of evaporation via a carbonised lotus leaf,
 406 and (c) pictures of lotus leaf before drying, after drying and after carbonisation (from left to
 407 right), showing the changes of hydrophilic properties by the evolution of the water contact
 408 angle. Reproduced from [54]. Copyright (2019), with permission from Elsevier.

409 *3.2.4. Bamboo*

410 Bamboo is a grass plant with mechanical properties similar to those of wood. Its internodal
 411 spacing is hollow and the section presents a porous structure due to vessels. To make an
 412 evaporation device, Sheng et al. used several sections of different dimensions assembled to
 413 obtain a disc shape (**Fig. 10**) [55]. In addition to being a porous structure for water transport,
 414 bamboo also has a fairly low thermal conductivity, $0.30 \text{ W m}^{-1} \text{ K}^{-1}$. To allow better
 415 photothermal properties, Sheng's team chose to deposit metallic nanoparticles such as Ag and
 416 Pd. The coated bamboo showed a high absorbance of 99% and in the end, this device was able
 417 to evaporate water at $12.3 \text{ kg m}^{-2} \text{ h}^{-1}$ under an irradiation corresponding to 10 suns (i.e., a
 418 MERCP1 of $1.23 \text{ kg m}^{-2} \text{ h}^{-1}$) for an efficiency of 87%.



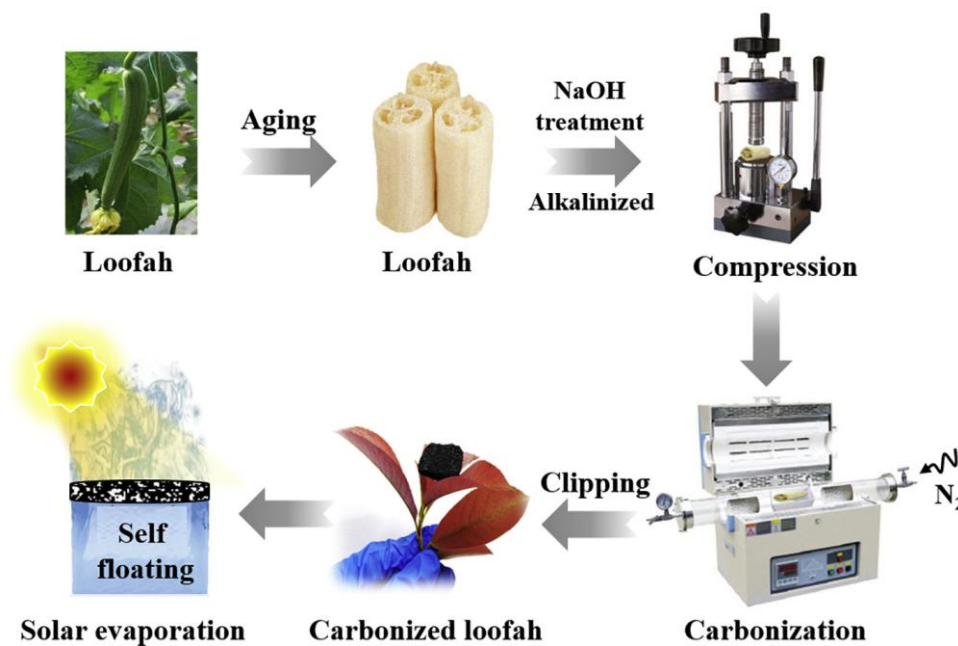
419

420 **Fig. 10.** Assembly of a bamboo-based WES. Reproduced from [55]. Copyright (2020), with
 421 permission from Elsevier.

422 3.3. Fruits and vegetables

423 3.3.1. Loofah

424 Loofah, a plant of the Cucurbitaceae family, is a sponge-like plant that has been used as a
 425 solar evaporation device in the form of biochar [56]. The process is illustrated in **Fig. 11** and
 426 involves a pre-treatment with ethanol and deionised water to clean the Loofah, followed by
 427 immersion in sodium hydroxide at 80 °C for 2 hours to remove the lignin. This was followed
 428 by pyrolysis under nitrogen at 500 °C. The result is a WES that produces $1.38 \text{ kg m}^{-2} \text{ h}^{-1}$
 429 under 1 sun illumination, with 85% efficiency.



430

431 **Fig. 11.** Process to obtain a biochar from Loofah. Reproduced from [56]. Copyright (2020),
 432 with permission from Elsevier.

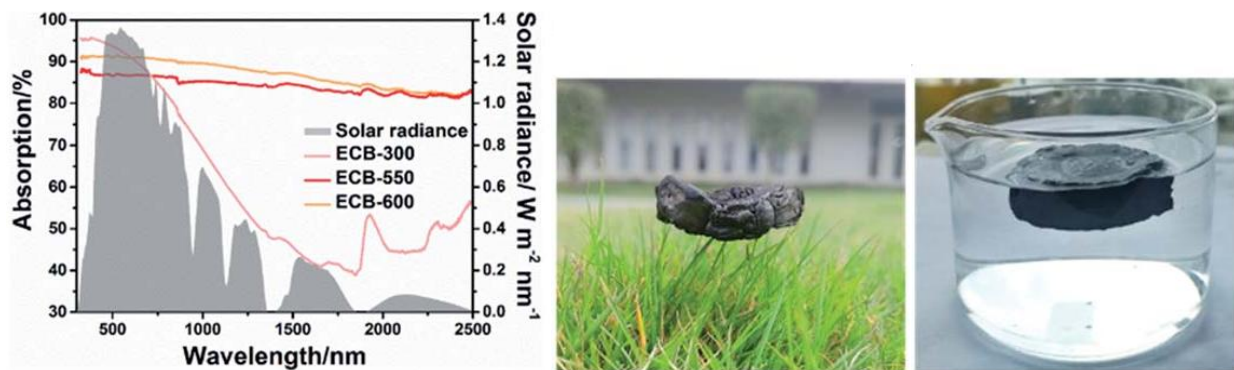
433 3.3.2. *Radish*

434 Radishes were cut vertically in the direction of growth and then carbonised at 500 °C [57].
435 The characterisation of the radish revealed a porous structure very similar to the vascular
436 network of other plants already encountered in the examples in this review article, which
437 ensures water transport to the surface and photon trapping, and the presence of surface
438 chemical groups responsible for its hydrophilicity. In addition, the carbonised radish
439 presented low density, low thermal conductivity and interesting photothermal properties. In
440 short, the radish biochar has all the properties necessary for solar evaporation. The
441 evaporation rate of carbonised radish was about $0.6 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 sun irradiation after
442 subtracting natural evaporation in the dark, which is lower than that of other typical bio-based
443 materials. To improve evaporation, two methods were used. First, the addition of an insulation
444 layer under the carbonised radish improved the rate to $0.7 \text{ kg m}^{-2} \text{ h}^{-1}$ under the same
445 conditions of irradiation. To further improve the evaporation, titanium nitride was used as an
446 additional coating on the carbonised surface and the resulting evaporation rate reached 1.18
447 $\text{kg m}^{-2} \text{ h}^{-1}$ for an efficiency of 72% under 1 sun irradiation.

448 3.3.3. *Carrot*

449 Another material for solar evaporation that has been created from edible roots is carrot
450 biochar [58]. The carrots were cut along the direction of growth with a thickness of about 1
451 cm. After being dehydrated in ethanol for 2 days and then dried, the slices were pyrolysed at
452 550 °C in argon for 30 min at a rate of 5 °C per minute. The carrot biochar presents a high
453 light absorption of 84% (**Erreur ! Source du renvoi introuvable.**) and a hydrophilic surface.
454 This biochar is able to produce $2.04 \text{ kg m}^{-2} \text{ h}^{-1}$ of water vapour with 127% efficiency (a value
455 once more based on Equation (5), which here again shows its limitations). It can also be noted
456 that the biochar retains its performance with a slight decrease in evaporation rate (0.24 kg m^{-2}

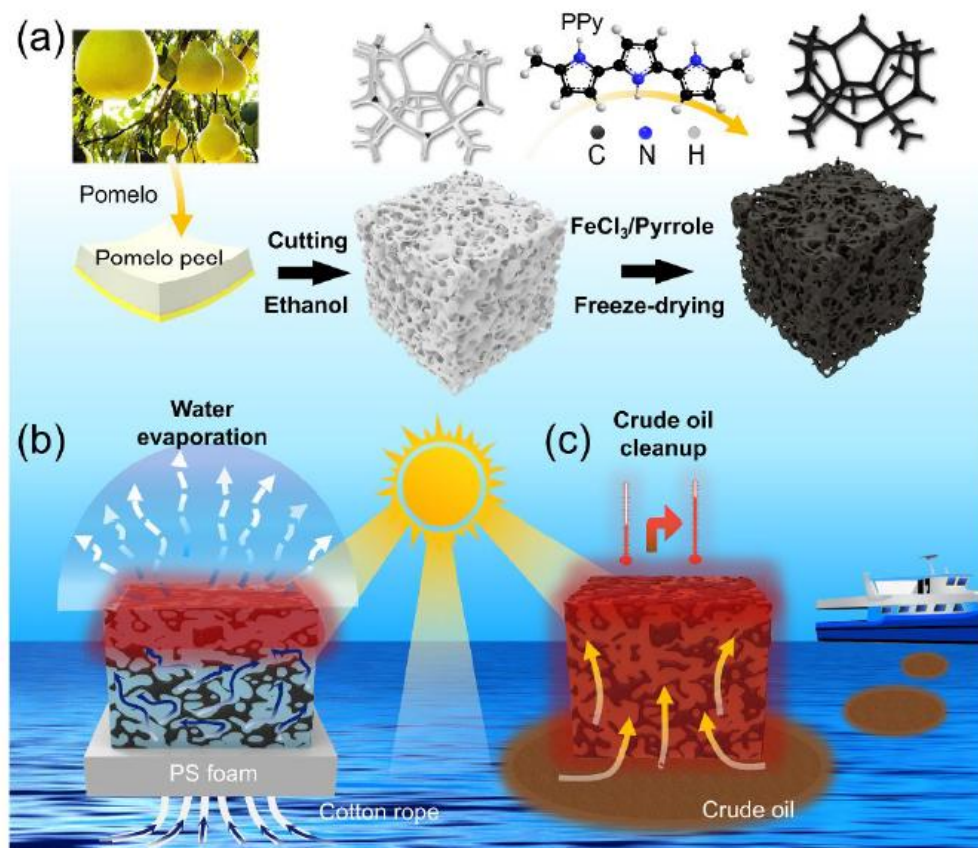
457 h^{-1}) for 4.7 hours after the light is turned off, showing that much of the energy is stored in the
458 system.



459
460 **Fig. 12.** A few characteristics of ethanol-treated-carrot biochar (ECB). From left to right:
461 solar spectral irradiance (AM 1.5 G) (right axis) and absorption (left axis) of ECB at different
462 pyrolysis temperatures ($^{\circ}\text{C}$); lightness of ECB-550; the same material, floating on water.
463 Reproduced with permission from [58]. Copyright (2019) The Royal Society of Chemistry.

464 3.3.4. Pomelo peel

465 Another atypical material suggested for solar evaporation is pomelo peel [59]. It is a food
466 by-product that is usually discarded, making it a perfect material to avoid synthetic precursors
467 for water transport. Besides, pomelo peel is thicker than usual vegetable peels, which makes it
468 more compatible with evaporation. Polypyrrole was chosen as a means of improving light
469 absorption, as it has already proven its capabilities and compatibility with bio-based materials.
470 As shown is **Erreur ! Source du renvoi introuvable.**, the pomelo peel was first cut to the
471 desired shape and then the yellow epidermis was removed as it is non-porous. It was then
472 soaked in ethanol to clean the structure and make it more porous. A series of polymerisation
473 processes followed to allow high photothermal properties using polypyrrole. The final product
474 was then freeze-dried and the result was a WES material with over 95% absorption. In the
475 same study, carbonised pomelo peel was also tested, which showed a more fragile structure,
476 but capable of evaporating water at a rate of $1.09 \text{ kg m}^{-2} \text{ h}^{-1}$. The freeze-dried polypyrrole-
477 pomelo peel composite, however, reached $1.29 \text{ kg m}^{-2} \text{ h}^{-1}$, which represents an efficiency of
478 80%.

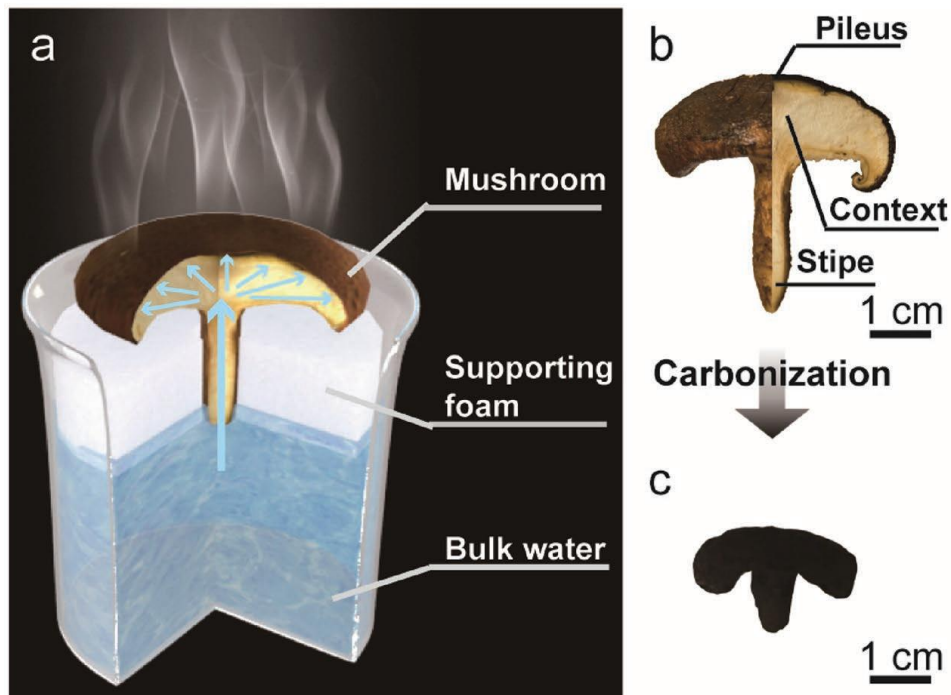


479
 480 **Fig. 13.** (a) Process for the production of a porous material from pomelo peel. Possible
 481 applications of this material: (b) water solar evaporation or (c) treatment of oil spills.
 482 Reproduced with permission from [59]. Copyright (2020) American Chemical Society.

483 3.3.5. Mushroom

484 Species not yet mentioned are fungi. Some authors explored the abilities of a well-known
 485 mushroom, the shiitake mushroom, as the main component of an evaporation device [60]. Its
 486 shape with a large round surface for light absorption and its stipe for water transport make it a
 487 suitable candidate for WESs (**Erreur ! Source du renvoi introuvable.**). The mushroom was
 488 pyrolysed at 500 °C for 12h and the resulting dark surface was capable of absorbing about
 489 96% of light. Hydrophilicity was present before and after carbonisation, as the surface
 490 functional groups remained the same. Combined with a porous structure, this resulted in a
 491 good capacity to transport water. This can be seen when evaporating without light, as the
 492 mushroom itself is capable of evaporating more than twice as much water as it would without
 493 it. This quantity is more than three times higher if the carbonised mushroom is used.

494 Furthermore, it is a relatively cheap product and carbonisation requires very little prior
495 process, only soaking in water for softening the mushroom and cleaning it. The resulting
496 water evaporation rate under 1 sun irradiation was $1.12 \text{ kg m}^{-2} \text{ h}^{-1}$ for the pristine mushroom
497 and $1.48 \text{ kg m}^{-2} \text{ h}^{-1}$ for the pyrolysed mushroom, which means an efficiency of 62% and 78%,
498 respectively.



499

500 **Fig. 14.** (a) Mushroom-based WES device, and mushroom anatomy: (b) before and (c) after
501 carbonisation. Reproduced with permission from [60]. Copyright 2017, Wiley-VCH.

502 **3.4. Other natural or bio-inspired materials**

503 Among the variety of living species available as precursors of materials for solar
504 evaporation, some unusual biomasses have been investigated: willow catkins, miscellaneous
505 plant wastes, algae or hollow carbon spheres that can be derived, for instance, from fish eggs.
506 Living matter, whether plant or animal, has also inspired researchers to create more efficient
507 evaporation systems as shown at the end of this section.

508 *3.4.1. Willow catkins*

509 Another plant derived biochar was created using willow catkins, a fluffy white blossom
510 that floats in the air or lie on the ground in spring [61]. After being activated by a 2 mol L⁻¹
511 KOH solution, the catkins were heated to 750 °C in a nitrogen environment at a rate of 5 °C
512 per minute. The resulting carbonised catkins were then washed with HCl until the pH
513 stabilised at 7. They were then added to a dopamine hydrochloride / Tris buffer solution,
514 stirred for 8h and filtered. The resulting membrane was able to produce an ER of 1.65 kg m⁻²
515 h⁻¹ with an efficiency of 90% under 1 sun illumination.

516 *3.4.2. Miscellaneous vegetable wastes*

517 Another biochar-based system has been proposed, but this time a variety of plant wastes
518 were used (banana and orange peels, fallen leaves, branches and bamboo) [62]. All these
519 wastes were carbonised and then crushed by hand and dissolved with ethylcellulose to obtain
520 a slurry. This slurry was then deposited on filter paper to form the steam-generating device.
521 This device had an evaporation rate of 1.21 kg m⁻² h⁻¹ with an efficiency of 80% while under
522 1 sun illumination.

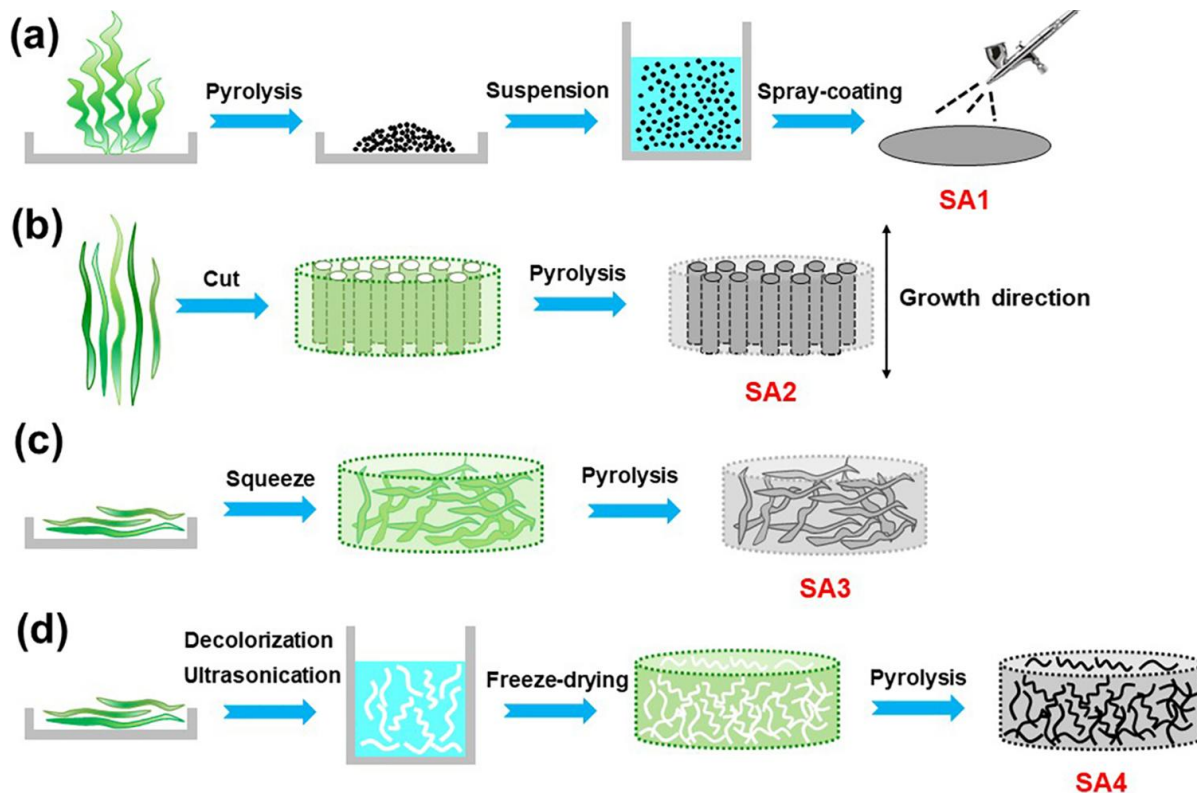
523 *3.4.3. Algae*

524 Algae bloom is a rapid development of algae in a specific area due to a disturbance of the
525 local ecosystem (fertiliser rejection, overfishing, etc.). The consequences on ecosystems and
526 on human health are multiple, especially a local lack of oxygen due to algae or bacteria
527 respiration during night or decomposition, respectively, strong odour and even potential
528 disease transmissible through fish consumption [63]. Therefore, harvesting these algae for use
529 may be a potential way to take advantage of this phenomenon while combating it.

530 The use of algae as water evaporation material makes sense because they live in water so
531 that they have a hydrophilic porous structure that provides pathways for water transport, and

532 they can be carbonised. Yang et al. first tested several routes to utilise the green algae
533 *Enteromorpha prolifera* [64]. The preparation processes are shown in **Fig. 15**. A first biochar
534 was obtained by direct pyrolysis and deposited by spray-coating onto a cellulose acetate
535 membrane. A second and a third biochar were made by orienting the algae in the direction of
536 growth or perpendicularly, respectively, followed by pyrolysis. A fourth biochar was obtained
537 after sonication, freeze-drying, and the resulting porous material, a cryogel, was pyrolysed. It
538 is useful to note that carbonised algae are hydrophilic. Each of the resulting photothermal
539 materials was placed on a polystyrene foam to act as a thermal barrier, equipped with a wick
540 to transport water. In the end, the measured water evaporation rate increased from the 1st
541 biochar to the 4th one, i.e., from SA1 to SA4 in **Fig. 15**. The most efficient material, SA4, led
542 to an evaporation rate of $1.23 \text{ kg m}^{-2} \text{ h}^{-1}$ and an efficiency of 84% while the least performing,
543 SA1, still reached $1.16 \text{ kg m}^{-2} \text{ h}^{-1}$ with an efficiency of 80%, thus demonstrating the relevance
544 of the use of algae for solar water evaporation.

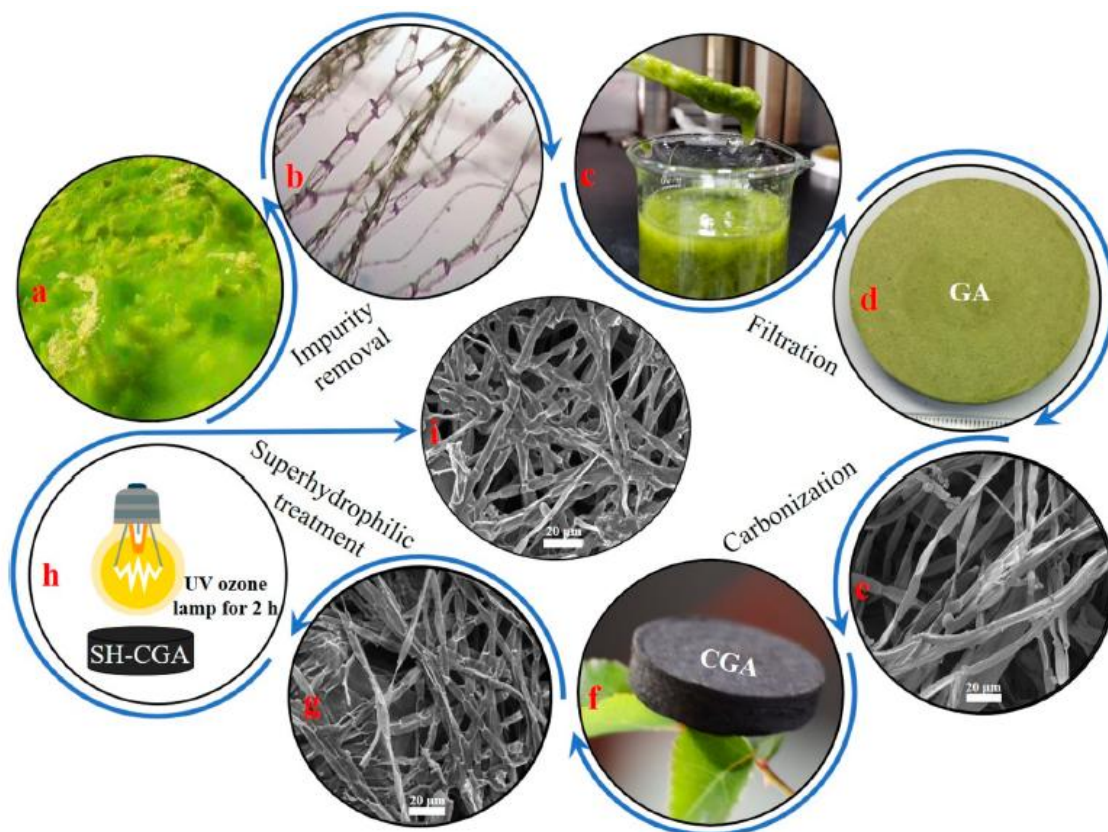
545 A similar study used the same algae to make a foam-like product, also supported on
546 polystyrene foam wrapped in cotton to avoid heating the bulk of water and providing water to
547 the surface. Results were best under a solar irradiation corresponding to 5 suns, with an
548 evaporation rate of $7.09 \text{ kg m}^{-2} \text{ h}^{-1}$ (i.e., a MERCP1 of $1.42 \text{ kg m}^{-2} \text{ h}^{-1}$) and an efficiency of
549 89% [65].



550

551 **Fig. 15.** Processes tested for producing WESs based on the *Enteromorpha prolifera* algae.
 552 Reproduced with permission from [64]. Copyright (2019) American Chemical Society.

553 Another study used green algae to create a superhydrophilic biochar [66]. Here, the
 554 pyrolysis was performed at 800 °C for 2h and the biochar was used without additional foam
 555 this time. Unlike the previous biochars presented in **Fig. 15**, which were hydrophilic, the
 556 present material initially had a water contact angle of 141°, meaning that it is hydrophobic. To
 557 make the surface of the biochar superhydrophilic, a photopolymerisation process of acrylic
 558 acid monomer was done at the surface, using benzophenone as a photo-initiator of the
 559 reaction. A water droplet placed on it was thus completely absorbed in 0.65 seconds. The
 560 product obtained is shown in **Fig. 16**. The evaporation rate achieved was 1.35 kg m⁻² h⁻¹ under
 561 1 sun with an efficiency of 83%.

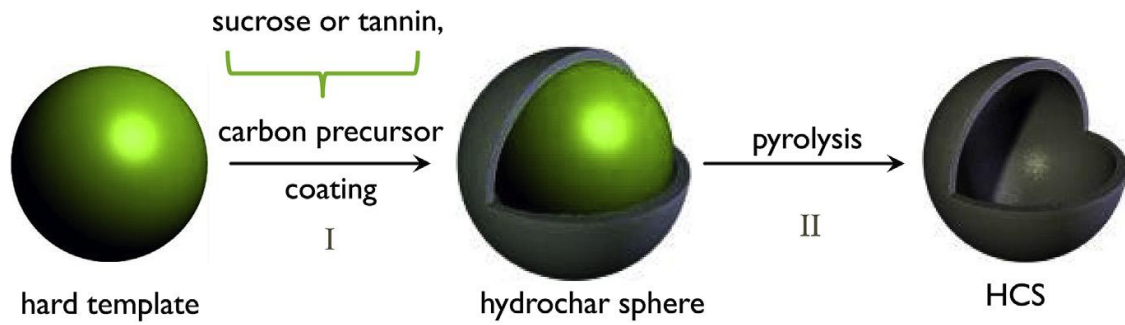


562

563 **Fig. 16.** Process to produce a WES based on superhydrophilic biochar derived from
 564 carbonised algae. Reproduced with permission from [66]. Copyright (2020) American
 565 Chemical Society.

566 3.4.4. *Hollow carbon spheres*

567 Hollow spheres are another type of material that can be used to improve the evaporation of
 568 water under solar irradiation. Unlike most of the systems presented here, these spheres do not
 569 require additional foam to float, precisely because they are hollow. In addition, the carbon
 570 allows them to have good light absorption with low emissivity. A manufacturing process for
 571 creating hollow carbon spheres is called hard-templating and is shown in **Fig. 17**. It consists
 572 of coating the surface of a sacrificial spherical template with a carbonaceous precursor, for
 573 example using a solution of monomers and various additives in an autoclave, to form a sphere
 574 coated with hydrochar. The subsequent pyrolysis step eliminates the internal template and
 575 converts the hydrochar surface layer into pure carbon. The result is a hollow carbon sphere.



576

hard template

hydrochar sphere

HCS

577 **Fig. 17.** Preparation scheme of hollow carbon spheres. Reproduced from [67]. Copyright
 578 (2019), with permission from Elsevier.

579 Hollow carbon spheres have been tested in [68] and reached $1.45 \text{ kg m}^{-2} \text{ h}^{-1}$ under an
 580 irradiation of 1 sun, which represents an efficiency of 63% taking into account the
 581 evaporation of water in the dark. Another recent study examined the effects of the size of the
 582 spheres, the nature of the carbon precursors used, the temperature at which the spheres are
 583 pyrolysed and the addition of metal salts to the solution used in the autoclave [67]. Using the
 584 biggest templates with sucrose as precursor, Fe^{3+} as graphitisation catalyst and a temperature
 585 of pyrolysis of 1500°C , the hollow carbon spheres presented an evaporation rate of 2.3 kg m^{-2}
 586 h^{-1} under 1 sun irradiation, for an efficiency of 80%.

587 While the precursors used (tannin and sugar, as shown in **Fig. 17**) are of biological origin,
 588 thus giving biosourced hollow carbon spheres, the templates used above were polymer beads.
 589 However, it is possible to use 100% bio-based materials to make such hollow carbon spheres
 590 by using commercial lumpfish eggs as templates [69].

591 3.4.5. Biomimetic materials

592 Although we do not know of any concrete examples where nature is directly used for solar
 593 evaporation, it can nevertheless be a source of inspiration for creating new materials. For
 594 example, the water lily was used by Xu et al. to create a device that reproduces its behaviour
 595 on water [70]. This bio-inspired system has three layers: a solar absorber at the top, a support
 596 layer at the bottom to float on the water, and a water chamber inside. This structure has been
 597 reproduced with a Cu-based solar absorber that rests on a polystyrene foam in such a way that

598 there is a gap between the two. The foam at the bottom has holes that allow water to fill this
599 gap. The measured evaporation rate was $1.27 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 sun irradiation, for an
600 efficiency of 77%.

601 Another study uses the liquid transportation properties of the asymmetric capillary ratchet
602 of the bird beak and the pitcher plant peristome surface [32]. It is carried out by 3D printing of
603 a resin loaded with sodium citrate particles that are removed after solidification to produce
604 micropores. CNTs form the photothermal layer, which allows more than 90% of the light to
605 be absorbed. The resulting evaporation rate under 1 sun illumination is $2.63 \text{ kg m}^{-2} \text{ h}^{-1}$ for an
606 efficiency of 96%.

607 **3.5. Gels**

608 Among the multitude of systems tested for solar evaporation, the most effective so far are
609 those based on gel. Gels, generally referred to as hydrogels or xero-/cryo-/aero-gels
610 depending on whether they are hydrated or have been dried by different methods, respectively
611 [71–73], are sponge-like or very light materials, respectively, which have a hydrophilic
612 porous structure and a low thermal conductivity. Hydrogels are the current leading materials
613 for solar water evaporation, as their evaporation rates are the highest. For example, under one
614 sun irradiation, a hydrogel based on polyvinyl alcohol (PVA) coupled with titanium
615 sesquioxide nanoparticles to absorb light achieved $3.6 \text{ kg m}^{-2} \text{ h}^{-1}$ for an efficiency of 90%
616 [74]. A PVA hydrogel coupled with polypyrrole achieved similar results of $3.6 \text{ kg m}^{-2} \text{ h}^{-1}$ for
617 an efficiency of 92% under the same conditions of irradiation [75]. Most gels thus typically
618 include PVA and a photothermal material to give them broadband light absorption properties.
619 This can be achieved through the use of metallic nanoparticles, graphene or polypyrrole, but
620 as the latter materials are generally expensive, biomass-based approaches such as those
621 suggested below should be preferred [76,77].

622 3.5.1. Aerogels

623 As mentioned before, algae in different forms have been tested. One of them, the fourth
624 material (SA4) in **Fig. 16**, was a cryogel (abusively called “aerogel” whereas it has not been
625 dried in supercritical conditions) that achieved an evaporation rate of $1.23 \text{ kg m}^{-2} \text{ h}^{-1}$ with an
626 efficiency of 84% [64]. Another cryogel (also improperly called aerogel for the same reason)
627 was produced from cellulose extracted from rice straw in the presence of reduced graphene
628 oxide used as photothermal material and sodium alginate used as strengthening agent [77].
629 The result is a material with a porous structure that can absorb 20 times its weight in water,
630 allowing it to continue producing steam long after it has been removed from water. It
631 therefore behaves like a sponge that does not need a continuous supply of water. An
632 evaporation rate of $2.25 \text{ kg m}^{-2} \text{ h}^{-1}$ has been measured, with 30% of this water evaporating
633 without any light energy, leading to a net ER of $1.29 \text{ kg m}^{-2} \text{ h}^{-1}$, which gives an efficiency of
634 89%. This means that a significant amount of energy is taken from the environment, allowing
635 a higher evaporation rate than usual.

636 Another system, shown in **Fig. 18**, used bacterial nanocellulose and reduced graphene
637 oxide to form a hydrogel [78]. Reduced graphene oxide was added during the growth of
638 *Gluconacetobacter hansenii* bacteria to form a hydrogel, which was then cleaned and freeze-
639 dried. The resulting cryogel (again referred to as aerogel in the original paper) then had a two-
640 layer structure, one (top) layer having photothermal evaporation capabilities and the other
641 (bottom) layer being adapted for water transport. This cryogel was only tested under the
642 equivalent of 10 suns, which gave an evaporation rate of $11.8 \text{ kg m}^{-2} \text{ h}^{-1}$ (i.e., a MERCP1 of
643 $1.18 \text{ kg m}^{-2} \text{ h}^{-1}$) for an efficiency of 83%.

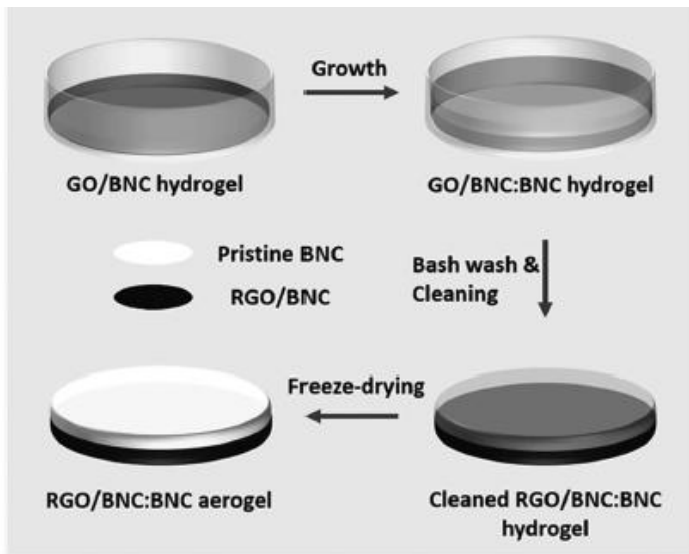
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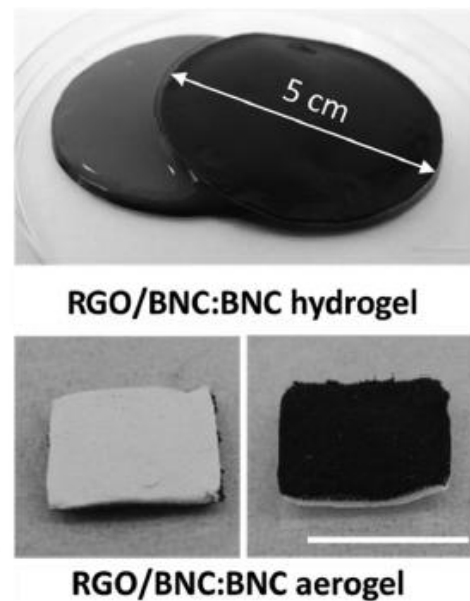
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(a)



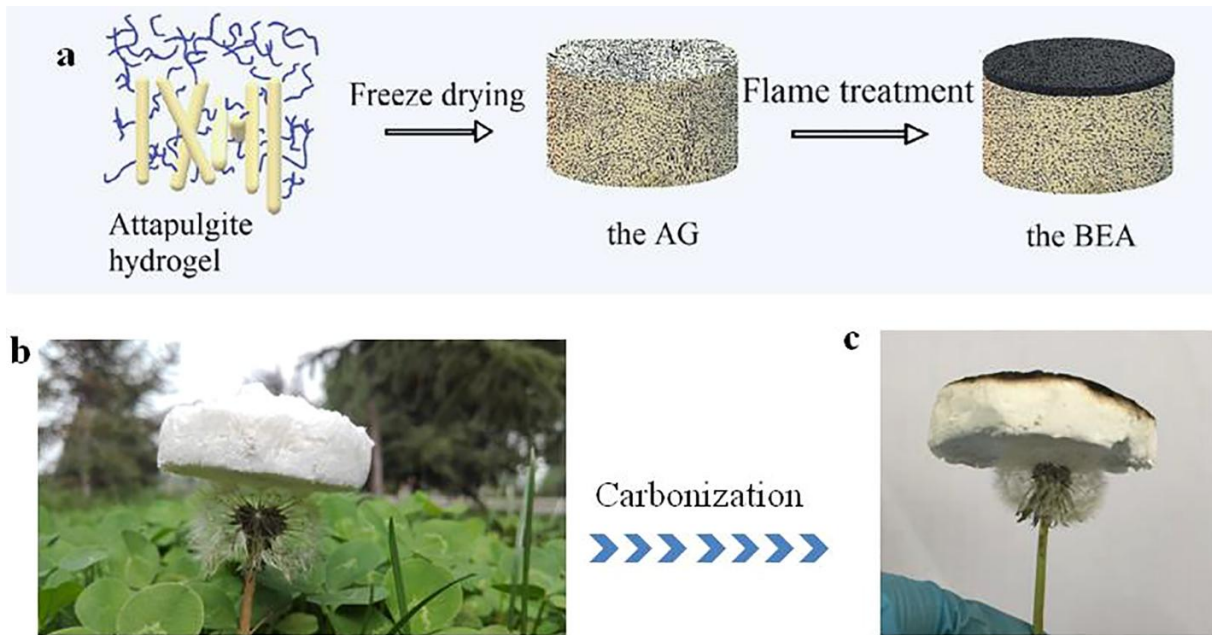
(b)



648

649 **Fig. 18.** (a) Process for the manufacture of bacterial nanocellulose (BNC)-based hydrogel and
650 aerogel; (b) photographs of the corresponding materials. Reproduced with permission from
651 [78]. Copyright 2016, Wiley-VCH.

652 Another unusual type of material found in nature is attapulgite clay. Although it is not bio-
653 based, it is a natural material so it is worth mentioning in the present review. In fact, the WES
654 made from this clay is based on an attapulgite – polymer composite, and this polymer could
655 also just as well be of bio-based origin. Jia et al. [79] therefore used this clay to produce a
656 two-layer composite. To do this, they first prepared an attapulgite – polyacrylamide
657 composite and then applied flame treatment with a butane torch. The surface of the resulting
658 lightweight two-layer composite (shown in **Fig. 19**) had a high light absorption of 99%, and
659 the composite structure had a porosity similar to that of attapulgite clay, which provides
660 sufficient pathways for the transport of water. Moreover, the thermal conductivity was 0.07 W
661 $\text{m}^{-1} \text{ K}^{-1}$, which is excellent for insulating the bulk water from incident energy. The resulting
662 evaporation rate was $1.2 \text{ kg m}^{-2} \text{ h}^{-1}$, which represents an efficiency of 85%.



663

664 **Fig. 19.** (a) Process of making a two-layer attapulgite – polyacrylamide composite; (b) the
 665 same composite on a dandelion before (b) and after (c) carbonisation of the upper surface.
 666 Reproduced from [79]. Copyright (2019), with permission from Elsevier.

667 *3.5.2. Hydrogels*

668 As mentioned at the beginning of section 3.5, the most efficient gels are hydrogels
 669 [33,74,75]. To date, only one study has reported a biomaterial used to prepare a hydrogel that
 670 can be used as WES, while other studies generally use hydrogels as precursors to make
 671 aerogels. The biomass-based hydrogel was made from glucomannan, a hemicellulose
 672 component in the cell walls of the *konjac* plant (*Amorphophallus konjac*), coupled with
 673 carbonised metal-organic frameworks nanoparticles as the solar absorbing additive and
 674 polyvinyl alcohol [76]. The water evaporation rate was $3.2 \text{ kg m}^{-2} \text{ h}^{-1}$ with an efficiency of
 675 90%. This rate is more than twice the average of all other systems. This is due to polyvinyl
 676 alcohol which is highly hydrophilic and, as the main polymeric molecular mesh, is capable of
 677 lowering the enthalpy of evaporation of water [3]. Water molecules indeed interact with fewer
 678 of their close neighbours through hydrogen bonds. Hydrogels have polar functional groups
 679 that can bind stronger with water molecules than the water molecules themselves [3].

680

Category	Type	Evaporation	Irradiation	MERCP1	Efficiency	Reference
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681 **4. Discussion**

682 *4.1. Performance of natural materials for solar evaporation*

683 Biomass has a very great potential because there are many ways to allow it to be the basis
684 of efficient evaporation systems while being a natural product with little or no value, and
685 possibly even a waste product, such as straw that is usually burned, which is harmful to the
686 environment, or the algae that swarm the coasts every year.

687 Table 1 lists most of the devices previously discussed category by category. Two
688 categories are dedicated to wood, as the number of studies is higher relative to other biomass
689 products. The first deals with carbonised wood, a category based only on transformation
690 processes without the use of foreign materials, while the second deals with coatings based on
691 metallic particles, among other things. The third category includes all other types of natural
692 (mainly biomass) products, such as non-wood plants, algae, and other more atypical raw
693 materials. It should be noticed that most of the materials in this category are biochars. The
694 fourth and last category is dedicated to gels.

695 The efficiency ranges from 53% for the laser-treated wood to 96% for the corn straw foam.
696 As previously said, this number alone does not express the level of performance of the
697 system. For this reason, the hybrid gel based on *konjac* plant of [76] shows only 90%
698 efficiency while evaporating almost twice as much water as corn straw foam of [51] that has
699 96% efficiency. Overall, carbonised wood subjected to 1 sun irradiation gives slightly lower
700 results than coated wood, with the exception of a few results at a higher solar intensity, for
701 which it has an efficiency greater than 80%. However, other carbonised biomass products,
702 such as the lotus seedpod, algae biochar and algae foam perform fairly well when carbonised.

703

		rate ($\text{kg m}^{-2} \text{h}^{-1}$)	(kW m^{-2})	($\text{kg m}^{-2} \text{h}^{-1}$)		
Carbonised wood	Basswood with drilled holes	1.04	1	1.04	75%	[80]
	Flames-treated basswood	1.05	1	1.05	72%	[42]
	Balsa wood	1.17	1	1.17	61%*	[81]
	Poplar with laser treatment	2.52	3	0.84	53%	[39]
	Wood	6.89	5	1.38	87%	[82]
	Flexible balsa & carbon nanotubes	11.22	10	1.12	81%	[19]
	Poplar	12.10	10	1.21	87%	[41]
	Basswood	12.20	10	1.22	90%	[83]
Coated wood	Basswood & CuFeSe ₂ nanoparticles	1.20	1	1.20	68%	[45]
	Crosswise basswood & graphite	1.20	1	1.20	80%	[40]
	Basswood & tungsten trioxide	1.28	1	1.28	83%	[46]
	Pine wood & polydopamine	1.38	1	1.38	87%	[36]
	Poplar & tannic acid – Fe ³⁺ complexes	1.85	1	1.85	90%	[38]
	Poplar & heat treatment and Au nanoparticles	4.02	3	1.34	84%	[39]
	Pine wood & polydopamine	7.54	3.5	2.15	135%	[36]
	Basswood & Pd nano particles	11.80	10	1.18	85%	[29]
	Basswood & graphene	14.02	12	1.17	83%	[84]
Other products based on natural or bio-inspired materials	Rice husk carbon foam	1.03	1	1.03	71%	[52]
	Rice straw	1.05	1	1.05	66%	[37]
	Radish biochar	1.18	1	1.18	72%	[57]
	Plant waste biochar	1.21	1	1.21	80%	[62]
	Algae biochar	1.21	1	1.21	83%	[64]
	Pomelo peel & polypyrrole	1.22	1	1.22	80%	[59]
	Water lily-inspired WES	1.27	1	1.27	77%	[70]
	Lotus seedpod biochar	1.30	1	1.30	87%	[53]
	Algae biochar	1.35	1	1.35	83%	[66]
	Loofah biochar	1.38	1	1.38	85%	[56]
	Hollow carbon spheres	1.45	1	1.45	63%	[68]
	Mushroom biochar	1.48	1	1.48	78%	[60]
	Willow catkin biochar	1.65	1	1.65	90%	[61]
	Corn straw foam	1.77	1	1.77	96%	[51]
	Carrot biochar	2.04	1	2.04	127%*	[58]
	Improved hollow carbon spheres	2.3	1	2.3	80%	[67]
	<i>Juncus effusus</i> fibrils	2.23	1	2.25	124%*	[50]
	Biomimetic 3D-printed structure	2.63	1	2.63	96%	[32]
	Lotus leaves	3.10	3**	1.03	74%*	[54]
	Algae carbon foam	7.09	5	1.42	89%	[65]
Bamboo & plasmonic particles	12.80	10	1.28	87%	[55]	

Gels	Attapulgite & poly acrylamide	1.20	1	1.20	85%	[79]
	Algae aerogel	1.23	1	1.23	84%	[64]
	Rice straw aerogel	2.25	1	2.25	89%	[77]
	<i>Konjac</i> glucomannan hybrid gel	3.20	1	3.20	90%	[76]
	Bacterial cellulose hydrogel	11.80	10	1.18	83%	[78]

704 **Table 1.** Natural materials for WESs reported in this review.

705 * Not mentioned in the original reference but calculated using Equation (5) with the enthalpy equation of [85].

706 ** Not mentioned in the original reference but deduced from the evaporation rate.

707 Some promising results stand out. These include pine wood with polydopamine which,
708 under 3.5 sun irradiation, is so efficient that the top layer of water boils and bubbles form and
709 burst. The authors hypothesised that when bubbles burst, the water near them “perspires” into
710 the air, which reduces the average energy required for evaporation [36]. Another remarkable
711 result is obtained with the *Juncus effusus* fibril device, which allows larger than usual
712 amounts of water to be evaporated due to its omnidirectional evaporation. Moreover, the
713 hybrid gel based on konjac plant [76] is, as previously mentioned, the system that evaporates
714 the most water under 1 sun irradiation and is close to the best hydrogels based on PVA
715 achieved to date [74,75].

716 **4.2. Ways to increase performance**

717 All these biomasses, with the few exceptions mentioned above, finally give rather similar
718 results, and this is quite normal since the porous structures are generally not very different
719 from each other and their chemical composition is also quite alike. So the only way to really
720 increase performance is, as we have seen, to:

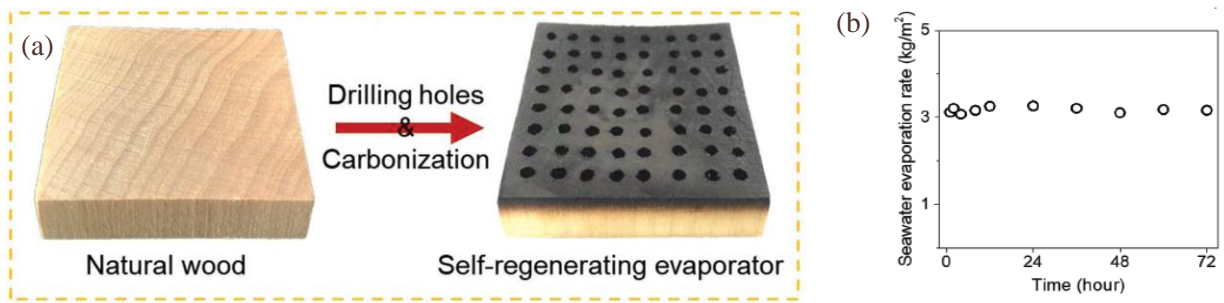
721 - Modify the surfaces by more or less complex treatments to darken the top of the materials
722 or to give them particular photothermal properties;

723 - Build systems from more suitable materials than biomass, which had proven to be
724 economically and environmentally interesting, but in a bio-inspired way. In this case, biomass
725 as such is no longer essential for itself, but it can be used as a source of inspiration to

726 implement resources that are not necessarily natural, as long as they prove to be more
727 efficient.

728 - Solve the problems of fouling and clogging by impurities and salts, which deserve
729 attention when the sustainability of performance and the life span of evaporation systems are
730 considered. Indeed, in addition to the efficiency of evaporation alone, recent studies have
731 begun to consider the longevity of the systems studied for seawater evaporation [14,24,65].
732 Given the salinity of seawater (3.5 wt.%), salt crystals form and tend to clog the pores
733 necessary for water transport and settle on the surface where evaporation takes place, making
734 the system less and less efficient. Two studies have been carried out on balsa wood. Zhang et
735 al. showed degradation by evaporation of seawater over several days and even hours when
736 evaporating Dead Sea water, which has a salt concentration of 27 wt.% [81]. On the contrary,
737 He et al. have shown that the efficiency remains constant for this material after 7 hours at
738 15% salinity under 6 suns [86]. The authors explained it by the bimodal structure distributed
739 in small pores allowing the transfer of water by capillarity to the surface, and in larger pores
740 allowing the evacuation of water with a high salt content to the bottom. These two studies
741 highlight the importance of the salinity level in comparing studies with each other. Based on
742 the previous observation of a hierarchical network of pores, one of the solutions developed for
743 wood was to drill holes, as shown in **Fig. 20(a)**. This method gives a very stable evaporation
744 rate over 100 h [80] for a salinity range of up to 20 wt.%.

745 On the same principle, bamboo has open channels that give it self-cleaning capabilities
746 with an efficiency of 87% at 3.1% salinity [55]. This also applies to corn straws [51], with an
747 efficiency of 94% at 20% salinity, which is remarkable because it does not require any
748 additional design. Basswood, on the other hand, has a self-cleaning capacity after exposure to
749 sunlight [29].



750

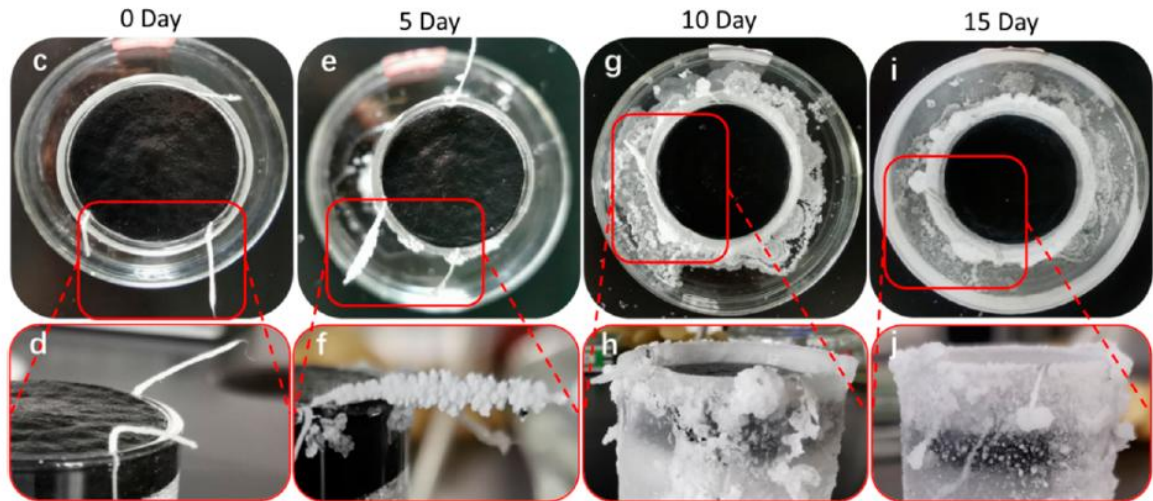
751 **Fig. 20.** (a) Method to avoid the effects of salt in a WES using seawater. Reproduced with
 752 permission from [80]. Copyright 2019, Wiley-VCH. (b) Rate of solar evaporation of seawater
 753 over time, using a *konjac* glucomannan hybrid gel. Reproduced with permission from [76].
 754 Copyright 2020, Wiley-VCH.

755 Hydrogels have been shown to be able to self-clean effectively through the diffusion and
 756 discharge of salt ions into the brine. The hydrogel developed by Zhou et al. showed no trace
 757 of crystallisation after 12 hours of testing for salinities between 5 and 20%, in contrast to a
 758 salinity of 25% where crystallisation was observed on the material, which greatly degraded
 759 the evaporation performance [11]. The performance of hydrogels does not degrade over time
 760 for unsaturated salt solutions (< 25 wt.%), which was confirmed by Guo et al. [76] (**Fig.**
 761 **20(b)**).

762 The water lily–inspired hierarchical design developed by Xu et al. is very interesting
 763 thanks to the complete separation between salt and water. Indeed, when the water is
 764 completely evaporated, the salt is stored under the WES with a constant WER throughout the
 765 process [70]. The concept of this system is to create a thin layer of water sandwiched between
 766 the upper hydrophobic absorber and the lower support that prevents crystallisation on the
 767 surface.

768 Another method was used to mitigate the effect of salt crystals in a layer around the WES
 769 by using the principle of the coffee-ring effect and the law of crystal nucleus growth [66].
 770 Cotton threads are placed on the rim of the container and when the NaCl solution soaks in
 771 cotton, it causes the salt to crystallise after evaporation. The advantage is that the layers of

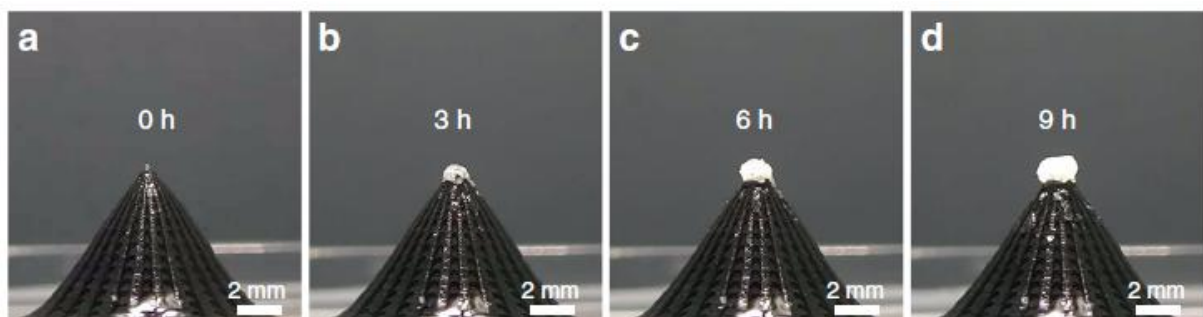
772 crystallised salt grow outside the evaporation system, so that the latter is not clogged and the
773 liquid phase is separated from the salt (**Fig. 20**).



774

775 **Fig. 21.** Photos showing the progressive rejection of salt rejection from an evaporation
776 structure based on superhydrophilic carbonised green algae, around which cotton threads were
777 installed [66]. Copyright 2020, American Chemical Society.

778 Wu et al. also used a salt crystallisation strategy outside the WES. To do this, thanks to the
779 design bio-inspired by a bird's beak by 3D printing, their conical system allows the salt to
780 crystallise at the top, allowing easy extraction of the crystals [32]. The system has a high
781 evaporation rate with an efficiency of more than 96% at 25% of salinity (**Fig. 20**).



782

783 **Fig. 22.** Time sequence of photos showing the localized crystallisation process at the top of a
784 biomimetic 3D evaporator inspired by birds' beaks [32]. Copyright 2020, Nature
785 Communications.

786 Finally, some studies have tested materials outdoors, i.e., under real conditions.
787 Surprisingly, the pine wood – polydopamine composite was found to be much more effective
788 under 1.04 sun outdoors than under 1 sun in a controlled environment. The evaporation rate
789 under real sunlight was indeed $2.13 \text{ kg m}^{-2} \text{ h}^{-1}$, i.e., higher by $0.70 \text{ kg m}^{-2} \text{ h}^{-1}$ than in the lab
790 [36]. The WES made from rice straw gave about $0.75 \text{ kg m}^{-2} \text{ h}^{-1}$ during sunny days of 9.5 h
791 under 0.8 to 0.9 sun (based on the original article measurements) [37]. Finally, the algae-
792 based biochar produced $0.95 \text{ kg m}^{-2} \text{ h}^{-1}$ under 0.8 sun ($\text{MERCPI} = 1.18 \text{ kg m}^{-2} \text{ h}^{-1}$) [64].

793

794 **5. Conclusion**

795 In this review, the existing variety of solar water evaporation systems based on biomass
796 and other natural products was reviewed. At present, wood has been tested from different
797 perspectives, from carbonising or coating to give it better photothermal properties, to drilling
798 holes to improve its durability in use, or cutting it perpendicularly to the longitudinal direction
799 to use its anisotropy as an advantage. Various plants have also been investigated in different
800 forms. First of all, their original shape allows them to be used as pipes for the stems, as
801 photothermal surfaces for the leaves, or in the form of foam due to their natural porosity.
802 Algae have also been used as a material for water evaporation devices, in the form of biochar
803 or even aerogel. Indeed, gels can be prepared from materials of natural origin, in order to
804 reduce their cost and environmental impact with respect to synthetic ones. Even more atypical
805 materials have been explored, such as food waste, fungi or clay. Finally, biomimicry also
806 appears to be a promising way to significantly improve the performance of solar evaporation
807 systems, even if in this case nature is no longer used as a resource but as a model. This
808 approach is particularly effective in increasing the longevity of the WESs, especially in the
809 presence of salt.

810 Overall, water evaporation systems based on natural materials, and in particular on
811 biomass, are more than capable of meeting the need for clean water production with efficient
812 conversion of solar radiation without the need of an additional energy source. However, as
813 some works have already shown, durability must be taken into account, as it can seriously
814 affect the efficiency over a few cycles. This is particularly the case when using these devices
815 to remove traces of oil or soil contaminants from the water, or when desalinating seawater, as
816 pollutants or salt can quickly clog up the systems. Durability is therefore a necessary criterion
817 when studying a material for solar evaporation and must be taken into account in future
818 studies. In addition, further investigation and modelling of the interaction of water within
819 materials will allow for more alternative ways to achieve higher evaporation rates.

820

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