



3D-Printed Absorbers for Solar-Driven Interfacial Water Evaporation: A Mini-Review

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Abstract. Solar-driven interfacial water evaporation (SWE) is considered as a promising sustainable solution for clean water production especially for remote and off-grid communities. Various approaches have been developed in the last decade to improve the evaporation and thermal efficiency of the system, and to make it more robust for long-term operation. In recent years, 3D printing has emerged as an attractive method to fabricate simple and complex absorber geometries for SWE. In this mini-review, we present the new developments of 3D-printed solar absorbers including the various designs, fabrication strategies, challenges and opportunities. This study hopes to provide more insights into the use of additive manufacturing for improving the absorber design and performance of SWE.

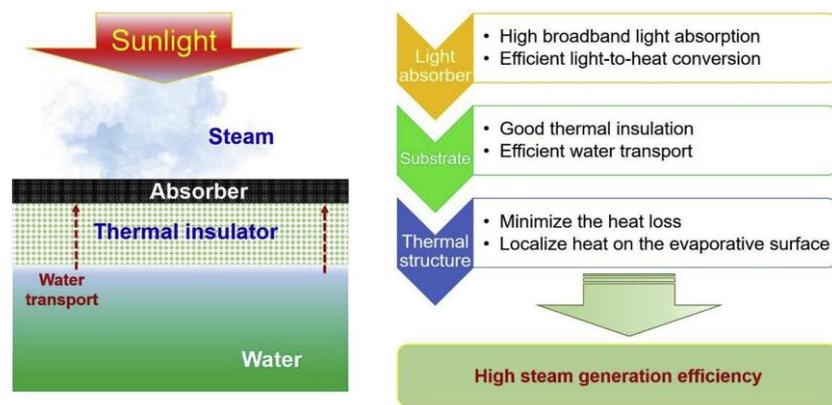
Keywords: Solar water evaporation, 3D printing, desalination, 3D absorber

(Received 2021-04-09, Accepted 2021-04-30, Available Online by 2021-04-30)

1. Introduction

Population growth and rapid urbanization has resulted in increasing water scarcity issues around the world. This has driven the rise of desalination technologies for the production of freshwater from unconventional yet abundant sources such as seawater and wastewater [1]. However, the current state-

of-the-art desalination technologies such as reverse osmosis and multi-stage flash desalination are mostly centralized and are energy-intensive which are heavily based on fossil fuel use. In recent years, solar-driven interfacial water evaporation (SWE) has attracted increasing interest as a decentralized desalination technology that can produce freshwater, especially in remote areas, utilizing solar energy making it more sustainable [2]. SWE works via the process of evaporation-distillation, wherein a photothermal material floating on the source water is used that can absorb solar light and convert it into heat to evaporate the water at the absorber-water interface (see Figure 1 for schematic) [3]. The water vapor is then condensed back by a condenser and collected as clean water. This desalination technology is mainly passive, wherein no pumps or moving parts are needed, and is attractive for application especially for remote areas where sunlight is abundant and connection to electricity grid is a challenge [4].



Solar-driven interfacial evaporation device

Figure 1. Schematic representation of the common solar-driven interfacial water evaporation system based on 2D-plane solar absorber and the effect of key components [3]

However, SWE still suffers from low water production and stability issues such as salt crystallization and heat losses for long-term use. The absorbers are either made of plasmonic nanoparticles [5], carbon-based materials [6], semiconductors [7], biomass [8], and polymeric materials. The most common design is 2D solar absorbers, where it is floated horizontally on top of the source water to enable evaporation, but still, they have low evaporation rate due to low overall effective surface area and high heat losses. To improve the performance, 3D absorber design has been considered which increases the overall surface area, and enables internal solar light reflection that can enhance the overall solar-thermal conversion efficiency [9]. In recent years, the 3D printing approach for the fabrication of 3D solar absorbers has attracted increased interest due to its ease of fabrication and the ability to make complex shapes with little geometrical constraints [10]. A number of new studies show good SWE performance of various 3D-printed absorber designs from cone-shapes, to hydratable plastics, to all-in-one evaporators, etc. Several reviews related to SWE have been published but none so far focusing on the potential of 3D printing for SWE. Thus, this mini-review will present the recent progress of the use and potential of 3D printing for the fabrication of absorbers for solar-driven interfacial water evaporation, and discuss its various challenges and opportunities.

2. 3D Printing Techniques for Solar-Driven Water Evaporation

3D printing is increasingly explored in the field of solar-driven interfacial water evaporation especially with the advent of new fabrication techniques and printable materials that are continuously developed. 3D printing offers a lot of potentials to ensure rapid prototyping of these materials [11]. In brief, 3D printing is a layer-by-layer fabrication technique that enables production of 3D structures according to a computer-aided design (CAD) model. Figure 2 shows the various steps in 3D printing process. Since

it is based on a CAD model, it can basically fabricate any designs from simple to very complicated geometries [12]. 3D printing can be done in various ways such as by material extrusion, laser sintering, vat polymerization, direct-ink writing (DIW), and jetting [13]. The accuracy, resolution and productivity vary depending on the type of printer and virgin material (e.g., thermoplastics, metals, ceramics, etc).

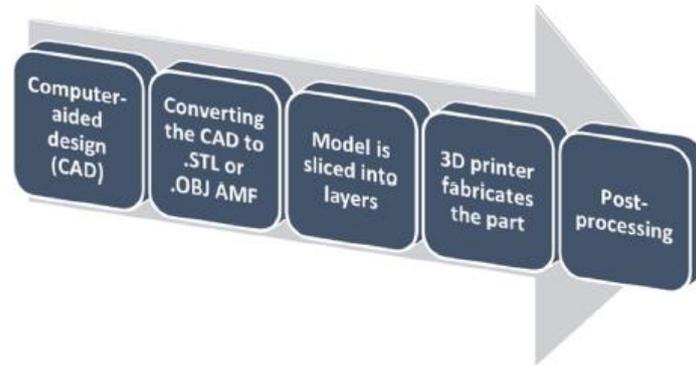


Figure 2. The five general steps in the 3D printing process [10].

In SWE, the absorbers are usually in the macro-scale and can also be designed to have microscale structures especially for water pathway channels. Material extrusion approach or fused deposition modeling (FDM) is one of the most common techniques used for SWE absorber preparation due to its fast processing and relatively cheap cost. A thermoplastic is usually used, and is melted and extruded in the printer following the 3D model design in the computer. There is an opportunity to combine the virgin material with photothermal nanoparticles before printing. This printing technique commonly requires post-processing. Another 3D printing method is digital light processing (DLP) (vat polymerization), wherein a thermoset photopolymer resin is cured upon exposure to an arc lamp. The light follows curing of pre-determined CAD model design at a single projection, making it fast and with good resolution. One study [14] employed DLP continuous 3D printing system to fabricate 3D absorber structures with surface distributed micropores for SWE. The base material was a polyacrylate-based resin that was incorporated with carbon nanotubes and a pore-former material, signifying the technique's versatility for use with composite resin material. In a recent study, DIW technique, a form of extrusion method, was utilized for the fabrication of a 3D hydratable plastic solar absorber. In DIW, the key consideration is to have a printable ink with the right rheological properties, i.e., is able to be extruded easily via the pneumatic air pressure from the 3D-printing system, and retain its shape immediately after extrusion without defects. Therefore, there is a need to play with the various fabrication parameters like ratio of polymer, solvent, and nanoparticles to achieve the right viscosity and consistency of the solution for writing. The size of the printed inks will also depend on the size of the nozzles. There is a great opportunity for this technique to use multi-materials by utilizing multi-nozzles with different solutions. The use of 3D printing in SWE is still at an early stage, but it looks very promising with still a lot of opportunities for further optimization and improvements.

3. Design and Performance of 3D-Printed Solar Absorbers

Recent studies have shown the positive enhancement in solar water evaporation performance when a 3D design is used for absorbers. Thus, 3D printing has come in handy for this application as it can produce complex shapes with high accuracy and scalability. Among the various 3D printing techniques, vertical printing, stereolithography, digital light processing (DLP), and extrusion methods have been so far used for SWE. This section will discuss some of the latest developments in terms of design and SWE performance of 3D-printed solar absorbers in literature.

One of the main issues for 2D flat solar absorbers is the direct contact of the absorber to the water surface, which can lead to high conduction heat loss and salt accumulation. Thus, some groups have tried isolating the absorber from water, which resulted to improvements in efficiency, however, it still

suffers from reflective light losses due to the 2D-plane geometry of the absorber [3]. To address this issue, 3D absorber designs have been tested with isolated absorber configuration. However, most of the reported 3D designs are just simple structures made from folding of materials or just simple fabrication methods, which has also limitations on their stability and the possible designs that can be prepared. Hence, 3D printing poses a great promise in the development of novel absorbers without any geometrical design limitations.

This was the approach taken by Cao et al. [15] when they fabricated a tree-inspired, cone-shape Janus solar absorber via 3D printing of acrylonitrile-styrene-acrylate (ASA) copolymer for SWE application. The 3D-printed cones were designed with various apex angles from 30-90°, which could easily be fabricated by 3D printing. The hydrophobic ASA itself acted as the solar absorber, which had a solar absorptivity of ~99.80% across a wide solar wavelength (200-2,200 nm). A hydrophilic air-laid paper was wrapped around the outside of the cone, forming a dual-wetting layer or a Janus design, i.e., an outer hydrophilic part, and an inner hydrophobic part, essentially isolating the evaporating surface from the water wicking surface. The lower narrow end of the cone was immersed in the source water, with an expanded polystyrene (EPS) foam wrapped around as a floater. This configuration enables the continuous wicking of water to the upper part of the cone via the air-laid paper, leading to water evaporation upon light-to-heat conversion at the absorber part. Under 1 sun illumination, the solar evaporation rate reached 1.713 kg/m²h which was stable for 14 days utilizing 3.5wt% NaCl solution. This high performance was attributed to the excellent heat localization effect, constant water supply to the absorber, and self-cleaning ability from salt crystallization.

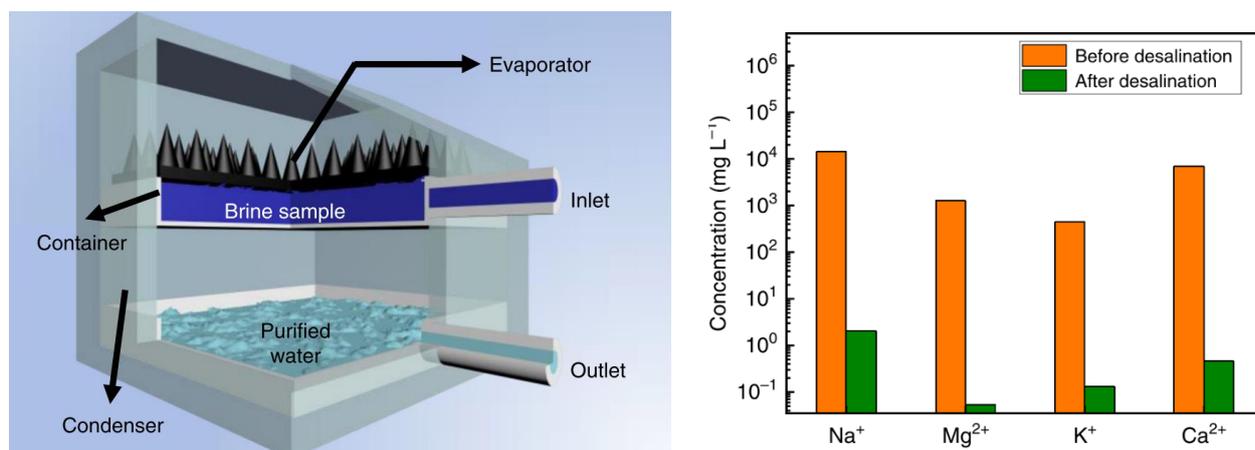


Figure 3. Solar desalination and durability of the biomimetic 3D evaporator. **a.** Scheme of the batch purification prototype which simulates the practical solar water purification apparatus using 3D evaporator. **b.** Measured concentrations of four primary ions in the actual seawater sample from Jiaozhou Bay, the Yellow Sea before and after desalination. Orange and green columns represent the metal ion concentrations before and after purification, respectively (images adapted from [14]).

Another study [14] utilized a biomimetic 3D cone-shape structure inspired from bird beak and pitcher plant peristome surface (see Figure 3). This cone-shape absorber was fabricated by size-refilling dependent DLP 3D printing of a polyacrylate-based UV curable composite resin containing carbon nanotubes (CNTs) and citrate sodium powder. The incorporated CNTs act as the photothermal material, while citrate sodium powder acts as pore inducer. The 3D printed parts with surface distributed micropores were then subjected to plasma post-treatment to endow hydrophilic property to the surface. Asymmetric grooves were provided along the cone that allow a continuous water suction pathway. The presence of the surface micropores together with the gradient microgravity array was found to help in the fast suction of water, even faster than a porous filter paper as a comparison. The 3D cone absorber

with absorptivity of $>90\%$ of input light was floated with the wide base touching the water, and SWE experiments were conducted at 1 sun irradiation. Results showed high evaporation rate of $1.72 \text{ kg/m}^2\text{h}$ in a closed system with 3.5 wt% NaCl solution for the biomimetic 3D cone absorber compared to $1.07 \text{ kg/m}^2\text{h}$ for a 2D plane absorber fabricated with the same materials. In an open system and at 25 wt% NaCl solution, the evaporation rate was found to be $2.63 \text{ kg/m}^2\text{h}$ with an energy efficiency $>96\%$. Interestingly at this high NaCl solution, salt crystallization only happened near the apex of the cone, and was easily detached. This high performance was attributed to the uneven heating and evaporation due to the cone structure, where near the apex part showed higher temperature due to thinner water film and faster evaporation, compared to the bottom wider part of the cone. In addition, the gradient liquid film thickness along the grooves also enabled constant water pumping and evaporation that helps in the continuous SWE process. The 3D cone design was found superior in SWE performance when compared to a 3D columnar structure with similar grooves and micropores as a fabricated control. The precise fabrication via 3D printing of the 3D cone absorber and its unique characteristics with grooves and micropores has definitely helped in the excellent performance of the SWE.

Li et al [16] utilized an extrusion 3D printing approach to fabricate an all-in-one solar evaporator for SWE. The design was a box-like evaporator with one open side (see Figure 4a and 4b). The upper part was made of CNT/graphene oxide (GO) layer that serves as the photothermal layer. Then below it is a GO/nanofibrillated cellulose (GO/NFC) layer with mesh-like structure that acts as a support and a water-wicking channel. In addition, four walls of GO/NFC were also 3D-printed, which contributes to the suction of the water towards the top photothermal material. All the parts were 3D-printed and formed as one structure (see Figure 4). The CNT/GO photothermal layer obtained high solar absorptivity ($>97\%$), and together with the high porosity of the absorber ($\sim 97.3\%$), this resulted to an evaporation rate of $1.25 \text{ kg/m}^2\text{h}$ under 1 sun illumination (see Figure 4f). This good performance was attributed to the integrated structure of the CNT/GO layer and the GO/NFC layer, ensuring a continuous supply of water to the CNT/GO layer, while facilitating heat localization and effective solar light-thermal conversion.

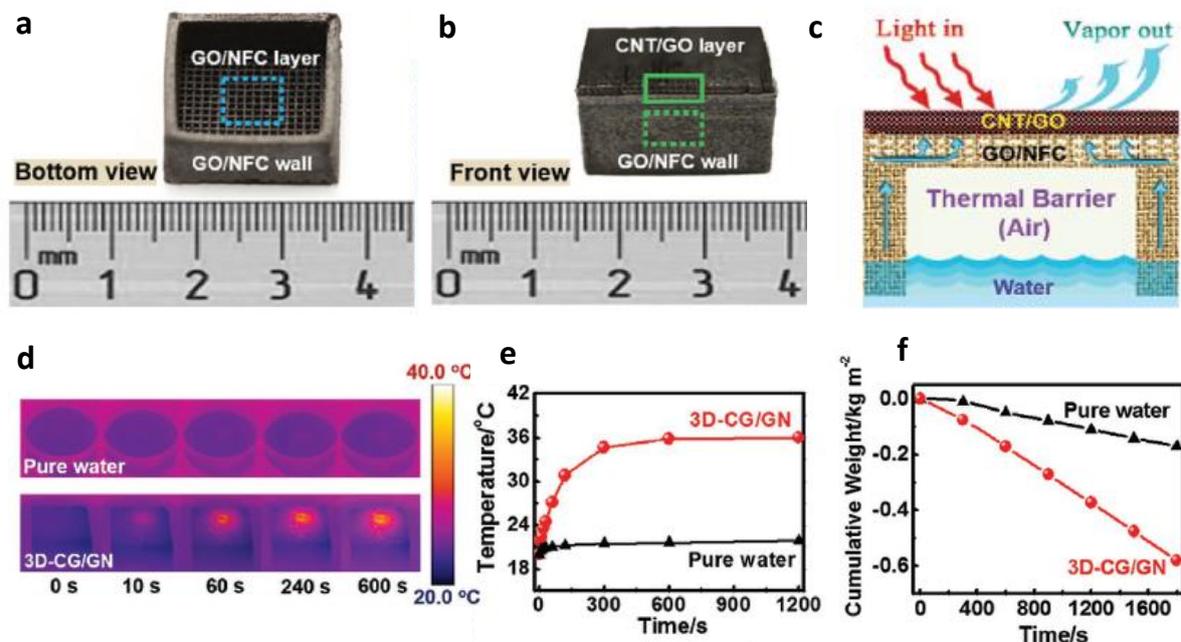


Figure 4. Photographic images of the 3D-printed evaporators: (a) bottom view, (b) front view; (c) schematic illustration of the SWE system; (d) infrared images of pure water only and that with the 3D all-in-one evaporator upon 1 sun illumination; (e) graph showing changes in surface temperature of pure water only and with the 3D evaporator with respect to time; (f) Mass change of water over time under solar illumination for pure water only and for the 3D evaporator (images are adapted from [16]).



Another study [17] by the same group designed a jellyfish-like solar absorber fabricated by vertical 3D printing technique. Carbon black/GO (CB/GO) and highly-concentrated GO (HC-GO) solutions were prepared and extruded using a 3D printer. First, the CB/GO layer was printed into a mosquito coil-like shape, and then HC-GO pillars at specified distances were vertically printed. After printing, the materials were placed in a freeze dryer and then annealed at 150°C to obtain the stable printed solar absorber structure. The integrated CB-GO with GO pillars structure was then embedded into an EPS matrix with matched holes for the GO pillars. The CB-GO layer serves as the photothermal material (high absorption of 99% at wide wavelength), while the GO pillars act as directed water transport channel (as they are hydrophilic due to functional groups), and the EPS foam is the insulating support and floater. Due to the directed water channel, there was less contact area between the absorber and the bulk water, thus decreasing the heat losses. This unique 3D-printed design displayed good energy conversion efficiency of 87.5% under one sun irradiation, and obtained an evaporation rate of 1.27 kg/m²h. The jellyfish-like design is interesting but only achieved lower than the theoretical evaporation rate limit perhaps due to the lower water pumping capacity from the few GO pillars.

Due to the challenge of controlled assembly of 2D building blocks, He et al. [18] utilized DIW technique to fabricate a carbon nitride-based hybrid aerogel with patterned microscopic structures as solar absorber for SWE. Various printing approaches were tested to check the viability of the DIW technique (see Figure 5). The resultant hybrid aerogel showed high visible light absorption and obtained 2.5 times greater activity compared to the control sample. Another interesting recent study by Koh et al. [19] also utilized DIW 3D printing technique to fabricate hydratable plastics made from amorphous regenerated cellulose with various designs. The hydratable plastics have two main components, the water transporting substrate (cellulose acetate), and the light absorbing surface (cellulose acetate with carbon black nanoparticles), both of which were 3D printed. The substrate was designed to have woodpile structure, formed by alternating perpendicular stacked layers with square pores to allow water wicking channels. The light absorber layer was also designed into two ways, one as a plate-like solid material, and the other one is a criss-cross woodpile structure. Results revealed that using 3D-printing technique has significantly improved the rehydration rate and exhibited long-term stability and anti-salt-fouling ability in evaporating saline water. The evaporation rate was 3.01 kg/m²h at 1 sun irradiation, which was way higher than the theoretical limit. This high performance was attributed to the ability of the hydratable plastic for vaporization enthalpy reduction, mainly due to the weaker cellulose-water hydrogen bonds and more deviation from non-linearity. At much concentrated solar irradiation (3 sun), it achieved >7 kg/m²h evaporation rate, which is the highest so far reported at such light intensity. This study signifies that with proper architectural design via 3D printing, rehydration rate can be improved which can lead to enhanced SWE performance.

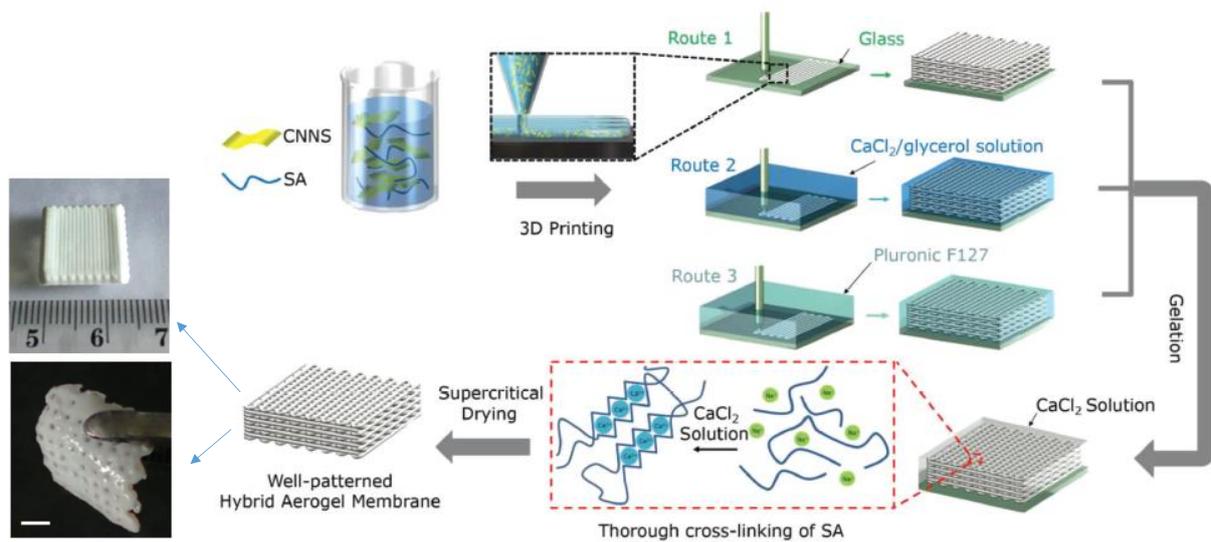


Figure 5. Schematic of the preparation and fabrication of the 3D-printed hybrid aerogel solar absorber. Photographic images of the fabricated materials can be seen on the two lower left images (adapted from [18]).

Based from literature, only few studies have yet used 3D printing for solar absorber fabrication and SWE application, but the trend is starting to increase. Compared with membrane fabrication for other desalination and water treatment processes, the structures for SWE absorber do not generally need very high printing resolution (micro to mm scale is enough), thus it presents good potential as a fabrication technique. Besides, there is good accuracy with 3D printing, which is very beneficial for the proper design and manufacture of absorbers leading to high evaporation rate performance as indicated in the studies mentioned above.

4. Challenges and Opportunities

Up until now, water shortage is a serious global issue that urgently needs to be addressed [16]. Hence, a technology that allows freshwater generation and offers reliability and efficiency are of great interest in dealing with this global water crisis, especially for people living in off-grid areas [20]. While there are emerging techniques being employed, there remain several challenges that require further study to fully understand the complexity of solar-driven interfacial water evaporation using 3D printing technology. 3D printing promotes sustainable manufacturing as it has many applications related to water and the environment. Generally, 3D printing has lesser waste compared with other manufacturing methods and highly complex/intricate designs may be produced. Though 3D printing looks promising for application in SWE, there are still some challenges that need to be addressed.

As absorbers are constantly subject to light irradiation, there is a need to further develop new materials that are chemically, thermally and mechanically robust and will not degrade easily for long-term operation and that can be 3D printed. Examples of such are high performance polymers to increase strength of materials for both solar absorption and water transport. The main consideration is the strength, weight, surface finish, etc. Strength is needed when cleaning the part/material. 3D printing is still limited in its capability to print at ultra-high resolution, though much more advanced printers are now being introduced. The capability to accurately print micro to nano roughness and pores would be very promising for SWE especially on providing precise wicking channels or surface roughness/grooves. Generally, 3D printing is still relatively more costly compared to other conventional fabrication techniques primarily due to slower fabrication times and the need for specific materials for printing [21]. This is also related to the upscaling capacity when printing large amounts or big size solar evaporators. The issue of safety during 3D printing due to emission of particulate matters and volatile



organic compounds is an issue that still needs to be addressed as its environmental and health impact is still not yet fully understood at this time.

Aside from these challenges, there are great opportunities for further development and study of additive manufacturing for SWE. One is the potential of 4D-printed materials, where the solar absorber can be designed with stimuli-responsive materials [22] enabling the opening or closing of water wicking channels when exposed to stimuli such as temperature, pH, etc. For example, it would be great to see a solar absorber with pores that open wide at lower temperature especially at night time when sun is not shining, which can lead to re-migration of precipitated salts to the bulk water for dissolution and maintain a clean surface. Another opportunity for research is the use of composite solutions for 3D printing. Many of the 3D printing works are based on single-material fabrication, but the versatility of 3D printing allows combination of materials [23] especially for SWE, where photothermal nanoparticles are usually needed in the polymeric matrix. 3D printing is a promising approach not only for the production of solar absorbers but also as a way to fabricate all-in-one evaporators or parts of SWE in an integrated design. Its potential is enormous especially if newer high-resolution 3D printers will become available, and increased accuracy and versatility in base material are used.

5. Conclusion

This study presents the various progress and developments of the use of 3D printing for absorber preparation in solar-driven interfacial water evaporation applications. So far, only few studies are available in literature utilizing 3D printing for SWE, but it presents an enormous potential. It can be used for the efficient and fast fabrication of solar absorbers, by the direct printing of polymeric absorbers, or printing of resins incorporated with photothermal materials. Additionally, all-in-one evaporators can also be directly prepared by 3D printing, with advantage of robust integrated design, and capability to fabricate complex structures. Results in literature show enhanced water evaporation performance of properly-designed 3D-printed absorbers, even surpassing the theoretical limit. However, it is also acknowledged that there are various challenges that still need to be addressed such as resolution limitation, overall cost, and health and environmental safety. Overall, 3D printing presents itself as a very exciting technique for rapid fabrication of efficient solar absorbers/evaporators for SWE, and further studies are ought to be done in this area.

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