Naturally Inspired Highly Stable Salt-Resisting Material for Solar Water Desalination

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Abstract: Solar desalination is a promising method for producing drinkable water, but salt accumulation on the evaporator surface leads to reduced light absorption. This study presents a nature-inspired self-driven salt-resistant material (NI-SRM) for a salt-free solar desalination system. The introduced material has great porosity to generate desirable capillary force to lift up water to the evaporator surface, which can function as water pumping channels. The concentration of salt solution in the absorber could not achieve saturation and produce salt via solar evaporation during the experiment. The NI-SRM had an evaporation rate of 3.02 kg·m⁻²·h⁻¹ under 1 sun irradiation and outstanding long-term stability for the desalination of high-salinity brine with no apparent salt deposition. An 80% efficiency was achieved for 24 h under 1 sun (10 kW·m⁻²). Through control experiments, the multifunctional NI-SRM was found to play a critical role in preventing salt accumulation over the surface under 1 sun. The newly developed NI-SRM had a higher evaporation rate with higher stability in a high-salinity brine solution. The developed material is environmentally friendly and cost-effective.

Keywords: nature-inspired salt-resisting material; solar-powered desalination; self-salt replenishment; multifunctional

1. Introduction

Environmental pollution and its abatement have long been a critical focus of research. The problem of removing pollutants from water and waste water has grown with rapid industrialization. Saw dust is used for removing heavy metals, dyes, oil, and other salts from water [1,2]. Fresh-water scarcity is now a major global issue. Solar vapor generation is one of the most promising strategies for desalination and water purification due to the availability of solar energy [3,4]. As a natural and sustainable resource, sunlight is an attractive option for converting large amounts of contaminated or saline water into clean water [5]. There are several techniques that have been used to promote solar water desalination, such as the long-term stable cost-effective solar desalination method [6], membrane filtration method [7], multistage flashing [8], polyaniline [9], carbon [10,11], adsorption [12,13], precipitation [13], carbon-based materials (e.g., graphene, aerogel, carbon nanotubes, and graphite) [14–16], solar-enabled desalination, the activation of coconut carbon [17], and the development of hydrophobic membrane [18]. In a one-step protocol, hydrophobic membranes for desalination and toxic organic pollutant removal were created using polyamide and PDMS (polydimethylsiloxane) chemistries. Polyamide and PDMS curing are orthogonal, and co-curing these networks imparts hydrophobicity to the thin
film composite membranes. The membranes have improved pesticide adsorption from the feed water while retaining excellent salt rejection capability (97 percent NaCl rejection), giving them a multifunctional character [19]. Another study reported the idea of a photo thermal membrane with self-healing hydrophobicity for interfacial solar heating based on polypyrrole (PPy) coated stainless steel (SS) mesh. The membrane was created by depositing PPy, a polymeric photothermal substance, onto an SS mesh substrate, then modifying the PPy coating with fluoroalkylsilane to achieve desirable hydrophobicity [20]. Kujawa et al. investigated the use of fluorine-free modifiers in the highly effective hydrophobization of ceramic membranes. The ceramic materials are then checked in the desalination phase using the membrane distillation (MD) technique. A significant aspect of the research was determining the effect of grafting agent sort and alteration conditions on membrane efficiency in MD [21]. For heat dissipation, a thermal-insulator layer in the form of double/multilayer structures, such as Aluminum Anodic Oxide (AAO)/metal nanoparticles, may be integrated into the construction of photothermal membranes [4]. Numerous studies have shown that hybrid membranes can effectively resist heat transfer in water. For example, carbonized mushrooms exhibited an optimal evaporation rate of 1.475 kg-m\(^{-2}\)h\(^{-1}\) under solar light (1 KW-m\(^{-2}\)) [22]. Despite significant attempts, three issues have hampered the practical implementation of these membranes. The first is the high cost of fabrication. The majority of photothermal membranes have been created using noble metals (such as Au) or complex fabrication processes. The second issue is the problem of portability and transportation, because most photothermal membranes (such as graphene foam and aerogel) are rigid and fragile. Salt removal during desalination is the third and most important challenge. Solid salt separation (such as NaCl and KCl) weakens photothermal membrane nanostructures while blocking incident sunlight. Many trace elements from water can be successfully adsorbed by activated carbon, but the high cost of activated carbon makes it uneconomical for large-scale applications [1]. Many agricultural byproducts have almost no commercial benefit, and others such as sawdust, which is abundant in lumber mills, often pose a disposal challenge. The use of sawdust for removing pollutants would benefit both the environment and wood agriculture: polluted waters would be purified, which constitutes a good application of sawdust. In recent years, scientists have focused on adsorbent materials. Sawdust is one of the most attractive products for eliminating contaminants from water and waste water, such as dyes, salts, and heavy metals.

A variety of experiments on the adsorption of dyes, toxic salts, and oil from water using sawdust as an adsorbent have been published [1,23,24]. Among the listed low-cost adsorbents, studies have shown that sawdust is the most promising for removing heavy metals, acid, basic dyes, and other undesirable materials from waste water. Researchers have been studying superhydrophobic plants in nature in recent years, and have discovered that geometric microstructure and surface chemical-composition control superhydrophobic surfaces, with water contact angles up to 150° [23,24]. Sawdust is a natural cellulosic fiber resource and popular byproduct of the timber and paper industries. As a result, sawdust is comparatively accessible and cheaper, making it an effective alternative and conventional adsorbent. On the other hand, sawdust can effectively adsorb oil content from an oil–water mixture due to its large surface area and low buoyancy. Charcoal is formed when organic matter is exposed to elevated temperatures in the absence of air or oxygen. Charcoal from wood has been produced for centuries for a variety of applications in different industries, such as medical [25], agricultural [26], environmental [27,28], and food [29]. One of the most common microporous adsorbents is activated charcoal, which has a well-developed pore structure. Activated carbon can be used in supercapacitors with effectively regulated pore size and pore-size distributions. In terms of cost and chemical stability, carbonaceous materials, which are mainly black in color and have different allotropes, are more promising for low-cost solar steam evaporation. Jia et al. recently investigated the solar-steam-evaporation properties of carbonized wood blocks of various
tree species, and reported that poplar wood had the maximal solar-to-vapor efficiency of 86.7% under 10 suns [30].

Carbon nanotubes (CNTs) and graphene are two examples of carbon nanomaterials that have received much attention. Chen et al. used a dip-coating technique to layer CNTs onto a chemically treated balsa wood membrane. Water was transported through tubular channels in the wood and evaporated from the CNT film surface with 65% energy-conversion efficiency under 1 sun illumination [31]. In addition, the carbon structure’s pore growth significantly improved [32].

Surface-salt accumulation on the evaporator adversely affects long-term effective solar desalination by increasing reflectance, which reduces solar light absorption [33].

In a typical desalination method, the absorber is generally located on top of the device, which is useful for producing a capillary effect to the pumped-up water. In the present study, a new nature-inspired material for solar desalination was developed with sea sand, saw dust, and charcoal as the main elements. In order to maintain hydrophobicity, Polytetrafluoroethylene (PTFE) was used. In total, 12 samples were prepared for water evaporation using the above-mentioned natural resources. The developed material featured with self-salt replenishment and efficient solar water evaporation. It is assumed that the developed material has the capability to circulate water itself in the absence of solar illumination. This phenomenon is commonly known as diffusion and advection.

2. Materials and Methods

The material was developed in this study for solar water desalination, and it is a mixture of naturally inspired salt-resistance materials (NI-SRMs). It is a combination of sea sand, activated charcoal, and sawdust with 50, 35, and 15 wt%, respectively, as shown in Figure 1. Sea sand was washed 3 times with the interval of 30 min with distilled water prior to its use to remove salt impurities. Sea sand was treated with a sodium hydroxide solution (NaOH) to develop a rough surface on the sorted sand particles to deposit the activated charcoal onto their surface. After completing the washing process, sea sand was dried in an electric oven at a temperature of 80 °C for 2 h to remove the moisture. After the treatment process, the prepared proportions of selected ingredients were mixed with overhead bench type stirrer at the speed of 120 rpm for the homogeneous distribution for 1 hour. For the development of the size-sorted mixture, the individual ingredients of the NI-SRM (sand, sawdust, and activated charcoal) were passed through a sieve. Four different mesh sizes (0.154, 0.4, 0.8, and 1.25 mm) were used for sorting the particle size. PTFE dispersions were prepared by the aqueous polymerization using more dispersing agents with agitation. PTFE was used to control the wettability of the material for evaluating the optimum solar water evaporation and salt accumulation resistance over the surface. Furthermore, the PTFE used in this study is to optimize hydrophobicity.

![Figure 1. (a) Illustration of prototype solar evaporator with NI-SRM compositions, (b) lab scale developed mechanism for collecting of clean water samples.](image-url)
2.1. Experiment Setup

The indoor solar-evaporation setup consisted of different devices that contributed to solar desalination, such as a xenon lamp light, which was used as the light source with a CEL-AM 1.5 light filter from Zhongjiaojinyuan, China. Light intensity and focus were controlled through a CEL-NP2000 optical power meter from Zhongjiaojinyuan. A Mettler Toledo ME204E weight scale with resolution of 0.1 mg was used to evaluate mass evaporation. The Mettler Toledo ME204E scale was connected to a computer using serial port to keyboard software Mettler, Toledo Company. All mass-evaporation data were saved on the computer during the experiment in time-step intervals.

It was difficult to monitor the surface temperature of the NI-SRM during the experiment because of the water evaporation from the surface of the evaporator. Therefore, a Flir (A650SC) thermal image camera was used to monitor surface temperature in real time, as shown in Figure 2.

![Experimental setup for solar water desalination.](image)

Figure 2. Experimental setup for solar water desalination.

2.2. Characterization

JEOL JEM 2100 and Zeiss SUPRA-55 were used for SEM characterization. SEM images were performed with an accelerating voltage of 20 kV. The majority of the study is based on the calculation of mass change, and a computer-interfaced Mettler Toledo ME204E scale was used. The experiments were carried out in a laboratory scale and each set of the mass-change values was investigated in 10 s intervals. The solar simulator from Zhongjiaojinyuan was used with CEL-AM1.5 intensity. Thermal illustration was measured using a UK manufactured Flir A650SC. An inductively coupled plasma test was conducted using a Thermo Scientific iCAP 6000 Series Inductively Coupled Plasma Spectrometer. Moreover, the surface area and pore volume of the developed material were obtained using Brunauer–Emmett–Teller (BET).

3. Results and Discussion

3.1. Characterization

The multifunctional microstructure of the well-sorted NI-SRM (0.154 mm) evaporator was depicted by scanning electron microscopy (SEM). The interconnected porous structure of the natural raw materials—sea sand and natural charcoal—was well-preserved after PTFE dispersion samples were heated for 30 min at 350 °C to stabilize the PTFE. The large
number of open channels is beneficial for preventing accumulation and rapid replenishment of the salt. The micropores have been observed in developed NI-SRM in this study. These micropores are helpful to prevent transportation of pollutants such as oil, wax, and other to the surface of evaporator.

The results revealed that with unchanged evaporation rate of NI-SRM under 1 sun of solar illumination for 7 days. However, we did not observe any physical salt accumulation over the evaporator. Nonetheless a very negligible amount of salt has been investigated in vessels and micropores in NI-SRM as shown in Figure 3.

![Figure 3.](image)

**Figure 3.** (a) Digital images of raw nature-inspired salt-resistance material, sea sand, sawdust, and activated charcoal. (b) Sample: NI-SRM uniformly sorted evaporator. (c) Interconnected porous structure of sorted NI-SRM (d) Zoomed view of narrow and large vessel channels (e,f) in micropores.

In this study, it has been investigated that, after 7 day of evaporation, there is no visible salt accumulation over the surface of the evaporator. As shown in Figure 4, there is no blockage in tracheid and vessels have been observed in this study. It is because of the developed material has self-salt replenishment capability.

![Figure 4.](image)

**Figure 4.** Scanning electron microscopy images of NI-SRM after 7 days of evaporation.
3.2. Wettablility Control

The solar water mass evaporation of unsorted-size NI-SRMs was investigated, with 60 wt% PTFE water-based dispersion form by the Aladdin brand CAS 9002-84-0. Distilled water was used as the PTFE solvent. The wettablility of materials was controlled using different concentrations of PTFE: 0.5, 1.0, and 5.0 wt%. Then, 100, 200, 500, and 1000 µL were collected from the prepared quantity of PTFE with the solvent and mixed with the prepared samples (mixture of sawdust, sea sand, and charcoal). After PTFE addition, the prepared sample was heated at 350 °C in a muffle furnace for the proper dispersion of PTFE for 30 min. All prepared samples are used for solar evaporation under 1 sun of solar intensity. The results were compared with PTFE dispersion 0.5 and 5.0 wt%, and 100 and 1000 µL volumes, respectively, as shown in Figure 5. The lowest water mass evaporation performance was found for 5.0 wt% PTFE compared with those of 0.5 and 1.0 wt%. A negligible change in mass evaporation was observed between the unsorted NI-SRM without PTFE and 0.5 wt% PTFE with a 100 µL mixture. However, unsorted sized NI-SRM with 1.0 wt% of PTFE and 100 µL quantity mixed prepared sample produced 16.98% higher mass evaporation than that from 0.5 wt% and without PTFE dispersion, as shown in Figure 5. Similarly, water-mass evaporation was investigated with 200 µL of PTFE blending in the NI-SRM. The 200 µL volume of PTFE produced a negligible reduction in water-mass evaporation as compared with that of 100 µL of PTFE.

![Figure 5. Control experiment of unsorted NI-SRMs with different concentrations of PTFE](image)

Figure 5. Control experiment of unsorted NI-SRMs with different concentrations of PTFE (a) 100 µL quantity mixed in NI-SRM, (b) 200 µL quantity mixed in NI-SRM, (c) 500 µL quantity mixed in NI-SRM, and (d) 1000 µL quantity mixed in NI-SRM.
The results revealed that a 0.5 wt% and 500 µL volume of PTFE had poorer evaporation performance than that without PTFE NI-SRM. However, 5.0 wt% had a much poorer evaporation performance than that of 0.5 and 1.0 wt%. The results show that 5.0 wt% PTFE blended with NI-SRM may increase the hydrophobicity, which is the main cause of the reduced water mass.

According to the evaluated results of the 1000 µL volume of PTFE blended with NI-SRM, 1.0 wt% PTFE had a higher evaporation rate than that of 0.5 and 5.0 wt%. Without PTFE, the blended NI-SRM produced 5.48% less evaporation than that of 1.0 wt% PTFE, but 7.23% higher than that of 0.5 wt%, and 41.10% higher than that of 5.0 wt% PTFE. The 1.0 wt% PTFE concentration and 100 µL volume were suitable for improving the hydrophobicity of NI-SRMs. However, 5.0 wt% PTFE was too limiting on the hydrophobicity in NI-SRMs, which may reduce capillary action, and permeability led to reduced evaporation in the system.

According to the evaluated results, Figure 6 clearly shows that 1.0 wt% produced a higher evaporation rate than those of 0.5 and 5.0 wt%. However, 100 µL PTFE mixed evaporator produced a higher evaporation rate in 0.5, 1.0, and 5.0 wt%, which had better overall efficiency than that of 200, 500, and 1000 µL. The results revealed that 1.0 wt% and 100 µL had better evaporation efficiency than that of the others because the higher wt% PTFE and volume increased the hydrophobicity and closed pores in the NI-SRMs, which led to the resistance of water uptake over the surface. By contrast, 0.5 wt% is not completely hydrophobic and, therefore, water uptake occurred over the surface over a long period of time. However, some new research has suggested that not all hydrophilic interfaces are suitable for high-efficiency water desalination, particularly for the top evaporative surface [20]. Being too hydrophilic on the surface of the evaporator can lead to surplus water covering the top surface, experiencing extra heat loss, which leads to decreased heat localization and high temperatures on the surface of evaporator, making it difficult to preserve self-sustained solar desalination [20].

![Figure 6. Overall evaporator efficiency of NI-SRM with different percentages of PTFE.](image-url)
3.3. Effect of Particle Size on Mass Evaporation

The mass-evaporation performance evaluations are very important for evaporators in solar desalination systems. The study of the evaporation of the newly developed NI-SRM with and without PTFE, and the method of sorted and unsorted nature-inspired evaporator material were investigated. The NI-SRM evaporator ran for 3600 s and was compared with the evaporation performance of other research under 1 sun of solar intensity. The evaporation performance of the NI-SRM evaporator was evaluated using the evaporation rate. The evaporation of different particle sizes of NI-SRM, namely, 0.154, 0.4, 0.8, and 1.25 mm, with PTFE 1.0 wt% and 100 µL was investigated. The results revealed that a uniform sorted size of 0.154 mm NI-SRM evaporator had an excellent and unchanged evaporation performance of 3.02 kg-m$^{-2}$, with negligible salt deposition were investigated. However, other control samples of the sorted NI-SRM, namely, 0.4, 0.8, and 1.25 mm with constant wt% PTFE (0.1 wt%) and 100 µL had a lower evaporation performance, as shown in Figure 7.

![Figure 7. Mass evaporation of different sorted sizes of NI-SRM with PTFE.](image)

3.4. BET and Surface-Area Analysis

An N2 adsorption–desorption isotherm and BJH curves of the fabricated samples were investigated. Figure 8b depicts the surface area and pore size distribution. All synthesized materials exhibited Type IV isotherms, and the hysteresis loop for all materials was of Type H3, which explains the slit-like pores of the material. There were two loops in the mentioned graph that indicated the appreciable adsorption of N2 gas in the hollow voids. This is attributed to the larger surface area (204.5 m$^2$/g). Similarly, the pore size distribution of the sample had an average size of 2.5 nm. The large pore size is attributed to the homogeneous distribution of the particles. A large surface area and wide pore sizes can be helpful for the accommodation of pollutants on its surface, thereby accelerating the purification process.

![Figure 8.](image)
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Figure 8. (a) N2 adsorption–desorption curves at room temperature (b) BJH pore size distribution of mesoporous sample.

3.5. Temperature Evaluation of NI-SRM

NI-SRM covers a wide wavelength range (220–2200 nm) in the solar spectrum regarding solar-power evaporation. Measurements of the rising-temperature performance were compared through unsorted NI-SRM capture via a thermal camera under AM 1.5 light, as is shown in Figure 9. Well-sorted uniform sized NI-SRM displays much faster and achieve high temperature than unsorted sized developed evaporator. The sorted NI-SRM temperature was 32.8 °C under room temperature, which was 7.5 °C above that of the unsorted NI-SRM (25.3 °C under room temperature). Figure 9 shows real time monitoring of temperature distribution during experiment under AM 1.5 light. Temperatures were tested using a Flir A650SC. Light absorption from 220 to 2200 nm was measured using a UV-3600 UV–VIS-NIR spectrophotometer from Shimadzu.

Figure 9. Solar thermal response of sorted and unsorted sized NI-SRM under AM 1.5 light.
The naturally abundant source material with higher porosity and capillary action was investigated. The interconnected uniformly sized particles generated a microstructure that helped to pump up saline water for evaporation. The uniformly sized NI-SRM produced a higher evaporation rate under 1 sun of illumination than others did. The NI-SRM material was better at preventing salt deposition over the surface because the higher porosity and capillary of the NI-SRM led to rapid water diffusion, which in turn, led to the fast replenishment of salt over the surface and vaporized water.

Here, the light-absorbance intensity of sorted NI-SRM with PTFE was higher than that for the unsorted sizes with and without PTFE as shown in Figure 10.

![Figure 10. Light absorption of sorted and unsorted sized NI-SRM with and without PTFE.](image)

### 3.6. Stability and Evaporation Rate of Sorted-Sized Evaporator

To further evaluate the stability test of our multifunctional well-sorted NI-SRM evaporator, artificial sea water solutions of 3.5 wt% NaCl were used under 1 sun, and no physical change in material was observed within 1 hour during experiment. With 3.5 wt% NaCl, the performance of the evaporator and evaporation rate remained stable for 7 days under 1 sun illumination. However, the results demonstrated no change in evaporation rate, as shown in Figure 11.
The high evaporation rate of 3.02 kg-m$^{-2}$h$^{-1}$ was obtained under 1 sun solar illumination and had good performance and no salt deposition was observed with artificial sea water (3.5 wt%). However, the NI-SRM evaporator worked efficiently and simultaneously replenished the salt during evaporation. The unsorted NI-SRM evaporator (irregular mixture) had comparatively unsorted numerous salt crystals progressively accumulating on its surface under equal amounts of solar illumination, which severely reduced the performance of the evaporator. The salt deposition was not observed in this work during the long-term stability test. The results were compared with those of the literature, and the evaporation rate was found to be higher than that of other studies, as shown in Table 1.

![Figure 11. Evaporation stability of different sorted sized NI-SRM evaporator under AM 1.5.](image)

Table 1. Comparison of evaporation rate and stability of the present study with the literature.

<table>
<thead>
<tr>
<th>Sr.</th>
<th>Authors</th>
<th>EV Rate (kg-m$^{-2}$h$^{-1}$)</th>
<th>Solar Condition</th>
<th>Stability</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zhao, Jianqiu et al.</td>
<td>1.31</td>
<td>1 sun</td>
<td>200 h</td>
<td>[34]</td>
</tr>
<tr>
<td>2</td>
<td>Yi, Luocai et al.</td>
<td>1.03</td>
<td>1 sun</td>
<td>-</td>
<td>[35]</td>
</tr>
<tr>
<td>3</td>
<td>Li, Renyuan et al.</td>
<td>1.30</td>
<td>1 sun</td>
<td>-</td>
<td>[36]</td>
</tr>
<tr>
<td>4</td>
<td>He, Yuming et al.</td>
<td>1.91 min to 1.21 max</td>
<td>1 sun</td>
<td>7 cycles</td>
<td>[37]</td>
</tr>
<tr>
<td>5</td>
<td>Hao, Dandan et al.</td>
<td>1.19</td>
<td>1 sun</td>
<td>-</td>
<td>[38]</td>
</tr>
<tr>
<td>6</td>
<td>Yin, Zhe et al.</td>
<td>1.9</td>
<td>1 sun</td>
<td>-</td>
<td>[39]</td>
</tr>
<tr>
<td>7</td>
<td>Wang, Yuchao</td>
<td>0.4 to 1.25</td>
<td>1 sun</td>
<td>2 h</td>
<td>[40]</td>
</tr>
<tr>
<td>8</td>
<td>Huang, Lu et al.</td>
<td>0.4 to 0.7</td>
<td>1 sun</td>
<td>12 cycles</td>
<td>[41]</td>
</tr>
<tr>
<td>9</td>
<td>Kou, Hui et al.</td>
<td>1.59 to 0.54</td>
<td>1 sun</td>
<td>0 to 8 h</td>
<td>[42]</td>
</tr>
<tr>
<td>10</td>
<td><strong>Present work</strong></td>
<td><strong>1.16 to 3.02</strong></td>
<td><strong>1 Sun</strong></td>
<td><strong>7 Days</strong></td>
<td></td>
</tr>
</tbody>
</table>
3.7. Evaluation of Surface Wettability of NI-SRM

Surface-wettability control is a critical factor for evaporators [43,44]. Patterned hydrophobic–hydrophilic surfaces are suitable for efficient water evaporation [45–48]. Furthermore, we introduced a microstructure of a salt-resistance mixture (sea sand, sawdust, and activated charcoal) wettability structure. Hydrophilicity promotes evaporation with reduced sunlight reflection; the available nature-inspired material's properties worked as a water transport mechanism to the top surfaces of the evaporator. The ability of the capillary for localized evaporation is key for evaporation, as observed in the NI-SRM material and capillary system.

The NI-SRM had a highest water evaporation rate of $3.02 \text{ kg.m}^{-2}\text{h}^{-1}$ on the optimized wettability structure, with higher stability under 1 sun (AM 1.5).

This work is beneficial to promote the wide application of nature-inspired abundant salt-resistance material and inspire the further optimization of cheap raw material into NI-SRM material. Sea sand and activated charcoal are naturally super hydrophilic materials due to their porosity, which is favorable for pumping water from the bottom to the evaporator layer for evaporation. Sawdust is hydrophobic, but when it was mixed with sea sand, it yielded better results. The dynamic contact angle was investigated using an optical tensiometer. The results revealed that 0.154 mm size-sorted NI-SRMs with PTFE takes 90 s to be completely submerged 5 µL water drop into the pores of NI-SRMs as shown in Figure 12b. The contact angle developed in this study was $125^\circ$ on initial condition which shows that the NI-SRM is superhydrophobic. It gives advantageous features if the material is superhydrophobic because it reduces the residence time of brine water inside NI-SRM pores. As a result of the depth of PTFE adjustment and the use of different concentrations of the salt-resistance content, excellent phenomena for effective solar evaporation were achieved.

Figure 12. (a) Dynamic contact angle evaluation setup, (b) results of change in contact-angle with time of sorted sized NI-SRM.

3.8. Water Purification

The collected water from the prototype NI-SRM solar collector had a concentration of Na+. A large amount of vapor was obtained during the irradiation process, which then condensed onto a vertical wall and was converted into a water stream after further evaporation and collected in a bottom-placed container as shown in Figure 2. The real time collection of purified water was investigated in this study. The results reveal that the production of desalinated water/purified water from artificial sea water was $1.7 \pm 0.10 \text{ kg.m}^{-2}$, whereas $1.16 \pm 0.10 \text{ kg.m}^{-2}$ were obtained from seawater as shown in Figure 13. Desalinated water was obtained from natural sea water using NI-SRM under 1 sun of Solar illumination. Natural sea water had a 31.7% lower evaporation rate than that of artificial sea water. It is
because, the natural sea water has several inorganic substances other than NaCl such as magnesium, calcium, potassium, sulfate, and others. It may lead to reduce the evaporation.

![Figure 13. Real time collected purified water results.](image)

3.9. Self-Salt Replenishment

The multifunctional sorted porous NI-SRM showed excellent salt rejection and water purification under solar energy over a long period of time. Figure 14 demonstrates the addition of 2.5 g NaCl in the NI-SRM evaporator. All salt crystals were dissolved within 3 h of exposure under an illumination intensity of 1 sun. The higher salt-discarding capacity was demonstrated in the following ways. First, the salt was dissolved by quickly forming a dense saline layer over the NI-SRM evaporator surface, which reached the saturation point, and the rest remained unsaturated.

![Figure 14. Visual observations of self-salt replenishment in absence of solar illumination during experiment. (a-f) Top view of Self-salt replenishment from NI-SRM with respect to time. (g-j) Side view of Self-salt replenishment from NI-SRM (k-m) The digital image of wick of the evaporator reveals that the visualized salt replenishment process in NI-SRM. The images show the developed salt path ways during salt-replenishment process.](image)
Brine with higher salinity has a higher density. Therefore, the concentrated brine surface gradually sank to the comparatively low-salinity brine of the bulk underneath due to the gravity effect. Moreover, due to the high concentration difference, salt on the NI-SRM evaporator surface could be transferred back to the high-concentration brine under regular diffusion. NI-SRM observed the multifunctional capillary process, and the tracheid was too narrow to allow for sufficient brine replenishment. The high-concentration brine gradually diffused to the surrounding large vessel channels through the pits. The nonporous and high-porosity surface area were dictated by the sorted fine particle sizes (0.154 mm). NI-SRM has a wide number of vessel channels and pores, which improve brine water circulation itself. In this study, the surface temperature of the evaporator is rapidly raised under 1 sun of solar illumination which is supportive for rapid evaporation. However, the surface temperature of the evaporator gets normal while solar light is not present. It was physically observed that the salt-replenishment mostly occurs while solar light is not present. This phenomenon is commonly known as diffusion and advection. As shown in Figure 14, the salt-rejecting capability of the system is aided by diffusion and convection induced by concentration variations between the top surface and the bulk brines solution underneath.

4. Conclusions

An integrated porous microstructure with a cost-effective, modular, and multifunctional evaporator could effectively solve the issue of salt accumulation during long-term solar desalination. The unique features of the developed multifunctional porous microstructure are its long-term stability and effectiveness in brine desalination. The rapid capillary pumping of massive vessel channels has great advantages. In the hydrophilic evaporator, water between the porous structure contributed to the rapid replenishment of salt from the surface-vaporized brine to avoid salt accumulation, ensuring easy and continuous clean water-vapor production. Under 1 sun irradiation, the NI-SRM absorber achieved a fast evaporation rate of 3.02 kg·m\(^{-2}\)·h\(^{-1}\) with excellent resilience and longevity in brine salinity (3.5 wt%). The NI-SRM evaporator could effectively reject excess salt while maintaining fast and steady evaporation speeds. The unsorted NI-SRM compared to the uniformly sized NI-SRM had visible salt crystals that gradually accumulated on its surface under similar operating conditions; these deteriorated the performance of the solar evaporator. Our NI-SRM evaporator offers the potential for the sustainable and scalable production of clean water from a variety of water sources, especially those with high salinity, due to its earth-abundant raw material, easily scalable preparation process, high evaporation quality, and salt-rejection capability.

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