Supporting Information

Vertically Aligned Janus MXene-Based Aerogels for Solar Desalination with High Efficiency and Salt Resistance

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1. Experiments and Methods

1.1 Synthesis of Ti$_3$C$_2$.

Ti$_3$C$_2$ (MXene) nanosheets solution was prepared by the following procedures: Firstly, 0.5 g LiF powder was slowly added into a pre-configured 10 mL 9M HCl solution. Secondly, 0.5 g of the MAX phase precursor (Ti$_3$AlC$_2$) powder was added to the above mixed solution in multiple portions, and then the Al layer was etched at 35 °C with magnetic stirring for 24 h. Thirdly, the product was washed with water and centrifuged for several times until the pH > 6. Fourthly, the above product was sonicated under ice bath and an Ar atmosphere conditions for 1 h. Finally, after centrifugation for another 1 h at 3500 rpm, the dark green supernatant of MXene nanosheets were collected. The concentration of Ti$_3$C$_2$ nanosheet dispersion was determined through filtering a certain volume of the suspension and measuring the weight of the film after vacuum drying.

1.2 Fabrication of MXene membrane.

MXene (Ti$_3$C$_2$) membrane was fabricated by the vacuum filtration. Briefly, 10 mg of exfoliated Ti$_3$C$_2$ was dispersed in 50 mL pure water to form Ti$_3$C$_2$ aqueous suspension. Then, this aqueous suspension was filtrated using a commercial PVDF membrane (~0.22 μm), thus a Ti$_3$C$_2$ thin-layer was stacked on upper surface of PVDF substrate.

1.3 Characterization.

Transmission electron microscopy (TEM, JEM-2100F) and scanning electron microscopy (SEM, Quanta 200 FEG) was used to analyze the morphology of the samples. Energy dispersive X-ray spectroscopy (EDX) was used for determining the chemical composition and crystallinity of samples. The crystallinity of the samples
was determined by X-ray diffractometer (XRD, EMPYREAN, PANalytical) using a diffractometer with Cu Kα radiation. X-ray photoelectron spectroscopy (XPS, VG ESCALAB250) was carried to analyze the elementary composition of samples. The optical transmittance and reflectance spectra of the surfaces of samples were recorded in the range of 200–2500 nm with an ultraviolet–visible–near-infrared spectrophotometer (UV-vis NIR spectra) equipped with an integrating sphere. The absorption efficiency was then calculated by $A = 1 - R - T$, where $R$ and $T$ are the reflection and transmission efficiency, respectively. FLUKE Ti 45 infrared camera were used to take infrared photographs. The mechanical strength of the samples was measured using a universal testing machine (AGS-X, Shimadzu Ltd., Japan). Water contact angle of samples was tested on an optical contact angle & interface tension meter (SL200KB, Kino, USA).

1.4 Water evaporation performance under 1-sun irradiation.

The water evaporation rate was calculated by the following equation:

$$v = \frac{d\dot{m}}{S \times dt} \quad (1)$$

where $\dot{m}$ is the mass of the evaporated water (g), herein, $\dot{m}_{Lig \ ht}$ (1.83 g) and $\dot{m}_{Dark}$ (0.09 g) are the mass flux under light and dark conditions for 3600 s, respectively, $S$ is the illuminated area (12.56 cm$^2$), $t$ is time (3600 s), and $v$ is evaporation rate (kg·m$^{-2}$·h$^{-1}$). Herein, the Janus VA-MXA with 40 mm diameter was used to solar evaporation experiment.

The energy conversion efficiency was defined as the following equation:

$$\eta = \frac{\nu h}{C_{opt} P_0} \quad (2)$$
where $\nu$ denotes the evaporation rate ($\nu = \nu_{\text{Light}} - \nu_{\text{Dark}}$). $\nu_{\text{Light}}$ (1.46 kg•m$^{-2}$•h$^{-1}$) and $\nu_{\text{Dark}}$ (0.07 kg•m$^{-2}$•h$^{-1}$) are the evaporation rate under light and dark conditions, respectively. $h_v$ refers to the water vaporization enthalpy (2260 kJ•kg$^{-1}$) in Janus VA-MXA, $P_0$ refers to the solar irradiation power of 1-sun (1 kW•m$^{-2}$), and $C_{\text{opt}}$ is the optical concentration on the surface of absorbers. Therefore, based on equations (2), the energy conversion efficiency ($\eta$) of Janus VA-MXA$_{15}$ is 87% under 1 kW•m$^{-2}$. 
Figure S1. Digital photographs of Janus VA-MXA with different diameters.
Figure S2. Digital photographs of Janus VA-MXA with different thicknesses (4 mm, 7 mm, 10 mm and 14 mm).
As shown in Figure S3a, the water evaporation rate of Janus VA-MXAs increased with the increasing of thickness of Janus VA-MXAs from 4 mm to 10 mm. This can be explained by that the thick light absorber was able to effectively prevent the photothermal layer from “direct bulk water contact”, thus only heating the water inside vertical channels of Janus VA-MXAs and decreasing heat loss. Therefore, the increasing of thickness of Janus VA-MXAs will result in the better thermal insulation. Figure S3b presented the infrared images of Janus VA-MXAs with different thicknesses at the same light irradiation time. These results further demonstrated that the thermal insulation ability of Janus VA-MXAs was enhanced with the increasing of thickness. In addition, it can be also found that the water evaporation rate of Janus VA-MXA with 10 mm thickness was higher than that of 14 mm thick Janus VA-MXA. This is due to that the thick Janus VA-MXA will cause poor water transportation because of the long distance of water transport.

Figure S3. (a) Water mass change over time under 1-sun illumination and (b) infrared images of Janus VA-MXA with different thicknesses at the same light irradiation time. The optimized thickness is 10 mm. Because the old FLUKE Ti 45 infrared camera was in malfunction, the new FLIR E6xt infrared camera was used to take infrared photographs.
Figure S4. TEM images of Janus VA-MXA (a) and (b).
Figure S5. AFM image and its height profile of Ti$_3$C$_2$ nanosheets.
Figure S6. XRD pattern of Janus VA-MXA.
Figure S7. XPS spectra of Janus VA-MXA.
Figure S8. SEM image of Janus MXA fabricated by 60 mg•mL\(^{-1}\) of Ti\(_3\)C\(_2\) concentration. It can be found that the vertically aligned structure disappeared and presented a chaotic and disordered pore channel.
Figure S9. Mechanical properties of Janus VA-MXA$_5$, Janus VA-MXA$_{15}$, Janus VA-MXA$_{25}$ and Janus VA-MXA$_{40}$. 
Figure S10. Saturated water content in Janus VA-MXAs per gram of corresponding dried samples.
Figure S11. Water transport rate showing the tunable water transport ability of Janus VA-MXAs.
Figure S12. (a) Janus VA-MXA$_{15}$, (b) Janus MXA and (c) MXene membrane.
Figure S13. Reflectance spectra of the MXene membrane, *Janus MXA* and *Janus VA-MXA*$_{15}$. 
Figure S14. Infrared images showing the temperature distribution of (a) Janus VA-MXA$_{15}$, (b) Janus MXA and (c) MXene membrane after irradiation for 300 s (FLUKE Ti 45).
**Figure S15.** Mass change of Yellow sea water over time with *Janus MXA*$_{15}$ under 1.0 to 4.0 sun irradiation.
Table S1. Comparison of vapour generation performance for Janus VA-MXA$_{15}$ and previous reports under 1 sun.

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Evaporation rate (kg·m$^{-2}$·h$^{-1}$)</th>
<th>Efficiency (%)</th>
<th>Salt resistance (d)</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Gold nanoparticles-filter paper</td>
<td>1.18</td>
<td>76</td>
<td>N/A</td>
<td>1</td>
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<tr>
<td>Polypyrrole coated stainless steel mesh</td>
<td>0.92</td>
<td>58</td>
<td>N/A</td>
<td>2</td>
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<td>Carbonized mushroom</td>
<td>1.47</td>
<td>78</td>
<td>N/A</td>
<td>3</td>
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<tr>
<td>Graphene oxide film-polystyrene foam</td>
<td>1.45</td>
<td>80</td>
<td>N/A</td>
<td>4</td>
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<tr>
<td>Porous N-doped graphene</td>
<td>1.50</td>
<td>80</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>Carbon nanotube-macroporous silica material</td>
<td>1.31</td>
<td>82</td>
<td>N/A</td>
<td>6</td>
</tr>
<tr>
<td>Polyvinyl alcohol-polypyrrole</td>
<td>3.20</td>
<td>94</td>
<td>28</td>
<td>7</td>
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<tr>
<td>Polypyrrole-melamine foam</td>
<td>1.57</td>
<td>90</td>
<td>30</td>
<td>8</td>
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<tr>
<td>Carbon black nanoparticles coating polymethylmethacrylate polyacrylonitrile</td>
<td>1.30</td>
<td>72</td>
<td>16</td>
<td>9</td>
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<tr>
<td>2D Ti$_3$C$_2$ MXene membrane</td>
<td>1.31</td>
<td>71</td>
<td>8</td>
<td>10</td>
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<tr>
<td>Vertically aligned Janus MXene aerogel</td>
<td>1.46</td>
<td>87</td>
<td>15</td>
<td>This work</td>
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Figure S16. Average temperature profiles along the cuvette axis within irradiation time of 3600 s. The distance is defined as a downward distance from the upper surface Janus VA-MXA\textsubscript{15} to bottom water.
**Figure S17.** Infrared images showing the temperature variation of *Janus VA-MXA*$_{15}$ after irradiation time of 300 s (FLUKE Ti 45). The center temperature reached up to 98.5 °C irradiating for 300 s, while the bottom temperature was only 29.4 °C.
To further show the highly efficient solar thermal utilization in the Janus VA-MXA, the average temperature variation of Janus VA-MXA$_{15}$ and VA-MXA was carried out. The top surface of Janus VA-MXA$_{15}$ can be identical heat to 49.3 °C at 180 s and the average temperature was gradually raised to 61.5 °C in another 100 s (Figure S18). In comparison, the average surface temperature of VA-MXA was only 41.6 °C after irradiation time of 3600 s. This can be explained by that the VA-MXA surface was coated by a mass of water because of its hydrophilicity, thus forming a water film. This water film will prevent VA-MXA surface from absorbing solar energy.

![Figure S18](image.png)

**Figure S18.** The variation of average temperature of Janus VA-MXA$_{15}$ and VA-MXA within irradiation time of 3600 s.
Figure S19. Mass change of Yellow sea water over time with Janus VA-MXA$_{15}$ and VA-MXA at first and 15th cycle test.
Figure S20. The absorption spectra of the Janus $VA$-$MXA_{15}$ and $VA$-$MXA$ before and after 15th cycle test.
Figure S21. Digital photos showing the long-term stability by soaking the Janus VA-MXA$_{15}$ into water for 15 d.
Table S2. Water quality parameters of four actual seawaters and salt water lakes.

<table>
<thead>
<tr>
<th></th>
<th>Yellow sea</th>
<th>Bohai sea</th>
<th>Alkali lake 1</th>
<th>Alkali lake 2</th>
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<tbody>
<tr>
<td><strong>pH</strong></td>
<td>7.9</td>
<td>7.9</td>
<td>9.6</td>
<td>9.3</td>
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<tr>
<td><strong>Salinity</strong> (%o)</td>
<td>31.0</td>
<td>30.0</td>
<td>12.0</td>
<td>76.0</td>
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<tr>
<td><strong>Basicity</strong> (mmol•L⁻¹)</td>
<td>20.4</td>
<td>21.7</td>
<td>36.3</td>
<td>87.7</td>
</tr>
<tr>
<td><strong>HCO₃⁻</strong> (mmol•L⁻¹)</td>
<td>15.4</td>
<td>18.4</td>
<td>12.1</td>
<td>12.5</td>
</tr>
<tr>
<td><strong>1/2CO₃²⁻</strong> (mmol•L⁻¹)</td>
<td>5.0</td>
<td>3.3</td>
<td>24.2</td>
<td>75.2</td>
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<tr>
<td><strong>Hardness</strong> (mmol•L⁻¹)</td>
<td>112.8</td>
<td>109.9</td>
<td>56.0</td>
<td>16.8</td>
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<tr>
<td><strong>Turbidity</strong> (NTU)</td>
<td>0.5</td>
<td>11.8</td>
<td>1.1</td>
<td>15.7</td>
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Figure S22. Measured Na\(^+\) concentrations of four actual brine samples before and after desalination.
References


