MXene Ti$_3$C$_2$: An Effective 2D Light-to-Heat Conversion Material

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ABSTRACT: MXene, a new series of 2D material, has been steadily advancing its applications to a variety of fields, such as catalysis, supercapacitor, molecular separation, electromagnetic wave interference shielding. This work reports a carefully designed aqueous droplet light heating system along with a thorough mathematical procedure, which combined leads to a precise determination of internal light-to-heat conversion efficiency of a variety of nanomaterials. The internal light-to-heat conversion efficiency of MXene, more specifically Ti$_3$C$_2$, was measured to be 100%, indicating a perfect energy conversion. Furthermore, a self-floating MXene thin membrane was prepared by simple vacuum filtration and the membrane, in the presence of a rationally chosen heat barrier, produced a light-to-water-evaporation efficiency of 84% under one sun irradiation, which is among the state of art energy efficiency for similar photothermal evaporation system. The outstanding internal light-to-heat conversion efficiency and great light-to-water evaporation efficiency reported in this work suggest that MXene is a very promising light-to-heat conversion material and thus deserves more research attention toward practical applications.

KEYWORDS: MXene, Ti$_3$C$_2$, light-to-heat conversion, photothermal, water evaporation

MXene, a new series of 2D materials composed of early transition metal carbides and/or carbonitrides and generally produced by selectively etching out the A layers from M$_{n+1}$AX$_n$ phases, where M is an early transition metal, A is mainly a group IIIA or IVA (i.e., group 13 or 14) element, X is C and/or N, and n = 1, 2, or 3, was first introduced by Gogotsi’s group in 2011 and has since been growing its family steadily and finding itself many exciting applications, including catalysis, battery, supercapacitors, molecular separation, etc.

Very recently, it has been reported that MXene and MXene-polymer composite films produced a record-breaking electromagnetic interference shielding effect, which is a direct result of excellent electromagnetic wave absorption property by pristine MXene and its composites. Furthermore, as a top-of-the-line electromagnetic interference shielding material, MXene allows negligible electromagnetic wave emission and the ultimate fate of the absorbed waves is to dissipate in the form of heat within the material. The discovery is thought-provoking and inspires us to look into MXene’s interaction with more ubiquitous electromagnetic waves present in our daily life: sunlight. Although there exists no prior art, we believe MXene’s excellent electromagnetic wave absorption and subsequent heat generation put it on the way to be an excellent light-to-heat conversion material.

Light-to-heat, also known as photothermal conversion, a seemingly primitive and ancient means of utilizing solar energy involves harvesting and converting solar irradiation by photothermal materials into heat as terminal energy for beneficial usage. Due to its operation simplicity, wide variety of materials of choice, and more importantly extremely high energy conversion efficiency compared to other means of solar energy harvesting (e.g., photovoltaic and photocatalysis), light-to-heat conversion has gained renewed research interest in the past decade and found itself certain niche applications, including steam generation, water desalination, cancer therapy, etc.

The pool of photothermal material is big and keeps growing and the popular nanosized photothermal materials with desirable performance include carbon black, carbon nanotubes, graphene, gold nanoparticle, aluminum, etc.
nanoparticles,\textsuperscript{30} black TiO\textsubscript{2},\textsuperscript{31} Ti\textsubscript{2}O\textsubscript{3},\textsuperscript{32} etc. A recent report rationed hollow bimetallic plasmonic mesoporous nanoshells and the sophisticated structure of the material significantly enhances light absorption and facilitates light-to-water-vapor generation.\textsuperscript{33} The aim of this work is to push MXene, more specifically Ti\textsubscript{3}C\textsubscript{2}, into the pool of photothermal materials to invite further scientific investigations. Very recently, Xuan et al. and Lin et al. both investigated MXene’s application to phototherapy under near-infrared and their results show outstanding in vitro/in vivo photothermal ablation performance of MXene on tumor cells.\textsuperscript{33,34} In this report, we measured, with carefully designed systems, the light-to-heat conversion efficiency of Ti\textsubscript{3}C\textsubscript{2} via means of droplet laser heating process and photothermal water evaporation efficiency by stacked MXene membranes. Our results confirmed that Ti\textsubscript{3}C\textsubscript{2} had an outstanding internal light-to-heat conversion efficiency (i.e., 100\%) and the MXene membrane with an underlying heat barrier achieved 84\% light-to-water-evaporation efficiency under 1 sun light illumination (1 kW/m\textsuperscript{2}), which is among the state of the art of such a system. This work demonstrates that MXene is a promising solar photothermal material and inspires more research efforts in the application of MXene for practical solar energy utilization.

RESULTS AND DISCUSSION

MXene Preparation. In this project, Ti\textsubscript{3}AlC\textsubscript{2} layered MAX phase was chosen as a raw material. The Al layers were etched by hydrofluoric acid (HF) aqueous solution. When the as-prepared HF treated MAX phase was immersed into DMSO in the presence of sonication, exfoliated single/few layered MXene flakes were formed. Figure 1a shows a SEM image of the HF treated MAX-phase powder. Clearly, after the aluminum layer removal from Ti\textsubscript{3}AlC\textsubscript{2}, an opened interspace was formed and the layered structure could be obviously observed. Figure 1b presents a SEM image of typical exfoliated MXene flakes whose size were 500 nm. The HRTEM image in Figure 1c shows the single crystallinity of the MXene sheet. From selective area electron diffraction pattern (SAED) pattern in Figure 1d, one can see that the prepared MXene in this work has a hexagonal symmetry and exfoliated MXene flake has single crystallinity, as demonstrated by the HRTEM image.\textsuperscript{33,36}

Measurement and Calculation of Light to Heat Conversion. Figure 2a presents the UV–vis-NIR absorption spectra (300–1300 nm) of MXene and CNT aqueous suspensions with the same mass concentration of 0.1 mg/mL. As can be seen, CNT absorbs broad spectrum from 300 to 1300 nm without any distinct absorption peak while MXene exhibits a basic absorption much higher than CNT material with an absorption peak around 800 nm. According to the solution to Maxwell equation, a higher conductivity of a material will generally lead to a higher extinction coefficient and thus to a better electro-magnetic wave absorption.\textsuperscript{37} It has been reported that MXene materials possess higher electric conductivity than CNT and reduced graphene oxide materials,\textsuperscript{3} two popular and effective photothermal materials in literature, which may help explain the MXene’s consistently higher light absorption than CNT (Figure 2a) in the entire wavelength range. This encouraging result inspired us to move on to measure the light-to-heat conversion efficiency of MXene.

To precisely evaluate the light-to-heat conversion efficiency of Ti\textsubscript{3}C\textsubscript{2} MXene, a droplet-based light absorption and heat measurement system was carefully established based on literature with certain modification and the system setup is schematically presented in Figure 3a. Briefly, an aqueous solution droplet with a known volume (9.0 μL) and containing MXene is hung at the tip of a one-end-sealed PTFE pipet. The selection of PTFE pipet is based on its hydrophobicity, which prevents the droplet from entering into the pipet, and on its poor heat conduction property due to its hollow structure. A single wavelength laser beam (i.e., 473 or 785 nm in this study), with power density of 82 mW and spot size of 0.85 mm in diameter, is shone right in the center of the droplet. The selection of the laser as the light source is because it is a perfect parallel light source and of its stable light power density. The laser light is partially adsorbed by MXene existing in the optical path of the laser beam inside the droplet (Figure 3b), which is a circular column with length of 2.6 mm and diameter of 0.85 mm. The adsorbed laser light energy by MXene is converted to heat and consequently temperature of the droplet increases (Figure S1). The droplet temperature is real-time recorded by a precalibrated IR camera. More details regarding the system setup can be found in Supporting Information.

Figure 2b shows the total temperature profile of the droplet in response to photothermal heating and subsequently natural cooling. As can be seen, there was a sharp temperature rise of the droplet soon as the laser was turned on, which is an indicator of instantaneous heat convection within the droplet. Figure S1 presents the IR photo of the droplet after 10 s of laser illumination. Upon the arrival of the equilibrium temperature of the droplet (35 °C), which was determined when the droplet temperature fluctuation was less than 2 °C, the laser was shut down and cooling process was initialized.

During the laser light induced heating process, part of the light energy was adsorbed and converted into heat energy by MXene sheets with a light-to-heat conversion efficiency (\(\eta\)), which is to be investigated in this experiment. Some of the gained heat energy is converted to the internal energy of the droplet system, indicated by a temperature increase of the droplet before an equilibrium state is achieved. Other heat
energy gets dissipated to the environment once the temperature of the droplet is higher than the environment. Therefore, the general governing energy balance of this system is described as eq 1:

\[ P\eta = \frac{dQ_i}{dt} = mC_p\frac{dT}{dt} + \frac{dQ_{ext}}{dt} \]  

(1)

Where \( P \) is the light power that is adsorbed by the droplet and \( Q_i \) is the heat energy gained by the droplet from the absorbed light energy, and \( \eta \) is the light-to-heat conversion efficiency of the MXene. \( m, C_p, \) and \( T \) are mass, heat capacity, and temperature of the droplet, respectively. \( Q_{ext} \) is the heat dissipated into the environment external to the droplet.

The absorbed light power \( P \) is evaluated from the difference between power of the incident laser beam (\( P_{inc} \) constant at 82 mW) and the outgoing light (\( P_{out} \)), which is calculated by using MXene light absorbance (\( A_\lambda \)) (eq 2).

\[ P = P_{inc} - P_{out} = P_{inc}(1 - 10^{-A_\lambda}) \]  

(2)

The determination of \( A_\lambda \) is based on Beer–Lambert law (eq 3).

\[ A_\lambda = KLC = -\log_{10}(P_{out}/P_{inc}) \]  

(3)

Where \( L \) is optical path length of the incident laser light in the droplet, 2.6 mm in this case (Figure 2b), \( C \) is the MXene concentration in the droplet, and \( K \) is MXene’s extinction coefficient. Hence, the determination of \( K \) is a key to this calculation. It is important to notice that, the extinction coefficient of Al(OH)\(_x^+\) containing Ti\(_3\)C\(_2\) MXene at 808 nm in the work by Xuan et al. is 29.1 L g\(^{-1}\)cm\(^{-1}\), which is quite comparable to the state of art NIR photothermal material.20 However, many factors that influence MXene’s extinction coefficient should be considered. According to Xuan et al.’s report, the calculated distinction coefficient difference between MXene obtained from TMAOH method and HF-DMSO method can be as high as 5.7 times, which they proposed to be attributable to the Al(OH)\(_x^+\) functionalization of their MXene flakes. Thus, presumably due to the different size and surface functional groups, among others, of the MXene flakes in this work, the extinction coefficient in the current study is different than the literature value.

Existing in the literature is a similar single droplet experiment conducted by Richardson et al. in 2009 in an effort to...
investigate the light-to-heat conversion efficiency of monodispersed 20 nm spherical gold nanoparticles. In this pioneering case, \(A_l\) by the gold nanoparticles was theoretically calculated based on the estimated number of the gold nanoparticles in the light path of the solution and \(K\) of a literature value for individual gold nanoparticles. However, directly applying the method reported by Richardson et al. to our system is deemed inappropriate as there is no existing \(K\) value for a specified occasion available in literature for MXene, an emerging material only recently discovered.

Instead, in this work, \(K\) was measured on a UV–vis-NIR spectrophotometer using cuvette for each sample with known MXene concentration. With \(A_l\) being measured directly on the spectrophotometer for any specific wavelength and \(L\) and \(C\) known, \(K\) is then calculated for each sample at both wavelength of the laser beams (eq 3).

With \(K\) being known now, \(A_l\) in the single droplet experiment can then be calculated accordingly for various MXene concentrations as shown in Table 1. As can be seen, our method of calculating \(A_l\) saves the trouble of having prior knowledge of number of particles and literature values of \(K\) for photothermal materials. Given the fact that the majority of photothermal materials are neither spherical in shape nor monodispersed in size, our method is a more universal process.

<table>
<thead>
<tr>
<th>Table 1. Light-to-Heat Conversion Efficiency Calculation Results</th>
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<tr>
<td>785 nm wavelength laser</td>
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<tr>
<td>(A_l)</td>
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<tr>
<td>0.10 mg/mL</td>
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<td>0.075 mg/mL</td>
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<td>0.050 mg/mL</td>
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473 nm wavelength laser

| \(A_l\) | \(K\) | \(T_{eq}\) (°C) | time to achieve \(T_{eq}\) (s) | \(F\) \((\times 10^{-4} J/(s °C))\) | \(\eta\) |
| 0.100 mg/mL | 0.48 | 18.5 | 36.5 | 25 | 3.440 | 1.038 |
| 0.075 mg/mL | 0.33 | 16.9 | 34.5 | 27 | 3.213 | 1.074 |
| 0.050 mg/mL | 0.25 | 19.2 | 31.1 | 30 | 3.391 | 1.054 |
| 0.025 mg/mL | 0.14 | 21.5 | 28.2 | 40 | 2.742 | 1.017 |

CNT 785 nm wavelength laser

| \(A_l\) | \(K\) | \(T_{eq}\) (°C) | time to achieve \(T_{eq}\) (s) | \(F\) \((\times 10^{-4} J/(s °C))\) | \(\eta\) |
| 0.100 mg/mL | 0.12 | 4.6 | 27.9 | 30 | 2.374 | 1.045 |

\[
mc_{P}dT + \frac{dQ_{ext}}{dt} = 0
\]  

Generally, the heat dissipation \(Q_{ext}\) of an object to its surrounding is proportional to the temperature difference between them, and therefore it can be expressed as the following:

\[
\frac{dQ_{ext}}{dt} = F(T - T_0)
\]

Where \(F\) is the proportional coefficient that describes heat loss process, \(T\) and \(T_0\) are the temperature of the droplet and its surrounding, in this case, ambient air.

Assuming \(T_{eq}\) is the maximum droplet temperature achieved when the equilibrium state is reached during the test, which is also the starting droplet temperature at the time when the laser is shut, we can deduce the expression for the temperature of the droplet (\(T\)) in this cooling stage from eqs 5 and 6 as follows (eq 6):

\[
T = T_0 + (T_{eq} - T_0)\exp\left(-\frac{F}{mc_{P}t}\right)
\]

The eq 6 can be further reorganized into eq 7, by which the \(F\) value can be calculated from the data collected in the cooling stage, namely the stage when laser light irradiation is off (Figure 2b).

\[
F = -\frac{\ln\left(\frac{T_{eq} - T_0}{T_0 - \bar{T}}\right)}{t}mc_{P}
\]

Figure 2c,d presents \(\ln((T_{eq} - T_0)/(T_0 - \bar{T}))\) as a function of time (\(t\)) for MXene aqueous droplet. A clearly linear correlation implies the \(F\) and \(mc_{P}\) can be regarded as constant in the small temperature range (20–40 °C) in our experiments. The calculated \(F\) values are listed in Table 1. Since the MXene concentrations in the tests are very low (i.e., 0.025, 0.05, 0.075, and 0.1 mg/mL) and thus it is believed that the MXene does not significantly contribute to the heat capacity of the droplet, therefore the mass and heat capacity of the droplets are calculated based on the volume of the droplets, the density (0.996 g/mL) and heat capacity (4.2 J/g) of pure water from literature. It is worth mentioning that, in a typical test, due to water evaporation the droplet volume shrinkage did happen but to a very small extent. First, the effect of droplet size shrinkage on light absorption path is minor (less than 0.2 mm). Second, in our calculation, the water evaporation induced heat loss is implicitly incorporated in the term \(F\). So no special treatment is given to the water evaporation induced size change of the droplet in the calculation.

At the equilibrium, the heat energy gained by the droplet is equal to energy output from the droplet by heat energy dissipation, and thus the temperature of the droplet remains constant. In this case, the energy balance equation can be described as

\[
P\eta = \frac{dQ_{in}}{dt} = \frac{dQ_{ext}}{dt}
\]

Combining eq 8 with eqs 2 and 5 leads to eq 9, which can be further reorganized into eq 10 for the calculation of light-to-heat conversion efficiency (\(\eta\)), which is the ultimate goal of the calculations.
The water generation efficiency at one sun was 10 mg. (b) Temperature time course of PDMS modified PVDF membrane and MXene-PVDF membrane in air under one sun illumination. In this measurement, a glass bottle was used to prevent shielding of IR irradiation. (d) Time-dependent water evaporation rate under one sun light irradiation by the MXene membranes with different MXene mass loadings.

\[
P_{in}(1 - 10^{-4})\eta = F(T_{eq} - T_0) \tag{9}
\]

\[
\eta = \frac{F(T_{eq} - T_0)}{P_{in}(1 - 10^{-4})} \tag{10}
\]

Thus, as one can see, in our method, the temperature profile of the droplet in the cooling stage is used to derive the \( F \) value, which is constant across all temperatures from 20 to 40 °C and is in turn used at the equilibrium stage in calculating \( \eta \). By following the procedure described above, light-to-heat conversion efficiency (\( \eta \)) were calculated for all tested concentrations and the calculated \( \eta \) in this work are listed in Table 1.

It has to be mentioned that, light scattering did exist both in the \( A_2 \) measurement and droplet heating experiments and were not explicitly counted in our calculations. (1) In the case of \( A_2 \) measurement, the scattered light was counted toward the measured absorbance. However, \( A_2 \) measurement is widely used in determining the extinction coefficient values of nanostructures because light scattering is quite weak therein.20,34 (2) In the case of droplet heating measurement, the irradiated laser beam passed through the center of droplet and the scattered light was partially absorbed by MXene in the surrounding area that was not directly irradiated by the laser beam. Thus, the light energy loss due to scattering can be very limited in this case.

Clearly, in all cases, the \( \eta \) of MXene is all close to unity (100%), indicating perfect light-to-heat conversion, no matter the wavelength of the laser source is 473 or 785 nm. In order to estimate the margin of error of our droplet heating system in estimating light-to-heat conversion efficiency, the experiment was repeated four times using 0.05 mg/mL MXene dispersion. By calculating light-to-heat conversion efficiency from the four batches, an error range was estimated to be at 5%. Therefore, our results demonstrate that MXene is a very promising photothermal material and more scientific efforts are justified to explore its further applications.

In parallel with the use of single wavelength laser sources, full visible spectrum laser and Vis plus NIR spectrum laser were also applied to the droplets and Figure S4 presents the time course of temperature profiles of CNT and MXene droplets with the same mass concentration under illumination of these two wide spectrum laser beams. It is clear that under both laser source illumination the droplet containing MXene showed consistently higher equilibrium temperature than the one containing CNTs. The result corroborates that MXene is an excellent photothermal material. Given the outstanding light-to-heat conversion efficiency of both CNT and MXene (Table 1), the lower equilibrium temperature of the CNT droplet is presumably due to its lower light absorbance than MXene (Figure 3a).

**Photothermal Water Steam Generation Under One Sun.** Having confirmed that MXene has an outstanding internal light-to-heat conversion efficiency with excellent light absorption capability, we moved on to test the efficiency of stacked MXene thin membrane for interfacial water steam generation. In this part, a simple vacuum-assisted filtration method, was utilized to fabricate stacked MXene membrane.39 Hydrophilic PVDF membrane with a pore size of 0.22 \( \mu \)m was selected as a substrate for filtration due to its suitable pore size, flexibility and chemical inertia. MXene sheets in the filtrating solution were retained and stacked to form stacked MXene membrane directly on the PVDF substrate. Although the prepared MXene membranes could be peeled off from the PVDF substrate to form self-standing ones, the MXene...
membranes were kept together with the supporting PVDF substrates to increase the mechanical strength and stability in the following tests.

Due to the hydrophilicity of the MXene membrane and PVDF substrate,9,10 the as-prepared MXene membrane sank in water. Therefore, poly(dimethylsiloxane) (PDMS) was grafted onto the membrane surface to decrease the surface energy. After this modification, the MXene-PVDF membrane is still wetted by water but able to self-float on top of water. Thanks to high transparency of PDMS, the PDMS modification shows negligible effect on the light absorption and reflection of the membranes (Figure 4a).

To optimize the thickness of MXene layer toward water evaporation performance, MXene membranes with different thickness were prepared by varying loading amount of MXene from 1.0 to 2.0, 3.0, 4.0, 5.0, and 10.0 mg in the filtering solutions. Roughly, 1.0 mg MXene corresponded to 0.75 μm thickness for the MXene layer according to the SEM observation (Figure S5). The MXene-PVDF membranes with 1.0 and 2.0 mg MXene loading amount show relatively high diffuse reflection in the visible light range as revealed in Figure 4a, which can be explained by the insufficient covering and thus incomplete MXene layers in these two cases cause by small MXene loading.

Figure 4b presents temperature time course of MXene-PVDF membrane versus PDVF substrate alone, both under one sun illumination. In a sharp comparison and as expected, the MXene-PVDF membrane achieved an equilibrium temperature around 75 °C while the PVDF substrate had only 30 °C at equilibrium. Figure 4c is the water temperature profile as a function of depth with the MXene-PVDF membrane self-floating on top of water bottle, which shows a sharp and clear high temperature zone (35.4 °C) at the air/water interface (inset) and thus provides a proof to efficient interfacial water heating by the self-floating MXene-PVDF membrane.

Figure 4d presents mass of water evaporated as a function of time for the MXene-PVDF membranes with varying MXene mass loading. It is clear that with the MXene mass loadings tested, the water evaporation is faster with increasing MXene mass. The light-to-water evaporation efficiency was calculated after light irradiation for 1 h when the evaporation rate was stable. The MXene-PVDF membrane with 10 mg MXene mass loading led to a light to water evaporation efficiency (EF) of 74% which compares very favorable against the water evaporation under light irradiation but without the membrane (30%) (Figure S7, Table S1).

It is known that, in addition to material’s intrinsic light-to-heat conversion efficiency, photothermal performance can be significantly enhanced by rationally designing surface structure to maximize light capture and employing suitable heat barrier to minimize heat loss to bulk water, among others.22,24,26,28,30,33 To achieve better EF of the system, a nonporous heat barrier of polystyrene foam was used and attached onto the back side of the MXene-PVDF membrane. The selection of the polystyrene foam is rational as it contains no water channel and thus blocks heat from transferring down to the bulk water while allowing water supply up to the photothermal material from the peripheral side of the foam. The design further concentrates the heat at the interfacial water region and thus can improve the water evaporation efficiency.26 Not surprisingly, with the rationally designed heat barrier, the light to water evaporation efficiency of 10 mg MXene–PVDF-PS membrane was boosted to 84% (Figure S8), which makes it one of the top performances in literature with similar testing system setup.22,41–44

CONCLUSION

In conclusion, in this work, a general procedure was developed based on a previously reported method to measure light-to-heat conversion efficiency of MXene with a droplet light heating system. The results showed that MXene had an outstanding internal light-to-heat conversion efficiency (∼100%), and MXene shows higher light absorption capability than CNTs. Exfoliated MXene was further made into self-floating thin membrane, which, in the presence of a heat barrier, produced a light-to-water evaporation efficiency 84%, comparable to the state of art photothermal evaporation system. This work thus demonstrates that MXene is a promising photothermal material.

EXPERIMENTS AND METHODS

Synthesis of Ti3C2. The synthesis of Ti3C2 was conducted using the method reported in previous literature.34,35 Briefly, an aliquot of 5.00 g MAX phase Ti3AlC2 powder (WVR chemicals, 97% purity) was immersed in 50 mL of 50 wt% hydrofluoric acid (HF, WVR chemicals) at room temperature along with magnetic stirring for 18 h to obtain a stable suspension. The suspension was then centrifuged, followed by washing with DI water until pH > 5. The obtained Ti3C2 powder was dried under vacuum at 60 °C overnight. The delamination of Ti3C2 was conducted using dimethyl sulfoxide (DMSO, Sigma-Aldrich). Briefly, 1.00 g of the previously obtained Ti3C2 dry powder was stir-mixed with 20 mL DMSO for 18 h at room temperature, followed by centrifugation at 3500 rpm for 5 min to collect the solid. The collected powder was dispersed in DI water at a mass ratio of 1:300, subsequently sonicated for 300 min with argon gas being continuously bubbled through the DI water during the sonication, and finally centrifuged at 3500 rpm for 30 min to remove unexfoliated particles.

 Pretreatment of Carbon Nanotube. An aliquot of 60 g of multivalled carbon nanotube (Sigma-Aldrich, 6–9 nm × 5 μm) was dispersed in a mixture of 70% nitric acid (60 mL) and 97% sulfuric acid (180 mL). The dispersion was then refluxed for 4 h at 70 °C followed by 2 h sonication. The as-treated dispersion was filtrated and washed by DI water thoroughly before its use.

Characterization. Transmission electron microscopy (TEM) images were taken on a FEI-Titan CT microscope operated at 300 kV. Scanning electron microscopy (SEM) images were obtained on a FEI Nova Nano 630s microscope. The vis-NIR spectrum was conducted on an Agilent Cary 5000 UV–vis-NIR spectrophotometer. Single wavelength laser sources utilized for light-to-heat conversion efficiency test were BWF-785–450 laser source (785 nm) and MBL-N-473B laser source (473 nm). Single wavelength photometer for transmitted laser energy detection was Newport 7936-R photometer. Broad spectrum white laser and IR laser for temperature profile comparison was conducted by a NKT superK EXTREME supercontinuum lasers equipped with a SuperK SPLIT spectral supercontinuum splitter. IR images were captured by a FLIR A655 infrared camera for temperature determination.

The emissivity of Ti3C2 powder was experimentally measured in this work. Briefly, MXene powder was scribbled on the surface of the hot plate whose temperature was maintained constant at 70 °C. Surface temperature of the MXene powder was read by both a thermal couple and IR camera, and the emissivity of the MXene was calculated based on the temperatures read from the thermal couple and the IR camera. The emissivity of Ti3C2 powder was measured to be 0.942 in this work.

Light-to-Heat conversion efficiency measurement. Light to heat conversion efficiency of MXene was measured by utilizing a
A droplet of MXene aqueous solution based on a literature method reported by Richardson et al.\textsuperscript{10} with some modification. Figure 3a shows the experimental setup. Briefly, a 9.0 μL (ul.) droplet of water (with a diameter of 2.6 mm) with varying concentrations of MXene (i.e., 0.100, 0.075, 0.050, and 0.025 mg/mL) was moved from a patterned superhydrophobic surface onto a one-end-sealed PTFE plastic pipet tip and hung there.

A laser beam with wavelength at 785 or 473 nm and incident power of 82 mW was shone right onto the center of the water droplet. Part of the light was adsorbed by the MXene sheets located in the light path, which led to the temperature increase of the entire droplet. A precalibrated infrared (IR) camera was employed to monitor the temperature change of the droplet during heat and later cooling processes. Upon the droplet temperature achieving its steady state, the laser was turned off and the droplet cooled down naturally due to heat dissipation. For the purpose of comparison, the measurement was also conducted with a droplet with CNT (Sigma-Aldrich, multiwalled carbon nanotube) concentration at 0.100 mg/mL.

**Fabrication of MXene Thin Membrane.** Vacuum assisted filtration method was used to fabricate MXene thin membranes with different thickness. Briefly, MXene aqueous suspension containing known mass of exfoliated MXene (i.e., 1, 2, 3, 4, 5, and 10 mg) was filtrated through a commercial hydrophilic PVDF membrane (Merck Millipore, GVWP, 0.22 μm). A thin MXene layer with stacked MXene sheets was formed on top of the PVDF substrate. The MXene thin membranes were first tested by directly shining simulated solar light (Oriel solar simulator) with intensity adjusted to one sun (1000 W/m\(^2\)) on top of the MXene membrane in air and the temperature of the membranes was recorded by IR camera.

**Water Evaporation Performance Under One Sun.** For photothermal water evaporation performance testing, a self-floating MXene-PVDF photothermal membrane was fabricated by modifying the previously prepared MXene thin membrane with PDMS functional groups. In more details, the MXene thin membrane along with PVDF substrate was moved to a 0.25 wt% PDMS hexane solution for 2 s for surface modification, followed by 60 °C heat treatment for 30 min.

DI water was placed in a cylindrical polypropylene (PP) container with a mouth diameter of 3.2 cm, and the MXene membrane with matching size was put and self-floating on the top of water. One sun solar light irradiation was illuminated from the top and onto the surface of the MXene membrane vertically. The distance between light source and membrane surface was 17.5 cm. The mass of the water evaporated was real time monitored by a digital balance (Mettler Toledo, d = 0.0001 g) connected to a PC. The water evaporation rate was calculated by the following equation:

\[
v = \frac{dn}{s \times dt}
\]

Where \(m\) is the mass of evaporated water, \(s\) is the illuminated area, \(t\) is time, and \(v\) is evaporation rate.

In the end, a polystyrene heat barrier was physically attached onto the bottom of the MXene membrane (10 mg) by two-side scotch tape and they together were tested for water evaporation rate using the otherwise same experimental conditions.

Light to water evaporation efficiency (EF) was calculated based on following equation:

\[
Q_s = \frac{dn \times H_s}{dt} = \nu \times H_s
\]

\[
EF = \frac{Q_s}{Q_e}
\]

Where \(Q_s\) is energy consumed for water evaporation, \(Q_e\) is the incident simulated solar light power (1000 W/m\(^2\)), \(m\) is the mass of evaporated water recorded by the balance, and \(H_s\) is the enthalpy of vaporization of water (2266 KJ/kg).

**REFERENCES**