Supplementary Materials for

The Elegance of Simplicity: A Cost-Effective Janus Membrane for All-Day Radiative Thermal Management Inspired by Complementary Photothermal Design

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Supplementary Calculations1：

Planck's blackbody radiation law was utilized to calculate the average emissivity of a two-mode membrane over a range of wavelengths. For any object in thermal equilibrium, the spectral absorptivity (α) and emissivity (ε) must be equal according to Kirchhoff's law based on the following equation:

$$\varepsilon = \frac{\int_{\lambda_{min}}^{\lambda_{max}} \varepsilon(\lambda)B(\lambda)d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} B(\lambda)d\lambda} \tag{1}$$

$$I_{BB}(\lambda) = \frac{c_1\lambda^{-5}}{\exp\left(\frac{c2}{\lambda T}\right) - 1} \tag{2}$$

$$\varepsilon(\lambda) = \alpha(\lambda) = 1 - R(\lambda) - T(\lambda) \tag{3}$$

Where c_1 is the first radiation constant (3.7418×10^8 W·μm^4·m^{-2}), c_2 is the second radiation constant (1.4388×10^4 μm·K), T is the temperature(K), $R(\lambda)$ is the reflectance at the corresponding wavelength. $\varepsilon(\lambda)$ refers to the emissivity, $\alpha(\lambda)$ is the absorbance, $T(\lambda)$ is the transmittance, MXene is not transparent, so its transmittance $T_{MXene}(\lambda)$=0.

The average solar absorption ratio $\bar{\alpha}$ of the thin membrane surface in the range of 0.3-2.5 μm is determined by:

$$\bar{\alpha} = \frac{\int_{0.3\mu m}^{2.5\mu m} \alpha_{solar}(\lambda,\theta) I_{solar}(\lambda) d\lambda}{\int_{0.3\mu m}^{2.5\mu m} I_{solar}(\lambda) d\lambda} \tag{4}$$

Where λ represents the wavelength of incident light within the range of 0.3-2.5 μm, and $I_{solar}(\lambda)$ is the standardized ASTM G173 global solar intensity spectrum.

Net heating power P_{heat} or cooling power P_{cool} was calculated based on the energy balance equation when the ambient temperature T_{amb} is equal to the membrane temperature Tc:

$$P_{heat} = P_{solar} + P_{atm} - P_{cond+conv} - P_{rad} \tag{5}$$

$$P_{cool} = P_{rad} - P_{solar} - P_{atm} - P_{cond+conv} \tag{6}$$

P_{solar} is the absorbed solar radiation. It can be calculated from the following equation:

$$P_{\mathrm{solar}} = \int \alpha(\lambda, T_c) I_{solar}(\lambda) d\lambda \tag{7}$$

Where λ is the wavelength, $\alpha(\lambda, T)$ represents the spectral absorptance of the MXene and Nylon, $I_{solar}(\lambda)$ is the solar intensity.

P_{atm} is the absorbed radiation power from the atmosphere. P_{atm} can be calculated from the following equation:

$$Patm = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \int_0^{\infty} I_{BB}(\lambda, T_{atm}) \varepsilon_{atm}(\lambda) \varepsilon(\lambda,\theta) \sin\theta \cos\theta \, d\lambda \, d\theta \, d\varphi \tag{8}$$

Where ε_{atm} is the emittance of the atmosphere.

P_{rad} is the radiation power of the membrane, which can be calculated from the formula:

$$P_{rad}(T) = \int \alpha(\lambda, T) I_{BB}(\lambda, T - T_{atm}) d\lambda \tag{9}$$

$P_{cond+conv}$ is the power lost owing to convection and conduction:

$$P_{\mathrm{cond+conv}}(T, T_{amb}) = h_c(T - T_{amb}) \tag{10}$$

Where hc is a combined non-radiative heat coefficient that captures the collective effect of conduction and convection, which generally ranges from 0 to 12 W m^{-2} K^{-1}.

Supplementary Calculations2:

To quantify the equivalence between UV-ozone treatment and natural sunlight exposure, we provide the following step-by-step calculation using standard formulas:

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1. Energy Delivered by UV-Ozone Lamp

$$E_{\text{UV-Ozone}}=I_{\text{UV-Ozone}}\times t_{\text{UV-Ozone}}$$

Where: $E_{\text{UV-Ozone}}$is the total energy delivered (in J/cm²), $I_{\text{UV-Ozone}}$ is the irradiance of the UV-ozone lamp (in mW/cm²), $t_{\text{UV-Ozone}}$ is the treatment time (in seconds).

For a 250W UV-ozone lamp with an irradiance of approximately $I_{\text{UV-Ozone}}$=25 mW/cm² and a 24-hour treatment ($t_{\text{UV-Ozone}}$=24×3600 s):$E_{\text{UV-Ozone}}$=25×(24×3600)=2160J/cm².

2. Energy Delivered by Natural Sunlight

The energy delivered by natural sunlight is given by:

$$E_{\text{Sunlight}}=I_{\text{Sunlight}}\times t_{\text{Sunlight}}$$

Where: E_{Sunlight} is the total energy delivered (in J/cm²), I_{Sunlight} is the average UV irradiance of sunlight (in mW/cm²), t_{Sunlight} is the exposure time (in seconds).

For typical UV-rich sunlight, I_{Sunlight} is approximately 0.3 mW/cm². The energy delivered in 1 hour of sunlight is: $E_{\text{Sunlight, 1h}}$=0.3×3600=1.08J/cm²

3. Equivalent Sunlight Hours

To determine the equivalent duration of sunlight exposure for the same energy delivered by UV-ozone treatment, we use the formula: $t_{\text{Equivalent Sunlight}}=E_{\text{UV-Ozone}}/I_{\text{Sunlight}}$=2160/1.08=2000 hours.

4. Equivalent Sunlight Days

Assuming an average of t_{Daylight}= 8 hours/day of UV-rich sunlight exposure:

Equivalent Sunlight Days=$E_{\text{quivalent Sunlight}}/t_{\text{Daylight}}$=2000/8=250 days.

Supplementary Figure:

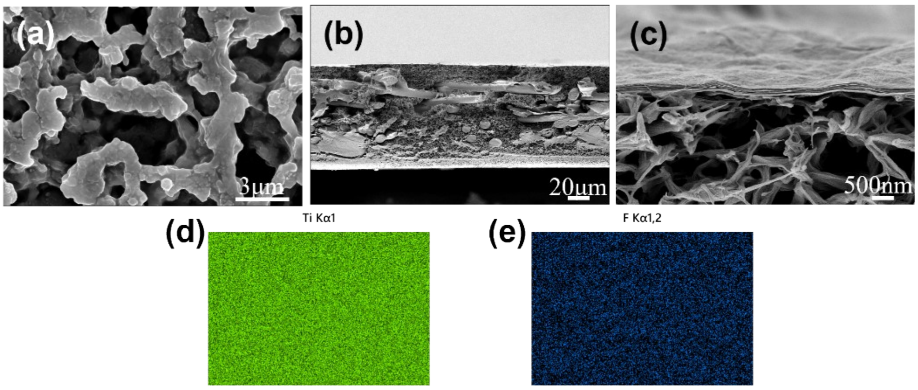

Fig. S1 SEM image of Nylon66 surface (a) and MN membrane cross-section (b-c). EDS image of Ti (d) and F (e) on MN surface.

The surface EDS results (Fig. S1d) show that the characteristic element Ti of MXene is uniformly distributed, which can indicate to some extent that MXene is uniformly sprayed onto the nylon membrane.

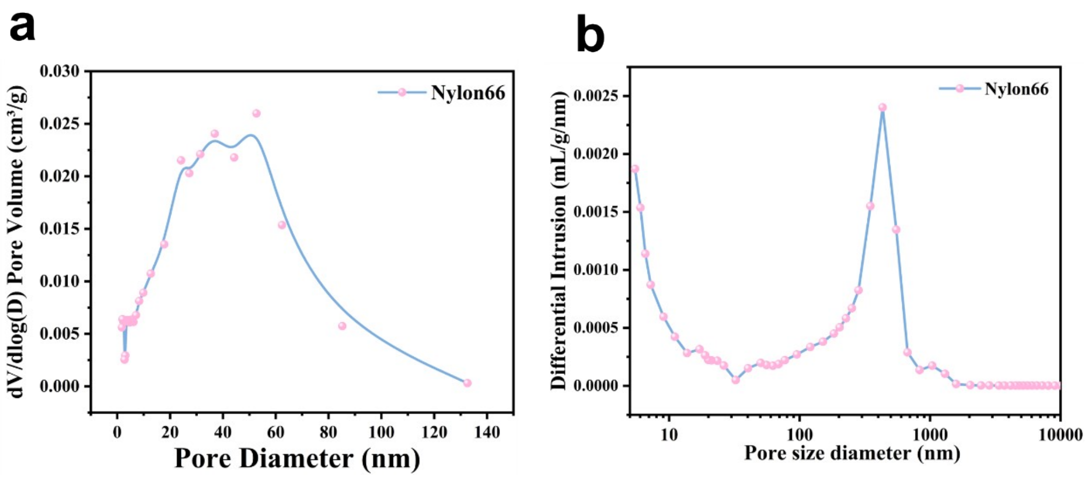

Fig. S2 Pore size distribution of Nylon66, (a)BET testing for micropores and mesopores, (b) mercury intrusion porosimetry testing for macropores.

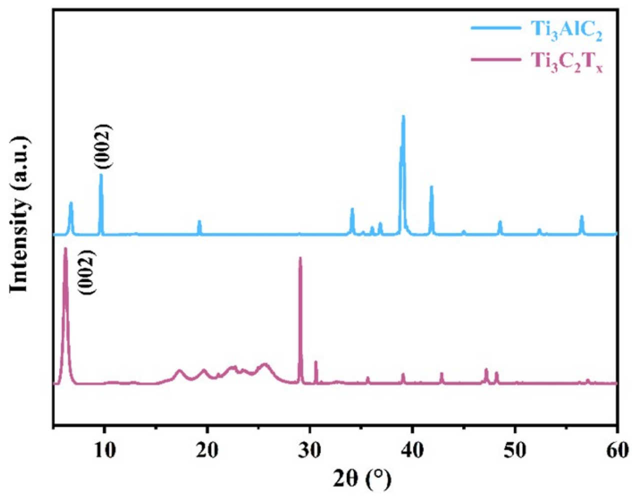

Fig. S3 XRD image of Ti_3AlC_2 and $Ti_3C_2T_x$.

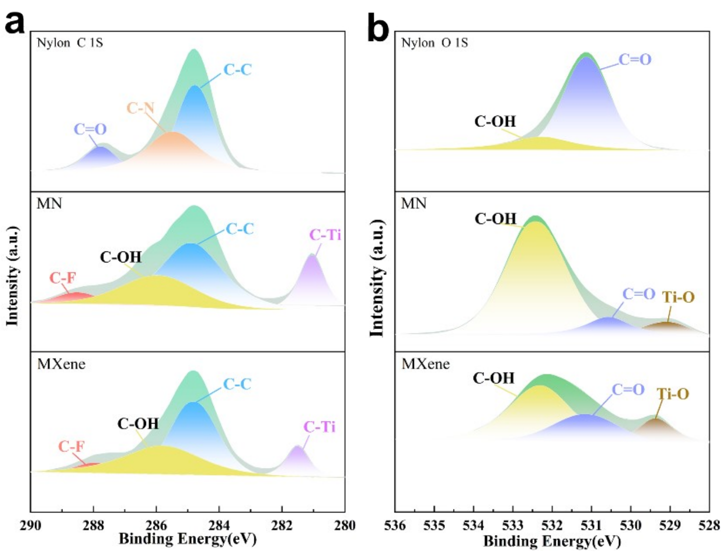

Fig. S4 High-resolution XPS spectrum of the C1s (a) and O1s (b) of Nylon66, MN membrane and pure MXene membrane.

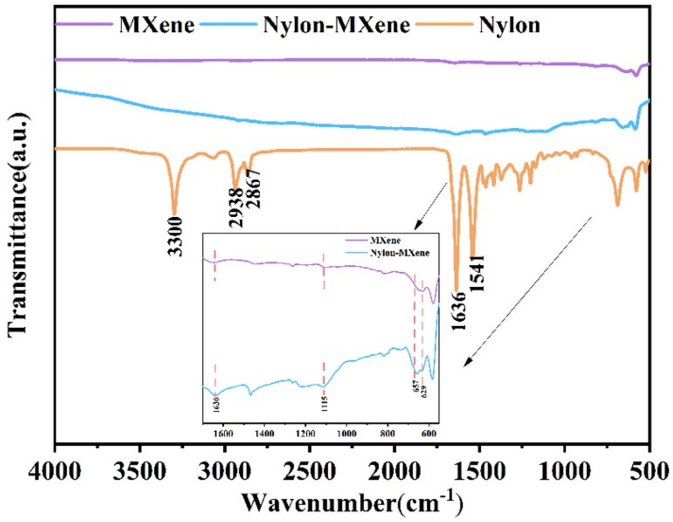

Fig. S5 FTIR images of MXene and MN membranes.

Fig. S5 reveal Nylon66's strong mid-IR absorption through amide vibrational modes (1636 cm^{-1} C=O, 1541 cm^{-1} N-H/C-N), while MXene's metallic nature manifests as weak Ti-O signatures (620-639 cm^{-1}) corroborating its high IR reflectivity.

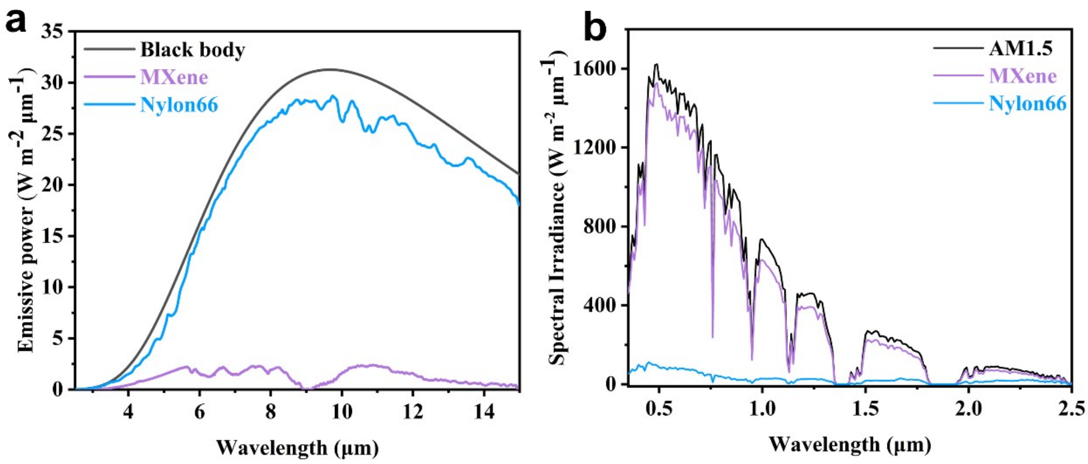

Fig. S6 MN membrane (a) Emissive power and (b) Spectral Irradiance.

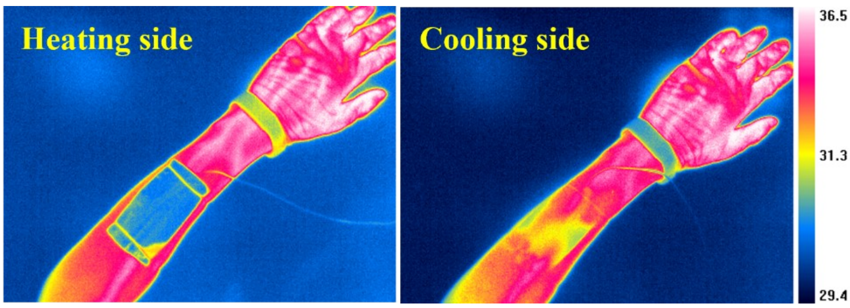

Fig. S7 Infrared image of MN membrane-applied arm.

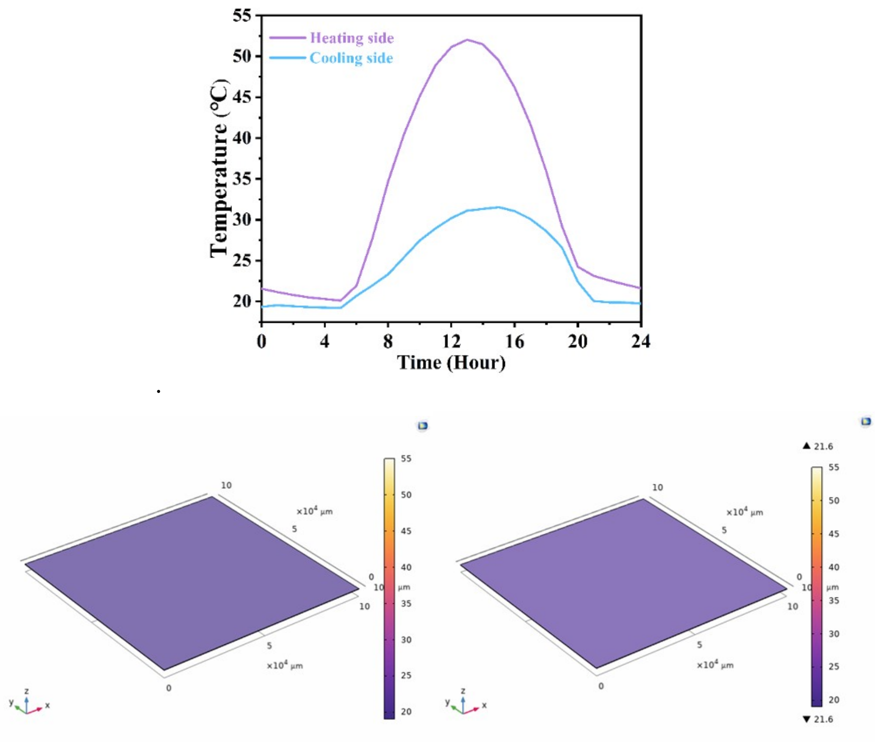

Fig. S8 Comsol simulates MN membrane temperature change on a sunny summer day in Chengdu. Left: Heating side; Right: Cooling side. Data from COMSOL meteorological station Wenjiang, Chengdu 2021.06.06.

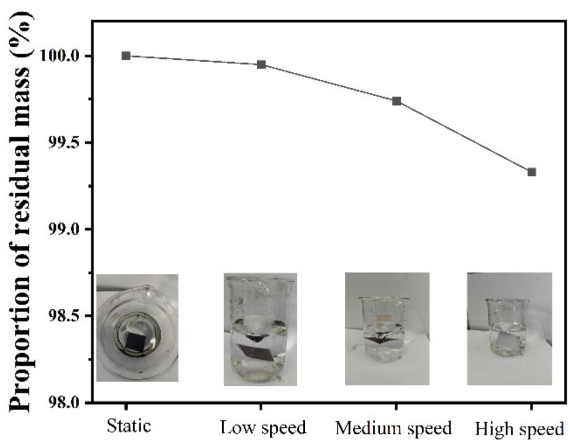

Fig. S9 Evaluation of washing performance.

Table S1. The MN membrane cost accounting per square meter.

Materials	Dosage	Unit Price (RMB/Yuan)	Total Price (RMB/Yuan)	Total Price (USD)
MAX (Ti_3AlC_2)	1 g	13/g	13	1.79
Nylon66 membrane	1 m^2	50/m^2	50	6.89
HF, 40 wt%	10 ml	0.08/ml	0.8	0.11
HCl, 37 wt%	10 ml	0.2/ml	2	0.28

LiCl	1 g	0.15/g	0.15	0.02
Total			65.95¥	9.09$

Prices from https://www.aladdin-e.com/zh_cn/.

1 USD = 7.26 RMB

Table S2. Comparison of the optical and thermal management performance of the membrane developed in this work with previously reported materials. The cooling performance comparison includes solar absorptance (α_{solar}, 0.3-2.5 μm), infrared emittance (ε_{IR}, 2.5-25 μm), and measured cooling/heating effects under corresponding conditions (T_{cool} and T_{heat}). Daytime and nighttime are denoted as D and N, respectively.

Samples	**Preparation method**	**Cooling Side**	**Heating side**	T_{cool} **(°C)**	T_{heat} **(°C)**
Dual-modal photonic textiles[1]	Polymer spunlace hot stretch weaving + silver/carbon nanoparticle coating	α_{solar}=0.11 ε_{IR}=0.89	α_{solar}=0.70 ε_{IR}=0.94	D:5.1 N:N/A	D:3.5 N:N/A
Biomass aerogel[2]	Biomass aerogels by blending gelatin and DNA, freeze-dried and annealed	α_{solar}=0.03 ε_{IR}=0.95	N/A	D:12 N:1.6	D:N/A N:N/A
Radiation-modulated thermoelectric fabrics[3]	Carbon nanotube printing on electrostatically spun fabrics	α_{solar}=0.969 ε_{IR}=0.968	α_{solar}=0.884 ε_{IR}=0.956	D:9.6 N:N/A	D:N/A N:27.1
Janus textiles[4]	MXene brushed on one side of commercial polyamide fabrics	N/A	ε_{IR}=0.67	N/A	Simulates skin :3.4 D:14.2 N:N/A
Janus membrane[5]	MXene sprayed onto the porous PVDF membranes (surface hydrophilic modification required)	α_{solar}=0.033 ε_{IR}=0.961	α_{solar}=0.757 ε_{IR}=0.116	D:9.8 N:11.7	D:8.1 N:N/A Joule Heating: (63.9°C at 5V).
Janus membrane[6]	Hydrophobic SiO_2 nanoparticles and graphene/carbon nanotubes sprayed on the surface of P(VDF-HFP)	α_{solar}=0.08 ε_{IR}=0.95	α_{solar}=0.90 ε_{IR}=0.71	D:13.3 N:N/A	D:11.4 N:N/A Joule Heating: (96.7°C at 8V).
Janus membrane (This work)	MXene sprayed on the surface of Nylon66 membrane with coral-like hierarchical porous structure	α_{solar}=0.062 ε_{IR}=0.928	α_{solar}=0.845 ε_{IR}=0.073	D:14.8 N:1.7	D:36.4 N:0.5 Joule Heating: 17.1°C·min^{-1} heating rate at 4 V

References

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