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Polymeric Membranes with Selective Solution-diffusion for Intercepting Volatile Organic Compounds during Solar-driven Water Remediation

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Keywords: microstructured membrane, solar evaporation, water purification, photothermal materials, volatile organic compounds

Abstract

Solar evaporation through a photothermal porous material provides a feasible and sustainable method for water remediation. Several photothermal materials have been developed to enhance solar evaporation efficiency. However, a critical limitation of current photothermal materials is their inability to separate water from the volatile organic compounds (VOCs) present in wastewater. Here, we report a micro-structured ultrathin polymeric membrane that enables freshwater separation from VOC pollutants by solar evaporation with a VOC removal rate of 90%. The different solution-diffusion

behaviors of water and VOCs with polymeric membranes facilitate their separation. Moreover, owing to increased light absorption, enlarged liquid-air interface, and shortened mass transfer distance, the micro-structured and ultra-thin configuration of the membrane helps to balance the tradeoff between permeation selectivity and water production capacity. The membrane is not only effective for evaporation of simulated volatile pollutants in a prototype, but can also intercept complex volatile organic contaminants in natural water sources and produce water that meets drinking water standards. With practical demonstration and satisfactory purification performance, our work paves the way for practical application of solar evaporation for effective water remediation.

Solar evaporation is considered a green and sustainable strategy for water remediation, and has wide applications in desalination, sterilization, and freshwater production.^[1-9] Water evaporation is an endothermic process at the water-air interface, where energized water molecules are transported from the liquid phase to the vapor phase.^[10-15] Hence, in contrast to heating up the bulk water, local heating at the water-air interface is an effective way to enhance the energy efficiency for solar evaporation.^[11, 16-19] In such systems, photothermal materials are the key elements that serve as light harvesters and light-to-heat energy converters.^[18, 20-22] To date, several strategies have been proposed for optimizing photothermal materials to enhance solar evaporation efficiency, including light-to-heat conversion enhancement,^[17, 23-27] heat energy loss management,^[14, 28-31] anti-fouling property^[32-33] and salt resistance improvement,^[22, 26, 34] water evaporation enthalpy regulation^[35-38], and others. All these strategies have contributed towards the improvement of the solar evaporation process; however, a critical challenge for current photothermal materials is to separate water from volatile organic compounds (VOCs). Current materials can separate water only from nonvolatile pollutants via phase transformation,^[38] but not VOCs which exist in the form of synthetic organics in wastewater, and biological organics derived from microbial metabolism in natural water.^[40-41] These organic pollutants could evaporate together with water, resulting in secondary pollution of distilled water, and could even be enriched in distilled water. Therefore, a photothermal material that allows easy penetration of water molecules but blocks the evaporation of VOCs is highly desired.

To separate freshwater from VOC pollutants via solar evaporation, the photothermal material must have the following characteristics: (1) It should exhibit good light-absorbing properties to enhance light-to-heat conversion efficiency. (2) Its interaction behavior with water and VOCs should be different, so that it allows water evaporation but suppresses the evaporation of VOCs. In this regard, inspirations can be drawn from selective permeable membranes in living organisms and chemical separation processes, which can effectively separate substances with different chemical or physical properties (e.g., cell membranes and reverse osmosis membranes).^[42-43] Mass transfer in these selective permeable membranes is primarily based on the solution-diffusion process, where substances first dissolve in the molecular mesh of the membrane from one side, then diffuse to the other side, finally escaping from the surface of the membrane.^[44] Generally, with chemicals, a high chemical affinity would enhance the dissolution process,^[42] while a small molecular size would facilitate the diffusion in membranes.^[45-47] (3) A high surface area is desired because it increases the contact area between water and the photothermal material, which enhances thermal transmission between them; it also enlarges the water-air interface, promoting steam generating efficiency.

Based on the above considerations, herein, we report the first demonstration of freshwater separation from VOC pollutants via solar evaporation using a rationally designed micro-pyramid structured polypyrrole (MPS-PPy) membrane as the photothermal material. Polypyrrole (PPy), a typical polar conducting polymer, exhibits excellent light-absorbing ability.^[48] It has a protonated molecular structure and offers

good affinity for polar water molecules.^[49-50] This was confirmed by the simulation results, which revealed that PPy has a stronger interaction with water molecules than with phenol molecules (a representative VOC) (**Scheme 1a**). Thus, compared to VOCs, water is easier to dissolve in the PPy membrane. Additionally, the smaller size of the water molecules facilitates their diffusion in the PPy membrane (Scheme 1b). Taking all these into consideration, the as-prepared MPS-PPy membrane shows selective permeability towards water and VOCs, where water evaporation is allowed while VOC evaporation is suppressed (Scheme 1c, 1d). Notably, the pyramid structure can not only reduce light reflection and enhance light-to-heat conversion efficiency, but also increase the membrane surface area, thereby enhancing water evaporation efficiency. Therefore, the pyramid structure balances the tradeoff between permeation selectivity and water production capacity. Ninety percent blocking of VOCs, and a water evaporating efficiency of $1.12 \text{ L m}^{-2} \text{ h}^{-1}$ under one sun irradiation were achieved. Finally, as a proof of concept, by employing the MPS-PPy membrane as the photothermal material, a portable system was built for seawater evaporation, and the ion concentration of the distilled water was observed to be much lower than the standards for drinking water recommended by the World Health Organization (WHO). Additionally, the MPS-PPy membrane was successful in producing freshwater from VOC polluted river water. The results clearly indicate the feasibility of using MPS-PPy membranes for efficient solar water purification.

The MPS-PPy membrane was fabricated through a template-assisted electropolymerization strategy using an indium tin oxide coated polydimethylsiloxane

(ITO-PDMS) pyramid structure as the working electrode. The fabrication process is shown in Figure S1. We first produced a silicon mold by combining photolithography and anisotropic etching of silicon. Then, using the silicon mold as a template, a PDMS pyramid structure was produced. The ITO-PDMS pyramid electrode was fabricated by sputtering ITO on the PDMS pyramid surface. PPy was deposited on the electrode surface via an electropolymerization process (more details can be found in the supporting information). To obtain a dense membrane, which facilitates the interception of VOCs, we conducted the electropolymerization process in an ice bath. The PPy membrane could be easily separated from the ITO surface by water because of the difference in surface energies of the PPy membrane (contact angle: 57 °) and the ITO electrode (contact angle: 22 °) (Figure S2), and a uniform MPS-PPy membrane was thus, successfully produced. The MPS-PPy membrane was dark black in color, implying an excellent light-absorbing capability. Further, the membrane was so lightweight (Density: 0.32 mg/cm² of the membrane with the thickness of 1 micron) that it could be hung by a single strand of human hair (**Figure 1a**). The as-prepared MPS-PPy membrane exactly copied the pyramid structure from its mold (Figure 1b). The side of the membrane facing the solution was rougher than the side adhered to the electrode (Figure S3), consistent with previous reports.^[51] The thickness of the membrane was optimized by adjusting the electropolymerization time (Figure S4). The ultrathin structure not only shortens the pathway of water in the PPy membrane to enhance steam generating efficiency, but also reduces the solid-gas interface area between the photothermal material and air significantly. As a result, energy spent in heating the

surrounding air (specific heat capacity of $1.0 \text{ kJ kg}^{-1} \text{ K}^{-1}$) and the penetrating steam (specific heat capacity of $2.0 \text{ kJ kg}^{-1} \text{ K}^{-1}$) can be saved. Therefore, the water evaporation efficiency can be further enhanced.

The excellent sunlight absorption capacity of photothermal materials can significantly enhance their solar evaporation performance. In this study, the as-prepared MPS-PPy membrane was very dark in color (Figure 1a), showing excellent absorption over the entire solar spectrum (Figure 1c), especially in the visible range, which is the main part of sunlight. The MPS-PPy membrane showed a reflectance of less than 2%, which was significantly lower than that of the flat PPy membrane (Figure 1c). This is because the pyramid structure could induce a gradient refractive index on the PPy-air interface.^[52-54] We fabricated PPy pyramids with sizes of 5 μm , 8 μm , and 20 μm . The 5- μm and 8- μm pyramids showed similar reflectance, which was consistent with the simulation results (Figure S5). Higher reflectance was observed for the 20 μm -sized pyramid. Finally, an 8- μm MPS-PPy membrane was selected for this study. Notably, the absorption capacity of the MPS-PPy membrane is comparable to that of most reported photothermal or photovoltaic materials.^[23, 54-56] The molecular orbital of PPy indicates that electrons in the antibonding orbitals can absorb light and jump to higher energy orbitals; therefore, strong light absorption by the PPy membrane is observed (Figure S6). When the MPS-PPy membrane was irradiated with 1 kW m^{-2} light, its temperature immediately increased from $\sim 25^\circ \text{C}$ to $\sim 60^\circ \text{C}$ (Figure 1d and 1e), which is approximately 5°C higher than that of the flat PPy membrane. This is attributed to the high light-harvesting efficiency of the MPS-PPy membrane. A hydrophilic surface

of the MPS-PPy membrane could promote the water penetration in it. The MPS-PPy membrane possesses a hydrophilic surface with a constant contact angel of 57° under different temperatures (Figure 1f), which demonstrates that wettability of the water to the membrane surface won't be affected by light irradiation. Interestingly, although it is hydrophilic, it can still spread out after rising to the water surface (Video S1). Therefore, the as-prepared MPS-PPy membrane can locally heat the water surface, which enhances the utilization of sunlight.

Compared to powder photothermal materials, the advantage of the MPS-PPy membrane is that it possesses a high tear strength with a Young's modulus of 154 MPa (Figure S7), so that it can suffer the force induced by tearing in a transferring process. As shown in Video S2, the MPS-PPy membrane can be transferred from one Petri dish to another, and the membrane expands as soon as it touches the water surface. In contrast, when the graphene membrane was handled in the same way (the fabrication method of graphene membrane can be found in our previous work^[57-58]), the membrane easily fractured during the transfer process (Video S3). Therefore, the good mechanical stability of the MPS-PPy membrane endows it with superior recyclability.

Providing pathways for water penetration is a basic requirement for photothermal materials used in solar evaporation. In this study, no obvious channels were observed in the as-prepared PPy membranes by SEM and HRTEM (Figure S8), and no porous characteristics were observed in the nitrogen adsorption-desorption analysis. The feature of nonporous membrane was further demonstrated by forward osmosis process (Figure S9).^[59] Even so, water could still penetrate the PPy membrane as can be seen

in Video S4. When a PPy membrane deposited on an ITO electrode was immersed in water, owing to the hydrophilic property of ITO surface, water penetrated the PPy membrane and water bubbles were formed at the ITO-PPy membrane interface. Moreover, these water bubbles could be gradually blown away by a nitrogen gun. In this process, the water penetrated the PPy membrane again and blown away by the nitrogen flow. To further confirm the water penetration, we used a PPy membrane to fully cover the neck of a glass tube and tightened it with parafilm. Subsequently, the whole device was placed on the water surface (Figure S10 and Figure S11). It can be observed that many water drops were condensed on the tube wall after irradiating the PPy membrane for 1 h (Figure S11d). In contrast, if the PPy membrane was covered with another layer of adhesive tape, no water drop was observed under the same irradiation conditions (Figure S11e, 11f). This phenomenon further verifies that water can penetrate PPy membranes.

A unique advantage of the MPS-PPy membrane is that it can intercept the evaporation of VOCs during the solar evaporation process because the PPy membrane shows different solution-diffusion behavior towards water and VOCs. The VOC intercepting behavior was demonstrated by using the MPS-PPy membrane for evaporating a phenol solution (5 mg L^{-1}). Phenol was selected because it widely exists in industrial wastewater and is highly toxic to humans. Moreover, it is volatile and has a smaller molecular size than other kinds of phenolic pollutants; thus, if phenol could be blocked by the PPy membrane, so will the other phenolics. As shown in **Figure 2a**, after evaporation through the MPS-PPy membrane, the concentration of phenol in the

distilled solution was significantly decreased, and more than 90% of phenol was blocked. Additionally, through repeated experiments, the VOC intercepting performance demonstrated outstanding recyclability of the membrane (Figure 2b). Simultaneously, no obvious influence of the VOC concentration on the VOC intercepting performance was observed (Figure S12).

The selective molecule penetration behavior in the PPy membrane can be considered as a pervaporation process and explained by the solution-diffusion principle.^[60-61] which includes the dissolution of molecules into the membrane surface on the feed liquid side, the diffusion process through the membrane matrix, and desorption from the membrane surface to achieve vaporization. As the third step of desorption is much faster than the previous two steps, the dissolution and diffusion behavior of the molecules are therefore, the determining factors of the entire process. Dissolution is a thermodynamic process, which can be described by Henry's law,^[62-63] while diffusion, as a dynamic process, conforms to Fick's law.^[64-65] Consequently, the permeate flux is described by the following equation:

$$J = \frac{SD}{L} \Delta p \quad (1)$$

where J represents the permeate flux, L is the thickness of the membrane, Δp is the partial vapor pressure difference between the solution sides (attached on the membrane) and vapor sides, and S and D are the solubility and diffusion coefficient of the molecule in the PPy membrane, respectively. Under certain conditions, Δp and L are constant; therefore, the permeate flux of different substrates is determined by the solubility and diffusion coefficient. When the small molecules permeate the polymer film, it can be

described as a transient state process from unsteady state to steady state. In such a case, the diffusion coefficient can be get by the commonly used time delay method.^[66-68] In details, the diffusion can be described by Equation (2).^[66-68]

$$\frac{Q_t}{Lc_i} = \frac{Dt}{L^2} - \frac{1}{6} - \frac{2}{\pi} \sum \frac{(-1)^2}{n^2} \exp\left(\frac{-Dn^2\pi^2 t}{L^2}\right) \quad (2)$$

Here, Q_t is the amount of material permeating the membrane, c_i is the concentration of the materials on the solution side, D is the diffusion coefficient, t is time, and n is an integer. When $t = \infty$, Equation 2 can be written as:

$$Q_t = \frac{Dc_i}{L} \left(t - \frac{L^2}{6D} \right) \quad (3)$$

The intersection point of the extension line of Q_t/Lc_i in the steady state and t is called the delay time (θ). From θ , we can obtain the diffusion coefficient D .

$$D = L^2/6\theta \quad (4)$$

Accordingly, we measured the diffusion coefficient of water and phenol (Figure 2c), and found that the D of water in PPy was approximately 7 times higher than that of phenol under the same conditions. The solubility differences of various substrates can be understood by qualitative experiments and theoretical modeling. As observed in Video S5, when the PPy membrane was placed on a filter paper pre-wetted by phenol and water, the PPy membrane only responded to water molecules rather than organic molecules, the membrane surface contacting to the water pre-wetted paper was swollen. Molecular dynamic simulations^[69-71] show that compared to phenol, water has a higher chemical affinity for the membrane (Scheme 1a), which together with the experimental observation, implies that water molecules are much easier to dissolve in the PPy membrane than phenol molecules. Hence, due to the higher diffusion coefficient and

solubility of water, phenol molecules were selectively intercepted during the solar evaporation process. In addition to phenol, the PPy membrane also showed good intercepting effect towards other volatile organic compounds, such as methylbenzene, ethyl acetate, acetone, ethanol, and aniline (Figure 2d, Figure S13). In contrast, when graphite, graphene, or PPy-coated carbon cloth was employed as photothermal materials, no obvious change in the concentration of phenol was observed (Figure 2a). The thickness of the PPy membrane has a great influence on the blocking of volatile organic molecules. Increasing the membrane thickness increase the blocking efficiency, as shown in Figure S14. More than 85% of the volatile organic molecules are blocked when the thickness of the membrane is larger than 960 nm. Moreover, we measured the flux of water and phenol in the PPy membrane under the irradiation of different light density (0.5 kw/m², 1 kw/m² and 1.5 kw/m², respectively). It can be found that with the increase of light density, both the flux of water and phenol increased, but water is always much easier to pass through the PPy membrane (Figure S15).

The outstanding photothermal conversion efficiency, enhanced light harvesting, and good mechanical properties of the as-prepared MPS-PPy membrane provides a unique opportunity for the solar evaporation system. As a proof of concept, we used the as-prepared MPS-PPy membrane for water evaporation. In a typical experiment, the MPS-PPy membrane was placed on a water surface (in a beaker) to act as a localized photothermal convertor, and a solar simulator was used to provide the photon flux. As shown in **Figure 3a**, under light irradiation with a power density of 7 kW m⁻², the surface of water gets heated up in less than 2 min, and steam was clearly observed.

Even though the water surface reaches a temperature of 58 °C, the temperature of bulk water remains unchanged (Figure 3b). The localized heat effect can significantly improve the efficiency of solar steam generation by inhibiting the energy consumption in the heating of bulk water. The MPS-PPy membrane induced a temperature difference of approximately 22 °C between the surface and bottom of water after 15 min of 5 kW m⁻² light irradiation (Figure 3c). In contrast, a difference of less than 0.5 °C was observed in the control group without the MPS-PPy membrane, indicating the absence of localized heating. To evaluate the performance of steam generation via the MPS-PPy membrane, we measured the weight loss of water under irradiation. An evaporation rate of 0.85 kg m⁻² h⁻¹ at 1 kW m⁻² irradiation was achieved, which is approximately 1.2 times higher than that of the flat PPy membrane (0.71 kg m⁻² h⁻¹), 2.25 times higher than that of pure water, and 3.21 times higher than pure water evaporation without irradiation (Figure 3d). The steam generation rate could be further improved to 1.12 kg m⁻² h⁻¹ (Figure 3d) by employing an insulating layer (polyurethane foam) between the MPS-PPy membrane and the water surface (Figure S16). The evaporation efficiency achieved here (~70.3%, calculating method can be found in previous work^[31]), is comparable to that reported in earlier studies.^[32, 72-73] Although the efficiency is not as high as the latest results,^[3, 8, 19] it can be enhanced by rational design of the evaporator.^[74] The evaporation rate could be further enhanced by increasing the irradiation power density (Figure 3e). Moreover, the MPS-PPy membrane and PPy-coated carbon cloth demonstrated similar steam generation efficiency (Figure 3f), although there are numerous micron-scale channels in the PPy-coated carbon cloth for

water and steam penetration (Figure S17). It demonstrates the efficient “solution-diffusion” behavior of water molecules in the PPy membrane. Further, no obvious decrease in the steam generation efficiency was observed after increasing the thickness of the PPy membrane (Figure S18). These results confirm the good adsorption and diffusion of water in PPy membranes. Additionally, the as-prepared MPS-PPy membrane exhibited solar evaporation performance comparable to that of the normally used photothermal materials, such as graphene and graphite (Figure 3g).

The MPS-PPy membrane has the merits of high photothermal efficiency and selective solubility-diffusion behavior towards water and VOCs, and is therefore expected to exhibit robust feasibility for efficient solar distillation to produce clean drinking water. Fabrication of photothermal membranes with a large area is a basic requirement for solar water evaporation. In this study, an MPS-PPy membrane with an area of $\sim 75 \text{ cm}^2$ was prepared (Figure S19) via template-assisted electropolymerization in a simple homemade electroplating apparatus (Figure S20). The prepared PPy membrane was employed as the photothermal material in a portable, all-in-one homemade solar evaporation device, whose appearance and principle are schematically shown in **Figure 4a** and Figure S21, respectively. Using a $15 \times 10\text{-cm}$ PPy membrane, $\sim 12 \text{ g}$ of water was produced by the device under natural solar irradiation for 1 h. The ion concentrations in distilled water were significantly lower compared to those in the source seawater (Figure 4b). They are much lower than the standards recommended by WHO for drinking water (Na^+ : 200 mg L^{-1} , K^+ : 12 mg L^{-1} , Mg^{2+} : 150 mg L^{-1} , Ca^{2+} : 75 mg L^{-1}). [75-76]

In addition to inorganic salts, complex VOCs present in common water sources can also be intercepted by the MPS-PPy membrane during solar distillation. In this study, raw water from the Songhua River of China was collected and pre-filtered through a 0.22-micron filter membrane before conducting solar distillation. Figure 4c shows the total organic carbon (TOC) concentration of the raw river water, and water distilled through conventional porous membrane (graphite felt, it was constructed from the random accumulation of graphite fibers with an average diameter of $\approx 10\ \mu\text{m}$, creating an interconnected porous structure^[77]), as well as MPS-PPy membrane. The raw river water contains around $17.52\ \text{mg L}^{-1}$ TOC, while the distilled water collected through conventional porous membrane has $10.86\ \text{mg L}^{-1}$ residual TOC, implying that organic matter in the river water has volatile components. The residual TOC was decreased to $3.88\ \text{mg L}^{-1}$ using the MPS-PPy membrane, which meets the TOC concentration requirement of Drinking Water Standards of China ($5\ \text{mg L}^{-1}$, GB5749-2006). This demonstrates that the MPS-PPy membrane can effectively intercept the evaporation of VOCs from river water during solar water purification. A fluorescence excitation-emission matrix (EEM) was employed to further identify the components of dissolved organics in water. The 3D-fluorescence spectra shown in Figure 4d and Table S1 indicate that the dissolved organics can be classified as tyrosine-like proteins, tryptophan-, fulvic acid-, and humic acid-like substances, and soluble microbial byproducts. Among them, the soluble microbial byproducts are predominantly protein-derived compounds, and the fluorescence is mainly produced by the amino acid tryptophan.^[78-79] The soluble microbial byproducts observed in the IV spectral region

and humic acid-like substances in the V spectral region are the predominant species in the Songhua River water (Figure 4d). After solar distillation through conventional porous membranes, most components observed in the I, II, III, and V spectral regions were removed due to poor volatility. However, soluble microbial byproducts were still found in distilled water, and were even enriched in concentration to some extent, which indicates the failure of conventional porous membranes in intercepting VOCs to ensure water safety. However, when the MPS-PPy membrane was used, not only the organic components in regions I, II, III, and V, but also the majority of volatile organics in region IV were effectively intercepted. This resulted in ~78% removal of organics from feedwater and therefore, provides a robust solution to produce drinking water from VOC polluted water.

In conclusion, we reported the development of a micropyramid-structured PPy membrane via a template-assisted electropolymerization process, which has selective permeability towards water and VOCs. During solar evaporation, 90% interception of the evaporation of VOCs was achieved. The VOC intercepting behavior of the MPS-PPy membrane is attributed to its selective solution-diffusion behavior towards water and VOCs, which was verified by simulation and experimental results. The micropyramid structure not only reduces light reflection, which enhances the photothermal efficiency of MPS-PPy membranes, but also increases the area of the air/PPy membrane interface, which can provide more surface area for steam generation. Therefore, the pyramid structure balances the tradeoff between permeation selectivity and water production capacity. Furthermore, the facile solution-based template-assisted

electropolymerization process permits the fabrication of thin, uniform, and large-area MPS-PPy membranes. All these features make the MPS-PPy membrane a good candidate for solar evaporation. It showed an evaporation efficiency of $1.12 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun (1 kW m^{-2}) irradiation. As a proof of concept, the MPS-PPy membrane was used for seawater evaporation in a natural environment. The ion concentration of the condensate met drinking water standards. Additionally, the MPS-PPy membrane was also successful in intercepting VOCs in river water. These merits unambiguously indicate the feasibility of using MPS-PPy membranes for solar water purification with efficient VOC interception. Besides, compared with catalytic oxidation alternative methods,^[80,81] the VOC interception based on solution-diffusion possesses the advantages of no need of expensive oxidants and no production of organic by-products.

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Scheme 1. (a) The chemical affinities of water and phenol with PPy, respectively. (b) Effects of molecule size on solution and molecule-membrane interaction on diffusion during the selective permeable process. (c) Schematic diagram of employing the MPS-PPy membrane for steam generation. (d) The selective permeable evaporation process via the MPS-PPy membrane.

Figure 1. (a) Digital photo of the MPS-PPy membrane prepared by template-assisted electropolymerization. (b) SEM image (top) and cross-sectional image (down) of the PPy pyramids. (c) Reflection spectra of flat and MPS-PPy membranes. Inset shows their digital photos. (d) The IR photograph of the flat and MPS-PPy membranes under the irradiation of 1 kW m^{-2} . (e) Temperature change of the MPS-PPy and flat PPy membranes under irradiation (1 kW m^{-2}). (f) Contact angle of water on PPy membrane at different temperatures. (g) Microscopic photo of a PPy membrane floating on water surface.

Figure 2. (a) Absorbance spectra of initial phenol solution (5 mg L^{-1}), and condensate from the steam generated by MPS-PPy membrane, graphite, graphene and PPY-coated carbon cloth, respectively. (b) Phenol concentration in the condensate from the steam generated by MPS-PPy membrane at different cycles. In each cycle, 3 L purified water was produced for per square meter PPY membrane. (c) The solution-diffusion behaviors of water and phenol via the MPS-PPy membrane under irradiation (1 kW m^{-2}), which can be used to calculate diffusion coefficient. (d) Normalized diffusion coefficient of different volatile chemicals in PPY membrane.

Figure 3. (a) Photo of the steam generated from the MPS-PPy membrane under irradiation (7 kW m^{-2}) and (b) its corresponding IR photograph. (c) Temperature difference between the top water surface and the bottom section in the beaker under light irradiation (5 kW m^{-2}). The black curve presents data of seawater with MPS-PPy membrane, while the red curve presents data without the membrane. (d) Weight of evaporated water against time in the following conditions: with MPS-PPy membrane and PU thermal insulator under irradiation, with MPS-PPy membrane under irradiation, with flat PPy membrane under irradiation, bare water under irradiation, with MPS-PPy

membrane but without irradiation, and bare water without irradiation. (e) Weight of evaporated water against time with MPS-PPy membrane under solar irradiation of 1 kW m⁻², 3 kW m⁻², 5 kW m⁻² and 7 kW m⁻², respectively. (f) Water evaporation rates by using MPS-PPy membrane and PPy-coated carbon cloth as the photothermal materials. (g) Water evaporation rates by using MPS-PPy membrane, graphene membrane and graphite membrane as the photothermal materials under different light densities.

Figure 4. (a) Photo of the solar distillation setup. (b) Ion concentrations of the initial seawater (Sentosa Singapore) and the water condensed from the steam generated by the solar distillation system. (c) Total organic carbon concentration and 3D-EEM spectra of the initial river water, water purified by the conventional porous evaporator (graphite felt) and MPS-PPy membrane. (d) 3D-fluorescence spectra of the dissolved organics in raw river water, distilled water through conventional porous membrane (graphite felt as control sample) and MPS-PPy membrane, respectively.

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TOC: A micropyramid-structured PPy membrane with selective solution-diffusion effect is employed as the photothermal material for solar water purification. The membrane is successful in intercepting the evaporation of volatile organic molecules in wastewater. Furthermore, high light-to-heat conversion efficiency and good mechanical strength make the membrane a promising photothermal material for practical solar water purification.

Keyword: microstructured membrane, solar evaporation, water purification, photothermal materials, volatile organic compounds

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