Article

A Scalable Prototype by In Situ Polymerization of Biodegradables, Cross-Linked Molecular Mode of Vapor Transport, and Metal Ion Rejection for Solar-Driven Seawater Desalination

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Abstract: Water scarcity in mass populated areas has become a major global threat to the survival and sustainability of community life on earth, which needs the prompt attention of technological leadership. Solar evaporation has emerged as a renewable energy resource and a novel technique for clean water production and wastewater treatment. Indeed, mounting a scalable solar evaporator including high evaporation efficiency and thermal management remains a significant challenge. Herein, we demonstrate a self-floatable, ecofriendly polypyrrole/wood sponge-based (PPy@WS) steam generator. The low-cost and easy to fabricate evaporator system consists of a single-step in situ polymerization of a 2-D (two-dimensional) hydrophilic wood sponge abundantly available for commercialization. The as-prepared PPy@WS solar evaporator exhibits excellent wettability and is super hydrophilic (contact angle $\sim 0^\circ$), salt-resistant, and has an excellent light absorption of $\sim 94\%$ due to omnidirectional diffusion reflection in PPy Nanoparticles (NPs). The capacity of the PPy@WS evaporator to absorb broadband solar radiation and convert it into thermal energy has enabled it to achieve excellent surface temperature (38.6°C). The accumulated heat can generate vapors at the rate of $1.62\text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ along with 93% photothermal conversion efficiency under one sun ($1\text{ kW}\cdot\text{m}^{-2}$). Moreover, the presented prototype possesses the capability to be installed directly without the use of any complex protocol to purify seawater or sewage with an efficient rejection ratio of primary metal ions present in seawater (approximately 100%). This simple fabrication process with renewable polymer resources and photothermal materials can serve as a practical model towards high-performance solar evaporation technology for water-stressed communities in remote areas.

Keywords: desalination; in situ polymerization; solar steam generation; wood pulp

1. Introduction

Freshwater has a pivotal role in the existence and survival of life on earth. The absence of quantity and quality of freshwater can phase out the continuity of civic life over the entire and only living planet [1]. Despite the massive abundance of water bodies on the Earth's surface, the major portion is ceased away due to sea, storm, and glaciers, whereas merely 3% of the total water content on earth is available as portable water [2]. Dwindling freshwater resources on Earth poses a seriously threatening situation leading towards intense water scarcity for its inhabitants. The commercial desalination technologies currently available (multistage flash or Multi-Effect Distillation) are not feasible economically and geographically for the remote area due to sophisticated infrastructure and require a high demand for energy consumption [3–5]. These desalination processes contribute to darker footprints of climate change and global warming [6]. Solar-driven water desalination is recognized as a minimum invasive solution to the foresaid problematic scenario due to abundant and inexhaustible energy resources. The solar energy received measures up to 3×10^{24} Joules per year by Earth, while merely 0.1% of this total energy is enough to meet the worldwide energy crisis annually. Efficient harvesting of solar energy over a wide spectral range is a key factor for producing purified fresh water in a remote area where the sun is the only abundant energy source [7]. However, a promising solar evaporating device with high efficiency has yet to be explored due to the privation of several features, i.e., low water yield, hydrophilicity, self-floating capability, scalability, and long-term sustainability, and self-dissolving potential against salt and multimedia rejection limits its practical implementation [8]. One of the supreme obstructions is the excessive heat losses in non-evaporation areas in solar-driven evaporation systems without optical concentration such as solar stills, and only 40–45% evaporation is achieved [9]. Appreciable efforts are being invested to address this pressing challenge. Indeed, there is still incomprehension for designing an appropriate thermally insulated evaporation structure to abstain from heat losses [10–12].

The interfacial evaporation approach has been assessed recently as a new technology for heat localization at the liquid-air interface instead of volumetric heating to minimize thermal losses, and output efficiency reaches 90% even under lower solar intensity [13,14]. This method selectively heats the evaporation portion of water, reduces the amount of photothermal material amount, exhibits great potential in optimizing the usage of solar energy, and offers additional means for engineering the solar evaporating device, which highly depends on the thermal management and control of heat losses [15]. Many researchers have employed the wood-based interfacial solar steam generation device due to its low tortuosity, mesoporous hierarchical structure and intrinsic good hydrophilicity, low thermal conductivity, and environmental stability [16,17]. For instance, Zhu et al. [18] reported the plasmonic wood-based solar steam generator decorated by metal nanoparticles and claimed to achieve 85% conversion efficiency under ten sun illumination ($10 \text{ kW} \cdot \text{m}^{-2}$). Inspired by the wood-based solar steam generation structural devices, we report the fabrication of a biodegradable wood sponge substrate-based solar steam generation device that has several advantages over natural wood, i.e., porosity, super hydrophilicity, lightweight, flexibility, robustness, thermal conductivity, and numerous aligned microchannel along with open pores occupied by both ends. A wood sponge is also known as a wood pulp loofa that is commercially available and derived from the wood pulp of trees [19]. The fibrous structural networking of the wood sponge serves as an open-porous assembly and enables it to float freely at the air-water interface [20]. It shows good stability under intense operating conditions and has the potential to be modified as an alternative material into man-made cellular materials. Water transportation is accomplished via capillary actions through a large number of vertically aligned microchannels on the surface of wood sponges that can collect and store water [21]. The wood sponge has relatively low thermal conductivity; thus, it also acts as a thermally insulating material. Moreover, the biodegradability of the wood sponge makes it an environmentally friendly material, and it is easily available commercially at a very cheap price [21].

The key component of the interfacial solar device is the efficient absorption over a broad spectral range of the solar spectrum, and its photo-thermal conversion is critical; thus, optical studies show that photothermal materials with high absorbance capacity indirectly increase the total energy of light by increasing solar energy absorbance [15]. Polypyrrole (PPy) is an intrinsically conductive polymer showing a significant light absorption coefficient due to the conjugated system, delocalization of electrons, and configurational features [22]. The conjugated system contains the integrated long chains of alternate single and double bonds. The neighboring carbon atoms mutually share Pz orbitals and form delocalized π -orbital over the polymeric chains as HOMO (Highest Occupied Molecular Orbital) and LUMO (Lowest Unoccupied Molecular Orbital) [23]. The delocalization in the one-dimensional half-filled orbitals facilitates electron mobility along the polymer chain [12,15]. Moreover, PPy is stable and inexpensive compared to many noble metal nano-particles in biomedical and bioelectronics applications [24]. It shows comparatively good biocompatibility and cytotoxicity compared to other carbon atoms [25].

In this research, we propose interfacial polypyrrole (PPy) deposited composite woody sponge as a self-floating, lightweight, thermally insulated, flexible, and highly efficient solar-thermal conversion steam generation device. The proposed device successfully delivered the core output functions essential for a highly efficient steam generation device with a higher solar-thermal energy conversion ratio (92%) and is super wetted (zero contact angle), has mechanical robustness, and can prevent salt accumulation within the structural matrix due to cross-linked porous assembly, conformal shape, and is easy to fabricate than compared to other complex fabrication procedures. The characteristic feature of semiconductive in situ polymerization of PPy owing to its high omnidirectional absorption (94%), self-floating ability as compared to polyurethane foam, etc., and thermal localization during the thermal conversion phenomena has distinguished it from existing evaporators. The unprecedented heat localization and excellent interfacial surface temperature sustainments are recorded for the PPy@WS solar steam generator ($38.6\text{ }^{\circ}\text{C}$ under $1\text{ kW}\cdot\text{m}^{-2}$), and it is distinguished from the prevailing prototypes. A comparatively high evaporation rate is recorded for the PPy@WS solar steam generator ($1.62\text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ under $1\text{ kW}\cdot\text{m}^{-2}$). Nonetheless, the pitch-black PPy photothermal layer exhibits outstanding thermal insulation ($0.2753 \pm 0.001\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), super hydrophilicity, and salt tolerance/stability under intense seawater conditions.

2. Materials and Methods

2.1. Materials

The required chemicals, which include $\text{MnSO}_4\cdot 4\text{H}_2\text{O}$, pyrrole, ethanol, and water spraying bottles, were purchased from BASF Chemical Industries Co., Ltd., Wuhan, China. Phytic acid (PA, 50 wt% in water) was acquired from Wuhan Guangfu's fine synthetic industry, Wuhan, China. The commercially available wood sponge was purchased from GOOD SELLER Co., Ltd., Zhejiang, China. All the chemicals were utilized directly without further purification process. Standard methods were employed to test thermal conversion, salt stability, robustness, hydrophilicity, absorption co-efficient, solar to vapor conversion efficiency, etc.

2.2. Device Fabrication

The semiconductive polypyrrole coatings were deposited over a wood sponge in order to enhance the absorption coefficient and diffuse reflection by employing a facile single-step in situ polymerization process. For this, 5 mL isopropanol was taken into a 200 mL beaker and followed by the addition of 0.85 mL pyrrole, and dissolved thoroughly. Subsequently, 1.85 mL phytic acid (50%, wt% in water) was added into the prepared solution and stirred until the formation of a dark brownish color solution, which indicates the completion of the reaction. The prepared product was labeled as solution A. The 5 mL distilled water was taken followed by the addition of 2.75 g ammonium persulfate and stirred using a magnetic stirrer until a homogeneous solution formed. This solution was labeled as solution B. Both

prepared solutions were transferred into commercial spraying bottles. The wood sponge substrate was crafted into a circular shape with the following dimensions: 3 cm diameter and 3 cm thickness. The as-prepared A and B solutions were sprayed by the B-A-B-A sequential order, as illustrated in Figure 1. The successive repetitions of the spraying order were followed until the formation of intensified pitch darkness, and homogeneous deposition of polypyrrole was achieved on the top surface of the circular-shaped wood sponge. The comparative mass change was calculated before and after the deposition of polypyrrole coatings on a device to estimate the deposited mass of polypyrrole, which came out to be ~28 mg. The detailed material characterization information has been provided in Supplementary Materials Note S1.

Figure 1. Schematic illustration of simplistic in situ polymerization of PPy nanoparticles over super hydrophilic wood sponge for solar-driven desalination.

2.3. Solar to Vapor Conversion Efficiency (η)

The solar to vapor conversion efficiencies of three fabricated evaporating systems including the PPy@WS steam generator were assessed by Equations (1) and (2) [13,15].

$$\eta = \frac{\dot{m}h_{LV}}{q_i} \quad (1)$$

$$h_{LV} = \lambda + C\Delta T \quad (2)$$

According to the equations, $\dot{m}$ depicts the evaporation rate under solar irradiance in the presence of a solar evaporator, or it is also termed as mass flux excluding bulk water evaporation without the solar evaporating device. Here, h_{LV} corresponds to enthalpy phase change during liquid-to-vapor state liquid-vapor state phase enthalpy, encompassing the phase change enthalpy along with sensible heat, and q_i denotes solar irradiance, e.g., $1 \text{ kW} \cdot \text{m}^{-2}$. C represents the specific heat capacity of water ($4.2 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), and λ is

a latent phase change from 2430–2256 kJ·kg^{−1} under 30 and 100 °C, respectively, while ΔT shows the temperature increase in water. Moreover, all experiments were carried out standard conditions and recorded, e.g., humidity (47%) and surrounding temperature (26 °C).

2.4. Energy Balance Equations (Heat Losses)

The energy balance equations for the WS@PPy steam generator were calculated by using thermal transport theory under one sun irradiation (1 kW·m^{−2}). The photothermal conversion efficiency of the WS@PPy steam generator was estimated by evaluating conductive heat losses in terms of heat transferred to bulk water ($Q_{Conduction}$), convective heat losses to the surrounding ($Q_{Convection}$), and radiative heat losses into the air ($Q_{Radiation}$), as indicated in Equations (3)–(5) [13,15].

The following equation calculates conductive heat losses.

$$Q_{Conduction} = Ak \frac{(T_1 - T_2)}{\Delta l} \quad (3)$$

In the above equation, A corresponds to the cross-sectional area of fabricated solar evaporating systems, while k shows heat transfer through conduction for bulk water, which is 0.6 W·m^{−1}·K^{−1}. Δl represents the length between two points inside bulk water where two thermocouples are connected to examine the temperature gradient between these two points.

The following equation calculates convective heat losses.

$$Q_{convection} = h (T_s - T_v) \quad (4)$$

In Equation (4), h represents the convective heat transport coefficient, which is approximately 10 W·m^{−2}·K^{−1}, while T_s and T_v are temperatures of the solar evaporating top surface and its vapors, respectively.

The following equation calculates radiative heat losses.

$$Q_{Radiation} = \varepsilon \sigma (T_s^4 - T_\infty^4) \quad (5)$$

Here, ε represents the emissivity of the top evaporating layer, which is presumed as (0.93) [26], and σ corresponds to the Stefan–Boltzmann constant (5.669 × 10^{−8} W·m^{−2}·K^{−4}), while T_∞ depicts the surrounding temperature. Of note, the top evaporating surface is occupied by hot vapors that are semi-transparent to the thermal radiation. However, radiative heat losses could be evaluated by taking maximum and minimum values, i.e., $T_\infty = T_a$ (ambient temperature) and $T_\infty = T_v$ (vapor temperature), respectively.

2.5. Solar-Driven Evaporation Setup

The solar steam generation experimental process was carried out by using a solar simulator (PLS-FX300HU, Beijing Perfect Light Technology Co., Ltd., Beijing, China) that is capable of generating a wide range of solar simulated intensities up to 10 kW·m^{−2} (10 suns). A standard 1.5 G AM spectrum with an optical filter was utilized. The self-floating and hydrophilic WS@PPy steam generator possessing 30 mm thickness was permitted to float over a petty dish filled with water (simulated seawater, heavy metal contaminated) and was exposed under one solar intensity (1 kW·m^{−2}). An advanced electronic balance (Mettler Toledo, ME204, Across International, Sparks, NJ, USA) fortified with a 0.001 g resolution was employed to record time-dependent mass change variation. After the stabilization of the entire evaporation system, all evaporation rates were measured under one solar intensity. An inductively coupled plasma-optical emission spectrometry technique (ICP-AES, E.P. Optimal 8000, Perkin Elmer, San Jose, CA, USA) was utilized for the comparative analysis of salt and heavy metals ions concentrations before and after treating water. All experimental measurements were performed at ambient environmental conditions, at ~26 °C

temperature, and ~44% humidity. Surface temperatures were recorded by employing a Hand-Held Optical Meter Model, Phase 1 Technology Corp., Deer Park, NY, USA.

3. Results and Discussion

3.1. Surface Morphology and Self-Floatability

A single-step in situ polymerization was carried out for the facile fabrication of a circular-shaped wood sponge and has distinguished it from the prevailing prototypes, as described in the device's fabrication procedure (Section 2.2). Eventually, a super hydrophilic solar-driven interfacial evaporation system with an interlinked porous structure enhances solar-to-vapor conversion efficiency powered by surface roughness, and optimized defect chemistry has been achieved. The strategy adopted resulted in an ultimate boost in absorption capacity and diffuse reflection. The schematic illustration of the PPy decorated superhydrophilic, lightweight, and flexible wood sponge is shown in Figure 2a.

Figure 2. (a) Schematic illustration of self-floatable and biodegradable in situ polymerized solar evaporator (PPy@WS) for efficient seawater desalination along with heavy metal ions rejection. (b) Photograph of exceptional lightweight PPy@WS solar evaporator stands alone over the leaf. (c,d) Morphologies of bare surface wood pulp sponge and in situ polymerized. (e) The contact angle for the super hydrophilic nature of water channels. (f) Self-floating PPy@WS solar evaporator.

The preparation of the PPy@WS solar evaporator involves a facile, single-step polymerization of the top surface of the wood sponge. The upper surface turns pitch dark upon the application of the polymerization process, with an enhanced solar absorption capacity due to the delocalization of electrons in a conjugated system of semi-conductive polypyrrole coating [12,27]. The biodegradable wood sponge with a 3D porous network can efficiently float over the water surface while the vertically interconnected water channels facilitate continuous water supply up to the photothermal layer and is insulated from downward thermal conduction. The incident light stimulates delocalized π -orbital electrons that absorb light and generate heat, which in turn evaporates water molecules approaching the air-water interface [15]. The lower intrinsic thermal conductivity ($0.2753 \pm 0.001 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) of the PPy@WS sponge restricts heat localization only on the upper matrix, thus enabling highly effective steam generation, as illustrated in Figure S1 (SI). Moreover, the microporous network of wood sponge substrate can potentially redissolve salt and other impurities back

into water due to self-regenerating capacity and, thus, sustain long-term stability without structural rupturing and surface fouling. Moreover, the hierarchical vertically aligned pores with low material packing density impart the wood sponge with ultra-lightweight and flexible properties. Figure 2b represents the digital photograph of the PPy@WS standing on a plant leaf without deforming the leaf, which can ensure its portability and excellent floatability. The surface morphology and microstructural investigation of simple wood sponge and PPy@WS were analyzed by Field Emission Scanning Electron Microscopy (FESEM, JSM7100F, Shimadzu, Kyoto, Japan). Figure 2c demonstrates a FESEM image of direct channels with a hierarchical vertical alignment forming open porous assembly on both ends to withstand a good potential for flexibility and efficient water pumping. The surface texture of the wood sponge is rough, which plays a key role in the diffusion of light when incident on the surface [20]. The cross-linked porous network of wood sponge along with rough surface morphology facilitates quick water pumping via capillary force up to the photothermal layer and quick vapor escape during the steam generation process. Figure 2d shows the surface morphology of the pitch dark in situ polymerized PPy@WS solar steam generator, revealing an enhanced roughness with an inset of complex structure coated over the cross-linked porous structure of the wood sponge. The intense polymerization of the top surface facilitates omnidirectional absorption by inducing multiple rays within the photothermal layer, enabling a high absorption coefficient and efficient solar steam generation. On the other hand, the lower matrix is prohibited for downward thermal passage due to the bad thermal conductivity of the wood sponge, thus restricting the immense heat localization up to the top surface. The observed surface morphology and microstructural investigation suggest the excellent potential of the PPy@WS device for excellent heat accumulation, self-floating capability, thermal insulation of lower matrix, and super-hydrophilicity of the device for quick water transport. Furthermore, the hydrophilicity of the as-prepared PPy@WS solar steam generator was investigated by the contact angle test, as shown in Figure 2e. The water droplet interacts with the PPy@WS surface and is absorbed quickly by the hierarchical porous assembly of the device within a short interval of 0.01 s. The observed wettability suggests the zero-contact angle of a water droplet and PPy@WS surface and affirms the sustainability of super hydrophilicity of the wood sponge after the polymerization process. The vertical channels impart excellent water transport relative to the device as well as outstanding self-floating potential over the water surface. Figure 2f represents the digital photograph of the PPy@WS solar steam generator floating over the surface of the water. The lower mass density and abundant end-to-end porous assembly provide exceptional floating capabilities to the PPy@WS solar steam generator along with facile water transport.

3.2. Chemical States and Solar Absorption

The XPS survey spectrum of the PPy nanoparticles was operated in order to inspect chemical materials and to perform element content analysis. As shown in Figure 3a, the XPS survey affirms the presence of C, N, O, and S on the surface of the sample. The prominent four main characteristics peaks appearing at 250.23, 285.95, 375.55, and 532.88 eV binding energies values are attributed to S2p, C1s, N1s, and O1s, respectively. The deconvolution of the peaks of two main elements, C and N, was accomplished by applying Gaussian fit to deeply investigate the changes in the orbital and homogeneous ion distributions over the long polymer chains. Figure 3b shows the high-resolution spectra on N1s resolved into three sub-peaks at 397, 402, and 402.5 eV corresponding to =N/–NH, –NH⁺ (polaron), and =NH⁺ (bipolaron). Figure 3c demonstrates C1s spectra, which are resolved into three main peaks at 284.0, 284.4, and 286.1 eV binding energies values assigned to the existence of C=N/C=N⁺, C=N⁺, and C=O bonds. Broadband solar absorption is one of the key components for ensuring a highly efficient solar steam generator. The PPy nanoparticles were characterized by Shimadzu UV–VIS–NIR UV-3600 double beam spectrophotometer, Kyoto, Japan over full spectral (200–2500 nm) length in order to enumerate the maximum solar light-absorbing potential for the development of an efficient solar steam generator.

As shown in Figure 3d, PPy nanoparticles potentially absorb the full spectral range and reveal outstanding absorption (94%) with minimum transmission (4%) and reflection (2%), which was calculated by the following absorption relation: $(1-T-R)$. The maximum solar absorption with excellent heat localization over the photothermal surface enables a potential relative to the PPy@WS device for being a promising solar steam generator for freshwater production.

Figure 3. Chemical states of in situ polymerized PPy NPs at the top surface of wood pulp sponge. (a) XPS survey of PPy@WS solar evaporator. (b) N1s spectra and (c) C1s spectra of PPy@WS solar evaporator. (d) UV-Vis's spectra of in situ polymerized PPy@WS solar evaporator over broadband range (250–2500 nm).

3.3. PPy@WS Solar Steam Generator

The PPy@WS manifests highly efficient steam generation due to the enhanced absorbing potential of solar energy, which can be featured due to its rough surface texture highly enhanced by in situ polymerization. The incident radiations suffer multiple diffuse reflections and scattering, which is critical for heat localization over the photothermal layer; thus, highly efficient solar steam generation is achieved [28–31]. Figure 4a–c shows the digital photograph of steam generation from PPy@WS solar steam generator when exposed under the simulated solar irradiance up to $3 \text{ kW} \cdot \text{m}^{-2}$. As observed from the figures, an enhanced solar steam generation rate is achieved upon increasing solar irradiation energy. The increased solar intensity increases the temperature of PPy@WS due to local heat generation by photothermal conversion, which increases steam generation, and ultimately an enhanced evaporation rate was achieved. In order to investigate enhanced solar energy absorption and elevated surface temperatures, we performed a comparative analysis of three systems for maximum surface temperature attainment under one sun illumination ($1 \text{ kW} \cdot \text{m}^{-2}$), which includes water, wood sponge, and PPy@WS solar steam generator, as shown in Figure 4d. Upon exposure to one sun illumination for 50 min, the maximum surface temperature of the self-floating PPy@WS solar steam generator was enhanced from 22.5°C to a steady-state temperature of 38.6°C . The temperature attained

by bulk water was 22 °C, which is much lower compared to PPy@WS. The wood sponge comparatively achieved higher surface temperatures (33 °C) than compared to bulk water but was significantly lower than the PPy@WS solar evaporator. This remarkable interfacial heat localization of PPy@WS proved its potential as a promising solar steam generator device as well as for heat accumulation applications. The surface temperature enhancement of the PPy@WS solar evaporator was also examined under solar intensities up to 3 kW·m^{−2}, as illustrated in Figure S2 (SI).

Figure 4. (a–c) Real-time demonstration of solar-driven steam generation via PPy@WS solar evaporator under different solar intensities up to 3 kW·m^{−2}. (d) Surface temperatures of pure water, simple wood pulp sponge, and PPy@WS solar evaporator under 1 kW·m^{−2}. (e) Mass changes of pure water, simple wood pulp sponge, and PPy@WS solar evaporator under 1 kW·m^{−2}. (f) Water evaporation rate via PPy@WS solar evaporator under 1 kW·m^{−2} for consecutive 20 cycles.

Furthermore, we designed a comparative analysis of three systems (bulk-water, wood sponge, and PPy@WS) for recording mass change and evaporation rate under one sun illumination, as shown in Figure 4e. The time-dependent mass change of the designed systems was measured by a weighing balance with 0.001 mg precision. After one hour of continuous exposure under 1 kW·m^{−2}, PPy@WS achieved a maximum mass change of 1.62 kg·m^{−2}, which is obvious from the plotted data in Figure 4e and is comparatively much higher than a wood sponge and pure bulk water. The mass changes under different solar intensities for the individual PPy@WS solar steam generator were also examined, as illustrated in Figure S3 (SI). Thus, we have successfully developed a highly stable, robust, and cost-effective steam-generating device via a facile method using commercially available materials, which efficiently achieved a higher steam generation rate and can be implemented in remote areas where the sun is the only abundant energy source. The evaporation stability of the device was examined by repeating steam generation experimental measurements over 20 cycles in order to detect any deformation in structure and evaporation rate. As shown in Figure 4f, a relatively stable evaporation rate is exhibited by PPy@WS solar steam generator.

The excellent solar-thermal conversion ability of the PPy@WS solar steam generator induced higher mass change rates, which achieved enhanced efficiency. Figure 5a represents the comparative analysis of three evaporation-designed evaporation systems, which shows a significantly higher evaporation rate (1.62 kg·m^{−2}·h^{−1}) and solar-to-vapor conversion efficiency (93%), excluding heat losses, i.e., conduction (3.9%), convection (1.78%), and

radiative (1.32%) heat losses using Equations (3)–(5). The heat localization and thermal management of any steam-generating device play a pivotal role in enhancing the efficiency of the system [7,32]. Thermal management and heat localization over a photothermal layer of PPy@WS solar steam generator were recorded via an I.R. camera under one solar irradiation, as demonstrated in Figure 5b. As obviously observed from the images, the temperatures increase gradually over time and achieved a maximum of $\sim 40^\circ\text{C}$ temperature within 25 min, while perfectly insulating the lower matrix from thermal conduction. Thus, the lower thermal conductivity of the wood sponge restrains the temperature on the interfacial surface preventing thermal conduction towards the bulk mass of water, thus imparting unique efficiency to the reported solar steam generation device. Moreover, PPy@WS possesses outstanding salt-resistance potential against salt and primary metal ion due to its vertically aligned microporous assembly of super hydrophilic wood sponge and affirms a purity standard of condensed water up to drinking water levels. As the cross-linked water transport channels allow water evaporation only through molecular mode, this phenomenon facilitates the purification of water by removing dissolved primary metal ions such as Na^+ , K^+ , Ca^{2+} , and Mg^{2+} and other contaminations. In order to check this, Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, Perkin Elmer, San Jose, CA, USA) was employed to check the concentration gradient of soluble salt ions (3.5 wt% NaCl , KCl , MgSO_4 , and CaCl_2), and the desalination potential of the PPy@WS solar steam generator was calculated by using simulated and condensed water. The results achieved from the ICP-AES are shown in Figure 5c, exhibiting a significantly lower concentration of Na^+ , K^+ , Ca^{2+} , and Mg^{2+} in the condensed water compared to the initial concentration in the simulated water. It is far below the standard of drinking water set by the World Health Organization; thus, the application of PPy@WS solar evaporator is up to the standards of drinking water.

Figure 5. (a) Comparative evaporation rate and corresponded efficiencies of pure water, simple wood pulp sponge, and PPy@WS solar evaporator under $1\text{ kW}\cdot\text{m}^{-2}$. (b) IR images captured during evaporation experiment of PPy@WS solar evaporator under $1\text{ kW}\cdot\text{m}^{-2}$. (c) ICP-OES profile reveals actual concentrations in stimulated seawater and condensed water.

4. Conclusions

In this report, wood sponge comparatively achieved higher surface temperatures (33°C) than bulk water but significantly is lower than the PPy@WS solar evaporator (38.6°C). This remarkable interfacial heat localization of the PPy@WS evaporating system proved its potential as a scalable efficient prototype evaporator. The acquired temperature

maximum of $\sim 40^\circ\text{C}$ within 25 min is indicative of perfect insulation of the lower matrix from thermal conduction ($0.2753 \pm 0.001 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). The cross-linked water transport channels allowed water evaporation only by using the molecular mode, which ensured the removal of metal ions from the water body. A much stable evaporation rate is exhibited by PPy@WS solar steam generator over 20 cycles, proving the stability of the device. Significantly higher evaporation rates ($1.62 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and efficiency (93%) compared to the wood sponge and many other steam generation systems were achieved.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/cryst11121489/s1>, Note S1: Material Characterization Information, Figure S1: Thermal conductivity of PPy@WS solar steam generator, Figure S2: Surface temperature of PPy@WS solar evaporator under different solar intensities up to 3 suns, Figure S3: Mass changes of water under PPy@WS solar evaporator under different solar intensities up to 3 suns.

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