Full bagasse bio-waste derived 3D photothermal aerogels for high efficient solar steam generation

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Abstract Nowadays, freshwater shortage, energy crisis and environmental pollution are the three major threats to human beings. Bio-waste is an important source of environmental pollutant emissions and a renewable resource with great potential. Herein, we develop a photothermal material based on bagasse for solar steam generation to relieve the freshwater crisis and mitigate environmental pollution caused by bio-waste. The mainly functional part of the solar-driven steam generator here is bagasse-based photothermal aerogel (B-PTA), which composes of carbonized bagasse (CB) and bagasse-derived cellulose fiber (BDCF). The B-PTA relying on CB can effectively absorb sunlight (~ 95%), resulting in a prominent light-to-heat ability. The B-PTA with DBCF has super-hydrophilicity, water transport and retention ability. Depending on the excellent light absorption and 3D water passageway, the B-PTA gives a water evaporation rate of 1.36 kg m\(^{-2}\) h\(^{-1}\), and achieves a photothermal conversion efficiency of 77.34% under 1-sun illumination (1 kW m\(^{-2}\)). The B-PTA shows remarkable stability that the efficiency without significant change after 20 cycles. In addition, the B-PTA can effectively desalt seawater and purify dye wastewater with natural sunlight. Therefore, turning bio-waste into valuable photothermal material for solar steam generation is possible. Due to the merits of low cost, scalability, environmental friendliness, B-PTA has the potential for real-world water purification.

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**Introduction**

The freshwater shortage, energy crisis, and environmental pollution are the three main challenges facing human beings in modern society (Delgado et al. 2020; Lewis 2007; Mir and Bicer 2021). Despite the fact, nearly three-quarters of the world is covered by water, the vast majority of the Earth’s water is mainly in the oceans and is saline. Resulting in less than 1% of water can be directly available by residents, and more than one-third of the world’s population is affected by freshwater scarcity (Liu et al. 2018; Ma et al. 2020; Ridoutt and Pfister 2010). Therefore, how to obtain freshwater from seawater is an urgent issue. Traditionally utilized desalination strategies, such as reverse osmosis membranes and thermal distillation technologies, require high cost and consume large amounts of energy (Feria-Díaz et al. 2021a, 2021b), which cannot be applied to all areas and will exacerbate the energy crisis. Solar energy, as a green and renewable resource, is inexhaustible and freely available on Earth. As a promising desalination strategy, interfacial solar steam generation (ISSG) has received extreme attention to moderate freshwater scarcity. The critical component of the ISSG device is the interfacial photothermal materials (PTMs). Usually, the PTMs include three essential functions: (1) broadband light absorption capability for high photothermal conversion; (2) hydrophilic porous structure for rapid water transport and vapor release; (3) excellent chemical and thermal stability for long-term application. Various efforts have been devoted to exploiting high efficient PTMs for solar steam generation. The reported PTMs involved in ISSG can be mainly classified into metallic plasmonic materials (Bae et al. 2015; Kiriarachchi et al. 2018; Liu et al. 2015; Zhou et al. 2016b), semiconductor materials...
achieved a water evaporation rate of 1.62 kg m\(^{-2}\) h\(^{-1}\) vertically aligned graphene sheets membrane and 1-sun illumination (Li et al. 2016). Qu developed photothermal conversion efficiency was up to 80% at graphene oxide film as the light absorber, and the absorption property. For example, Zhu exploited a PTMs due to their chemical stability and broadband graphene, have been widely investigated to prepare steam generation. Carbon-based materials, especially band, which is difficult to achieve high efficient solar semiconductor materials is their narrow absorption (Zhang et al. 2020b). The main disadvantage of semiconductor materials is their narrow absorption band, which is difficult to achieve high efficient solar steam generation. Carbon-based materials, especially graphene, have been widely investigated to prepare PTMs due to their chemical stability and broadband absorption property. For example, Zhu exploited a graphene oxide film as the light absorber, and the photothermal conversion efficiency was up to 80% at 1-sun illumination (Li et al. 2016). Qu developed vertically aligned graphene sheets membrane and achieved a water evaporation rate of 1.62 kg m\(^{-2}\) h\(^{-1}\) with photothermal conversion efficiency of 86.5% under 1-sun irradiation (Zhang et al. 2020b). The main disadvantage of semiconductor materials is their narrow absorption band, which is difficult to achieve high efficient solar steam generation. Carbon-based materials, especially graphene, have been widely investigated to prepare PTMs due to their chemical stability and broadband absorption property. For example, Zhu exploited a graphene oxide film as the light absorber, and the photothermal conversion efficiency was up to 80% at 1-sun illumination (Li et al. 2016). Qu developed vertically aligned graphene sheets membrane and achieved a water evaporation rate of 1.62 kg m\(^{-2}\) h\(^{-1}\) with photothermal conversion efficiency of 86.5% under 1-sun irradiation (Zhang et al. 2017). It is well known that graphene is expensive. Therefore, graphene-based PTMs are difficult to apply in the real world for solar steam generation. Bio-waste, with its freely available, abundant carbon and cellulose sources, which can be acted as light absorbers and water transporter, respectively, is a good candidate for the development of PTMs in real-life application.

Biomass, according to statistics, the global annual production is about 146 billion tons, and a large number of by-products are generated from agriculture and industry such as the paper industry and forest mining (Alvarenga et al. 2019; Anderson et al. 2013; Börjesson et al. 2017). Approximately 30 billion tons of bio-waste are yielded from agricultural production each year, which will cause serious environmental problems if they are not disposed of reasonably (Demirbaş 2005; Laurijssen et al. 2010; Qian et al. 2020). In contrast, bio-waste is an important source of preparing carbon (Abbasi and Abbasi 2010; Kang et al. 2019). Recently, bio-waste has attracted great interest in developing valuable PTMs for solar steam generation. Zhang reported a solar steam evaporator based on carbonized lotus seedpod with excellent light absorption capacity (~99%), and photothermal conversion efficiency could reach 86.5% under 1-sun irradiation (Fang et al. 2018). He also fabricated a 3D-structured carbonized sunflower head, which evaporation efficiency was up to 100.4% with the evaporation rate of 1.51 kg m\(^{-2}\) h\(^{-1}\) under 1-sun irradiation (Sun et al. 2020). However, carbonized bio-waste like lotus seedpod and sunflower head become friable due to loss of water, making them not easy to be carried. Xu fabricated a photothermal aerogel (PTA) composed of reduced graphene oxide and cellulose fiber derived from bio-waste rice straw with the chemical crosslinking method, and the mechanical performance was improved. This PTA has achieved a high evaporation rate of 2.25 kg m\(^{-2}\) h\(^{-1}\) with an energy conversion efficiency of 88.9% under 1-sun illumination (Storer et al. 2020). However, the obvious drawback is the expensive reduced graphene oxide. Liu exploited bio-waste rice straw as the carbon source to reduce cost and manufactured a solar steam generation device that mixed the bacterial cellulose and carbonized leaves of rice straw as the light absorber and designed the culms as excellent water pumps. The photothermal conversion efficiency could be up to 75.8% (Fang et al. 2019). Therefore, bio-waste, as a source of carbon and cellulose, can potentially be utilized to prepare PTA for solar steam generation.

Bagasse, as a bio-waste, is the byproduct of the sugarcane processing industry and is composed of approximately 50% cellulose, 25% hemicellulose and 25% lignin (Cardona et al. 2010; Sun 2004; Torgbo et al. 2021). As the source of carbon and cellulose, bagasse has the potential to be manufactured into PTA. In this work, we exploited bagasse bio-waste to fabricate PTA with the chemical crosslink method. The PTA was composed of carbonized bagasse (CB) for light absorption and aerogel from bagasse fiber for water transportation. The water evaporation rate of bagasse-based photothermal aerogel (B-PTA) can be reached to 1.36 kg m\(^{-2}\) h\(^{-1}\) and the photothermal conversion efficiency is approximately 77.34% under 1-sun illumination. This strategy of using bagasse as the raw materials to fabricate B-PTA provides an idea of converting bio-waste into valuable photothermal
material for alleviating freshwater shortage, energy crisis and environmental pollution. The freely available bio-waste will facilitate the applications of the solar steam generator in the real world.

Experimental section

Materials

Bagasse used in the experiments was obtained from a local sugarcane juice store. Sodium alginate (SA) was purchased from Shanghai Aladdin Co., Ltd., China. Sodium hydroxide, sodium chloride, calcium chloride, potassium chloride, magnesium chloride, magnesium sulfate, methylene blue, hydrochloric acid and ethanol (> 95%) were supplied by Sinopharm Chemical Reagent Co., Ltd., China.

Preparation

Pretreatment of bagasse

The bagasse was rinsed with tap water and then soaked in ethanol for two days to remove the residual sucrose, and then the bagasse was washed with deionized water and dried at 80 °C for one day.

Preparation of CB

Pretreated bagasse (5 g) was placed in a tube furnace for 2 h at 600 °C in N$_2$ atmosphere (about 30 ml min$^{-1}$) with a ramp rate of 5 °C min$^{-1}$. The carbonized bagasse was soaked in 1 M HCl (30 mL) for 1 h and washed with deionized water to neutral. The treated bagasse was dried at 80 °C for 2 h and put into the ball mill for 30 min to obtain the CB.

Preparation of BDCF

Pretreated bagasse (2 g) and 3 M sodium hydroxide solution (80 mL) were added to a 100 mL Teflon stainless steel autoclave. Following the autoclave was sealed and heated at 180 °C for 12 h. BDCF was obtained by filtering the resulting mixture and washing it with deionized water to neutral.

Preparation of B-PTA

BDCF (2 g), CB (1 g) and 5 mg mL$^{-1}$ SA (200 mL) were added to a 400 mL beaker and stirred for 20 min to obtain a mixture, which was added to a plastic container (height: 5 cm, diameter: 3 cm) for freeze-dried. The obtained samples were soaked in CaCl$_2$ solution (50 g L$^{-1}$) for 12 h, washed several times with tap water and deionized water, respectively, and then freeze-dried. Following the Ca$^{2+}$ cross-linked aerogel was prepared named B-PTA-1 for solar steam generation. The diagram of preparation B-PTA is shown in Fig. 1. B-PTA-0, B-PTA-0.5 and B-PTA-1.5 were prepared with the above method by using 0 g, 0.5 g and 1.5 g of CB instead of 1 g of CB, respectively.

![Fig. 1 Schematic illustration depicting the fabrication of B-PTA from bagasse for solar steam generation](image-url)
Sample characterization

The morphology and structure were characterized using JEOL InTouchScope (JSM-IT500) scanning electron microscopy (SEM). XRD patterns were measured on a Rigaku Ultima IV diffractometer with a Cu Kα radiation source. Raman spectra were carried out on a Themor DXR532 780 nm semiconductor laser. Fourier transform-infrared (FT-IR) spectra were measured by a Thermos Nicolet FT-IR spectrophotometer (model 6700). X-ray photoelectron spectroscopy (XPS) analyses were carried out on a Thermo Scientific K-Alpha+ with an aluminum potassium micro-aggregation monochromatic X-ray source. Static contact angles (SCAs) were measured by a contact angle meter (OAC20, DaraPhysics) through the static sessile drop method. UV–Vis-NIR spectra were recorded by a contact angle meter (OAC20, DaraPhysics) through the static sessile drop method. UV–Vis-NIR spectra were recorded by a contact angle meter (OAC20, DaraPhysics) through the static sessile drop method. 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Fig. 2  SEM images of B-PTA-1 at different magnifications (a–c); the element mapping of the B-PTA-1 (d); XRD patterns of B-PTA-0, B-PTA-1 and BC (e); Raman spectra of B-PTA-1 (f)

Fig. 3  FT-IR spectra of B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 (a); XPS survey scan (b) and high-resolution C 1 s spectra of B-PTA-1 (c); time-lapse snapshots of absorption of a water droplet by B-TPA-1 (d); water transportability of B-PTA-0, where black dashed line shows the border between wet and dry areas on B-PTA surface (e)
spectrum of the C 1 s peak includes three components: aliphatic C–C (20.56%), hydroxyl carbon C–O (47.66%) and carboxy carbon O–C=O (31.78), which are consistent with the FT-IR proving the B-PTAs have hydrophilicity.

The hydrophilicity, water transport and storage capacity of B-PTAs are significant in the solar steam generation device. The hydrophilicity of the B-PTA was demonstrated through water contact angle measurement as shown in Fig. 3d. When a water drop was wetted within 30 s as shown in Fig. 3e, demonstrating that the B-PTA-0 could effectively transport water in the interconnected hierarchical porous networks. Moreover, the water hold ability of B-PTA-1 was researched as shown in Fig. S6. 0.232 g B-PTA-1 (height: 1 cm, diameter: 3 cm) can hold a weight of approximately 5.305 g water, which is 23 times the weight without any obvious deformation. All the results manifest that the B-PTAs have hydrophilicity, water transport and capacity storage.

The light absorption abilities of B-PTAs were investigated through UV–Vis–NIR spectrophotometer and weighted by the standard air mass 1.5 global (AM 1.5 G) solar spectrum as shown in Fig. 4a. The average integrated absorption of B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 in the wavelength range from 300 to 2500 nm is 51, 93, 95 and 96%, respectively. In the whole spectrum, B-PTA-0.5 exhibits stronger light absorption than B-PTA-0, which indicates that the CB can effectively enhance the light absorption ability of the B-PTAs. In addition, the absorption ability of B-PTA-1 and B-PTA-1.5 is similar and slightly stronger than B-PTA-0.5, which implies that B-PTA-1 is the best candidate for solar steam generation. In consideration of the excellent light absorption abilities, the light to heat capacities of the B-PTAs were researched. The temperature change of the B-PTAs under 1-sun illumination was traced through an IR camera. The top surface temperature of B-PTA-0 increased from 29.1 °C to 42.0 °C in the first 1 min and kept up near 48.7 °C after continuing to light for 8 min as shown in Fig. 4b. Relatively, the top surface temperature of B-PTA-0.5, B-PTA-1 and B-PTA-1.5 sharply increased from 27.8 °C, 28.8 °C and 27.8 °C to 62.4 °C, 71.3 °C and 71.3 °C in the first 1 min, respectively, and maintained near 81.2 °C, 85.3 °C and 84.9 °C with the extension of illumination for 8 min as shown in Fig. 4c–f. When the light turned off for 1 min, the top surface temperature of B-PTA-0 decreased to 33.6 °C, and B-PTA-0.5, B-PTA-1, B-PTA-1.5 sharply dropped to 41.4 °C, 39.1 °C, 40.1 °C, respectively. The top temperature rise and fall rates of B-PTA-1 and B-PTA-1.5 were close to each other and faster than that of B-PTA-0.5, demonstrating that the photothermal capacity is B-PTA-1.5 ≈ B-PTA-1 > B-PTA-0.5 > B-PTA-0. These results are consistent with UV–Vis-NIR studies.

Solar steam generation of B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 were investigated and the top surface temperature of the wet B-PTAs were recorded by IR camera under 1-sun irradiation. The top surface temperature of B-PTA-0 increased from 22.4 to 27.8 °C after 3 min of irradiation, and continuously rose and kept at an average of 33.8 °C after 15 min of illumination as shown in Fig. 5a. Compared with B-PTA-0, the top surface temperature of B-PTA-0.5 was higher under the same condition, and stabilized at an average of 37.0 °C after 15 min of irradiation. Similarly, the top surface temperature of B-PTA-1 was higher than B-PTA-0.5, and kept at an average of 39.5 °C after 15 min of irradiation. The results indicate that the increase of CB leads to the top surface temperature of the B-PTAs rising, which is in favor of solar steam generation. Moreover, the top surface temperature change of B-PTA-1.5 is similar to B-PTA-1 under the same condition even if the CB content is higher than B-PTA-1, implying that B-PTA-1 has the optimal CB content for solar steam generation. These results are consistent with UV–Vis–NIR and light to heat research.

To systematically evaluate the photothermal ability of the B-PTAs, the evaporation rates and efficiencies were accurately recorded through an electronic balance under 1-sun irradiation. The time-dependent water mass change plots of the B-PTAs are presented in Fig. 5b. The mass change of water for B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 within 1 h are 0.57, 0.85, 0.96 and 0.96 g, respectively. The diameter of the B-PTAs is 3 cm. The calculated evaporation rates under 1-sun irradiation are 0.81, 1.20, 1.36 and 1.36 kg m⁻² h⁻¹, respectively. The dark field evaporation rates of B-PTA-0, B-PTA-0.5, B-PTA-1 and
B-PTA-1.5 are 0.25, 0.23, 0.24 and 0.24 kg m\(^{-2}\) h\(^{-1}\), respectively. The solar energy conversion efficiency (\(\eta\)) is calculated through the following equations (Li et al. 2018a, 2018b):

\[
\eta = \frac{m(H_{LV} + Q)}{I}
\]

\[
H_{LV} = 1.91846 \times 10^6 \left[ T_1 / (T_1 + 33.91) \right]^2
\]

**Fig. 4** Absorption spectra of B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 together with solar spectral illumination (AM 1.5G, purple area) (a); time-dependent surface temperatures change of dry B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 B-PTA-1.5 are 0.25, 0.23, 0.24 and 0.24 kg m\(^{-2}\) h\(^{-1}\), respectively. The solar energy conversion efficiency (\(\eta\)) is calculated through the following equations (Li et al. 2018a, 2018b):

\[
\eta = \frac{m(H_{LV} + Q)}{I}
\]

\[
H_{LV} = 1.91846 \times 10^6 \left[ T_1 / (T_1 + 33.91) \right]^2
\]
\[ Q = c(T_1 - T_0) \]

where \( m \) stands for the net water evaporation rate (kg m\(^{-2}\) h\(^{-1}\)). \( H_{LV} \) represents the liquid–vapor phase change enthalpy. \( Q \) is the sensible heat (J kg\(^{-1}\)). \( I \) represents the power density of solar illumination. \( T_1 \) is the temperature of evaporation (K), \( T_0 \) is the initial temperature of the water. \( c \) is the specific heat capacity of bulk water (4.2 J g\(^{-1}\) K\(^{-1}\)). Based on the above equation, the net evaporation rates of B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 are 0.56, 0.97, 1.23, 1.48 kg m\(^{-2}\) h\(^{-1}\), respectively.
1.12 and 1.12 kg m\(^{-2}\) h\(^{-1}\), respectively. The corresponding photothermal efficiencies are 38.38\%, 66.81\%, 77.34\% and 77.47\% as shown in Fig. 6a. These results indicate that the evaporation efficiency of the B-PTAs increases with the increase of BC content, and the B-PTA-1 is the best candidate for solar steam generation. The evaporation performance of B-PTA-1 keeps stable for 20 cycles with each cycle maintained for 1 h as shown in Fig. 6b, which demonstrates that B-PTA-1 has excellent stability for solar steam generation performance. The photothermal efficiency of B-PTA-1 is higher than the graphene and rice-straw-fiber-based 3D photothermal aerogel (high: 1 cm, diameter: 3 cm), which is 73.60\% (Storer et al. 2020). Therefore, using freely available bio-waste bagasse to replace expensive graphene to manufacture solar steam generation material is possible. In addition, we have compared the evaporation rate of B-PTA-1 under 1-sun with previously carbonized bio-waste based solar steam evaporators (Fig. 6c), such as carbonized corn straw (1.50 kg m\(^{-2}\) h\(^{-1}\)) (Zhang et al. 2020a), carbonized corn straw with aerogel (1.36 kg m\(^{-2}\) h\(^{-1}\)) (Li et al. 2021), carbonized E. prolifera (1.30 kg m\(^{-2}\) h\(^{-1}\)) (Yang et al. 2019), carbonized kelp (1.35 kg m\(^{-2}\) h\(^{-1}\)) (Lin et al. 2019), carbonized pomelo peel (1.78 kg m\(^{-2}\) h\(^{-1}\)) (Gu et al. 2020), carbonized rice husk (1.03 kg m\(^{-2}\) h\(^{-1}\)) (Fang et al. 2020), carbonized rice straw (1.20 kg m\(^{-2}\) h\(^{-1}\)) (Fang et al. 2019) and carbonized willow (1.65 kg m\(^{-2}\) h\(^{-1}\)) (Zhang et al. 2020c). The evaporation rate of B-PTA-1 is average to the above-reported bio-waster based photothermal materials.

To verify the practical application of B-PTA-1 for desalination, an apparatus for collecting evaporator water was designed to detect ion concentrations of evaporation water under natural sunlight. The diameter of B-PTA-1 in outdoor experiments is about 11 cm (Fig. S7), which can generate about 13 ml water under 1-sun irradiation for 1 h in theory. During the water evaporation progress, the generated steam was condensed into water drops and adhered to the surface of the spherical glass container as shown in Fig. S8, and about 80 mL evaporated water was collected from 9:00 to 18:00 on May 24th, 2021. The ion (Na\(^{+}\), K\(^{+}\), Ca\(^{2+}\), Mg\(^{2+}\)) concentrations of evaporated water were tested through the ICP-OES method as shown in Fig. 6d, which are significantly decreased

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**Fig. 6** Photothermal efficiency of B-PTA-0, B-PTA-0.5, B-PTA-1 and B-PTA-1.5 (a); cycle evaporation performance of B-PTA-1 under 1-sun illumination (b); comparison of B-PTA-1 with previous bio-waste evaporators (Table S1) (c); the measured concentrations of cations in a simulator seawater sample after solar thermal desalination (d); the UV–vis spectra of methyl blue solution (5 mg/L) before and after solar thermal purification (the inserts show the color of the solutions) (e).
to several orders of magnitude, and satisfies the drinking water standard defined by WHO (Raymond-Whish et al. 2007). The desalinated water can be regarded as clean and safe. To evaluate the application of B-PTA-1 in purifying dye wastewater, methyl blue (20 mg/L) was employed as raw water for evaporation testing. About 30 ml evaporated water was collected from 11:00 to 3:00 on May 25th, 2021 as shown in Fig. S9. The purified water becomes colorless, the characteristic absorption peaks of methyl blue are disappeared and the absorbance is close to zero, indicating extremely low concentration methyl blue exists in collected water as shown in Fig. 6e. The results manifest that the B-PTA-1 can effectively desalt seawater and purify dye wastewater.

Conclusion

In summary, a solar steam generator was manufactured from bio-waste bagasse. CB was composited with bagasse fiber to form a porous structure, light absorber and super-hydrophilicity B-PTA. Photothermal efficiency of B-PTA was affected by the content of CB. B-PTA-1 had the optimal water evaporation rate, which was 1.36 kg m^{-2} h^{-1} with photothermal efficiency of 77.34%. The B-PTA presented excellent stability and efficiency without a significant decrease after 20 cycles. In addition, simulator seawater and dye wastewater can be efficient purification with natural sunlight. Collected desalination was satisfied the drinking water standards. Applying low cost, scalability, environmental friendliness B-PTA to practical application is possible. This work indicates that turning bagasse bio-waste into valuable solar steam generators for mitigating environmental pollution, energy short and freshwater crisis is promising.

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Authors’ contributions JX: Conceptualization, methodology, Writing–review & editing. ZZ: Synthesis, characterization and analysis. YL: Synthesis and characterization. JY: Synthesis and characterization. YW: Synthesis and characterization. BL: SEM characterization. WW: Data analysis. SP: Methodology. XM: Conceptualization and methodology. YG: SEM analysis. ML: Conceptualization and supervision. JP: Data analysis and check the manuscript.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent This article does not contain any studies or researches with human participants nor animals performed by any of the authors which violate ethical standards.

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