A Barbeque-Analog Route to Carbonize Moldy Bread for Efficient Steam Generation

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HIGHLIGHTS
Barbeque-analog route provides feasibility of carbonization of natural materials
Carbonized moldy bread enables sustainable reconversion of food wastes
The evaporation efficiency stays high even at high relative humidity

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A Barbeque-Analog Route to Carbonize Moldy Bread for Efficient Steam Generation

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SUMMARY
Sustainable reconversion of the large quantities of food waste generated every day is pivotal for a green urban development in future. Herein, we put forth a sustainable and cost-effective way to re-purpose a commonly used food waste for solar steam generation, an important part of water desalination. Making use of moldy bread, a new route for steam generation is demonstrated. The moldy bread was converted into a solar absorber by a simple and cost-effective carbonization process mimicking outdoor barbeque cooking. Carbonizing food waste to facilitate better absorption of sunlight for effective evaporation of water is an unprecedented concept in this field. Interestingly, the carbonized bread repurposed from the food waste served as an effective solar steam generator with an efficiency as high as 71.4% under 1 sun illumination. The structural and thermal absorption properties of the carbonized bread facilitated efficient solar energy absorption, heat management, and water transpiration in the system.

INTRODUCTION
Solar energy is expected to have a profound impact on human future development as well as be the key to tackle the serious environmental and energy challenges the world faces today (Creutzig et al., 2017). Besides the strong urge to develop more eco-friendly and cost-effective energy harvesting technologies (Cheng et al., 2018; Ravi et al., 2017, 2018; Fan, 2017; Carlé et al., 2017; Singh et al., 2017), the pursuit of utilizing this abundant energy source in addressing some of the environmental and social issues like water crisis has also gained immense research interest in recent times (Pile, 2017; Gençer et al., 2017). Enormous efforts are made in desalination of seawater to mitigate the ill effects of water deficit emerging in various parts of the globe. Among all the available approaches to desalinate water, solar-driven steam generation has drawn tremendous attention, and exciting advances in this technology were witnessed in recent years (Lou et al., 2016; Sunwade et al., 2015; Zhou et al., 2016; Mohammadassajadi and Hiawang, 2017; Sharon and Reddy, 2015; Zhang et al., 2015b; Zhu et al., 2017). Apart from desalination and the associated applications, such as water purification and wastewater treatment, steam generation has immense applications in burgeoning fields like power generators and actuators (Yang et al., 2017b; Ma et al., 2013; Chen et al., 2015; Cavusoglu et al., 2017; Zhang et al., 2015a; Arazoe et al., 2016). The concept of using water vapor and environmental moisture to generate electricity and transduce mechanical energy is patenting rising. To catch the tide, devising effective ways of steam generation will be critical. Of late, this idea has gained momentum with numerous new solar absorber materials being reported. However, improving scalability and reducing the overall cost is still a major concern. For instance, plasmonic nanomaterials-based absorbers are known to be an effective way to localize solar heat. The traditionally employed noble metals in the system, although effective in solar absorption and heat localization, have a limitation of high material cost. However, the use of plasmonic aluminum nanoparticles is promising thanks to the low cost and is believed to be a disruptive innovation for future in this field (Zhou et al., 2016; Knight et al., 2013). On the other hand, graphene-based absorbers show promising prospect and practical value by cutting down the material cost, and limitations regarding scalability can be overcome by simplifying the fabrication process (Hu et al., 2017; Li et al., 2017; Jiang et al., 2016). Besides this, photoreceivers developed with fully reusable materials have offered a distinctive way to enhance holistic practicability and reduce overall cost (Liu et al., 2017a; Wang et al., 2017).

In light of this, the focus has recently been shifted from those cost- and energy-intensive material systems to naturally abundant materials to minimize fabrication cost and achieve easy scalability (Zhu et al., 2017; Xu et al., 2017; Xue et al., 2017; Chen et al., 2017; Liu et al., 2017b, 2017c; Jia et al., 2017). Two crucial requirements for such a material system would be (1) to have a broad range of optical absorption and (2) to render highly efficient heat localization. To achieve this, natural materials are typically subjected to carbonization.
process before putting into service. As described in previous studies and based on general experience (Zhu et al., 2017; Xu et al., 2017), fabrication of a single carbonized layer (e.g., wooden surface) is typically much simpler than that of a bulk material such as mushroom, which requires tube furnace and protective gas. Nonetheless, it has been found that heat-treated wood shows better decay resistance compared with non-treated wood (Kamdem et al., 2002; Vukas et al., 2010; Esteves and Pereira, 2008), which would be very likely to limit the practical sustainability and endurance of wood-based device without a carbonized “root” when permanently soaked in complex water environment, e.g., seawater (Fojutowski et al., 2014). The use of expensive and energy-intensive bulk carbonization procedures, though, can aid in the development and study of a laboratory-scale product; for better scalability it is also crucial to lower down the production cost by devising more productive and cost-effective process routes, even if the raw material employed is cheap and abundant. Herein, mimicking the outdoor barbecue cooking, we propose a modified heating approach by using charcoal as the heat source and a tailored furnace, which is made of aluminum foil, to shield the loads from being burnt into ashes. Moreover, we have selected one of the most common household food wastes, moldy bread, as the material of interest (Lin et al., 2013). It is for the first time that a material system developed from food waste is introduced in this field, and our findings suggest that the unique porous structure of the moldy bread makes itself an ideal candidate as steam generator (Yuan et al., 2016). The overall solar steam generation efficiency of the carbonized bread reached as high as 71.4% under 1 sun illumination as its surface temperature stabilizes, and it is noteworthy that the achieved efficiency was obtained under a high relative humidity (RH) of around 70%, which is way higher than in most previous studies (Hu et al., 2017; Xu et al., 2017; Xue et al., 2017; Yang et al., 2017a; Ito et al., 2015; Zhang et al., 2015b). It is also noteworthy that by using moldy bread and cost-effective carbonization approach, the final cost is lowered greatly. In short, the use of moldy bread, which is one of the commonly generated food waste, and a facile and cost-effective carbonization approach has greatly cut down the overall cost both at the material and process levels.

RESULTS AND DISCUSSION

Setup of Barbeque-Analog Carbonization Approach

In traditional barbecue cooking, food is heated without being transformed into ashes; this inspired us to imitate a similar heating system as used in barbecue. By this approach, the need for any energy-intensive furnace in the carbonization process is circumvented. As shown in Figures 1A and 1B, the newly designed carbonization setup consists of three main parts: an aluminum tray at the bottom, a stack of charcoals as the heat source, and a homemade furnace on the charcoal pile. The aluminum tray can not only safely contain everything but also minimizes the heat loss caused by air flow. The furnace structure plays the key role to prevent the bread loaded inside from being burnt into ashes. Each furnace is made with a pair of commercially available aluminum bowls, as shown in Figure 1C. The two aluminum bowls were bent and twisted to fit each other firmly (Figure S1), and an enclosed chamber could hence be achieved to load raw materials. The enclosed chamber prevents the entry of outside oxygen, thereby eliminating the possibility of sustained combustion inside the chamber. More importantly, a small hole was drilled on the chamber top to allow internally generated gas to disperse out when heating. The results confirm that the small vent hole does not undermine the ongoing carbonization or cause any combustion in the aluminum furnace. It should be noted that the entire setup can be repeatedly used to cut further cost.

Characterizations of Carbonized Moldy Bread

A slice of moldy white bread was collected as shown in Figure 1D, with the green stains on bread indicating the mold colonies. Through the aforementioned heating approach, carbonized bread with a low shrinkage (10%–15%) was successfully obtained, as presented in Figure 1E. More details with respect to its microstructure were revealed by means of scanning electron microscopic (SEM) images, which are shown in Figures 1F–11. At first glance, both the top-view images (Figures 1F and 1G) and cross-sectional images (Figures 1H and 1I) manifest the porous structure of carbonized bread. It is obvious that more pores can be found on the flank than the top surface, and minor pores are also identified in cell walls apart from major pores, implying that the cell walls have a hollow structure. Furthermore, tiny cavities are spotted on cell walls under larger magnification. The size of pores varies widely and hierarchically: major pores are several hundred micrometers large, minor pores are within 100 μm, and for cavities, the average size is no more than 5 μm. These unique hierarchical pores essentially contribute to the large porosity (≈90%) and extremely low specific mass (0.202 g cm$^{-3}$, Figure S3). Capillary effect induced by the porous structure ensures that sufficient water can be pumped up to the heating zone instantaneously to evaporate, and also the vast surface area provided by the sophisticated structure enables high efficient light absorption and high rate of vapor
generation. Besides, the carbonized bread shows excellent hydrophilicity (Video S1), which strengthens water supply in conjunction with capillary effect. All features depicted above jointly account for productive steam generation by carbonized moldy bread.

This preliminary conclusion is supported by optical measurements and thermal conductivity tests. The optical transmittance and reflectance of carbonized moldy bread were measured under dry and wet conditions, respectively, in the wavelength range 300–1,300 nm (Figure S4). Transmittances under the two conditions are extremely low (≈0%), indicating no light is able to penetrate through the carbonized sample. Results on reflectance suggest that less light was reflected when the sample was immersed in water. To conclude, the light absorption of carbonized moldy bread stays at a high level under both conditions,

Figure 1. Heating Setup for Bulk Carbonization and Characterization of Carbonized Moldy Bread
(A and B) Photographs of the heating setup before and after ignition, respectively.
(C) A pair of aluminum bowls for homemade furnace fabrication.
(D) Moldy bread used in this study. The green spots on bread indicate moldy colonies.
(E) Moldy bread after carbonization.
(F and G) Top-view SEM images of the carbonized moldy bread under different magnification.
(H and I) Cross-sectional SEM images of the carbonized moldy bread. The blue and red dashed circles embedded in SEM images identify the minor-pore structure inside cell walls and the tiny cavities on the wall surface, respectively.
See also Figures S1–S5.
although wet bread leads to a slightly higher absorption than the dry one, which are 97.5% and 96%, respectively. Thermal conductivity tests were conducted to assess its performance on heat localization, shown in Figure S5. Interestingly, similar results were obtained when comparing with previous reports (Ghasemi et al., 2014; Xue et al., 2017; Liu et al., 2017c): the thermal conductivity of the bread sample in dry condition (0.0985 Wm\(^{-1}\)K\(^{-1}\)) is remarkably lower than that of the one filled with water (0.4241 Wm\(^{-1}\)K\(^{-1}\)). The low thermal conductivity can be explained by the highly porous structure, and the gap between wet bread and pure water (\(\approx 0.6000\) Wm\(^{-1}\)K\(^{-1}\) at ambient temperature), which is 0.1759 Wm\(^{-1}\)K\(^{-1}\), is due to the cell walls’ interior hollow structure where water cannot be delivered. Low thermal conductivity enables the harnessed solar heat to be confined to the illuminated surface only instead of being dissipated to the bulk water beneath. Therefore heat loss during illumination is reduced and the conversion efficiency is promoted significantly.

**Performance on Steam Generation**

The steam generation performance of carbonized moldy bread will be elucidated extensively in this section. Surface temperature was recorded at first by using an infrared camera, with the photographs shown in Figure 2A, and temperature was then extracted and plotted in Figure 2B. Under 1 sun illumination, the
Dry surface can reach a higher temperature than the wet surface: on the one hand, the maximum temperature in dry condition is as high as 66°C, and it is only 44°C when soaked in water; on the other hand, the average temperature of the wet surface is about 20°C lower than that of the dry surface (39.1°C and 60.1°C, respectively). The likely reasons accounting for the temperature drop from dry condition to wet are as follows: (1) evaporation necessarily consumes solar heat, (2) heat may be dissipated to the bulk water, and (3) as we observed, water fluid tends to inundate the surface area, and as a result, solar heat is misappropriated by the surface water instead of directly being received by the black absorber. The speculations can be proved by the surface temperature distribution according to infrared images. Dry carbonized bread achieved a good uniformity, whereas the soaked sample could not. It is believed that this surface temperature non-uniformity can be translated into surface water distribution non-uniformity. The reason is as follows. If more water floods up to the surface, its temperature would appear to be lower due to excessive heat dissipation, and vice versa. Another result of the non-uniform surface property is the small gap between maximum temperature and average temperature under illumination. Even though there are issues like uniformity and heat loss, the carbonized moldy bread still performs competitively in terms of surface temperature under 1 sun intensity when compared with cutting-edge technologies (Chen et al., 2017; Xu et al., 2017; Zhu et al., 2017; Wang et al., 2017). It is expected that the methods that can minimize the temperature disparity and increase the wet surface temperature will be critical for further efficiency improvement.

The main measurements of steam generation by using this novel carbonized moldy bread are shown in Figure 3. For each test in Figure 3A, mass change of water was tracked every 10 min under 1 kWm⁻² solar irradiation and a complete 1-hr evaporation journey was recorded. As we can see in the control dark experiments, both carbonized bread and pure water had a low evaporation rate, but after light was
switched on, evaporation loss of bread sample was over four times higher than that of pure water, which are 0.96 kg m$^{-2}$ and 0.22 kg m$^{-2}$ respectively. The evaporation efficiency ($\eta$) is the metric employed to evaluate the performance of steam generators, which is defined by the following equation (Liu et al., 2017c):

$$\eta = \frac{\dot{m} h_{LV}}{I}$$  (Equation 1)

where $\dot{m}$ is the mass flow rate, $h_{LV}$ refers to the total enthalpy of sensible heat and latent heat of water vaporization, and $I$ denotes the input power density of solar irradiation, which is 1 kW m$^{-2}$ in this study. The overall 1-hr efficiency of carbonized moldy bread is 66.6%, and it is only 11.2% for water. To get an in-depth understanding of water evaporation relying on solar absorber, we dissected the 1-hr process and collected data points of real-time performance every 10 min, and the related results are shown in Figures 3B and 3C. It should be noted that each point in this graph stands for the last 10 min’ performance only. Apparently, the efficiency over the first 10 min’ illumination is particularly lower than the rest, which implies that the first 10 min’ inefficient evaporation dragged down the overall efficiency. If only the remaining 50 min are taken into account with the first 10 min being left out, the final overall efficiency would be 71.4% instead of 66.6%. It also occurred to pure water, although the effect is less conspicuous. The reason for this has been revealed in Figure 2B: the absorber takes the initial minutes to raise its temperature, and as a result, evaporation over that period is bound to be inactive. We also notice that its performance fluctuated greatly even after the temperature stabilized, and surprisingly, the real-time efficiency once reached as high as 78.9%, suggesting that further improvement would be highly possible. We wish to highlight that all the results were obtained at a

| Materials                                               | Temperature [°C] | Relative Humidity [%] | Efficiency(1-Sun) [%] |
|---------------------------------------------------------|------------------|-----------------------|-----------------------|
| Flame-Treated Wood (Xue et al., 2017)                   | 26               | 40                    | 72                    |
| Functionalized Graphene (Yang et al., 2017a)            | 22               | 60                    | 48                    |
| Vertically Aligned Graphene Sheets Membrane (VA-GSM) (Zhang et al., 2017) | 25               | 22                    | 86.5                  |
| 3D-Printed Evaporator (3D-CG/GN) (Li et al., 2017)      | 20               | 30                    | 85.6                  |
| Graphene Oxide (GO)-Based Aerogels (Hu et al., 2017)    | 25               | 45                    | 83                    |
| Carbon Nanotube Modified Flexible Wood Membrane (F-Wood/CNTs) (Chen et al., 2017) | 20               | NA                    | 65                    |
| Hydrophobic Photothermal Membrane (Zhang et al., 2015b)  | 22               | 50                    | 58                    |
| Multifunctional Porous Graphene (Ito et al., 2015)      | 24               | 14                    | 80                    |
| Carbonized Mushroom (Xu et al., 2017)                   | 28               | 41                    | 78                    |
| Aluminum Nanoparticle-Based Plasmonic Structure (Al NP/AAM) (Zhou et al., 2016) | 24               | 48                    | 57                    |
| Double-Layer Structure (DLS) (Ghasemi et al., 2014)     | 24               | 31                    | 64                    |
| Plasmonic Absorber (Liu et al., 2017a)                  | 35               | NA                    | 76                    |
| Carbonized Moldy Bread                                 | 21               | 70                    | 71.4                  |

Table 1. Performance Comparison of Solar Steam Generators under 1 Sun Intensity and Respective Experimental Temperature and Relative Humidity
high ambient humidity level of around 70%, which explains why the evaporation efficiency of pure water in this report is much lower than that in previous studies. Temperature and RH are able to impose decisive impact on water evaporation (Deng et al., 2017), hence we have particularly summarized previous absorber materials and compared their efficiency, surrounding temperature, and RH with this work in Table 1. Notably, high efficiency appears to be more likely to occur when the system operates under low RH. Owing to the local humid climate, the RH in our study is the highest on the list; however, its efficiency remains at a competitive level. We believe the performance of carbonized bread could be boosted dramatically if a low laboratory RH could be achieved. However, very little information is currently available regarding the precise relations between RH and artificial steam generation, and we believe further effort on this issue will significantly extend our knowledge in this field. Besides, the stability of carbonized moldy bread was tested under 1 sun illumination for 50 cycles with each cycle lasting for 1 hr (Figure 3D). By ruling out the first cycle, which was underperforming due to the warm-up period, the average evaporation rate of the remaining 49 cycles is about 0.92 kg m\(^{-2}\)h\(^{-1}\), which is consistent and comparable with the above highlighted results.

Conclusions

Inspired by barbeque, we have developed a simple and feasible heating method to carbonize natural materials for steam generator preparation, and we demonstrate a common food waste, moldy bread, as an efficient solar absorber. This heating approach shows superior feasibility over the conventional energy-intensive process routes in large-scale material carbonization and makes it possible that competitive solar evaporator can be readily produced outside the laboratory. In terms of steam generation, the carbonized moldy bread still exhibited sufficiently good performance at a high humidity level (70%). The average conversion efficiency was 66.6% by reckoning a 1-hr evaporation cycle, and when the surface temperature stabilized, the average efficiency reached 71.4%. In addition to the great feasibility, the overall cost of carbonized bread is slashed because of the great availability of food wastes and the readily accessible carbonization method. Moreover, we propose that if industrial waste heat could be recovered and used for bulk carbonization (Ismail and Ahmed, 2009), it would be very likely to accomplish mass production and a further huge reduction in cost.

METHODS

All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Transparent Methods, five figures, and one video and can be found with this article online at https://doi.org/10.1016/j.isci.2018.04.003.

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AUTHOR CONTRIBUTIONS

S.C.T. and Y.Z. designed the study, and Y.Z. performed all the experiments. Y.Z., S.C.T., and S.K.R. wrote and revised the paper. J.V.V. assisted Y.Z. with data analysis and result discussion.

DECLARATION OF INTERESTS

The authors declare no competing interests.
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Supplemental Information

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Figure S1. Homemade furnace for carbonization. Related to Figure 1 and Transparent Methods. (a) Two aluminum bowls were prepared for furnace fabrication. (b) One bowl was bent into a shape as shown in the photo to hold bread. (c) The other one was bent to fit the bottom bowl. (d) Top-view of the assembled furnace. Small vent holes were drilled as indicated by dotted circle. (e) Bottom-view of the assembled furnace. The two bowls were inosculated tightly so that little air can sneak into the inside chamber.
Figure S2. Furnace temperature as a function of time throughout a complete carbonization process. Related to Figure 1 and Transparent Methods. The peak occurred in the first hour, which was due to limited quantity of charcoal used.
Figure S3. Specific weight of carbonized bread. Related to Figure 1. 1.101 g cm\(^{-3}\) is obtained when the sample is saturated with water. The actual specific weight (0.951 g cm\(^{-3}\)) is usually smaller than the theoretical 1.101 because the soaked sample cannot hold all the water when weighting it. By comparing the specific weights under completed dry and water-saturated conditions, the porosity was then estimated to be about 90%.
Figure S4. Optical measurements of carbonized moldy bread including reflectance(a) and transmittance(b). Related to Figure 1. Rough reflectance estimations for dry and wet conditions are 4% and 2.5%, respectively. The transmittance for both conditions is about 0%. Therefore, the light absorbance for dry carbonized moldy bread is equal to (1-4%-0%), which is 96%, and 97.5% for wet condition.
Figure S5. Thermal conductivity of dry (a) and wet (b) carbonized moldy bread. Related to Figure 1.
TRANSPARENT METHODS

Fabrication of Carbonized Moldy Bread
The moldy bread used in this study was collected locally and for the sake of repeatability, only white bread, measuring 10 x 10 x 1.5 cm, was selected. The other tools and materials including the aluminum tray, aluminum bowl and charcoal were all purchased from local market. The moldy bread was then fit into the aluminum furnace for carbonization, and DIY of the furnace was shown in Figure S1. For every batch, 300~500 grams charcoal was used. The temperature of this tailored furnace was recorded throughout the heating process by using a Fluke 62 Mini Infrared Thermometer, and the temperature curve as a function of time was displayed in Figure S2. Considering only the temperature of the exterior surface of the furnace was obtainable, the actual temperature of the inner chamber is believed to be higher than detected. After the heating process, a small piece (27 cm²x1.5cm) of the carbonized bread was cut to test.

Characterization of Carbonized Moldy Bread
Morphologies and inner structure of carbonized bread were examined by Zeiss Supra 40 FE SEM. The infrared photographs in this study were obtained by using a FLIR ONE infrared camera, which was also employed for thermal conductivity measurements. The thermal conductivity of carbonized bread was obtained based on steady-state method: the sample bread was sandwiched by two glass slabs with known thermal conductivity, and beneath the set-up a metal heatsink was used to maintain the lower glass slab at a constant low temperature, meanwhile, certain heat flux was received by the upper glass slab. Thermal conductivity of the sample was then calculated by Fourier Law. Optical measurements were conducted with an Agilent CARY-7000 UV-VIS-IR spectrophotometer equipped with a sophisticated angular resolved reflectance accessory. Transmittance (T) and reflectance (R) of the reported materials were obtained by scanning a wavelength range of 300-1300nm, and the absorptance (A) was then calculated according to the relation: A=1-T-R.

Steam Generation Measurements
The carbonized bread was placed in a petri dish which was filled with shallow water. It should be assured the water height must be lower than the thickness of bread sample before every test. Samples were illuminated under one-sun intensity with a solar simulator (Newport 92250A-1000, AM1.5). Weight loss was carefully recorded with a properly calibrated electronic balance (Sartorius CP224S). All tests were conducted at the room temperature of ~21°C and the RH was around 70%(±1%).