Fabrication of photothermal carbon nanodot materials coated with luffa evaporation structure for solar energy water evaporation

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ABSTRACT

Solar water evaporation is considered one of the most sustainable and environmentally friendly technologies. To achieve good evaporation performance, a combination of materials with good photothermal conversion efficiency and good evaporation structure is required. In this study, we used carbon nanodots as a photothermal material made that synthesis by hydrothermal of urea and citric acid. At the same time, luffa possessing advantages such as good water transport and easy attachment of carbon nanodots was chosen as the evaporation structure. The results showed that carbon nanodots material had an average size of less than 5 nm and a good absorption range in the wavelength of 200-800 nm. The absorption range of the material has expanded to the near-infrared region (NIR region), increasing the ability to absorb sunlight and convert it into heat energy, subsequently, improving the evaporation efficiency. The carbon nanodots/ luffa composite structure showed a high evaporation rate of 1.25 kg.m^{-2}h^{-1} under 1 sun irradiation (1 kW.m^{-2}).

Keywords: Carbon nanodots; Absorption area; Luffa; Evaporation rate.

1. INTRODUCTION

Currently, many countries around the world, including Vietnam, are facing the problem of lack of clean water due to climate change, population explosion and polluted water sources from economic development. Reverse osmosis (RO) membrane technology is a method commonly applied today to filter saline water to create clean water for daily use. However, this method has high investment and maintenance costs and requires a large power source, so it is difficult to apply in areas with difficult conditions and remote islands. Compared to using RO membrane technology, salt water distillation using solar energy is a solution with great potential to solve the problem of lack of clean water in areas with limited facilities, coastal areas, military units on islands with small environmental impact, low cost and no dependence on the power grid. Carbon nanodots (CDs) are zero-dimensional carbon nanomaterials with high photothermal conversion efficiency. Typically, CDs have a crystalline or amorphous carbon core structure with a size less than 10 nm and a surface covered with functional groups containing oxygen, nitrogen, or sulfur [1, 2]. Based on functional groups on the surface, CDs are easily functionalized, thereby changing their absorption spectrum and optical properties. CDs can be easily manufactured in large quantities and at low cost from organic chemical precursors or naturally occurring organic substances through various methods such as laser etching, hydrothermal, and wave use [3]. To date, CDs have been widely researched and applied as photothermal materials for cancer treatment [4, 5]. CDs have also been studied and applied as light absorbing materials in evaporation water systems using solar energy [6-8].

Recently, the performance of water distillation systems has been significantly improved by using advanced materials with high photothermal conversion efficiency and interfacial water evaporation methods. Interfacial evaporation concentrates solar heat transfer at the water-air interface and only the water at the surface is heated (interfacial heating). Therefore, the interfacial evaporation water system limits heat loss to the water mass below, while reducing heat loss due to radiation and convection, thereby achieving high energy conversion efficiency.

In this study, we used the hydrothermal method to fabricate CDs photothermal materials and simultaneously coating them to luffa to form a CDs/luffa evaporation structure. CDs material had a broad absorption range of solar light from 200 to 800 nm with high photothermal efficiency. The carbon nanodots/luffa composite structure shows a high evaporation rate of 1.25 $kg.m^{-2}h^{-1}$ under 1 sun irradiation (1 $kW.m^{-2}$).

2. EXPERIMENT

2.1. Experimental material

The chemicals used in the experiment are listed in table 1:

Table 1. *Experimental materials.*

No.	Name of material, chemicals	Chemical formula	Origin
1	Acid citric	$C_6H_8O_7$	China
2	Urea	CH_4N_2O	China
4	Natri hydroxit	NaOH	China
5	Natri sulfite	Na_2SO_3	China
6	Hydrogen	H_2O_2	China

2.2. Experiment preparation

2.2.1. Carbon nanodots preparation

- *Step 1: Stirring*

6 g of citric acid and 12 g of urea were added into 40 ml of deionized water and stirred with a magnetic stirrer for 30 mins.

- *Step 2: Hydrothermal*

Take 30 ml of the above solution and put it into a 50 ml Teflon autoclave and heated at 160 ºC for 4 hours. After the hydrothermal process, the product solution was dried at 80 ℃ by drying oven

- *Step 3: Dialysis purification*

The resulting product was mixed with deionized water and dialysed by 12 kDa dialysis bag for 4 days. The water was changed twice a day.

- *Step 4: Centrifuge and dry*

After the dialysis process, the obtained solution was centrifuged with a rotation speed of 12000 rpm for 10 min to remove large particles.

The resulting product was dried at a temperature of 80 ºC for 24 hours, we obtained carbon nanodots in powder form.

2.2.2. Fabrication of evaporator

Luffa was treated by cooking the luffa sponge in a mixture solution (500 mL) of sodium hydroxide (NaOH, 60 g) and sodium sulfite (Na_2SO_3, 9 g) at 100 ℃ for 2 h. Subsequently, the luffa sponge was washed with deionized water and further cooked in 10% H_2O_2 solution at 100 ℃ for 30 mins to completely remove the residual lignin.

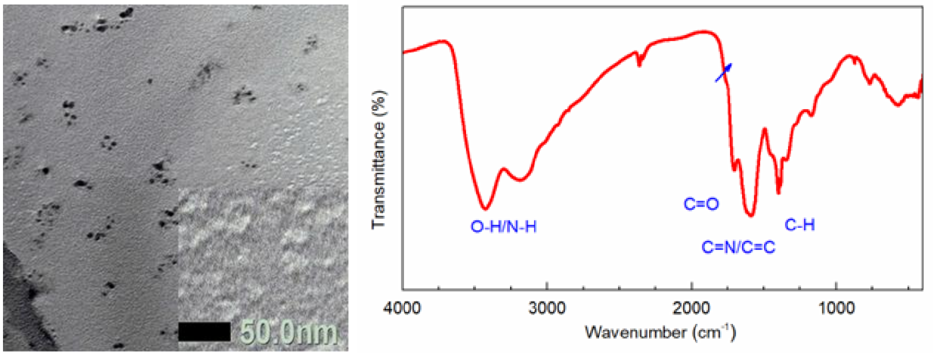
To prepare CDs/luffa composites, treated luffa were immersed and treated with 125 mL CDs solution (80 mg/mL) in a 250 mL Teflon autoclave at 140 ℃ for 2 h. After the reaction, the obtained composites were washed with water and dried at 80 ℃ for further characterization.

3. RESULTS AND DISCUSSION

3.1. Characterization of CDs

The structure of CDs is characterized by a transmission electron microscopy (TEM, JEOL JEM 2100) as shown in figure 1a. TEM images showed that CDs particles with an average size of less than 5 nm.

The FTIR spectrum of CDs (Figure 1b) shows the presence of many different bonds such as O−H and N−H (3100 – 3500 cm^{-1}), C=C and C=N (1630 cm^{-1}), C −H (1380 – 1450 cm^{-1}).



a) *b)*

Figure 1. *TEM image and FTIR image of CDs.*

3.2. Photothermal properties of CDs

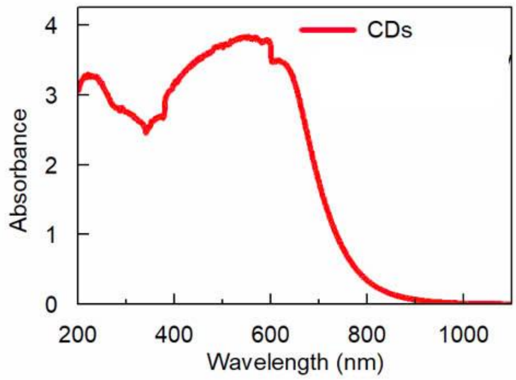


Figure 2. *Absorption spectrum of CDs.*

The obtained CDs material was black, showing very good ability to absorb sunlight. The absorbance spectrum (figure 2) showed that CDs have a good absorption range in the wavelength of 200-800 nm, showing that the material's absorption region has expanded to the near-infrared region (NIR region), which will increase its ability to absorb sunlight to convert into heat energy, helping the evaporation process achieve higher efficiency.

3.3. Photothermal conversion efficiency

To evaluate the photothermal conversion ability of CDs, CDs were illuminated with a xenon lamp simulating sunlight (CEL-HXF300-T3, Aulight) with an energy density of 1 kW/m^{-2} (1 sun). The photothermal conversion efficiency of CDs was measured based on the experimental model as previous report [9].

CDs solution (1 mL) with a concentration of 200 µg/mL was contained in a quartz cuvette (10 mm), placed horizontally and illuminated with an energy density of 1 kW/m^{-2}. The temperature of the solution was measured by a K-type temperature probe (Tenmars, TM-321N). The light absorbed by the CDs solution was measured by measuring the density of light energy transmitted through the cuvette before and after the solution. After the solution temperature reaches a stable value, the Xenon lamp is turned off and the solution temperature continues to be measured to determine the heat emitted to the environment by the solution (figure 3). The result showed that after turning on the light, the solution temperature increased rapidly, then remained stable at 28.1 ºC, showing the good photothermal conversion ability of the material.

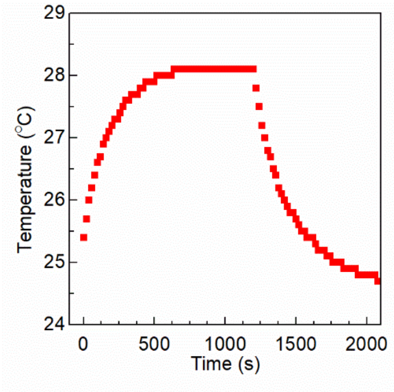


Figure 3. *Temperature changes when the Xenon lamp is turned on and off.*

The photothermal conversion efficiency η_{int} of CDs was determined based on the following formula [9]:

$$\eta_{int} = \frac{hs(T_{max} - T_0) - Q_{dis}}{I_{in}} \tag{1}$$

In which: *h*: Heat transfer coefficient; *s*: Surface area of solution; T_{max} and T_0 are the highest temperature of the solution 28.1 °C and the ambient temperature 24.5 °C, respectively; Q_{dis} is the heat emitted by the absorption of the quartz cuvette when containing pure water solution; I_{in}: Light absorbed by CDs.

hs will be calculated according to the following formula:

$$\tau_s = \frac{mC}{hs} \tag{2}$$

Where m is the mass, C is the specific heat of water.

τ_s will be calculated from the following formula:

$$\ln\left(\frac{T_t - T_0}{T_{max} - T_0}\right) = \frac{-t}{\tau_s} \tag{3}$$

Where T_t is the temperature at time t according to figure 3. The calculation results are as shown in figure 4.

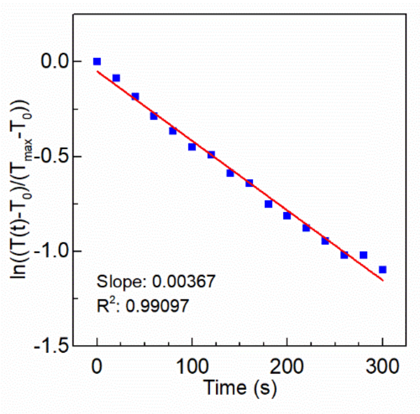


Figure 4. *Line fit coefficient τ_s.*

Q_{dis} is the heat emitted due to the absorption of the quartz cuvette when containing pure water solution, calculated according to the formula:

$$Q_{dis} = hs(T_{max} - T_0) \quad (4)$$

In which T_{max} and T_0 are the maximum temperatures when irradiating a 1sun lamp in pure water solution and T_0 is the ambient temperature.

I_{in}: Absorbed light of CDs is the difference in power under the cuvette when irradiating 1 sun in pure water solution and CD solution.

From there we will calculate hs the value 15.34mW/°C, T_{max} and T_0 are 28.1 °C and 24.5 °C respectively; Q_{dis} has a value of 31.37 mW; I_{in} has a value of 23.94 mW. The photothermal efficiency will be 99.6%. This showed that the photothermal conversion efficiency of the material was high, helping the surface evaporation process in the evaporation structure to achieve high efficiency.

3.4. CDs/luffa composites

Figure 5. *CDs/luffa composites and SEM image.*

CDs/luffa structure was fabricated by attaching CDs onto the 3D porous structure of luffa. Natural luffa were chemically treated to remove lignin before being coated with CDs. The shape of the luffa had changed from a cylindrical shape to a ribbon-like shape with a height of about 0.6 cm after treatment, with good mechanical durability. The image of the treated luffa shows that the 3D porous structure of the luffa remains after chemical treatment (figure 5). Different luffa fibers are stacked on top of each other to form a 3D porous structure with different porosity. The morphology and structure of luffa fibers were further characterized by SEM revealing micro-sized pore structures in luffa fibers.

These results showed that small-sized CDs can be uniformly coated on the surface of luffa fibers without clogging the micro-sized tubes of luffa fibers, allows for efficient light absorption and vapor diffusion into the atmospheric environment during evaporation. At the same time, the capillary tubes transport water through the luffa fibers by the capillary absorption effect through the microscopic holes that connect these tubes and bring water to the outer surface of the luffa fibers, conveniently, beneficial for water transport in luffa. This helps the evaporative structure absorb heat from the environment.

By the way, the evaporation test showed that the evaporation rate reached 1.25 $kg.m^{-2}h^{-1}$ under 1 sun irradiation (figure 6), significantly higher than when not illuminated (only 0.56 $kg \cdot m^{-2} \cdot h^{-1}$), superior to direct bulk water heating or other structure like nanofluid structure (less than 1.2 $kg.m^{-2}h^{-1}$ under one sun and slow response time to the change in solar intensity) [10-11].

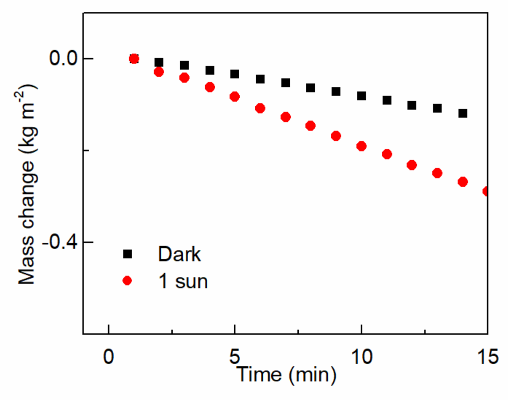


Figure 6. *Mass changes of evaporation structure under 1 sun irradiation.*

4. CONCLUSIONS

In this study, we used a hydrothermal method to fabricate CDs photothermal materials combined with attaching CDs to luff fibers through to form a CDs/luffa composite evaporation structure. CDs possess a high photothermal conversion efficiency reached 99.6%, evaporation rate of 1.25 $kg.m^{-2}h^{-1}$ under 1 sun irradiation. The results of this research can be applied to create clean water using solar energy, which is a sustainable, environmentally friendly solution and has the potential for widespread application to solve freshwater shortages in off-grid or remote areas.

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TÓM TẮT

Chế tạo vật liệu quang nhiệt carbon nanodots ứng dụng trong cấu trúc bay hơi bằng xơ mướp cho quá trình nước bay hơi sử dụng năng lượng mặt trời

Bay hơi nước bằng năng lượng mặt trời được coi là một trong những công nghệ bền vững và thân thiện nhất với môi trường. Để đạt được hiệu suất bay hơi tốt cần có sự kết hợp giữa vật liệu có hiệu suất chuyển đổi quang nhiệt và cấu trúc bay hơi tốt. Trong nghiên cứu này, chúng tôi sử dụng carbon nanodots làm vật liệu quang nhiệt được chế tạo từ urea và acid citric bằng phương pháp thủy nhiệt. Đồng thời, xơ mướp với các ưu điểm như vận chuyển nước tốt và carbon nanodots có thể gắn lên dễ dàng đã được lựa chọn làm cấu trúc bay hơi. Kết quả cho thấy, vật liệu carbon nanodots thu được có kích thước trung bình nhỏ hơn 5 nm, có vùng hấp thụ tốt trong bước sóng 200-800 nm. Vùng hấp thụ của vật liệu đã mở rộng đến vùng cận hồng ngoại (vùng NIR), tăng khả năng hấp thụ ánh sáng mặt trời để chuyển đổi thành năng lượng nhiệt, từ đó giúp quá trình bay hơi đạt hiệu suất cao. Ngoài ra, cấu trúc carbon nanodots/ xơ mướp cho thấy khả năng tốc độ bay hơi cao đạt 1.25 $kg.m^{-2}h^{-1}$ dưới mật độ công suất chiếu xạ 1 sun (1 $kW.m^{-2}$).

Từ khoá: Carbon nanodots; Vùng hấp thụ; Xơ mướp; Tốc độ bay hơi.