



# Carbon dots-modulated covalent triazine frameworks with exceptionally rapid hydrogen peroxide production in water

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## ABSTRACT

Carbon dots (CDs) are incorporated into the interlamination of covalent triazine frameworks (CTFs) for significantly enhanced photocatalytic H<sub>2</sub>O<sub>2</sub> production. Benefiting from CDs-induced rapid nucleation and growth of CTFs on their surface, it can be realized to achieve 13.5-fold increase in hourly productivity and the unique nanoscale sandwich structures featuring excellent charge separation properties. The resultant photocatalyst allows both the oxygen reduction reaction and water oxidation reaction to generate H<sub>2</sub>O<sub>2</sub> at the same time, exhibiting H<sub>2</sub>O<sub>2</sub> yield exceeding the production rate of the pure CTFs 22.6 folds and a solar-to-chemical conversion efficiency of 0.16%. The experimental results reveal that CDs play multiple roles in CTFs, including timely extraction and storage of photoexcited holes and the creation of intermediate bands favoring long wavelength light absorption and utilization. Besides, CDs-induced surface polarization electric field in the interlamination of CTFs can be modulated by simply adsorbing alkali metal ions to further facilitate the carrier separation and migration. As thus, the promising H<sub>2</sub>O<sub>2</sub> production efficiency is achieved.

## 1. Introduction

Covalent triazine frameworks (CTFs) have attracted considerable interest on account of their unique structures and good stability [1,2]. These features make CTFs useful for various applications in photocatalysis, gas/molecular adsorption and separation, energy storage and conversion and others [1–5]. Previous works have demonstrated that crystalline CTFs with well-ordered molecular and porous structures is highly beneficial to charge separation and transfer, which is a process whereby photoexcited electrons and holes arrive at the reaction interface, mostly deciding photocatalytic activity [6–8]. Nevertheless, obtaining crystalline CTFs is still extremely difficult due to the poor reversibility of the conjugated bond, which is not conducive to the self-adjustment [9]. Presently most of the reported CTFs exhibited low crystallinity or amorphous structure, thereby limiting their photocatalytic performance. To improve separation and transfer of charge carriers on CTFs, another feasible strategy is to introduce electron-donating and -accepting units with different electron affinities and ionization potentials into the skeleton of CTFs [5,10,11]. By incorporating acetylene or diacetylene moieties into polymer networks, for instance, photocatalytic H<sub>2</sub>O<sub>2</sub> production of CTFs is dramatically

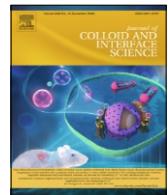
promoted by suppressing charge recombination [12]. Similarly, Huang et al. [13] also reported that H<sub>2</sub> evolution rate of CTFs was significantly enhanced after the incorporation of benzothiadiazole and thiophene moieties. However, this strategy generally suffers from costly reactive monomers as well as inefficient, stringent or intricate preparation steps.

Carbon dots (CDs) with ultra-small size (<10 nm) consist of crystalline graphitic cores surrounding with the surface terminal polar groups, which bridge the gap between the molecular and the nanoscale world due to their unique molecular-like behavior [14]. Therefore, CDs are easily incorporated into organic and inorganic semiconductor nanomaterials to serve as charge donor/acceptor and reservoir, facilitating charge transfer and suppressing the recombination of photo-carriers [15–17]. Moreover, CDs possess many advantages regarding low cost, high stability, friendly environment and tunable optical properties [18–20]. In light of these considerations, numerous CDs-related hybrid architectures have been developed for the implementation of various solar energy conversions [14,21–25]. Although Chen et al. have prepared CDs/CTFs through an impregnation approach for photocatalytic H<sub>2</sub> evolution [26], unfortunately in situ incorporating CDs into CTFs for the photosynthesis of H<sub>2</sub>O<sub>2</sub> is not reported until now.

Since studying isolated components is no longer sufficient to solve

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## Carbon dots-embedded amorphous nickel oxide for highly enhanced photocatalytic redox performance



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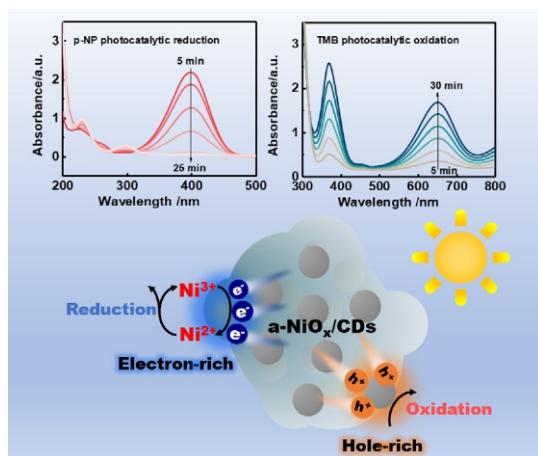
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### GRAPHICAL ABSTRACT

Carbon dots embedded into amorphous nickel oxides overcome the internal consumption of photocarriers and effectively improve their transfer efficiency, resulting in the boosted photocatalytic activity in the redox reactions and antibacterial activity under visible light.



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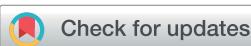
Nanocomposite

### ABSTRACT

Amorphous materials reveal promising prospects in photocatalysis for the abundant active sites and tunable electronic configuration due to the lattice flexibility. However, the intrinsic lattice distortion could also cause the self-trapping effect and results in the recombination of photogenerated carriers. This disadvantage could be modified by the small size of amorphous domains for reducing charge migration distance. For this purpose, carbon dots (CDs) are introduced as the heterogeneous nucleus to regulate the configuration and composition of the amorphous nickel oxides for efficient utilization of photocarriers in catalytic reactions. The resultant nanocomposites a-NiO<sub>x</sub>/CDs show the densely distributed CDs embedded in the amorphous nickel oxide with dual valences of Ni<sup>2+</sup> and Ni<sup>3+</sup>, and they reveal superior activities in photocatalytic oxidation and reduction compared with the single amorphous nickel oxide. The extraordinary photocatalytic performance is attributed to the synergistic function of their excellent separation efficiency of photoinduced charges and the cyclic conversion between Ni<sup>2+</sup> and Ni<sup>3+</sup> in the

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## A carbonized carbon dot-modified starch aerogel for efficient solar-powered water evaporation<sup>†</sup>

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Solar-powered water evaporation shows prominent advantages in extracting fresh water. To achieve high photothermal-conversion efficiency, development of efficient solar evaporators is highly pursued. Here, a new solar evaporator made of a carbonized carbon dot-modified starch aerogel (C-CDSA) was developed. Benefiting from the introduced carbon dots (CDs) that promoted the polymerization and carbonization of starch chains, C-CDSA exhibited a three-dimensional (3D) interconnected porous structure with a larger pore size and thinner pore wall as well as higher porosity. Due to the low carbonization temperature (270 °C) and the feature of CDs with rich oxygenated groups, a higher content of oxygenated groups was preserved in C-CDSA, which not only ensured the super hydrophilicity but also contributed to water activation. By virtue of the structural and compositional advantages, C-CDSA showed enhanced light harvesting, desired thermal insulation, fast water transportation and superiority in reducing the water evaporation enthalpy. Therefore, the designed low-cost and eco-friendly C-CDSA not only exhibited a high evaporation rate of 2.29 kg m<sup>-2</sup> h<sup>-1</sup> with an energy conversion efficiency of 93.5% under 1.0 sun irradiation, but also showed stable water evaporation performance in acidic, alkaline, high-salt (10 wt%) and organic pollutant solutions, holding great promise for practical solar water evaporation applications.

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### 1. Introduction

Highly efficient utilization of solar energy has captured the interest of both academic research and industry because of its great promise in solving the energy crisis, environmental pollution and other issues.<sup>1</sup> Solar-powered water evaporation is an efficient way that harnesses solar energy to generate heat, which can then be used to power water distillation/desalination.<sup>2–7</sup> This technology is prized for its low cost, environmental friendliness, independence from electricity and complex infrastructure, showing prominent advantages compared to reverse osmosis<sup>8</sup> and electrodialysis technologies.<sup>9</sup> An ideal solar water evaporator should exhibit some critical features: broadband light harvesting, ability to balance energy and water management, and capability to reduce the water evaporation enthalpy.<sup>10,11</sup> To realize a high photothermal-conversion efficiency, many efforts have been made to develop efficient solar water evaporators.<sup>12–21</sup> Recently, biomass-based evaporators have attracted increasing attention due to some unique advantages, such as an inherent porous structure,<sup>22–25</sup> the

potential to form hydrogels,<sup>26</sup> environmental friendliness and low cost.<sup>27,28</sup> Nevertheless, the further design and optimization of the inherent porous structure of biomass-derived evaporators would be restricted.<sup>24</sup> And the biomass materials themselves usually do not exhibit light absorption ability, and need to be integrated with solar absorbers (plasmonic noble metals, carbon nanotube, graphene oxide, *etc.*),<sup>29</sup> giving rise to increased cost and complicated manufacturing processes. Besides, the physicochemical stability of biomass-derived evaporators remains challenging.<sup>26</sup> Therefore, more studies on the development of efficient biomass-derived solar evaporators and strategies are highly needed.

Here, a new solar water evaporator made of a carbonized carbon dot-modified starch aerogel (C-CDSA) was constructed *via* a facile and scalable method. Specifically, starch, widely used to synthesize hydrogel-based food, was selected as the raw material to form the porous framework due to its easy availability, eco-friendliness and low cost.<sup>29–32</sup> Carbon dots (CDs) with intriguing properties (*e.g.*, rich oxygenated groups and ability to intimately integrate with other materials), having the potential to tailor the properties of other materials,<sup>33–36</sup> were introduced during the formation of starch aerogel (SA). Besides, based on technical and economical considerations, carbonization was adopted due to its merits of simplicity and easy operation.<sup>22,37,38</sup> The introduced CDs, which promoted the polymerization and carbonization of starch chains, played

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## Chemical treatment of biomass wastes as carbon dot carriers for solar-driven water purification



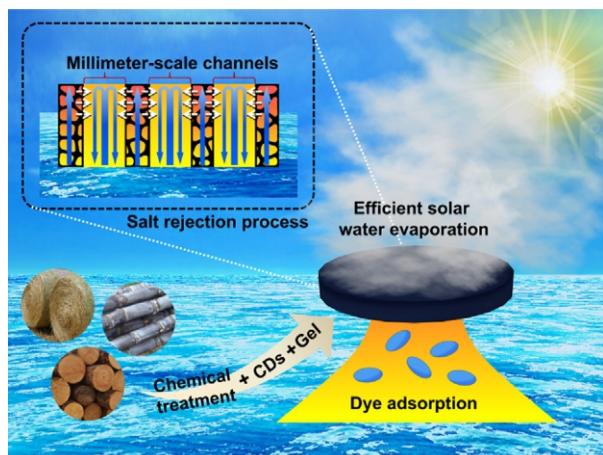
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### GRAPHICAL ABSTRACT

A universal method was provided for constructing the solar-driven interfacial evaporation system with effective energy conversion and superior water hydration abilities using cellulose nanofibrils from different biomass wastes and carbon dots.



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### ABSTRACT

A purely chemical method is demonstrated to treat a variety of biomass wastes for extracting cellulose nanofibrils (CNFs) with a consistent property. By hydrothermal reaction, carbon dots (CDs) can be easily grafted on the surface of CNFs to act as photo-thermal agents and enable fast water evaporation rate at  $2.5 \text{ kg m}^{-2}\text{h}^{-1}$  with about 96.45% solar-to-vapor efficiency under one sun irradiation. This derives from good hydration ability of this system, which lowers the evaporation enthalpy. Moreover, this system not only adsorbs dye contaminants effectively by the formation of hydrogen bonds, but also possesses long-term antifouling solar desalination by means of rationally drilled millimeter-sized channels. Given the sustainable biomass resources and scalable fabrication process, this work offers a promising strategy towards construct low-cost evaporators with the excellent water purification performance.

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## Solar-irradiated carbon dots as high-density hot spots in sponge for high-efficiency cleanup of viscous crude oil spill†

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A rational architecture of photothermal layers on the scaffold surface of porous sorbents is highly desirable for the targeted delivery of sustainable solar energy to power the oil spill remediation process, but its realization remains challenging. Here, we report a novel solar-heating superhydrophobic sorbent system that is created by the *in situ* chemical reaction of carbon dots (CDs) and commercial porous sponge (CPS), effectively reducing the viscosity of crude oil and speeding up the oil adsorption rate. The superior solar-to-heat conversion together with the excellent heat management endow our presented sorbent system with a crude oil absorption capacity of nearly 60 g g<sup>-1</sup> within a very short time under one-sun irradiation, which is significantly faster than previously reported sorbents fabricated by dip-coating methods. This feature is mainly attributed to the decoration of homogeneous and high-density CDs on CPS. Given the fundamental design principle, low operating cost, and fast oil-recovery rate, this work provides possibilities for solar-powered large-area crude oil spill remediation.

## 1. Introduction

Frequent crude oil spills not only incur an enormous loss of valuable resources but also cause severe harm to marine ecosystems and long-term contamination of the environment.<sup>1–3</sup> Therefore, a fast and efficient oil-recovery technique is highly desired to eliminate the environmental and ecological impacts of oil spills. Conventional oil remediation approaches using membrane/sePARATOR filtration, *in situ* combustion at the spill site, chemical dispersants, skimmers, vacuum

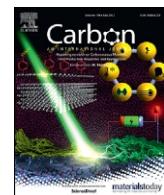
technologies and others not only suffer from low efficiency and toxic by-products but also require rigorous operational restrictions and consume a huge amount of energy, time as well as resources.<sup>4–9</sup> As a comparison, the adsorption-based oil-water separation technique by means of huge oil storage capability inside of highly porous materials is endowed with a simple and energy-saving advantage.<sup>10,11</sup> However, porous adsorbent materials generally work for low-viscosity oil, while for viscous crude oil (viscosity >1000 mPa s) their adsorption performance remarkably deteriorates under similar test conditions due to the sluggish flowability at room temperature.<sup>12</sup> Although this issue can be addressed by electric-power-generated heat to reduce the viscosity of crude oil,<sup>13</sup> it is not easily transferable to real situations of large-area off-shore oil spills. Solar energy is abundant, sustainable, and environmentally benign and can be directly converted into heat through photothermal materials for reducing oil viscosity.<sup>14–16</sup> This on-the-spot available energy supply is highly ideal for the emergency remediation of oil spills in off-shore areas, in which electric power is always insufficient to meet the demands. Unfortunately, designing a novel porous sorbent system with a high-efficiency solar-to-heat conversion function to reduce viscosity and thus significantly enhance the recovery efficiency of crude oils remains a daunting challenge so far.<sup>17–19</sup> For instance, a carbon nanotube (CNT)-modified polyurethane (PU) sponge can merely adsorb heavy oil 20 times its own weight under one-sun illumination, though it possesses nearly full sunlight absorption.<sup>14</sup> By substituting Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene for CNT, the adsorption ability of the PU sponge can reach above 40 g g<sup>-1</sup> for crude oil.<sup>20</sup>

Carbon dots (CDs, fluorescent carbon-based nanoparticles less than 10 nm in size) possess unique solar energy harvesting, transfer and conversion properties through the tailoring of their surface/interface states.<sup>21</sup> In particular, CDs and their assemblies can perform highly efficient solar-to-heat conversion *via* π-band optical transitions or nonradiative recombination processes.<sup>22</sup> Moreover, CDs have a good thermal insulation feature owing to their imperfect crystalline structure surrounding a surface shell containing numerous heteroatom

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# Electrochemical oxidation reconstructs graphene oxides on sponge for unprecedentedly high solar water evaporation



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## ABSTRACT

Although carbon nanomaterials are featured with low cost, outstanding solar-harvesting ability, ultrahigh stability and easy availability, their constructed evaporators still possess low evaporation rate so far under natural sunlight condition. Herein, we present an efficient electrochemical oxidation method to tailor chemical compositions and microstructures of graphene oxides (GO) upon porous melamine sponge (MS) for establishing ultrafast solar water evaporation system. Thanks to superior water activation property resulted from electrochemical oxidation, the afforded evaporation system is able to significantly reduce the water vaporization enthalpy, thereby exhibits a high evaporation rate of  $3.47 \text{ kg m}^{-2} \text{ h}^{-1}$  with the solar-to-steam conversion efficiency of 97.4% under one-sun irradiation, which outweighs all of reported evaporators constructed by congeneric photothermal materials. Furthermore, this evaporation system displays outstanding mechanical performance and satisfactory tolerance to various harsh conditions. With long-term stability and good durability, this evaporation system provides a possibility of large-scale water purification with natural sunlight to meet the world ever-increasing demands for freshwater.

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## 1. Introduction

Solar-driven water evaporation (SDWE) using photothermal materials has emerged as a promising solution to address water scarcity as a major global risk [1]. Comparing with existing technologies of clean water production, it does not suffer from the burden of electricity input, complex infrastructure as well as the expense of environment [2]. Traditionally, SDWE system possesses low evaporation efficiency owing to poor solar absorption and serious heat losses. With environmental sustainability and economic development, the recent surge in demand for high-efficiency SDWE stimulates the ongoing pursuit of advanced photothermal materials and novel architectures [3–5]. By rationally designing nanomaterials as solar absorbers, an interfacial evaporation strategy has been proposed to merely heat the evaporative section of water rather than the entire bulk water [6–8]. This strategy not only suppresses volumetric heating to improve evaporation performance, but also minimizes the cost of SDWE by reducing the photothermal materials usage. To date, various candidates such as

carbon nanomaterials, hybrid hydrogels, metallic plasmonic nanoparticles and semiconductor nanostructures have been examined as solar absorbers [9–15]. Hereinto, carbon nanomaterials are featured with low cost, outstanding solar-harvesting ability, ultrahigh stability and easy availability, thereby many of them including graphene oxide-based aerogels, reduced graphene oxide, porous graphene, vertically aligned carbon nanotubes and others have been explored for steam generations [16,17]. However, the achieved water evaporation rates are always less than  $2.0 \text{ kg m}^{-2} \text{ h}^{-1}$  under one sun illumination, which is significantly lower than that of hybrid hydrogel materials, though many efforts have been made.

On the one hand, a good thermal conductivity of carbon nanomaterials with crystalline structure could be unfavorable for solar-to-heat localization at the water-air interface, leading to low evaporation rates. On the other hand, the weak interaction of them with water molecules only imparts the limited intermediate water, which is believed as activated water that can be transformed into vapor by less thermal energy in contrast with bulk water, in the photothermal material conversion layer of SDWE system. Thanks to effective water activation and the reduced vaporization enthalpy, the hybrid hydrogel evaporators have demonstrated a high

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# Sponge-Supported Reduced Graphene Oxides Enable Synergetic Photothermal and Electrothermal Conversion for Water Purification Coupling Hydrogen Peroxide Production

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To address the freshwater scarcity issue and the environmental impact of wastewater disposal, herein a novel efficient strategy to enhance the performance of solar-driven interfacial evaporation technique is developed to purify salt-containing wastewater and seawater for sustainable clean water production. This strategy enables photovoltaic electricity to power photothermal conversion for rapidly vaporizing brine using commercial melamine sponge (MS)-supported reduced graphene oxides (MS@rGO). The record-high performance with an evaporation rate of  $9.02 \text{ kg m}^{-2} \text{ h}^{-1}$  along with a solar-to-vapor efficiency of 287.4% in 7 wt% salt brine is achieved under 1 sun and optimized voltage applied. During evaporating brine, MS@rGO can also efficiently catalyze oxygen reduction for the sustainable production of  $\text{H}_2\text{O}_2$  to serve as the broad-acting disinfecting agent in the condensed water. Because applying voltages can facilitate the movement of salt ions in brine, the presented system is endowed with excellent salt-resistance and superior ability of extracting photogenerated electrons, significantly improving the energy utilization efficiency. Therefore, this design provides a new way for highly efficiently applying solar energy in saline wastewater purification and seawater desalination with low cost.

## 1. Introduction

Fresh water is one of the most vital resources for the development of human life.<sup>[1,2]</sup> With an expanding population, urbanization, and climate change, not only producing great amounts of wastewater but also clean water scarcity are formidable challenges of human society.<sup>[3,4]</sup> To address this issue, seawater desalination and wastewater treatment provide an ideal solution to meet sustainable water supplies.<sup>[5]</sup> However, current technologies of water purification, especially for treating seawater and salt-containing wastewater, suffer from

vast energy consumption and capital costs.<sup>[6]</sup> Accordingly, research thrusts have been inspired by the need for low-cost approaches to generate clean water from saline wastewater and brine with minimum infrastructure and energy requirement.<sup>[7–9]</sup>

By utilizing abundant and renewable energy source, solar-powered water evaporation can separate water from salts and contaminants, analogously to the replenishment of land freshwater in the natural hydrological cycle.<sup>[10–12]</sup> Thus, solar energy could be used to implement eco-friendly, low-cost, electricity-independent, and decentralized water purification.<sup>[13]</sup> Due to the inefficient use of solar energy, the traditional evaporation ponds possess very low evaporation rate (ER), which is key to gain a low-cost zero-liquid discharge technology, and require vast land areas. Recently, a new technology for solar evaporation enhancement has emerged in which the emphasis is to avoid wastefully heating

bulk water and instead conduct surface heating by localizing solar-converted heat energy at the air–water interface.<sup>[14–16]</sup> There have been various prototypes employing innovative solar absorbers and unique architectures for powering interfacial water evaporation, which achieve not only a solar-to-steam conversion efficiency of >90% but also a superior salt-resistant function.<sup>[17–21]</sup> Unfortunately, these evaporators still face low ER with less than  $4.0 \text{ kg m}^{-2} \text{ h}^{-1}$  in saline wastewater under 1 sun ( $1000 \text{ W m}^{-2}$ ), thereby hindering their application in water recovery for reuse.<sup>[22,23]</sup> Recently, we proposed a photovoltaic (PV) electricity-assisted evaporator for accelerating steam generation where PV electricity enables the photoinduced electrons from the nanomaterial-based absorber more efficiently to convert into heat for rapidly vaporizing brine.<sup>[24]</sup> While as-prepared system can achieve ultrahigh ER, its complicated structure and fabrication cause high operating costs. Clearly, design simplicity and scalability are required for large-scale brine evaporation.

For practical application, the reduced graphene oxide (rGO) materials not only are easily produced on a large scale and much stable in rigorous circumstances such as highly acid and alkali conditions, but also possess outstanding light absorption and excellent photothermal transduction due to the resonant induction by edge-oxygen motion of mobile electrons localized in the vicinity of the oxygen.<sup>[25,26]</sup> Therefore, the rGO is one of the most

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# Electricity-Boosted Solar-to-Vapor Conversion upon Fiber-Supported CDs@CuS for Rapidly Vaporizing Seawater

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**A novel proof-of-concept strategy to enhance the evaporation rate (ER) and solar conversion efficiency of the solar-driven interfacial evaporation (SDIE) technique is presented. This strategy is able to employ photovoltaic (PV) electricity for powering photothermal convertor, thus the photoinduced electrons from the nanocomposite of carbon dots (CDs) and CuS can be fully converted into heat for rapidly vaporizing seawater. The presented system enables a steam generation rate of above  $6.66 \text{ kg m}^{-2} \text{ h}^{-1}$  with a solar-to-vapor efficiency of up to 183% in 3.5% salt brine under one sun. Such high performance is ascribed to the instantaneous release of more heat energy within the confined photothermal layer, resulting in the vaporization of more water adsorbed in this layer. Moreover, the experimental results reveal that the solar evaporation performances of the presented system are determined by the applied voltages and interfacial charge transfer efficiency of the sunlight harvesting agent under constant solar illumination.**

## 1. Introduction

Sunlight is arguably the most abundant renewable energy. Although photovoltaics (PV) provide an important prospect in solar utilization, the biggest issue in using PV is fluctuations in insolation and hence the popular solution is to be joined up with batteries to balance energy supply and demand.<sup>[1,2]</sup> But presently energy storage devices and battery-charging systems still face expensive, bulky, low-efficiency, and inflexible problems, leading to serious mismatches between the energy generation and storing technology.<sup>[1,2]</sup> Alternatively, renewable PV electricity enables water to convert into low-cost and pure hydrogen, which is believed as one of the most promising energy carriers for the future, by means of electrochemical water splitting.<sup>[3–5]</sup> Thus, the PV power is able to be utilized to the hilt without incurring the burden of the grid. Commonly, excess salts and various ions in seawater can severely deactivate the catalysts

and induce undesirable side reactions during the hydrogen evolution process.<sup>[4,6]</sup> Therefore, seawater as a vast resource on the earth remains difficult to be utilized for hydrogen generation, whereas the availability of clean water can't be adequate for future needs.<sup>[7,8]</sup> To address this global crisis, desalination has been developed as one of the predominant solutions. However, the currently available membrane-based techniques still suffer high cost and vast energy consumption, limiting their wide application.<sup>[9,10]</sup>

Solar vaporization is regarded as an efficient, sustainable, and low-cost method for seawater desalination to produce clean water.<sup>[8,9,11–13]</sup> By selectively heating the evaporative portion of water rather than the whole body of water, the solar-driven interfacial evaporation (SDIE) approach

not only successfully achieves a solar-to-vapor conversion efficiency of >90% under one sun, but also minimizes the quantity of photothermal materials used.<sup>[11,14–17]</sup> Based on this technique, some novel difunctional systems have been even developed to fulfill concurrent clean water and electricity generation by coupling judicious photothermal materials and solar steam system.<sup>[8,18,19]</sup> Unfortunately, the evaporation rate (ER) is not sufficiently high yet for practical use. Most solar evaporators exhibit the ER with much lower than  $4.0 \text{ kg m}^{-2} \text{ h}^{-1}$  under natural sunlight by far.<sup>[20–23]</sup> This issue is majorly caused by the intrinsic heat requirement of water vaporization. While developing new nanomaterials, e.g., hydrogel, may be feasible to reduce the energy demand of water vaporization,<sup>[9,12,24]</sup> their capacity to activate water is uncontrollable until now. Thus, there is a need to develop available technologies and novel materials for enhanced ER that can take full advantage of solar energy with minimum infrastructure.<sup>[25–27]</sup>

Here, we demonstrate a new proof-of-concept system that enables solar and electric heating to be localized at the surface of the solar absorber, whereupon the renewable PV electricity can be integrated into this system. To this end, the specific nanocomposites that copper sulfides and carbon dots (CDs@CuS) are simultaneously coupled with conductive fibers serve as the heat convertor. When it runs, the applied voltage allows photoinduced electrons from CDs@CuS to contribute water vaporization besides heating water confined in the photothermal layer, resulting in synergistic improvement of solar-to-vapor conversion efficiency significantly. Consequently, our presented system gives rise to a higher ER than the sum of solely solar and electric heating vaporization with a solar-to-vapor efficiency of up to

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# Combining carbon dots with $\text{WO}_{3-x}$ nanodots for utilizing the full spectrum of solar radiation in photocatalysis

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## ABSTRACT

Artificial photocatalytic systems represent a promising and available technology to directly convert sunlight into usable energy resources. Unfortunately, the current photocatalysts often absorb an only small range of sunlight spectra, hence greatly limiting the utilization efficiency of solar energy. Herein, we firstly developed a hybrid system that combines carbon dots (CDs) and oxygen-deficient  $\text{WO}_{3-x}$  nanodots through a mild solvothermal method. This hybrid system features the heterojunction structure with dimensions smaller than 15 nm and can effectively utilize the full spectrum of solar radiation in photocatalytic oxidative reactions. In hybrid system, the CDs can enhance visible light harvesting ability of  $\text{WO}_{3-x}$  nanodots and deliver their photoinduced carriers to the intermediate energy bands induced by oxygen-deficient of  $\text{WO}_{3-x}$ . After further excitation with low energy photons, then more chemically useful carriers can be generated to participate fully in catalytic activation and reaction processes, resulting in 3.2 times higher photocatalytic activities of CDs@ $\text{WO}_{3-x}$  than  $\text{WO}_{3-x}$  nanodots.

## 1. Introduction

Interest in photocatalytic synthesis has been inspired in part by the realization that sunlight is a green and sustainable energy source [1]. Nevertheless, the inherent energy band configuration of a semiconductor limits its light absorption spectral range within a very short wavelength region of solar radiation [1–3], causing a big challenge to utilize the full spectrum of solar radiation in photocatalysis. Tailoring the vacancies in the lattices of traditional semiconductor photocatalysts such as  $\text{TiO}_2$ ,  $\text{WO}_3$ , has great potential for creating sub-band gap states below the conduction band [4–6]. Thus the electrons can be excited from the valence band (VB) and sub-band gap states to the conductor band (CB) or from the VB to sub-band gap states by lower energy photons, and so this leads to a considerably broadened absorption [5]. By introducing oxygen vacancies and further hydrogen treatment, for instance, the color of  $\text{TiO}_2$  can be tuned from white to black[7]. Although  $\text{WO}_3$  is also a nonstoichiometric oxide similar with  $\text{TiO}_2$ , many oxygen-deficient tungsten suboxide ( $\text{WO}_{3-x}$ ) have stable crystal phase, not just surface reduced  $\text{WO}_3$  [8–10]. By localized surface plasmon resonance (LSPR) effects induced by oxygen vacancies, the  $\text{WO}_{3-x}$

exhibits a strong near-infrared (NIR) absorption ability [8,11–15], but suffers from the deficiency of visible light capture.

Although the sub-band gap states can be generated by oxygen vacancies, let them become photocatalysis-active and they still have a favorable energetic location for the desired reaction and have sufficient lifetimes for excited carriers to migrate surface and participate in a photochemical reaction [4,7]. This implies that the increased light absorption cannot guarantee increased photoactivity. An essential prerequisite for achieving ideal photocatalytic performances requires highly efficient separation and transfer of photoinduced charges from sub-band gap states to avoid charge recombination in inside and surface [2,3]. To inhibit undesirable recombination of photoinduced charges, designing proper heterogeneous photocatalytic system has become an effective strategy towards the high charge-separation efficiency [2,3,16].

As a new class of fluorescent carbon-based nanomaterials, carbon dots (CDs) with several nanometers possess broad visible light harvesting and multiphoton absorption abilities as well as excellent photoluminescence and other favorable properties, thereby promising diverse applications in photocatalysis, photovoltaic cells, energy storage,

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## A bifunctional nanozyme of carbon dots-mediated Co<sub>9</sub>S<sub>8</sub> formation

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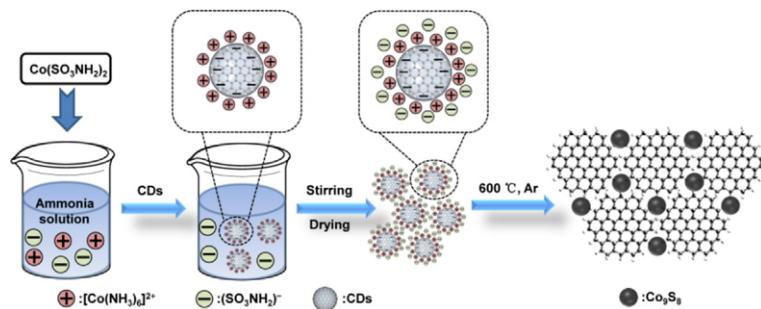


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### GRAPHICAL ABSTRACT

A novel nanocomposite that ultrasmall Co<sub>9</sub>S<sub>8</sub> nanocrystals are incorporated into porous carbon nanosheets formed by splicing carbon dots is achieved, and shows bifunctional enzyme-like activities without exerting any external energy.



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### ABSTRACT

Controlling the size of nanocrystals and inhibiting their agglomeration are of paramount importance for achieving ideal catalytic performance. Here we discovered that carbon dots (CDs) are not only able to serve as reductants but also as stabilizers of ultrasmall Co<sub>9</sub>S<sub>8</sub> nanocrystals by means of their surface terminal groups. As a result, ultrasmall Co<sub>9</sub>S<sub>8</sub> nanocrystals are incorporated into porous carbon nanosheets formed by splicing CDs. The resultant nanocomposites display a rich pore structure accompanying with large specific surface area and outstanding bifunctional performances to mimic the catalytic activity of peroxidase and oxidase without exerting any external energy. More importantly, the unique architecture endows Co<sub>9</sub>S<sub>8</sub> nanocrystals with high stability and good durability. The nanocomposites have been demonstrated as a colorimetric sensor for detection of ascorbic acid with a superior anti-interference ability as well as a detection limit of 0.2 μM. Our findings open new synthetic opportunities by tuning the interaction of CDs with the surrounding environment and enable advanced applications such as biomedicine and catalytic transformations.

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### 1. Introduction

Carbon dots (CDs), as a new class of zero-dimensional (0D) fluorescent nanomaterials, have aroused considerable interest on account of their excellent electronic, optical, physicochemical properties as well as low cost and a wide range of applications such as biomedicine, chemical sensing, photo- and electro-catalysis,

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## High reaction activity enables carbon dots to construct multicomponent nanocomposites with superior catalytic performance†

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Multiphase nanocomposites can be employed in powerful bottom-up design strategies for achieving advanced architectures with superior properties and multiple functionalities, but their disadvantages are that they are intricate, with costly and stringent preparation processes. Herein, we report a simple and universal method for the synthesis of multicomponent nanocomposites by means of the high affinity for metal ions and strong reduction activity of carbon dots (CDs). The nanocomposite FeNS@PC, consisting of Fe cores surrounded by the shells of Fe<sub>7</sub>S<sub>8</sub> and FeN<sub>0.0324</sub>, can be produced on a porous carbon matrix stemming from CD splicing via simple pyrolysis. Thus, CDs act as reducing agents and also are confined where the nucleation reaction occurs, thus avoiding nanoparticle aggregation. By harmonious interaction with all components, FeNS@PC exhibited superior catalytic performance in activating hydrogen peroxide and persulfate into reactive HO and SO<sub>4</sub> radicals, which are the dominant active species for decomposing the pollutant tetracycline. Therefore, this work highly broadens the utilization of CD-mediated strategies for the future precise construction of novel catalysts and nanocomposite fabrication.

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### 1. Introduction

Nanocomposites combine two or more disparate components in a single nanosystem and represent a bottom-up design strategy for achieving advanced architectures with superior properties and multiple functionalities derived from the integration of unusual materials.<sup>1–5</sup> Although many nanocomposites have been fabricated and their combined and synergistic effects have already been demonstrated in their optical, electronic, and catalytic properties,<sup>6–8</sup> there is continuing interest in preparing new hybridization materials with an increasing number of material components as well as controllable shapes, sizes, and morphologies.

There has been great interest in carbon dots (CDs) because they are quantum dots composed of a nontoxic element, and their ever-growing popularity is attributed to their fast, facile, and inexpensive synthetic routes, their scalability for mass production, and their tunable surface functionalities.<sup>9,10</sup> In addition to their low cost and environmental friendliness, CDs

are also endowed with the ability to intimately integrate with other nanomaterials. Thus, they have served as coupling components to improve the performance of many catalysts through synergic interaction, bandgap alignment, light adsorption enhancement, morphology modulation, or promotion of charge transfer.<sup>11–17</sup>

Due to the high stability and dispersibility of CDs under hydrothermal conditions, hydrothermal approaches have been utilized to prepare CD-based heterostructures. During the formation process, CDs usually act as heterogeneous nucleating agents rather than reactants. Although CDs can enable noble metal and copper salts to act as elemental metals through their electron-donor capabilities under light irradiation or hydrothermal reaction conditions,<sup>18,19</sup> it is difficult to induce the reduction of active metal ions, such as iron and cobalt ions.

By the different affinities of reactive surface groups, specific CDs have been used to design probes for sensitive and selective detection of various metal ions, such as Fe<sup>2+/3+</sup>, Mn<sup>2+</sup>, Hg<sup>2+</sup>, Pb<sup>2+</sup>, and others.<sup>20–22</sup> In consideration of this phenomenon, metal ions could be spatially confined on the surface of CDs through adsorption. Previous works have reported that CDs can efficiently prevent growth and aggregation of the nuclei formed on their surface while they are spliced into two-dimensional (2D) carbon nanosheets through surface group reactions under high temperature.<sup>23–28</sup> Unfortunately, thus far,

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## Carbon dot-boosted catalytic activity of $\text{CaO}_2$ by tuning visible light conversion<sup>†</sup>

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External auxiliary methods, including UV illumination, Fenton reagent addition and  $\text{O}_3$  aeration, are broadly used to activate self-generated  $\text{H}_2\text{O}_2$  from  $\text{CaO}_2$  for toxic chemical removal, wastewater remediation, and even cancer therapy. However, these techniques are commercially unfeasible or bring new contaminants into the environment when used. Herein, we present a novel method of tuning visible light conversion to facilitate the release and activation of  $\text{H}_2\text{O}_2$  by virtue of the integration of  $\text{CaO}_2$  with biocompatible carbon dots ( $\text{CaO}_2/\text{CDs}$ ). This totally green catalyst can be facilely synthesized in solution without heating or extra pressure, and exhibits a 2.1 times higher catalytic activity compared to single  $\text{CaO}_2$ . The incorporation of CDs not only induces more photogenerated carriers but also tunes their reactions to activate the  $\text{H}_2\text{O}_2$  generated from  $\text{CaO}_2$ , giving rise to a high yield of the superoxide radical instead of the hydroxyl radical during the catalytic process. Thus, the CDs significantly enhance the catalytic performance of the  $\text{H}_2\text{O}_2$  released from  $\text{CaO}_2$  with the help of light energy.

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## Introduction

Catalytic reactions dominate the metabolism of plants and animals and constitute approximately 85% of the production of industrial chemicals. It has always been a significant research motivation to explore environmentally friendly catalysis with high charge transfer efficiency.  $\text{CaO}_2$  is only composed of the mild calcium ion and oxygen element, which will not cause harm to the environment or to living organisms. As a versatile and completely green material, it has been extensively investigated in water treatment and environmental remediation, and has even been applied in chemodynamic therapy recently.<sup>1</sup> In addition,  $\text{CaO}_2$  itself reserves the potential active substance  $\text{H}_2\text{O}_2$ , which plays a significant role in the catalysis of organic pollutants. Alternatively,  $\text{O}_2$  could be *in situ* generated by  $\text{CaO}_2$  to overcome hypoxia-induced problems both in cellular engineering and aquaculture.<sup>2,3</sup> Moreover, despite the hydroxyl radical ( $\cdot\text{OH}$ ), with its superb oxidation ability, being generally present in the  $\text{CaO}_2/\text{Fenton}$  system, the superoxide radical ( $\cdot\text{O}_2^-$ )<sup>4</sup> and singlet oxygen ( ${}^1\text{O}$ )<sup>5,6</sup> have also been reported to be created from  $\text{CaO}_2$ -generated  $\text{H}_2\text{O}_2$ . The reactive oxygen species

(ROS) effectively react with organic compounds, such as 2,4,6-trinitrotoluene, toluene, and 2,4-dichlorophenol, through electron transfer, hydrogen abstraction, and electrophilic addition reactions.<sup>7</sup>

However, despite the above-mentioned advantages of  $\text{CaO}_2$ , there are still several practical issues that need to be resolved. Firstly,  $\text{CaO}_2$  possesses a wide bandgap, so the amount of generated ROS depends on sufficient charge carriers that are afforded by external stimuli, such as ozone or ultraviolet (UV) radiation.<sup>8</sup> However, this strategy is economically unfeasible considering the barely satisfying carrier availability as well as the costly expenditure.<sup>9</sup> Secondly, Fenton or Fenton-like systems as advanced oxidation processes (AOPs)<sup>10</sup> have conspicuous catalytic activity as a result of the transformation between metal ions ( $\text{M}^{n+}/\text{M}^{(n+1)+}$ ) and  $\text{H}_2\text{O}_2/\cdot\text{OH}$ , whereas the narrow applicable pH range (2.0–4.0) and the instabilities of  $\text{Fe}^{2+}$  and  $\text{Cu}^{2+}$  have hindered their commercial application in alkaline heterogeneous catalysis. Nowadays, developments in photocatalysis provide a promising approach for using  $\text{CaO}_2$  to build green and high-efficiency catalytic systems. Considering this, developing a proper photocatalyst with high charge carrier separation efficiency has become a central issue.

Over the past years, carbon dots (CDs) have emerged as promising metal-free photocatalysts with properties such as ease of synthesis, excellent photostability, and high biocompatibility.<sup>11–13</sup> Due to their highly efficient capture of solar energy and outstanding electron-transfer efficiency, they are particularly beneficial for applications in photocatalytic degradation, water splitting, and photodynamic therapy (PDT).<sup>14–16</sup> The strategy of integrating CDs with  $\text{CaO}_2$  could endow the

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# Assembling carbon dots on vertically aligned acetate fibers as ideal salt-rejecting evaporators for solar water purification



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## ABSTRACT

A low-cost and anti-salt-fouling system to perform solar interfacial water purification in long-term stability is considered to be a promising ways to solve freshwater scarcity crisis globally. However, the present self-regenerating solar evaporators are still confronted with challenges in terms of the relatively low evaporation rate, unsatisfactory solar-to-vapor efficiency, intricate or costly preparation steps. Herein, we present a novel and controllable system established by assembling carbon dots (CDs) on vertically aligned acetate fibers (VAAFs) with very low thermal conductivity and excellent water transport capacity. As-prepared VAAFs@CDs-T can spontaneously reject salt accumulation through rapid fluid convection within the evaporating interfaces and simultaneously sustain efficient heat localization. Thus, it not only possesses superior salt-rejection capability in long-term operation, but also enables considerably high water evaporation rate at  $2.6 \text{ kg m}^{-2} \text{ h}^{-1}$  with 93.9% solar-to-steam efficiency under one sun even treating with 20 wt% salt solution and industrial wastewater. Total materials cost of this system is merely \$15.01 m<sup>-2</sup>, outperforming most previous solar evaporators in the cost-effectiveness. Moreover, CDs can be replaced with other zero-dimensional materials and hereby achieving further enhanced evaporation efficiency is hopeful for this system.

## 1. Introduction

Solar-driven water purification from seawater or wastewater has emerged as one of the most economic, sustainable and promising solutions to meet the increasing freshwater demand [1,2]. This mainly thanks to the advent of solar interfacial water evaporation (SIWE) technique with ideal solar-to-steam conversion efficiencies [2–4]. The most prominent feature of SIWE is the position of the light-to-heat conversion agent, which is at the interfaces between liquid water and the above air [5]. Such special configuration not only localizes solar heat at the water-air interface avoiding wastefully heating underlying bulk water, but also offers remarkably larger surface area for rapid steam release [2,5–7]. Obviously, the photothermal material in SIWE system is a key component influencing final conversion efficiency since it determines sunlight capture and following photothermal conversion [2,5,8].

Comparing with semiconductor and plasmonic materials, carbon-based nanomaterials show higher potential for large-scale applications owing to their excellent sunlight harvesting, low cost, and environmental friendliness [6,8–13]. Bulk carbon black, active carbon and

graphite are able to absorb broad-band light absorption visible light due to the  $\pi$ -band's optical transitions [6,14,15], but their absorption properties are limited by a moderate reflection of 5–10% at air-dielectric interface. Although this limitation can be overcome through large amount of microcavities formed by assembling carbon nanostructures like graphene, carbon nanotube, these crystalline carbons with their high inherent thermal conductivity enabling fast heat dissipation in the whole material are actually unfavorable for heat localization [6,8,16–18]. Accordingly, these black materials showed relatively low water evaporation rate as well as photothermal conversion efficiency. By contrast, carbon dots (CDs) are quasi-spherical carbon nanoparticles consisting of carbon cores that can be surrounded by shells containing numerous hydrophilic functional groups such as carboxylic acids, epoxies, alcohols, carbonyls and amines [19–22], thus own an ideal geometry in terms of heat preservation [8,23]. The nature of these groups arises from the precursors and the preparing conditions employed in the CD synthesis [20–22]. In particular, these functional groups control the interaction of the CDs with the surrounding environment in terms of solvation, reactivity, binding and others [19,20,22]. For instance, surface hydrophilic groups of the CDs can form various hydrogen bonds

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# A Gelation-Stabilized Strategy toward Photothermal Architecture Design for Highly Efficient Solar Water Evaporation

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**Constructing a solar-driven interfacial evaporation system with effective energy confinement and conversion abilities is highly desired for seawater desalination and wastewater purification without the need of a complex and costly infrastructure. Herein, a powerful universal approach for the bottom-up design of the photothermal conversion system using 0D nanoparticles is reported. That is, the integration of nanoparticles with cotton fibers (CFs) is first formed by surface adsorption and then reinforced by in situ cross-linked polyvinyl alcohol chains. The developed photothermal architecture exhibits a superior water evaporation performance, excellent durability, and high adaptability in various environments. By this approach, the resulting system of carbon dots assembled on the surface of CFs is able to evaporate water with a rate of  $2.32 \text{ kg m}^{-2} \text{ h}^{-1}$  and a solar-to-vapor efficiency of 93.6% under 1 sun irradiation, remarkably superior to the evaporators made by other black photothermal sheets. Thereby, the presented method enables potentially low-cost, abundant, and tunable 0D nanomaterials for rationally designing ideal solar conversion structures.**

## 1. Introduction

As an efficient solution to resolve freshwater shortage crises, the solar-driven interfacial water evaporation (SIWE), technique has recently gained tremendous attention due to its high solar-to-steam conversion efficiency and transformative industrial potential in seawater desalination, water purification, and regeneration.<sup>[1–6]</sup> Recently, a variety of photothermal structures and systems with antifouling and/or generator functions were developed for addressing the challenges of the water–energy nexus based on the SIWE technique.<sup>[4,7–11]</sup> A prominent feature of the SIWE technique lies in the position of the photothermal

materials, which is at the interfaces between liquid water and the above air.<sup>[3,6]</sup> Such special configuration not only localizes solar-converted heat at the water–air interface, avoiding wastefully heating underlying bulk water, but also offers remarkably larger surface area for rapid steam release.<sup>[3,6,12,13]</sup> Clearly, the photothermal material in the SIWE system is the first critical component affecting final conversion efficiency as it determines solar radiation harvesting and following light-to-heat conversion.<sup>[1,3,4]</sup> A variety of solar-absorbing materials are developed and explored currently, such as low-dimensional carbon nanomaterials, hydrogel-based composites, covalent organic frameworks, organic/inorganic composite complex and plasmonic particles.<sup>[1,3,4,14–18]</sup> In comparison, it can be found that the materials with nearly 100% absorption of the full-spectrum solar radia-

tion did not achieve the same evaporation rate (ER) and some even exhibited a lower ER than those with the inferior absorbance.<sup>[15,19–24]</sup> This has been attributed to the differences of heat losses, particularly induced by conduction loss to the photothermal material itself. For instance, the high thermal conductivity of the materials can make solar-converted heat diffuse quickly, thus limiting heat-to-vapor conversion.<sup>[1,12,21,25,26]</sup> Another factor may be ascribed to invalid solar-to-heat conversion of the photothermal materials, i.e., a part of photoinduced heat hardly enables water to become vapor.<sup>[21,27]</sup> Therefore, an increasing trend toward the design of high-efficiency solar photothermal materials for improving ER has attracted a huge amount of attention.

A hydrogel-based solar evaporator that solar absorbers were grafted with in the polymeric gel network was newly demonstrated to have higher ERs.<sup>[5,15,28]</sup> Unfortunately, only a very few organic matter-based photothermal materials, i.e., polypyrrole and metal–organic frameworks, were successfully hybridized with gel network without changing the mechanical and evaporation properties of hydrogels.<sup>[15,28]</sup> In addition, the hybrid hydrogel fabrication usually undergoes repeatedly freezing–thawing processes, incurring the consumption of a large amount of liquid nitrogen. Accordingly, a facile and low-cost approach without the need for stringent, tedious, or intricate preparation steps is still needed for future large-scale production and practical application of photothermal materials. 0D nanoparticles possess low thermal conductivity, large specific surface, diverse

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## Boosting chemoselective reduction of 4-nitrostyrene via photoinduced energetic electrons from *in situ* formed Cu nanoparticles on carbon dots<sup>†</sup>

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**Chemoselective hydrogenation of structurally diverse nitroarenes is a challenging process that often requires precious metal catalysts and proceeds in an organic solvent. Herein, a convenient and stable hybrid nanocatalyst combining carbon dots and copper nanoparticles is developed as an ideal alternative for this transformation. The as-prepared nanocatalyst achieves over 99% selectivity for the formation of 4-aminostyrene at 100% conversion of 4-nitrostyrene in an aqueous solvent under visible light irradiation. Compared with other reported catalysts, our presented catalyst shows more superior hydrogenation selectivity and stability as well as lower material cost. This high efficiency could be originated from the nanocatalyst's ability to synergistically control surface hydrogen species released from ammonia borane and energetic "hot" electrons induced by visible light irradiation for the selective reduction reaction. Compared with other reported catalysts, our presented nanocatalyst is better for the realization of energy-saving chemical processes by introducing solar energy.**

Enhancing the selectivity and activity of catalysts is of paramount importance for the realization of energy-saving chemical processes.<sup>1,2</sup> For instance, the manufacture of functionalized anilines, which are pivotal intermediates for the pharmaceutical, polymer, agrochemical, and fine chemical industries,<sup>1,3,4</sup> highly depends on noble metal catalysts that can selectively reduce aryl nitro groups without affecting other easily reducible functionalities.<sup>3,5,6</sup> However, these precious metals possess the disadvantages of high cost and limited availability. Therefore, using more Earth-abundant alternatives to catalyze the same reaction is attracting much interest.<sup>1,7</sup> Non-noble metal Cu nanostructures are not only cheap but

can also capture visible light *via* the localized surface plasmon resonance (LSPR) effect.<sup>8,9</sup> Unfortunately, nanometer Cu usually suffers from poor chemical stability during catalytic processes. In this context, various substrate-supported Cu nanoparticles (CuNPs),<sup>8,10–12</sup> such as graphene-supported CuNPs,<sup>8</sup> WO<sub>2.72</sub>-supported CuNPs,<sup>10</sup> and Sm<sub>2</sub>Co<sub>17</sub>-supported CuNPs,<sup>11</sup> have been developed to inhibit their oxidation in the presence of molecular oxygen, and they have been applied for chemoselective hydrogenation of aryl nitro to amine groups.<sup>8,10,11</sup> Nevertheless, these developed catalysts only work in organic solvents, exerting huge pressure on the environment and cost of manufacturing.<sup>13</sup> In contrast, water is of low cost and has relative abundance and ecological advantages. As a solvent with many unique properties such as a large temperature window in which it keeps in the liquid state, high heat capacity, and extensive hydrogen bonding, water may be also endowed with inherent functions to enhance the rates and affect the selectivity of organic reactions. Besides, the supports also possess some unique nanomaterial properties, providing a synergistic platform for catalytic reaction.<sup>10,11</sup> Thus, exerting external stimuli to improve both selectivity and activity of the as-prepared heterogeneous catalysts simultaneously is highly desirable.

Ammonia borane (AB) and borohydrides are regarded as safe, mild and inexpensive reagents for applications in reduction processes of modern organic chemistry.<sup>14,15</sup> Hydrogen species are released from AB or borohydrides to the surface of catalysts and then are utilized to reduce nitro-aromatics to aromatic amines for the realization of hydrogenation reaction under ambient conditions.<sup>16</sup> When another reducible functional group, *e.g.* vinyl group, is present in the structure of nitro-aromatics, this hydrogenation process becomes complex since there is competition between two reduction reactions,<sup>10</sup> thereby often giving rise to poor selectivity.

Carbon dots (CDs) are composed of carbon cores that are surrounded by shells containing surface functional groups and they have been found to possess excellent optical and luminescence properties, photo-induced electron transfer, and elec-

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We present an efficient method toward rational design and fabrication of multicomponent photocatalysts using carbon dots (CDs) for solar-driven chemical reactions with super selectivity and activity. CDs act not only as a reductant to enable metallic Cu formation but also as a hole trapping agent to hinder side reactions. By simple pyrolysis of the mixture of the Cu source, CDs and NaH<sub>2</sub>PO<sub>4</sub>, the Cu<sub>3</sub>P–CDs–Cu nanocomposite is produced and shows a good sunlight harvesting property. Under one sun irradiation, Cu<sub>3</sub>P–CDs–Cu can catalyze ammonia borane (AB) for selective hydrogenation of 4-nitrostyrene (4-NS) to 4-aminostyrene (4-AS) in an aqueous solvent at room temperature, achieving 100% selectivity and beyond 99% conversion rate within a few short minutes of reaction time. The superior performance of Cu<sub>3</sub>P–CDs–Cu is attributed to the formation of the all-solid-state Z-scheme photocatalytic system, eliminating the high-energy holes—active species attacking C=C groups in 4-NS—from Cu<sub>3</sub>P. Meanwhile, metallic Cu promotes the migration and transport of excited electrons from the interior to the surface and interface, accelerating the activation of AB for selective reduction of 4-NS to 4-AS.

## Introduction

For the sustainable development of human society, sunlight-driven chemical reactions have emerged as an economical and green approach for solar energy storage and utilization to address global challenges of energy shortage and environmental pollution.<sup>1–4</sup> Hereinto, the photocatalyst is responsible for light harvesting and conversion to produce excited electrons

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## Solar-accelerated chemoselective hydrogenation of 4-nitrostyrene to 4-vinylaniline with carbon dot-induced Cu over Cu<sub>3</sub>P in the absence of any sacrificial reagent<sup>†</sup>

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and holes, which can initiate or accelerate specific reduction and oxidation reactions.<sup>3,5–8</sup> Nevertheless, the photo-generated electrons and holes from photocatalysts can be not only dissipated by their combination, but can also be involved in unwanted reactions lowering solar-energy conversion efficiency.<sup>9–11</sup> Although adding sacrificial reagents to preferentially clear unwanted carriers or their derivatives can efficiently hinder side reactions,<sup>12,13</sup> this technique is commonly limited by the difficulty of purification and separation of the final product as well as high cost. Apart from efficient light harvesting, fast charge separation and transfer,<sup>7,14–16</sup> rational design of photocatalysts with highly selective catalytic performance is hence highly desirable for fine chemical synthesis.

Aromatic amines as important intermediates for the fine chemical, pharmaceutical, polymer and agrochemical industries are generally produced by the reduction of nitro compounds.<sup>17–20</sup> Catalytic reduction of simple nitro compounds is readily conducted with various commercial catalysts, but the selective hydrogenation of a nitro group with H<sub>2</sub> or other reducing agents in the presence of other easily reducible groups, e.g. olefinic groups, is more difficult.<sup>18,21–24</sup> The earliest success in selective hydrogenation of functional aryl nitro was principally due to the use of noble metal–Au, Pt, Ru and Pd-based catalysts.<sup>10,11,25</sup> However, the limited availability and exorbitant price of these noble metals have motivated us to develop more earth-abundant alternatives including oxide-supported Cu, Ni and Fe.<sup>2,22,26,27</sup> Although these catalysts are effective, they often suffer from stringent and intricate fabrication processes, work in organic solvents or under drastic conditions (high temperature, high H<sub>2</sub> pressure), and require hours of reaction time.<sup>2,13,28,29</sup>

Carbon dots (CDs) comprise discrete carbon-based nanoparticles with size less than 10 nm, possess unique properties of photo-induced electron transfer, carrier reservoirs and photoluminescence.<sup>30,31</sup> In particular, CDs can adsorb metal ions through surface groups and subsequently serve as a reductant to reduce them to the corresponding metal on the particle surface.<sup>32,33</sup> By this means, we have successfully fabricated



## Research Paper

## Origin of sonocatalytic activity of fluorescent carbon dots

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## ABSTRACT

Although ultrasound-induced reactive oxygen species (ROS) have been believed to be primary intermediates for the realization of sonodynamic therapy and sonocatalytic reactions, the mechanism of ROS production under ultrasound has not been well clarified till now. Here we discovered that ultrasound cavitation can break up oxygen-containing groups on the surface of carbon dots (CDs) to generate ROS, giving rise to a novel mechanism different from as-reported those. The bond cleavage of oxygen-containing groups contribute transient oxygen free radicals ( $\bullet\text{O}^-$ ) that involve in the subsequent formation of ROS by quickly reacting with hydrogen ions and water, thereby leading to a twice higher sonocatalytic activity of CDs than  $\text{TiO}_2$ . Moreover, the sonosensitizer function of CDs can be tuned by pH values of the surrounding environment that determine the generation and evolution reaction of oxygen free radicals under ultrasound irradiation. This finding paves a new way to design multifunctional sonosensitizers and utilize them in various fields.

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## 1. Introduction

Ultrasound (US) is a kind of periodic mechanical sound wave with a frequency beyond the limit of human hearing (>20 kHz) [1]. Due to its easy operation, deep penetration depth and high security, US has been widely utilized to sonodynamic therapy (SDT) and the removal of industrial organic pollutants by activating sonosensitizers to generate reactive oxygen species (ROS) [2,3]. At present, two representative and plausible mechanisms i.e. sonoluminescence and pyrolysis, are always used to describe the ROS generation under US (Scheme 1) [4–6]. Specifically, the gas bubbles induced cavitation effect around the surface of sonosensitizers can break up to generate sonoluminescence under US irradiation. By its excitation, the sonosensitizer could induce electron–hole pairs with subsequent generation of ROS in the solution like photocatalysis [4,7–9]. During the collapse of gas bubbles induced by cavitation effect, the resulted high local temperature could cause water pyrolysis to generate  $\bullet\text{OH}$  radicals serving as the second mechanism [10,11]. However, the above two mechanisms remain elusive for understanding the formation processes of radical species.

Under US irradiation, the nanoparticles e.g.  $\text{TiO}_2$ ,  $\text{ZnO}$  as sonosensitizers offer more nucleation sites for the formation of cavitation bubbles through reducing the cavitation threshold. After undergoing expansion, compression and impulsive collapse, the resultant cavitation bubbles by nanoparticles convert into the energy finally and then transfer heat (up to 10 000 K) and pressure (81 MPa) to the surrounding microenvironment [2]. Since the nanoparticles lie in the center of cavitation bubbles, their surface as well as the surface adsorbate will be subjected to the impact of extreme heat and pressure induced by cavitation effect. This phenomenon may result in breaking and making chemical bonds on the surface of nanoparticles, triggering the formation of radical species upon bubble collapse. Carbon dots (CDs) are quasi-spherical fluorescent nanoparticles with dimensions smaller than 10 nm and consist of graphitized  $\text{sp}^2$  carbon cores that are surrounded by the outer shells containing rich groups such as  $-\text{COOH}$ ,  $-\text{OH}$ ,  $\text{C}-\text{O}-\text{C}$  and  $-\text{NH}_2$  [12,13]. If the CDs serve as sonosensitizers, the outer shell of them is first confronted with the shock of cavitation bubbles under US irradiation. Thus US-generated extreme conditions could break apart the groups on the surface of CDs, giving rise to transient active species capable of ROS production by quickly reacting with surrounding environment. CDs have found numerous applications in photocatalysis, sensors, drug delivery, bioimaging, optoelectronic devices and nanocomposites due to their unique properties and excellent biocompatibility [14–17]. Particularly, the CDs including of graphene quantum dots (GQD) has been

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# Boosting adsorption of heavy metal ions in wastewater through solar-driven interfacial evaporation of chemically-treated carbonized wood



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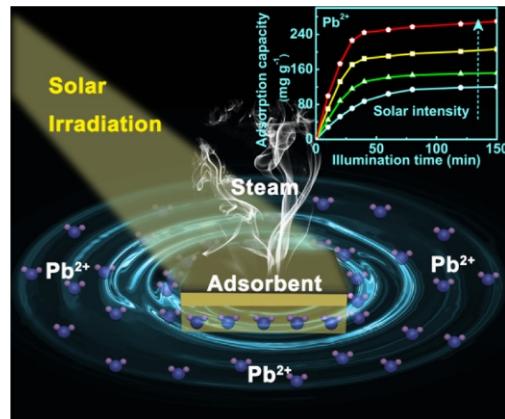
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## HIGHLIGHTS

- Solar-drive water evaporation is used for improving heavy metal ion adsorption capacity.
- Carbonized wood is used as all-in-one solar absorption and metal ion adsorption system.
- The adsorption capacity of  $\text{Pb}^{2+}$  is enhanced by over 225% under solar irradiation of  $3 \text{ kW}\cdot\text{m}^{-2}$ .

## GRAPHICAL ABSTRACT



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## ABSTRACT

Once the adsorbent is selected, almost introducing larger specific surface area and more surface functional groups becomes the only way to improve its adsorption performance. However, this approach is generally limited in practical application for intricate and costly engineering steps. Herein, we provided a novel avenue for boosting adsorption activities towards specific metal ions in wastewater. Solar-driven interfacial water evaporation produces the localized temperature field and concentration gradient of metal ions inside small pores, endowing with a new sorption mechanism. By using chemically-treated carbonized wood as all-in-one solar absorption and metal ion adsorption system, we achieved higher water evaporation rate and heavy metal ion removal efficiency than carbonization-only wood reported previously. In particular, this system exhibited a strong dependence of specific metal ion adsorption capacity on solar intensity.  $\text{Pb}^{2+}$  adsorption capacity was enhanced by over 225% with the solar intensity increased to  $3.0 \text{ kW}\cdot\text{m}^{-2}$ . This could originate from the formed temperature field localized specially on the surface of adsorbents that not only induces  $\text{Pb}^{2+}$  concentration gradient near to solid-liquid interface but also activate inactive adsorption sites. Besides, the chemical-treated & carbonized wood showed excellent cyclic stability and can be directly utilized for wastewater treatment, recovery and reuse.

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# All-in-One Solar Interfacial Evaporation System with Highly Effective Heat Management and Water Collection

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**Although solar-driven interfacial water evaporation (SDIWE) exhibits a rapid evaporation rate upon exposure to the open air and solar-to-steam conversion efficiency close to 100%, the efficient freshwater collection from a compactly closed SDIWE system remains a big challenge due to the suppressed steam generation on high local humidity near the water evaporation front. Herein, a low-cost and auto-floating SDIWE system is capable of transferring the latent heat of condensation (LHC) to the water localized in the photothermal layer without any auxiliary facilities. It allows the limited liquid water to absorb the energy of LHC yet rejects the downward heat conduction from the photothermal layer. As such, the water in the photothermal layer can be preheated significantly, not only reducing humidity but also promoting vapor generation. Compared with the commonly single-slope evaporator, the clean water productivity of the presented system enhanced by 130% under one sun irradiance. Benefiting from its long-term stability and superior salt-rejection function, the presented system shows great potential for sustainable and practical application in freshwater production using natural seawater.**

on high local humidity near the water evaporation front.<sup>[8]</sup> Although the collection installations much larger than the evaporation area and with auxiliary facilities (e.g., airflow assistances, extra condensers) are able to reduce local humidity for a closed system, high capital, and operating costs will be involved, restricting their industrial applications considerably.<sup>[9–12]</sup>

Many parameters such as shape of the condensation cover, inclination angle, surface roughness and its wettability, potentially influence the condensation of vapor generated in a commonly single-slope evaporator.<sup>[13–15]</sup> Consequently, numerous efforts including of wettability alteration of the condensation surface and surface renewal using a vibration technique have been made to enhance condensate production.<sup>[13,16]</sup> Nevertheless, the energy efficiency and water collecting rate achieved are still unsatisfactory so far. As we all know, the majority of the accumulated energy

inside a solar evaporator is released in the form of latent heat during the condensation process.<sup>[17,18]</sup> But, few attempt to utilize latent heat of condensation (LHC) to improve water collecting efficiency. In a typical SDIWE system, photothermal conversion is localized at the surface of solar absorber and enables fast heat transfer to water surrounding absorber. If the LHC and its induced temperature polarization across the photothermal layer can preheat the water surrounding absorber, the vapor generation, and condensation rate could be effectively improved to accelerate liquid water production. This proposition is essentially relevant to the vapor and energy management. Thus, to design a novel SDIWE system that can harvest the LHC for fast water collection is extremely attractive.

In this contribution, we design, build and test a low-cost and stable SDIWE system capable of transferring the LHC to the water localized in the photothermal layer. This system allows the limited liquid water to absorb the energy of LHC yet rejects the downward heat conduction from the photothermal layer. As such, the water of evaporation front can be preheated significantly, not only reducing humidity but also accelerating vapor generation. Comparing to the commonly single-slope evaporator, the clean water productivity of our presented system enhanced by 130% under one sun light intensity. Moreover, benefitting from its long-term stability, low raw material cost and ideal salt-rejection function, it presented the great potential for sustainable and practical application in freshwater production using natural seawater and polluted water.

## 1. Introduction

Facing freshwater scarcity and ever-increasing demand for it in industry, agriculture, energy, and municipal sectors, necessitates the rapid advancement of technologies that can have access to clean water from brine or polluted water.<sup>[1–3]</sup> Solar-driven interfacial water evaporation (SDIWE) is a promising technology for applications in desalination and sewage purification, as it exhibits solar-to-steam conversion efficiency close to 100% and transformative industrial potential.<sup>[4–6]</sup> By rational photothermal structure architecting, the SDIWE system can achieve a very rapid evaporation rate upon exposure to the open air.<sup>[7]</sup> However, the effective freshwater collection from a compactly closed SDIWE system remains a big challenge due to the suppressed steam generation

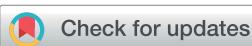
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The performance of photocatalysts highly relies on the carrier quantity transferred from the bulk to the surface during the catalytic process. However, the polarization electric field induced by charge accumulation at the surface easily causes recombination, and thus leads to the decrease of the charge quantity involved in the chemical reaction. Here we presented a carbon dot-based composite ( $\text{CDs}@\text{CuO}_x$ ) and discovered that it can eliminate the charge accumulation by means of chemical reaction triggered by the self-supplying peroxide. Moreover, the *in situ* generated  $\text{O}_2$  and the enlarged band gap induced by carbon dots synergistically reduced the reaction barrier from  $\text{O}_2$  to a superoxide radical ( $\text{'O}_2^-$ ), and thus helped to form the rapid chemical reaction loop of  $\text{'O}_2^-$ ,  $\text{H}_2\text{O}_2$  and  $\text{O}_2$ . This rapid chemical conversion promptly consumed photoinduced electrons and holes to eliminate the surface polarization and remarkably boosted the photocatalytic activity of  $\text{CDs}@\text{CuO}_x$  by attaining a 35 times higher maximum reaction rate than  $\text{CuO}_x$ .

Photocatalysis is an economical and practical strategy for chemical production and pollutant removal since it takes advantage of solar energy and promotes the chemical reaction significantly without producing new wastes and other resources consumption.<sup>1</sup> It has been widely applied in the organic synthesis, water splitting, environmental remediation, and  $\text{CO}_2$  reduction.<sup>2–4</sup> The mechanism mainly ensures that the catalysts generate electron ( $e^-$ ) and hole ( $h^+$ ) carriers under the irradiation to directly participate in the chemical reactions or form chemical active radicals like hydroxyl radical ( $\text{'OH}$ ), superoxide radical ( $\text{'O}_2^-$ ), persulfate radical ( $\text{'SO}_4^-$ ) to facilitate the

## Triggering photocatalytic activity of carbon dot-based nanocomposites by a self-supplying peroxide†

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chemical process and transform solar energy to chemical energy.<sup>5,6</sup> Therefore, the absorption spectral range, the separation efficiency of light-induced charges and their transfer velocity are all restraining factors for photocatalysis.

Accordingly, various photocatalysts have been reported to promote the energy conversion efficiency,<sup>7</sup> and the primary approaches<sup>8–10</sup> are no more than light absorption improvement, band gap regulation and charge carriers separation adjustment. However, without rapid transfer, the charge accumulation on the surface can gradually induce the formation of an electric field. It has the same polarity with the newly generated electric charges that can severely prevent the continuous energy conversion. Therefore, the charge carrier accumulation on the surface is a major challenge for sustained promotion of photocatalytic activity.

The accelerated active radical formation ability of  $\text{H}_2\text{O}_2$  caught our attention since it is frequently used in Fenton and Fenton-like catalysis and  $\text{H}_2\text{O}_2$  can instantly turn into  $\text{'OH}$  to oxidize the substrates in the presence of  $\text{Fe}^{2+}/\text{Fe}^{3+}$ ,  $\text{Cu}^{+}/\text{Cu}^{2+}$  or their compound.<sup>11,12</sup> However, consumption goes along with the reaction and additional  $\text{H}_2\text{O}_2$  should be intermittently put into the system. Therefore, collaborating the property of self-supplied peroxide with other materials provides a novel perspective for photocatalysts design. Moreover, the photo-response effect is the principal factor for the photocatalysts, hence, carbon dots (CDs) are employed considering their extraordinary photo-carrier generation and separation ability,<sup>13,14</sup> wide wavelength response range,<sup>15</sup> and easy integration with other composite.<sup>16,17</sup> Herein, we presented a facile strategy to prepare carbon dots (CDs)-based nanocomposite ( $\text{CDs}@\text{CuO}_x$ ) to address the issue of carrier accumulation in the photocatalyst.

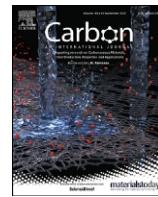
It is exciting to discover that the small amount of copper superoxide in  $\text{CDs}@\text{CuO}_x$  can trigger the reaction and increase the reaction velocity by nearly 35 times compared with  $\text{CuO}_x$ -alone. It generates self-supplying peroxide or directly combines with the photo-induced holes to produce  $\text{'O}_2^-$  to participate in the oxidation reaction in the acid or alkaline condition,

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† Electronic supplementary information (ESI) available: Chemicals and materials, instrumentation and characterization, electrochemical analysis, and other supporting figures. See DOI: 10.1039/d1ta01097b



# Boosting photocatalytic activity through *in-situ* phase transformation of bismuth-based compounds on carbon dots and quantification analysis of intrinsically reactive species in photocatalysis

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## abstract

As a photocatalyst, both BiO<sub>2</sub>COOH and (BiO)<sub>2</sub>CO<sub>3</sub> are only active under UV light irradiation. In this contribution, a room-temperature approach is firstly demonstrated to develop *in situ* incorporation of green carbon dots (CDs) into BiO<sub>2</sub>COOH (CDs@BiO<sub>2</sub>COOH) by taking advantage of the residual HCOOH for preparing CDs. As-prepared CDs@BiO<sub>2</sub>COOH is endowed with broad visible light absorption. By the reaction with NaBH<sub>4</sub>, BiO<sub>2</sub>COOH is subsequently transformed into (BiO)<sub>2</sub>CO<sub>3</sub> at room temperature, forming a new heterostructure of CDs@BiO<sub>2</sub>CO<sub>3</sub>. Not only does this heterostructure display exceptionally stronger visible light harvesting capability than CDs@BiO<sub>2</sub>COOH due to the introduction of more structural defects in the process of phase transformation, but it also possesses more superior degradation ability for the organic pollutants under visible light. Its photocatalytic activity is raised to over 7 times comparing to BiO<sub>2</sub>COOH. Accordingly, a facile and room-temperature synthesis strategy is presented for large-scale production of CDs@BiO<sub>2</sub>CO<sub>3</sub> with highly efficient use of sunlight. To understand photocatalytic mechanism, we offer a unique technique for the quantification and the kinetics evaluation of the intrinsic reactive species produced in photocatalysis as well.

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## 1. Introduction

Research on photoredox and photocatalysis has been inspired in part by the realization that sunlight is effectively an inexhaustible energy source [1–3]. Nevertheless, the utilization of visible light in photocatalysis is fundamentally challenging because single-component photocatalysts tend not to have wide light-absorption range and strong redox ability [3–5]. Recent study has begun to design proper heterogeneous photocatalytic systems to overcome aforementioned problems [5–11]. These systems could be simultaneously endowed with broad visible light-absorption range and the high charge-separation efficiency [6,8–10]. While useful, there is a striking short of strategy to enhance the intrinsic activity of photocatalysts, which mainly originates from the chemical composition

and structure of the catalyst material instead of its geometrical structuring and heterogeneous interface [5,12]. Since the intrinsic activity of a photocatalyst determines the reactivity and reaction kinetics in catalysis, more active sites are needed to be created in catalyst material for improving the photocatalytic performance.

The Sillén phase compounds usually possess layered structures, with alternating (BiO)<sub>2</sub><sup>2+</sup> sheets and X layers (X = halogen, COOH, CO<sub>3</sub><sup>2-</sup>, or other ion group) [13–18]. Currently, some advances have been made in the controlled preparation of the sillén structure BiOX with different morphologies and their uses for the photo-degradation of organic pollutants [7,13–17]. Among these bismuth-based semiconductors, some compounds such as BiO<sub>2</sub>COOH and (BiO)<sub>2</sub>CO<sub>3</sub>, are only responsive under UV light [14–17,19,20], limiting their utilization in the conversion of solar energy. To exploit them working under visible light, it has been developed to modify their wide band gaps by the doping and hybrid technology [16,17,19–21]. Both BiO<sub>2</sub>COOH and (BiO)<sub>2</sub>CO<sub>3</sub> belong to Sillén phase compounds, but have different anion groups in alternative stacking of (BiO)<sub>2</sub><sup>2+</sup> layers. The *in situ* transformation of BiO<sub>2</sub>COOH to (BiO)<sub>2</sub>CO<sub>3</sub> could produce

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<sup>1</sup> These authors contributed equally to this work.



## Cerium-mediated photooxidation for tuning pH-dependent oxidase-like activity



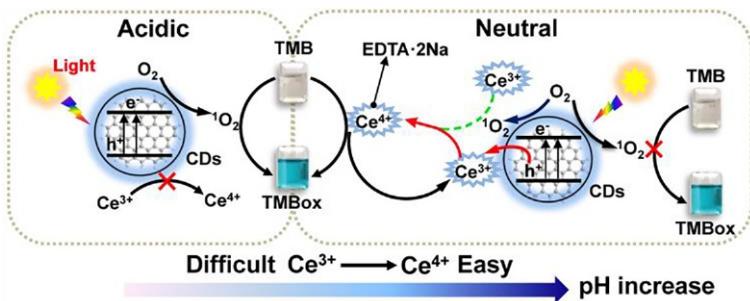
Shijia Li, Ernan Pang, Chao Gao, Qing Chang, Shengliang Hu\*, Ning Li\*

North University of China, School of Energy and Power Engineering & School of Material Science and Engineering, Taiyuan 030051, PR China

### HIGHLIGHTS

- A new light-controlled nanozyme with tunable oxidase-like activities is presented.
- Its activity can be regulated by the concentration ratio of carbon dots and Ce<sup>3+</sup> ions.
- It can perform optimally at neutral pH values for catalytic oxidation of TMB.
- Ce<sup>3+</sup> ions act as catalytic mediators to break pH-dependent activity of carbon dots.

### GRAPHICAL ABSTRACT



### ARTICLE INFO

**Keywords:**  
Carbon dots  
Nanozyme  
Photooxidation  
Catalytic oxidation

### ABSTRACT

Industrial and medical applications of most nanozymes are often limited by their pH-dependent activities as well as by weak response to external stimuli. Here we report a light-controlled nanozyme possessing tunable oxidase-like activities without incurring the burden of pH effects. This nanozyme comprises carbon dots (CDs) and Ce<sup>3+</sup> ions and its activities can be regulated with rational design of their concentration ratio. Unlike previously reported nanozymes, yet it can perform optimally at neutral pH values for catalytic oxidation of 3,3',5,5'-tetramethylbenzidine (TMB). We find that its unique attribute originates from pH-dependent ability of CDs to reversibly switch from Ce<sup>3+</sup> to Ce<sup>4+</sup> under visible light irradiation. Therefore, our presented nanozyme can be applied in real environment and be simultaneously remotely-controlled by visible light.

### 1. Introduction

Functional nanomaterials with enzyme-mimicking activities, defined as nanozymes, are currently attracting considerable interest owing to their unique advantages over natural enzymes, e.g. low cost, durability, robustness to harsh environments, ease of mass production and storage [1,2]. Since the high activity is one of the prerequisites for their applications [3–5], many related strategies have been developed including size and morphology regulation, composition design as well as metal ion modifications [6–10]. Nevertheless, most peroxidase- and

oxidase-like nanozymes show obviously pH-dependent activities for chromogenic substrates, e.g. 3,3',5,5'-tetramethylbenzidine (TMB), which is widely employed as a typical horseradish peroxidase substrate in various bioassays [11,12]. In general, the ability of nanozymes to oxidize TMB decreases dramatically as the pH value increases from 4.0 to 7.0 [9,12–14]. At pH 7.0, many nanozymes even lose their activities completely to its oxidation. For instance, Fe<sub>3</sub>O<sub>4</sub> nanoparticles exhibited maximum peroxidase-like activity at pH 3.5 but full deactivation at pH 7.0 for TMB [11]. Similarly, Nitrogen-doped porous carbon nanospheres with multienzyme mimetic activity also displayed the pH-

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# A Cu<sub>2</sub>O-CDs-Cu three component catalyst for boosting oxidase-like activity with hot electrons

Fu Li<sup>a,1</sup>, Ning Li<sup>a,1</sup>, Chaorui Xue<sup>a</sup>, Huiqi Wang<sup>a</sup>, Qing Chang<sup>a,\*</sup>, Hantao Liu<sup>a</sup>, Jinlong Yang<sup>a,b</sup>, Shengliang Hu<sup>a,\*</sup>

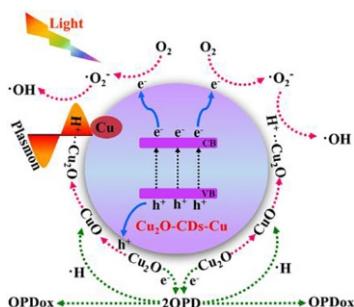
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<sup>b</sup> State Key Laboratory of New Ceramics and Fine Processing, Tsinghua University, Beijing 100084, PR China

## HIGHLIGHTS

- A Cu<sub>2</sub>O-CDs-Cu three component catalyst with enzyme-like activity is developed.
- The obtained catalyst possesses remarkably high catalytic oxidation reaction rate.
- Chemically useful energetic electrons induced with illumination promote catalytic oxidation activity.
- The mechanism of catalytic conversion of o-phenylenediamine to phenazine-2,3-diamine is disclosed.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

### Keywords:

Hot carrier  
Heterogeneous catalysis  
Cuprous oxide  
Carbon dots  
Plasmonic nanostructure  
O-phenylenediamine oxidation

## ABSTRACT

More challenges are faced for the design of an ideal multi-component photocatalyst because it is required to attain synergies of each component function. In order to boost light-driven chemical conversions, here we provide a Cu<sub>2</sub>O-CDs (carbon dots)-Cu three component oxidase-like catalyst that can effectively yield chemically useful energetic electrons under visible light irradiation. This catalyst shows light-boosting oxidase-like activity for catalytic oxidation of o-phenylenediamine (OPD) and remarkably high reaction rate. By Michaelis-Menten model fitting, the obtained maximum reaction rate reaches to 9.47 μM min<sup>-1</sup>, which is much larger than other analogous nanozymes reported previously. Moreover, we carefully demonstrated the roles of each component played in light-boosting oxidase-like catalytic reaction and offered an insight into the mechanism of OPD oxidation in the presence of Cu<sub>2</sub>O-CDs-Cu. This work could open a promising route to ideal catalysts that can effectively couple thermal and photonic stimuli to drive oxidase-like activity.

## 1. Introduction

Plasmonics as energy input is a sustainable approach to boost light-driven chemical conversions [1]. To control over light and photochemistry, however, plasmonics requires the help of metallic

nanostructures capable of concentrating light into nanoscale volumes [1–4]. This can lead to the production of intense electric fields, highly energetic (“hot”) electrons and holes. The hot electrons relax by locally heating the nanostructures [3,5,6]. All these phenomena can be utilized to efficiently manipulate, enhance, and drive chemical transformations

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# Carbon dots-stabilized Cu<sub>4</sub>O<sub>3</sub> for a multi-responsive nanozyme with exceptionally high activity

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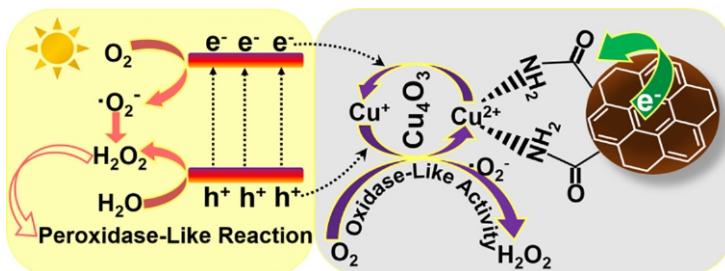
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## HIGHLIGHTS

- A CDs-stabilized Cu<sub>4</sub>O<sub>3</sub> nanozyme is firstly prepared by the hydrothermal method.
- The obtained nanozyme exhibits high stability and multi-enzyme-mimetic activity.
- The nanozyme activity can be boosted by multiple kinds of external stimuli.
- The CDs play a key role in sustaining Cu<sup>2+</sup>/Cu<sup>+</sup> redox couples.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

### Keywords:

Nanozyme  
Carbon dots  
Paramelaconite  
Catalysis  
Heterostructure

## ABSTRACT

A novel nanocomposite of carbon dots-stabilized paramelaconite (CDs@Cu<sub>4</sub>O<sub>3</sub>) is firstly reported and investigated as a stimuli-responsive nanozyme. The CDs@Cu<sub>4</sub>O<sub>3</sub> is a more robust catalyst without incurring the burden of easy denaturation or decomposition and behaves as oxidase and peroxidase mimetics. The activity of CDs@Cu<sub>4</sub>O<sub>3</sub> is up to 3.6 times higher than that of pure cuprous oxide nanoparticles and can be boosted by multiple kinds of external stimuli including of light irradiation, temperature, pH and oxidizing agent. We find that carbon dots play the key roles in facilitating the generation of Cu<sub>4</sub>O<sub>3</sub> and sustaining Cu<sup>2+</sup>/Cu<sup>+</sup> redox couples that are required for the catalytic reaction to proceed quickly. This nanocomposite endowed with ease of preparation, versatility and high stability is expected to be wide uses for biotechnology, environmental treatment, and organic synthesis.

## 1. Introduction

Copper oxides are fascinating materials because of their low-price, unique optical properties and electronic configurations as well as exciting prospects for numerous applications [1]. As a member of copper oxides, paramelaconite (Cu<sub>4</sub>O<sub>3</sub>) is a metastable intermediate compound between the cupric and cuprous oxide phases and has mixed valency, containing an equal number of Cu<sup>+</sup> and Cu<sup>2+</sup> ions in its tetragonal

crystal structure (*I4<sub>1</sub>/amd*) [2–7]. Unlike Cu<sub>2</sub>O and CuO, Cu<sub>4</sub>O<sub>3</sub> is less known owing to its scarcity and the complexities of its fabrication [5]. The major reason is the difficulty to simultaneously stabilize Cu<sup>+</sup> and Cu<sup>2+</sup> species via conventional aqueous chemistry [3,5–7]. To date, it was demonstrated that Cu<sub>4</sub>O<sub>3</sub> can be produced by several methods, such as sonochemical technique, chemical vapor deposition, laser ablation and solvothermal reaction [2,3,5–7]. Although these methods suffer from low purity and yield, Cu<sub>4</sub>O<sub>3</sub>-contained nanostructures were

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## Self-assembly carbon dots for powerful solar water evaporation

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#### Keywords:

Carbon dots

Assembly

Photothermal conversion

Solar steam generation

### ABSTRACT

Solar-driven water vaporization is considered one of the most sustainable technologies to solve water scarcity. However, the advanced design solar absorber system is still required for highly efficient steam generation. Here we develop a novel system for water evaporation through assembly of carbon dots within microchannels of processed wood. Not only is a dual-layer structure including of heat barrier and water transport channel formed, but also the modulation of carbon dot energy structures in favor of photothermal conversion is realized synchronously. This system exhibits higher water evaporation rate and energy efficiency for solar to steam generation than other black photothermal sheets (e.g. carbon nanotube, graphene, graphene oxide). On the one hand, the constructed size-dependent vaporization enthalpy theory shows that the micropores are beneficial to reduce vaporization enthalpy of water. On the other hand, the presented direct evidences for the roles of oxidation functional groups in solar thermal evaporation demonstrate that hydroxyl groups can improve solar-to-heat efficiency. Therefore, tailoring pore sizes and surface functional groups could be an efficient method for solar-to-vapor systems.

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## 1. Introduction

Fluorescent carbon dots (CDs) with tunable emissions have inspired intensive research efforts due to outstanding optical brightness, resistance to photobleaching, excitation/size-dependent emission property, excellent biocompatibility, low toxicity, low cost, and abundance of raw materials in nature [1–3]. They have shown potential applications in area of chemical sensors, bioimaging probes, photocatalysts, light-emitting diode, and so on [1–7]. More attractive photophysical properties have been found so far from the composites of CDs and inorganic nanomaterials or organic molecules rather than single particle of CDs and their assembly [5]. This is because CDs can act as either electron donors or electron acceptors when coupled with semiconductor materials [8]. The photogenerated electron/hole transfers could occur in heterostructures and suppress radiative recombination in CDs (Fig. 1a). So CDs can be used to improve solar conversion efficiency through

promoting charge separation and transfer in heterostructures [1,2,5,9]. Presently, CDs-based heterostructures have exhibited attractive abilities in pollutant degradation, CO<sub>2</sub> reduction, H<sub>2</sub> production and organic synthesis [2,4,5].

Without appropriate surface protection, however, the assemblies of CDs always create a series of new energy levels at the interfaces of CDs (namely interface states) due to the interactions between surface groups (e.g., O-related groups). Nonradiative recombination of photoinduced electrons will thus occur, cause fluorescence quenching, and release heat (Fig. 1b) [9–12]. Hence, the proper regulation for CD assemblies will also make it applicable to converting solar energy into heat as terminal energy for beneficial usage. The light to heat conversion has also gained intensive research interests in the past decade and found important applications, including steam generation, water desalination, cancer therapy, etc.

Water scarcity has become one of the most serious global challenges of our human being. With respect to this issue, harvesting light energy and converting it to heat for assisting water evaporation is an efficient technological solution to water shortage. To realize more efficient and economic evaporation, a new concept, named “Air-Water Interface Solar Heating (AWISH)” has been put forward and developed because it can restrict heat generation at

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时间：2022年11月01日 18:10 作者： 点击率：[3027] 次

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近年来，我校坚持推进“立德树人”根本任务，牢固树立“四个意识”，坚决做到“两个维护”，深入贯彻“四个服务”方针，扎实开展“双一流”建设，对标高水平大学，在上述领域取得了一系列显著成绩。

23:31 2023/8/20

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科学研究

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学科概况 >

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科研动态 > **我院胡胜亮教授上榜“全球顶尖前10万科学家排名”榜单**

发布时间：2021年11月26日 18:21 作者： 来源：科研与学科建设科 点击数：432次

国内全球学者库网站 (<http://www.globalauthorid.com/WebPortal/EliteOrder>) 公布了2021年“全球顶尖前10万科学家排名”，我院胡胜亮教授上榜“全球顶尖前10万科学家排名”榜单，位列50250。

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二〇二〇年十二月



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2021年10月

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晋工信创新字〔2019〕230号

## 山西省工业和信息化厅 山西省教育厅 关于公布2019年山西省研究生教育 创新中心名单的通知

各相关高校、企业：

根据《关于建立校企研究生教育创新中心及有关工作的通知》及《关于印发山西省研究生教育创新中心考核评价试行办法的通知》的要求，在有关院校及共建企业、单位共同申报的基础上，经省工信厅、省教育厅组织专家进行评审，现确定山西省先进金属成型研究生教育创新中心、山西省智慧水利研究生教育创新中心、山西省煤层气利用研究生教育创新中心等21户研究生教育创新中心为山西省研究生教育创

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山西省电站智能优化控制研究生教育创新中心与山西大学既有山西省电站控制研究生教育创新中心在建设名称、内容、模式等方面重叠，建议山西大学合并建设。

各有关高校的研究生教育管理部门负责统一协调管理本校的各研究生教育创新中心建设工作。请各中心依据省工信厅、省教育厅有关规定不断完善中心体制和组织机构建设、校企导师遴选和学生培养、培养计划制定及合作项目落实等工作，并正式以省级中心开始运行。

附件：2019年山西省研究生教育创新中心名单



2019年12月31日

附件

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当前位置： 首页 > 政务公开 > 政府信息公开专栏 > 法定主动公开内容 > 重点领域公开 > 教育信息

## 关于拟立项省级现代产业学院的公示

时间：2023-08-15 17:20 来源：山西省教育厅 收藏 打印 字体：放大 正常 缩小

根据《山西省教育厅关于开展现代产业学院培育建设工作的通知》（晋教高函〔2023〕30号）要求，经组织评审，拟立项11个省级现代产业学院。现予以公示。

公示期为2023年8月15日至8月21日。公示期间，如有异议，请以书面形式向省教育厅高等教育处反映，并提供必要的证据材料，以便核实查证。以单位名义反映的须加盖本单位公章，以个人名义反映的应署真实姓名、身份证号，写明联系电话。逾期及匿名不予受理。

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拟立项省级现代产业学院

序号	总体情况	建设领域	学校名称	学院名称
1	重点产业链	特钢材料	太原理工大学	极薄金属与特种轧制产业学院
2		风电装备	山西大学	风电装备产业学院
3		氢能	太原理工大学、 太原工业大学	氢能产业学院
4		光伏	山西能源学院、 中北大学	新能源（光伏）产业学院
5		合成生物	山西大学	合成生物学学院
6	重点专业领域	平遥推光漆	山西大学	推光漆学院
7		太谷药销	太原理工大学	玛钢智能材料产业学院
8		平遥牛肉	山西农业大学	平遥牛肉产业学院
9		定襄法兰	太原科技大学	定襄法兰产业学院

# 山西省人民政府学位委员会文件

晋学位办〔2022〕1号

## 山西省人民政府学位委员会办公室关于公布 2021年山西省优秀博士、硕士学位论文的通知

各研究生培养单位：

根据山西省人民政府学位委员会《山西省优秀学位论文评选办法》和《山西省人民政府学位委员会办公室关于上报2020—2021学年度研究生学位论文和推荐2021年山西省优秀博士、硕士学位论文的通知》文件要求，经各研究生培养单位推荐及专家复核复查，并经省教育厅公示无异议，共确定2021年度优秀博士学位论文87篇、优秀硕士学位论文169篇（详见附件），现予以正式公布。

希望各研究生培养单位对入选的优秀学位论文作者和指导教师给予表彰奖励，鼓励广大研究生和导师在学术上积极进取、敢于创新，产生更多的高水平论文。希望受到表彰的研究生指导

教师保持荣誉，再接再厉，在高层次人才培养中做出新贡献。

附件：2021年山西省优秀博士、硕士学位论文名单



(此件主动公开)

抄送：驻厅纪检组

## 2021年山西省优秀博士、硕士学位论文名单

序号	单位名称	论文题目	作者	导师	论文编号
105	山西师范大学	魏晋南北朝琅琊王氏书信研究	吴志建	赵继红	2021YS077
106	山西师范大学	筋膜枪放松对运动性肌肉疲劳的影响研究	文新平	李海伟	2021YS078
107	山西师范大学	新中国高中语文教材选文的变迁与启示	韩庆	范晓东	2021YS079
108	山西师范大学	核心素养视域下批判性思维指标体系的构建与运用	侯雪梅	张海珠	2021YS080
109	山西师范大学	直接移动平面法在几类分数p-Laplacian方程中的应用	侯文文	张丽红	2021YS081
110	山西师范大学	二维磁性材料CrI <sub>3</sub> 缺陷的第一性原理理论研究	王睿	杨国晖	2021YS082
111	山西师范大学	现实与浪漫的中和——维亚尔及其作品研究	王涵琳	金小民	2021YS083
112	山西师范大学	抗战时期成都电影放映业研究（1945年以前）	邱熠真	周婧	2021YS084
113	山西财经大学	高铁服务供给对中国区域创新合作的影响研究	吴亚君	赵康杰	2021YS001
114	山西财经大学	产品市场竞争、融资约束与公司现金持有同伴效应	徐文静	张文龙	2021YS002
115	山西财经大学	我国农村一二三产业融合对农民收入的影响研究	赵可霖	郭建宇	2021YS003
116	山西财经大学	基于复杂网络理论的系统性金融风险研究	石琳枫	绳德磊	2021YS004
117	山西财经大学	基于空间聚类的分层抽样方法改进研究	张涛	米子川	2021YS005
118	山西财经大学	基于区块链技术的社会治理伦理问题研究	闫姝	武晓峰	2021YS006
119	山西财经大学	图像重构优化计算研究	李一轩	李杰	2021YS007
120	山西财经大学	创投网络对企业创新绩效的影响机理：基于网络结构视角的研究	周倩兰	常红锦	2021YS008
121	山西财经大学	加计扣除强度、费用归类操控与企业研发投入效率——兼论内部控制与税收监管的调节作用	冯艺	吴秋生	2021YS009
122	山西财经大学	正念型领导对团队工作重塑的影响：团队韧性和团队开放性的作用	岳峰凯	薛继东	2021YS010
123	山西财经大学	山西省医疗服务与医疗保险协同机制研究	周佳卉	耿晋娟	2021YS011
124	山西财经大学	我国体育产业与健康产业融合测度与评价	刘龙飞	柴王军、陈林会	2021YS012
125	山西财经大学	协同信息搜索中的用户学习投入研究——基于协作能力和时间压力	李小敏	王昌	2021YS013
126	山西财经大学	税收优惠对高新技术企业全要素生产率的提升效应研究	张亚璟	昝志宏	2021YS014
127	山西财经大学	审计项目组组建与运行有效性研究——以LX会计师事务所为例	白杨	吴秋生	2021YS015
128	山西财经大学	高质量转型发展背景下太原市人才引进政策研究——基于政策工具视角的人才引进政策比较研究	支黎茹	白彬	2021YS016
129	山西财经大学	业绩承诺未达标的成因及经济后果——基于金马股份重大资产重组的案例研究	史文娟	赵毅	2021YS017
130	中北大学	不同应力条件下含LPSO相稀土镁合金的变形机制研究	孟瑛泽	吴耀金	2021YS145
131	中北大学	某防空车载火箭炮行进间发射动力学与控制研究	孙志群	李强	2021YS146
132	中北大学	小尺寸破片对单兵防护装备的侵彻性能研究	唐昌州	智小琦	2021YS147
133	中北大学	钴酸铜电极材料的制备及超级电容器性能研究	孙家乐	徐春菊	2021YS148
134	中北大学	铁、镍二硫配合物及其碳纳米管复合物的合成与电化学性能研究	李建荣	赵培华	2021YS149
135	中北大学	全钒液流电池用两性离子交换膜的制备及性能研究	刘蕾	王超	2021YS150
136	中北大学	钠离子电池正极材料Na <sub>3</sub> V <sub>2</sub> (PO <sub>4</sub> ) <sub>3</sub> 的改性研究	程军	何振峰	2021YS151
137	中北大学	基于电磁感应的有色金属分类研究	杜月	张志杰	2021YS152
138	中北大学	基于液态金属电极的可拉伸压电增强型摩擦纳米发电机研究	杨昌君	丑修建	2021YS153
139	中北大学	氮空位原子自旋传感器小型化集成关键技术研究	邓胜礼	唐军	2021YS154
140	中北大学	MEMS矢量型高分辨率海洋湍流传感器的设计与实现	张文君	薛晨阳	2021YS155
141	中北大学	多波段低分辨率图像同步超分与融合方法研究	田嵩旺	蔺素珍	2021YS156
142	中北大学	一类带有收获率的捕食者食饵系统的全局分析	姚金辉	李桂花	2021YS157
143	中北大学	光功能金属-有机框架物的合成及荧光性能研究	唐婧	王晓晴	2021YS158
144	中北大学	纤维负载碳点杂化凝胶太阳能水蒸发系统的设计与应用	张伟	胡胜亮	2021YS166
145	中北大学	一维压电结构中的弯曲波与扭转波	魏程鹏	薛春霞	2021YS159
146	中北大学	大学生炫耀性体育消费行为研究	雷猛猛	曹电康	2021YS160
147	中北大学	CL-20基含能薄膜的微喷涂直写成型及性能研究	孔胜	安崇伟	2021YS161
148	中北大学	HNS起爆药衍生物及其溶剂化合物的制备与晶体结构研究	曹慧智	曹雄	2021YS162
149	中北大学	负载型贵金属催化剂的制备及催化CO氧化反应机理的研究	冯晓庆	梁金虎	2021YS163
150	中北大学	窄粒度分布含能复合微球的膜乳化辅助制备及性能研究	王杰超	安崇伟	2021YS164
151	中北大学	FOX-7基不敏感传爆药的配方与性能研究	付健博	王保国	2021YS165
152	中北大学	垂直排列醋酸纤维基光热转化系统的设计及其应用研究	周浩阳	胡胜亮	2021YS167

# 山西省人民政府学位委员会文件

晋学位办〔2021〕1号

## 山西省人民政府学位委员会办公室 关于公布 2020 年山西省优秀博士、硕士学位论文的通知

各研究生培养单位：

根据山西省人民政府学位委员会《山西省优秀学位论文评选办法》和《山西省人民政府学位委员会办公室关于上报 2019—2020 学年度研究生学位论文和推荐 2020 年山西省优秀博士、硕士学位论文的通知》文件要求，经各研究生培养单位推荐及专家复核复查，并经省教育厅公示，共确定 77 篇优秀博士学位论文和 156 篇优秀硕士学位论文（详见附件），现予以正式公

布。

各研究生培养单位要认真学习领会习近平总书记关于研究生教育的重要指示精神和李克强总理批示精神，深入学习贯彻全国和我省研究生教育会议精神，认清形势，把握机遇，推动形成研究生教育高质量发展的动力和合力。广大导师和研究生要恪守学术道德、遵守学术规范，在学术上积极进取、敢于创新、勇攀高峰，努力产生更多高水平的学术成果，推动我省研究生教育再上新台阶。

附件：2020年山西省优秀研究生学位论文清单



(此件主动公开)

序号	学校名称	类别	姓名	一级学科名称	论文题目	导师姓名
76	山西师范大学	硕士	郭俊莉	地理学	乌鲁木齐河流域中下游地区土地利用变化的时空特征及生态影响	李曼
77	山西师范大学	硕士	王英	中国史	山西现存善财童子五十三参壁画调查与研究	侯慧明
78	山西师范大学	硕士	魏华	物理学	活性粒子在障碍物环境中的非平衡动力学行为研究	张进军 潘俊星
79	山西师范大学	硕士	任雪燕	数学	两类分数微分方程的最值原理及其应用	王国涛
80	山西师范大学	硕士	张苗	生物学	蟹鳃虱亚科（等足目：寄生亚目：鳃虱科）的分类、地理分布及系统发育分析	安建梅
81	山西师范大学	硕士	冯蕾	心理学	自我损耗对亲社会行为的影响：道德自我形象的作用	韩琴
82	山西师范大学	硕士	宁耀辉	材料科学与工程	(类) 石墨烯二维材料量子反常霍尔效应的第一性原理研究	张会生
83	山西师范大学	硕士	段嘉新	教育硕士	初中语文阅读教学中文本体式的教学特征研究	朱晓民
84	山西师范大学	硕士	李洁	教育硕士	基于倡导联盟理论的新中国小学语文课程目标政策变迁研究	范晓东
85	山西师范大学	硕士	赵莉蓉	教育硕士	部编版初中历史教科书“材料研读”栏目运用研究	仝建平
86	山西师范大学	硕士	郭宏霞	体育硕士	基于扎根理论的优秀中小学体育教师特征研究——以CCTV《我是体育教师》为例	李海伟
87	中北大学	硕士	高鹏程	航空宇航科学与技术	挤压AZ80镁合金轮毂关键部位疲劳行为研究	郭拉凤
88	中北大学	硕士	王帅	兵器科学与技术	输运热对炸药快烤响应特性影响的研究	智小琦
89	中北大学	硕士	李馥	材料科学与工程	碳点与铜氧化物复合材料的制备及其类酶催化性能研究	胡胜亮
90	中北大学	硕士	林震	电子科学与技术	基于GaAs pHEMT工艺的毫米波宽带混频芯片设计	年夫顺
91	中北大学	硕士	凌浩	信息与通信工程	声辐射力增强的近红外光血流测量技术研究	尚禹
92	中北大学	硕士	刘月鑫	材料科学与工程	2D MOF基复合材料的设计、制备及电容性能研究	王延忠
93	中北大学	硕士	盛安	材料工程	低反射电磁屏蔽复合材料的结构控制与性能研究	杨雅琦
94	中北大学	硕士	赵雪婷	材料工程	RTM工艺用快速固化环氧树脂体系的研究	张彦飞
95	中北大学	硕士	许睿轩	兵器工程	喷射结晶器流场数值模拟及超细FOX-7制备技术研究	王晶禹
96	中北大学	硕士	王爽	安全科学与工程	MOFs基复合粒子的构筑及其对AP热分解催化研究	安崇伟
97	中北大学	硕士	罗婷婷	材料工程	NC/GAP基亚微米复合含能纤维的制备及性能研究	王毅

# 山西省人民政府学位委员会文件

晋学位办〔2020〕2号

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## 山西省人民政府学位委员会办公室 关于公布 2019 年山西省优秀博士、硕士学位论文的通知

各研究生培养单位：

根据省学位委员会《山西省优秀学位论文评选办法》和《山西省人民政府学位委员会办公室关于上报 2018—2019 学年度研究生学位论文和推荐 2019 年山西省优秀博士、硕士学位论文的通知》文件要求，在各研究生培养单位推荐的基础上，经过“省内初评、省外送审、会议终审”三个评审环节，我们评选确定了 74 篇优秀博士学位论文和 134 篇优秀硕士学位论文(详见附件)，现予以正式公布。

希望各研究生培养单位对入选的优秀学位论文作者和指导

教师给予表彰奖励，鼓励广大研究生和导师在学术上积极进取、敢于创新，产生更多的高水平论文。希望受到表彰的研究生指导教师保持荣誉，再接再厉，在高层次人才培养中做出新贡献。

附件：2019年山西省优秀研究生学位论文清单



(此件依申请公开)

抄送：驻厅纪检组

序号	单位名称	学科名称	论文名称	作者	层次	导师
94	山西财经大学	法学	政府间事权与支出责任相适应的法治路径研究	张向宇	硕士	薛建兰
95	山西财经大学	马克思主义理论	习近平教育公平观研究	苏昱	硕士	张二芳
96	山西财经大学	管理科学与工程	研发投入跳跃、TMT专业异质性对组织失败的影响研究	李文霞	硕士	赵文
97	山西财经大学	管理科学与工程	面向缺值数据的信用评估贝叶斯网络模型研究	吴建爱	硕士	吕亚丽
98	山西财经大学	工商管理	资产减值准备计提与股价崩盘风险	杨华	硕士	吴秋生
99	山西财经大学	工商管理	智能制造背景下企业服务创新与绩效提升研究——基于知识共享视角	杜泽民	硕士	米俊
100	山西财经大学	工商管理	涉旅组织吸纳旅游微信公众号的影响因素和作用机理研究	申田莉	硕士	冯珍
101	山西财经大学	工商管理	共享型领导对员工创新行为的影响研究——以知识场活性为中介变量	杨霞	硕士	杨金风
102	山西财经大学	农林经济管理	山西省农业碳排放的测度及影响因素研究	张瑞玲	硕士	刘宇虹
103	山西财经大学	公共管理	耕地占补平衡指标易地交易价格体系研究——以山西省为例	付晓亚	硕士	王瑞雪
104	中北大学	体育学	西方身体哲学视域下运动伦理审视	解忍	硕士	张晓丽
105	中北大学	化学	基于界面调控设计高摩擦稳态多功能环氧涂层的研究	李孟宇	硕士	李巧玲
106	中北大学	机械工程	微通道内大分子悬浮液流动的eDPD模拟研究	刘宇翔	硕士	刘汉涛
107	中北大学	仪器科学与技术	柔性可拉伸压电纳米发电机制备及其性能研究	牛旭时	硕士	丑修建
108	中北大学	仪器科学与技术	锥面共形阵列天线波束切换技术研究	徐洪成	硕士	张斌珍
109	中北大学	材料科学与工程	钴酸锌电极材料的合成及其电化学性能研究	韩兴荣	硕士	徐春菊
110	中北大学	化学工程与技术	二氧化钛Janus粒子的制备及其降解高浓度有机废水的研究	师艳婷	硕士	张巧玲
111	中北大学	化学工程与技术	偶氮苯硝基衍生物的合成研究	曹俊岩	硕士	王建龙
112	中北大学	航空宇航科学与技术	ZrB <sub>2</sub> 基超高温陶瓷及其连接件的抗烧蚀与热冲击性能研究	李盼	硕士	原梅妮
113	中北大学	兵器科学与技术	影响熔铸混合炸药慢烤特性的因素研究	刘子德	硕士	智小琦
114	中北大学	兵器科学与技术	乳液型粘结体系/CL-20基炸药油墨的设计及应用基础研究	李千兵	硕士	安崇伟
115	中北大学	兵器工程	舰船易损性分析中船用钢的等效靶研究	黄松	硕士	尹建平
116	中北大学	材料工程	锰钴金属氧化物电极材料的制备及超级电容器性能研究	廖凡	硕士	陈慧玉
117	中北大学	材料工程	热电池用锰酸锂正极的掺杂改性研究	宋恒旭	硕士	侯华
118	中北大学	安全工程	CL-20基含能晶体结构及热性能研究	刘广瑞	硕士	苟瑞君
119	太原科技大学	应用经济学	高铁效应、生产性服务业集聚与制造业升级	张蕊	硕士	乔彬
120	太原科技大学	机械工程	新型复合结构衬套界面间相互作用机理与试验研究	夏全志	硕士	王建梅
121	太原科技大学	光学工程	基于TDLAS的调制光谱技术及其在气体检测中的应用	邵李刚	硕士	李传亮
122	太原科技大学	材料科学与工程	4H-SiC辐射缺陷的低温光致发光光谱研究	王慧军	硕士	王凯悦
123	太原科技大学	计算机科学与技术	基于萤火虫和细菌觅食的耦合算法	王叶闻	硕士	崔志华

**山西省教育厅**  
Shanxi Provincial Education Department

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主题词：	
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**山西省教育厅关于公布2021年山西省一流课程立项名单的通知**

时间：2021年09月20日      晋教高〔2021〕8号      字体：大 中 小 关闭

各普通本科高校：

根据《山西省高等学校精品共享课程立项建设与认定办法（试行）》精神和《山西省教育厅关于开展2021年山西省一流课程认定工作的通知》要求，省教育厅对各校申报的一流课程进行了评审，并对评审结果进行公示。现将立项名单予以公布（详见附件）。

各高校要承担主体责任，持续加强课程建设，提供配套经费支持，对课程运行情况进行监督和管理。山西省一流课程的建设期和培育期均为2年，认定有效期为5年，对通过立项认定的课程，要不断拓宽课程共享范围，应向高校和社会开放并提供不少于5年的教学服务，着力打造具有高阶性、创造性和挑战度的“金课”。

附件：2021年山西省一流课程立项名单

中北大学	60	飞机机翼数字化装配虚拟仿真实验	赵熹	虚拟仿真实验教学课程
	61	立体构成模型搭建虚拟仿真实验	李仁伟	虚拟仿真实验教学课程
	62	减速器参数化虚拟仿真及校验实验	孙虎儿	虚拟仿真实验教学课程
	63	传统固态发酵虚拟仿真实验教学项目——以山西老陈醋为例	王芳	虚拟仿真实验教学课程
	64	网络故障分析虚拟仿真实验项目	梁志剑	虚拟仿真实验教学课程
	65	注塑成型工艺与典型模具结构认知虚拟仿真实验	付一政	虚拟仿真实验教学课程
	66	高分子材料挤出型材及其微观形貌分析虚拟仿真实验	王志强	虚拟仿真实验教学课程
	67	跨境电商物流——Wish邮客户下单虚拟仿真实验	温丽琴	虚拟仿真实验教学课程
	68	大国兵器	尹建平	线上课程
	69	大美三晋	杜鹃	线上线下混合式课程
	70	Python程序设计基础	井超	线上线下混合式课程
	71	英美文学史及作品选读	曹小琴	线上线下混合式课程
	72	工程传热学	刘汉涛	线上线下混合式课程
	73	高等数学	王鹏	线下课程

# 中共山西省委教育工作委员会

晋教工委组函〔2023〕7号

## 中共山西省委教育工作委员会 关于发布2022年度教育系统党建创新案例的通知

各市委教育工委，各高等学校党委：

为深入学习贯彻习近平新时代中国特色社会主义思想，贯彻落实党的二十大精神，切实用党的创新理论指导实践，推动工作，根据中共山西省委教育工作委员会《关于开展党建创新案例征集活动的通知》（晋教工委组〔2022〕26号），要求全省教育系统各级各类学校党组织积极参与党建创新案例申报，形成一批主题突出、鲜活生动、示范性强的党建创新案例。经专家评审，共评选出优秀党建创新案例86个，其中高校63个、中小学校23个（见附件）。

要加强党建创新案例的学习宣传工作，充分利用“两微一端”、网站主页等多种形式进行宣传。要组织各级党组织充分利“三会一课”、主题党日、业务培训、工作交流等多种形式开展学习，对标找差，推广经验，进一步提升党建工作质量。

附件：2022年度教育系统党建创新案例

### 附件

#### 2022年度教育系统党建创新案例

##### 一、高校党建创新案例

1. 山西大学 以“四融四悟”激活科研育人 把论文写在祖国大地上
2. 山西大学 党建引领创新驱动 思想铸魂立德树人

##### 发展

20. 山西财经大学 “五+”促进“五融合”创新党建新模式
21. 中北大学 “12345”工作法构建高校学生党员教育管理体系
22. 中北大学 “党建领航，军工铸魂”创新实践三全育人新格局