



REVIEW ARTICLE

Rice Husk-Derived Materials for Solar Driven Interfacial Water Evaporation: A Short Review

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Abstract

The increasing demand for sustainable freshwater production has driven interest in solar-driven interfacial evaporation (SDIE) as an energy-efficient desalination and wastewater treatment technology. Among various photothermal materials, rice husk is an abundant agricultural byproduct that offers a low-cost, carbon-rich, and porous alternative to synthetic absorbers. This short review summarizes recent advances in rice husk-derived materials for SDIE, focusing on their key photothermal properties, fabrication strategies, and evaporation performance. Rice husk-derived carbon (RHC) exhibits excellent light absorption (up to 99.4% across the solar spectrum), ultra-low reflectance (<5%), high light-to-heat conversion (temperature rise of 20.9°C under 0.4 kW·m⁻²), and improved hydrophilicity and porosity when appropriately modified. Fabrication approaches are broadly classified into filler-based methods (e.g., membrane composites, coated cellulose papers) and foam-based strategies (e.g., self-standing foams, melamine sponge composites). The evaporation performance of rice husk-derived materials varies depending on structural design: standalone RHC coatings achieve evaporation rates of 2.09 kg·m⁻²·h⁻¹ with ~93.5% efficiency, while advanced architectures such as hydrogels, Janus evaporators, and trilayered composites (SiC/C + silica aerogel + carbonized wood) reach up to 4.21 kg·m⁻²·h⁻¹ and 94.9% efficiency. Some designs also improve long-term stability (>84 hours in brine), salt resistance (edge-only crystallization), and dual-mode functionality (nocturnal atmospheric moisture adsorption coupled with daytime evaporation). In conclusion, rice husk-derived carbon materials offer tunable, cost-effective, and sustainable solutions for SDIE. Future research should prioritize real-world testing, scalable fabrication, and further enhancement of cycle stability and salt management.

Keywords: Rice husk, photothermal, solar driven interfacial water evaporation, evaporation rate, carbon materials.

Introduction

Solar-driven water purification has attracted attention as a sustainable approach to address rising energy demands in desalination and wastewater treatment [1]. Among various strategies, solar driven interfacial evaporation (SDIE) has emerged as an efficient technique by confining heat at the air–water interface, thereby minimizing thermal losses and improving evaporation performance, as shown in Figure 1. To enhance this process, a wide range of photothermal materials has been developed, including plasmonic metals [2], semiconductors [3], carbon-based materials [4], and biomass-derived structures [5]. Carbonaceous materials, in particular, have been widely explored due to their strong light absorption, thermal stability, and tunable porous structures. More recently, biomass-derived materials have gained growing interest as low-cost and sustainable alternatives, offering inherent hierarchical porosity and surface functionalities that are beneficial for water transport and heat localization.

However, solar-driven water purification faces several challenges, such as salt accumulation. Salt accumulation can occur when salt-containing water and in this case, water undergoing desalination is continuously evaporated, leaving salt behind on the surface and within the pores of the material. Generally, factors influencing salt accumulation include high evaporation rates and, in large scale applications, feeding failures caused by capillary resistance, which increases as the transport distance of the water increases. Meanwhile, the driving capillary pressure is limited by the material's pore structure and the constant surface tension of the liquid. Thus, as the lateral dimensions of the evaporator increase, the capillary pressure can no longer compensate for the energy loss due to viscosity. This salt accumulation will eventually clog the water flow path which functions as the flow from the source to the evaporator surface thereby reducing water supply capacity and causing evaporation performance to decline after prolonged use of the evaporator. Another challenge lies in material structures that lack strength and durability. This leads to reduced photothermal efficiency and indicates low cycling durability [6–8].

Among these, rice husk represents a promising material due to its abundance as an agricultural byproduct and its unique composition, characterized by high silica content and carbon-rich structure. These features enable the formation of porous photothermal materials with enhanced light absorption and structural stability.

1. Light Absorption

Rice Husk-Based Carbon (RHC) possesses excellent light absorption ability. An RHC coated paper demonstrates a broad absorption profile from ultraviolet to near-infrared wavelengths (200–2250 nm). The film with a dose of 0.08 g RHC exhibits high light absorption of over 85% across the entire region of interest, resulting in rapid steam generation, thus meeting the requirements for an efficient solar absorber [9].

2. Light-to-Heat Conversion

RHC demonstrates great photothermal properties for membrane distillation due to its high carbon content (38.5%), which enables ultra-low light reflectance (<5%) and excellent broad-spectrum light absorption. This results in a good light-to-thermal conversion capability with a temperature rise of 20.9°C (an 83.6% increase) under 0.4 kW·m⁻² full-spectrum irradiation [10].

3. Hydrophilicity

The XRD pattern and EDS spectrum of the RHC suggest the existence of amorphous carbon and monoclinic SiO₂ in the sample. Also a presence of S in RHC (0.77%), which was introduced during the modification process with H₂SO₄, which may exist in the form of sulfonate surface groups. As a result, light absorption and hydrophilicity were enhanced [9]. Sulfonate is highly hydrophilic, polar, and often anionic over a wide pH range, increasing water solubility and aiding in water retention.

4. Porosity

The apparent surface porosity of the photothermal polyvinylidene fluoride membrane was determined at 45.3%, which was higher than the pristine membrane's 38.6%, aligning with observations from the SEM images. The enhanced surface porosity could be linked to two key factors. Firstly, the incorporation of porous RHC 600-EC (extracted carbon powder) contributed to the increased porosity by introducing additional voids within the membrane structure [11].

This review summarizes recent advances in rice husk-derived materials for solar-driven water evaporation, focusing on fabrication strategies, evaporation performance, and remaining challenges.

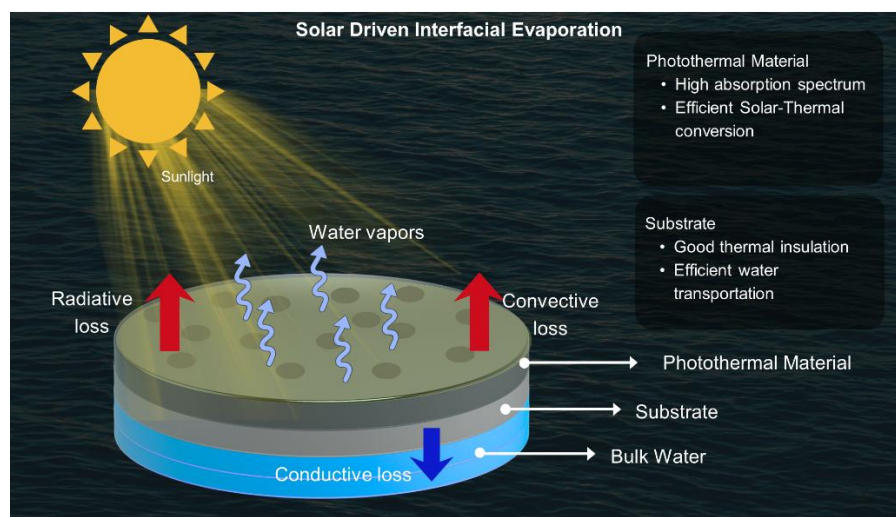


Figure 1. Schematic of solar-driven interfacial evaporation system.

Fabrication Strategies

Fabrication strategies for rice husk-derived photothermal materials can generally be classified into 2 main approaches, as shown in Figure 2.

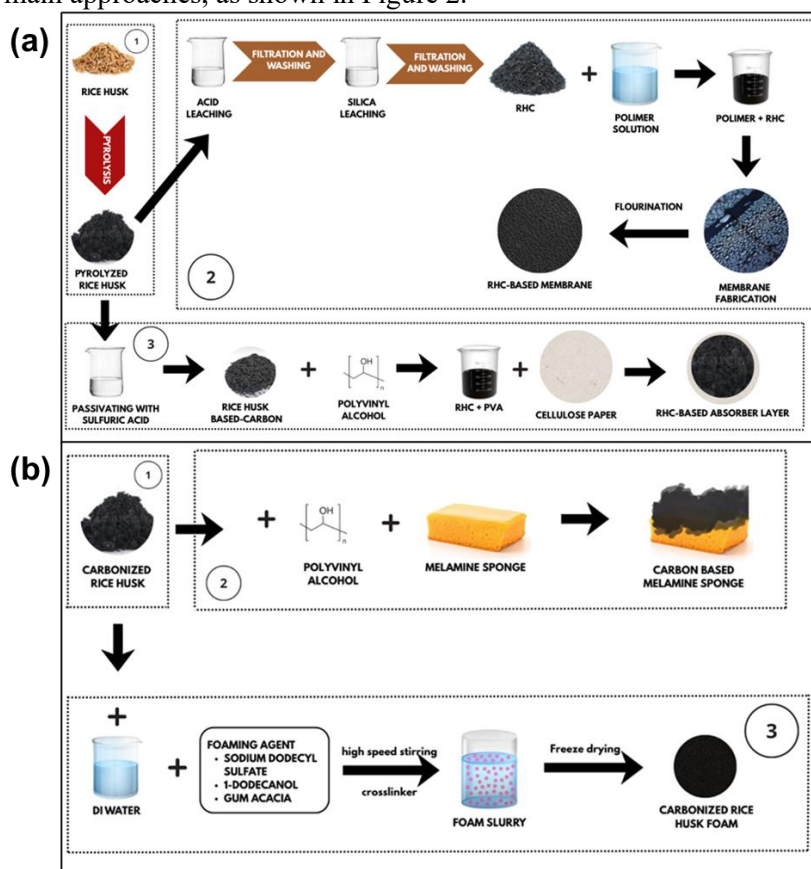


Figure 2. Schematic overview of fabrication strategies for rice husk-derived photothermal materials, including (a) filler fabrication and (b) foam-based strategies.

Rice husk (RH) is widely utilized in solar-driven interfacial evaporation (SDIE) systems as an organic precursor that requires size reduction to increase its specific surface area, thereby

enhancing light absorption and photothermal efficiency. In most applications, RH is incorporated as a filler within photothermal materials, either by blending it with a substrate or by fabricating it into membrane-based composites. RH can be thermochemically converted into rice husk ash (RHA) and rice husk carbon (RHC), both of which exhibit photothermal properties with the different result. However, according to *Chia et al.*, RHC demonstrates superior photothermal performance due to its higher carbon content. Their study reported that the light-to-thermal conversion capability of RHC was significantly higher than that of RHA, achieving a temperature increase of 83.6% under light treatment of 0.4 kWh for 90 minutes [10]. In membrane-based synthesis, RH undergoes pyrolysis followed by acid leaching to remove residual metal oxides. The material is then washed and subjected to silica leaching to eliminate silica content. The resulting purified RHC is subsequently characterized and used as a filler in polymer-based composite membranes. Membrane fabrication involves blending the polymer matrix with RHC, followed by structural formation and a fluorination step to enhance surface hydrophobicity, which is essential for efficient vapor transport in desalination applications as shown in part (i) number 2 [11]. An alternative synthesis approach involves directly integrating RHC onto a supporting layer, such as cellulose paper. Cellulose paper contributes to improved evaporation performance by providing rapid capillary pathways for water transport, a porous structure that increases the effective wetted surface area, and favorable thermal management that localizes heat at the air–water interface. This localization maintains a thin evaporation layer and minimizes heat loss to the bulk water. In contrast to membrane-based systems, hydrophilicity is deliberately introduced by incorporating polyvinyl alcohol (PVA). The RHC–PVA mixture is deposited onto the cellulose substrate through a vacuum assisted process, ensuring strong adhesion and uniform distribution as shown in part (i) number 3 [9]. Despite differences in fabrication, both approaches share a common initial pyrolysis step of RH prior to further treatment. Another synthesis strategy involves foam-based structures. In general, this approach utilizes pre-prepared RHC and can be categorized into two methods. The first involves combining RHC with PVA and integrating the mixture into a melamine sponge to produce a carbon-based melamine composite as shown in part (ii) number 2 [12]. The second method focuses on forming RHC into a self-standing foam structure. This is achieved by dispersing RHC in deionized water with the addition of foaming agents such as sodium dodecyl sulfate (SDS), 1-dodecanol, and gum acacia. The resulting foam slurry is then subjected to freeze-drying to generate a porous carbonized rice husk foam as shown in part (ii) number 3 [13].

Evaporation performance

The performance of SDIE is typically evaluated based on key parameters such as evaporation rate, solar-to-vapor efficiency, light absorption, and stability duration. Recent studies on rice husk-derived materials for SDIE applications demonstrate a wide range of evaporation performances, as summarized in Table 1.

The rice husk-derived carbon materials demonstrate versatile and high-performance photothermal capabilities for water purification. *Nguyen et al.* demonstrated an RHC-based floating solar steam generation system reaching a high evaporation rate of $2.09 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ under 1 sun with >85% ion removal efficiency [9]. *Chen et al.* engineered a resilient RHC-based hydrogel with a sponge-like architecture that achieved a stable evaporation rate of $1.77 \pm 0.05 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ for 25 wt% high-salinity brine over 84 hours, with edge-only salt crystallization and ~94% solar-to-vapor efficiency under 1 sun illumination [14]. *Alkhawlan et al.* developed a bio-inspired hybrid aerogel coupling nocturnal atmospheric moisture adsorption ($0.28 \text{ g} \cdot \text{g}^{-1}$ at 30% RH) with daytime solar evaporation, enabling 24-hour autonomous water production ($2.7 \pm 0.3 \text{ L} \cdot \text{day}^{-1}$ from a 0.25 m^2 panel in arid field conditions) at a low levelized water cost of \$0.38–0.40 per m^3 [15]. In *Fang et al.* research, rice husk is carbonized as photothermal layer and the leaves of rice straw and rice husk was employed as water pathways, which achieves an evaporation rate of $1.2 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ with an efficiency of 75.8% [16]. *Wang et al.* created a 3D porous foam matrix by combining polyurethane (PU) with carbonized rice husk powder, which serves as the

hydrophilic bottom layer. They then modified the upper layer with hydrophobic polypyrrole (PPy) to complete the Janus design. Which achieved evaporation rates of $1.33 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ for brine and $1.29 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ for wastewater under 1 sun illumination [17]. *Wu et al.* created a trilayered evaporator system made of SiC/C composite (Top) as the main photothermal material, sodium silicate aerogel (Middle) as thermal insulator, and carbonized natural wood (Bottom) as water transporter, which achieves evaporation rate of $4.21 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and a solar-to-vapor efficiency of 94.94% [18].

Table 1. Summary of evaporation performance.

Materials	Evaporation Rate Flux ($\text{kg m}^{-2}\text{h}^{-1}$)	Efficiency	Light Absorption	Stability Duration	Ref.
Rice Husk Char	2.09	93.5%	80%	5 cycles	[9]
Hybrid Aerogel from Rice Husk Biochar, CaCl_2 , and Plasmonic Material	1.34	86%	93.4%	84 hours (25 wt% brine)	[15]
Rice Husk Biochar Porous Hydrogel	1.77 ± 0.05	94%	>94%	>8 hours / 200 cycles	[14]
Carbonized Rice Husk Foam	1.2	71 %	92 %	8 hours	[16]
Carbonized Rice Husk/Polypyrrole Janus	1.33 (Brine) 1.29 (Wastewater)	-	-	4 hours	[17]
Carbonized Natural Wood + Silica Aerogel + SiC/C Composite from rice husk	4.21	94%	99.4% (SiC/C) 90.2% (CNW)	4 hours/20 cycles	[18]

Collectively, these studies confirm that rice husk-based carbon materials, whether as powder, floating evaporator, hydrogel, or hybrid aerogel, offer tunable, cost-effective, and sustainable solutions for diverse water purification scenarios which ranging from membrane distillation and high-salinity brine desalination to off-grid atmospheric water harvesting.

Challenges and Future Perspectives

Despite the significant progress achieved in rice husk-derived materials for SDIE, several challenges remain that limit their practical implementation. Such challenges are: inadequate knowledge of salt accumulation during continuous operation, difficulties managing repeated wet and dry conditions with wind, failure against harmful organisms growing in real wastewater, and

the lack of testing for the technology under realistic conditions where moisture levels and sunlight patterns constantly change.

While edge-only crystallization and other techniques have potential to increase stability up to 84 hours, there is still much research that needs to be done for effective long-term salt management. Most studies focus on synthetic brines (25 wt%) for durations shorter than 100 hours, but in practical applications, it takes more than 30 days of continuous operation to test performance against pore clogging and salt creep. To overcome this, future designs should incorporate gradient-porosity structures (larger pores at the bottom for salt backflow, smaller pores on top for heat localization), self-cleaning mechanisms (e.g, periodic system flushing), and Janus wettability designs (hydrophobic top, hydrophilic bottom) to limit crystallization to the material's edge. The long-term mechanical durability of materials made from RHCs is largely unexplored. The majority of studies indicate only 20-200 cycles of testing, which often fails to simulate the mechanical fatigue caused by cyclic wet-dry conditions and wind/wave action in field deployments. Further studies should concentrate on strengthening structural integrity by utilizing flexible polymer binding agents, such as PVA or chitosan, that do not diminish porosity, creating compressible self-standing foams with proven elastic recovery under cyclic compression, and using natural fibers (e.g., jute, coir) as a reinforcing scaffold for RHC coatings.

The issue of biofouling from organic matter and instability of illumination in real wastewater is not well understood for RHC materials. The current research primarily uses synthetic water, and there has been little data on the formation of biofilms that can interfere with water channels and reduce light absorption. In the future, it may be beneficial to incorporate antibacterial agents (such as silver or copper oxide nanoparticles) into the RHC composite. Future research should verify the materials' authenticity by using genuine secondary effluent or algae-rich water and evaluating their self-cleaning capabilities, as photothermal heating can cause lethal effects on numerous microbes at a surface temperature of over 60°C. Almost all of the reported evaporation performances are established on laboratory conditions with stable 1-sun illumination (1000-10000 W/m²) and constant ambient conditions. Field validation is lacking for fluctuating irradiance (200-1000 W/m²), wind, and humidity. The literature contains only one study that provides field data for an outdoor pilot trial. Future studies must align with local weather data, such as solar flux, temperature, relative humidity, and wind speed, to correct the gap. Furthermore, it is necessary to optimize thermal insulation layers (such as aerogel) to minimize convective heat losses during windy conditions.

The economic viability of any technology depends on a thorough analysis of techno-economics (TEA) and the environmental viability depends on life-cycle assessment (LCA). A cost-per-liter or payback period analysis has not been published for the current research on SDIE based on RHC. Although RH is an inexpensive feedstock, pyrolysis, acid leaching, and freeze-drying can result in energy and chemical processing expenses. However, A bottom-up cost analysis is necessary in future research to identify cost-driving steps and propose less expensive alternatives. Several recent studies have demonstrated the value of this approach to RH valorization. A 1-t/day system with a proven financial viability and 3-5 years of payback, while accounting for bio-coal sales and carbon credits revenue at the same time, has high internal returns. The lack of a comprehensive LCA for RHC-based evaporators does not provide evidence of their environmental sustainability as an agricultural byproduct. By using chemicals like H₂SO₄ and HF to remove silica and harnessing significant amounts of energy, pyrolysis creates environmental footprints that need to be quantified. By using a cradle-to-grave LCA, it is possible to determine the global warming potential (GWP), water depletion, and ecotoxicity of these materials in comparison to synthetic graphene. Earlier LCA investigations on comparable systems demonstrated substantial climate mitigation potential, with net negative greenhouse gas emissions (1.25 kg CO₂-eq per functional unit) associated with torrefaction of municipal solid waste (MSW) rice husk blends [19]. Thus, RHC-based systems could have a favorable environmental profile, but this must be empirically verified.

By addressing these specific challenges with targeted research, rice husk-derived photothermal materials can move beyond promising lab results to become a truly sustainable and scalable solution for global water purification.

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