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ENHANCING SOLAR STEAM GENERATION USING OXIDATION OF CARBONACEOUS  
MATERIALS: EXPANDED GRAPHITE AND AEROGELS

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ENHANCING SOLAR STEAM GENERATION USING OXIDATION OF CARBONACEOUS  
MATERIALS: EXPANDED GRAPHITE AND AEROGELS

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## ABSTRACT

The growing global demand for sustainable clean water solutions has intensified research into solar-driven interfacial evaporation (SDIE) systems. This work investigates the photothermal performance of expanded graphite (EG)-based materials modified via hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) oxidation and noncovalent functionalization with 1-pyrenebutyric acid (PBA) for enhanced solar steam generation. A double-layer architecture, comprising a photothermal top layer (expanded graphite or aerogel based) and a thermally insulating carbon foam substrate, was employed to promote heat localization and efficient water delivery.

Surface treatments were designed to improve water affinity while preserving the structural integrity of the graphitic framework.  $\text{H}_2\text{O}_2$  treatment introduced oxygen-containing groups, while PBA functionalization leveraged  $\pi$ - $\pi$  stacking to achieve surface carboxylation. Material characterization using SEM, XPS, and XRD confirmed successful surface modification without disrupting the lattice structure.

Photothermal testing under 1 sun illumination revealed that untreated EG achieved an evaporation rate of  $0.97 \text{ kg/m}^2\cdot\text{h}$ . In comparison,  $\text{H}_2\text{O}_2$ -treated EG reached  $1.26 \text{ kg/m}^2\cdot\text{h}$  (78.72% efficiency), while PBA-EG achieved  $1.3 \text{ kg/m}^2\cdot\text{h}$  (81.61% efficiency), demonstrating the role of tailored surface chemistry in enhancing water uptake and thermal confinement. Additionally, GO-aerogel and GnP/GO aerogel-based configuration were explored for their lightweight and porous structure, though performance was moderate which was limited by their structural stability and interfacial coupling. The GO-aerogel showed an evaporation rate of  $1.12 \text{ kg/m}^2\cdot\text{h}$ , while the GO-GnP aerogel showed an evaporation rate of  $1.22 \text{ kg/m}^2\cdot\text{h}$ , respectively.

Furthermore, X-ray photoelectron spectroscopy and Raman analyses showed that the PBA treated EG has a high C/O ratio of 9.48 and low Raman  $I_D/I_G$  ratio of 0.037 so it has very low structural defects. The study also explored the thickness effect on the evaporation rate and the overall efficiency, and we found that certain optimum thickness of solar absorber is necessary to have a better performance. These findings highlight the potential of low-cost, surface engineered EG as a scalable photothermal material, and provide insight into design strategies for solar driven interfacial systems.



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## NOMENCLATURE

| Symbol     | Description                          | Units                     |
|------------|--------------------------------------|---------------------------|
| $\eta$     | Solar-to-vapor conversion efficiency | %                         |
| $Q$        | Input solar energy                   | W or J                    |
| $m$        | Mass of evaporated water             | kg                        |
| $\Delta H$ | Enthalpy of water vaporization       | J/kg                      |
| $t$        | Irradiation time                     | s or h                    |
| $A$        | Illumination area                    | m <sup>2</sup>            |
| $T$        | Temperature                          | °C or K                   |
| $P$        | Solar intensity (illumination power) | W/m <sup>2</sup>          |
| $\lambda$  | X-ray wavelength (Cu K $\alpha$ )    | nm (typically 0.15406 nm) |
| $\theta$   | Bragg angle                          | degrees (°)               |
| $d$        | Interlayer spacing (from XRD)        | Nm                        |
| $n$        | Diffraction order (Bragg's Law)      | Dimensionless             |

## ABBREVIATIONS

| Abbreviation | Full Form                            |
|--------------|--------------------------------------|
| EG           | Expanded Graphite                    |
| PBA          | 1-Pyrenebutyric Acid                 |
| SDIE         | Solar-Driven Interfacial Evaporation |
| XPS          | X-ray Photoelectron Spectroscopy     |
| XRD          | X-ray Diffraction                    |
| GO           | Graphene Oxide                       |
| GnP          | Graphene Nanoparticles               |
| SEM          | Scanning Electron Microscopy         |
| FWHM         | Full Width at Half Maximum           |

|               |                                 |
|---------------|---------------------------------|
| GIC           | Graphite Intercalation Compound |
| Cu K $\alpha$ | Copper K-alpha (X-ray source)   |

## Chapter 1

### INTRODUCTION

#### 1.1 Background and Motivation

The escalating global demand for clean water has intensified research into sustainable and efficient water purification technologies. Among various approaches, solar-driven processes have gained considerable attention, as the solar energy received by earth in a single hour exceeds the total annual global energy consumption.<sup>1</sup> Traditional solar steam generation relies on heating the entire water volume, which leads to substantial energy losses through reflection, radiation, and convection.<sup>2</sup> These systems often require strong solar concentration and, in some cases, vacuum conditions to reduce thermal losses. The generated steam typically remains in thermal equilibrium with the bulk liquid, thereby limiting overall efficiency.<sup>3</sup>

An alternative approach involves suspending nanoparticles in a liquid to create what is known as a nanofluid. This setup allows the heat to be absorbed throughout the entire volume of the liquid, helping maintain a consistent temperature and improving heat transfer, which reduces energy loss from the surface.<sup>4</sup> Amjad et al.<sup>5</sup> reported that gold nanofluids, under high solar intensity, achieve uniform temperature distribution and photothermal conversion efficiencies approaching 90%. In their experiments, adding 0.04 wt% gold nanoparticles boosted photothermal conversion by ~95% over pure water. Similarly, Wang et al.<sup>6</sup> demonstrated that zirconium carbide (ZrC) nanofluids can significantly enhance solar steam generation efficiency due to their stable optical and thermal properties.<sup>6</sup> They found that ZrC particles produce a steep temperature gradient at the water surface, which reduces heat loss to the bulk and has the potential to improve the evaporation efficiency. Another approach involved the development of a solar steam generator utilizing wick materials wrapped with graphene nanoparticles. This design reached an energy efficiency of up to 80%, attributed to the enhanced solar absorption and capillary action facilitated by the graphene-coated wick.<sup>7</sup> Despite these advancements, several challenges continue to hinder the widespread adoption of nanofluid-based systems. Bocanegra et al.<sup>8</sup> identified nanoparticle sedimentation as a critical issue, leading to deterioration in thermal performance over time. Their study emphasizes that without careful stabilization, sedimentation becomes the primary barrier to nanofluid

application. Another study emphasized on the importance of standardized preparation protocols to ensure reproducibility and performance consistency of nanofluids.<sup>9</sup> This study points out that without proper mixing and sonication procedures, reproducibility of nanofluids suffers. A fundamental limitation remains related to dependence on high optical concentration to achieve efficient steam generation output, which introduces challenges such as complex optical alignment, increased capital costs, and enhanced thermal losses.<sup>3</sup>

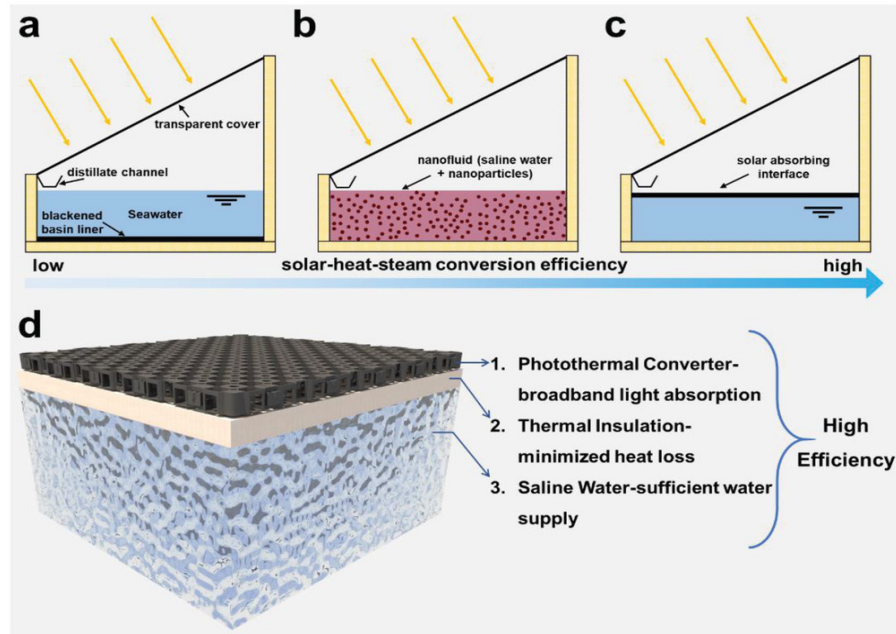


Figure 1: Comparative illustrations of traditional solar evaporation methods and solar interfacial evaporation techniques. a) Traditional solar still utilizing bottom heating, resulting in low energy conversion efficiency. b) Solar volumetric evaporation enhanced with nanoparticles, offering moderate efficiency. c) Solar interfacial evaporation employing heat localization for high energy conversion efficiency. d) Diagram outlining the main components of a solar interfacial evaporation system and their specific roles in enhancing conversion efficiency.<sup>10</sup>

Looking for more efficient way, solar-driven interfacial evaporation (SDIE) has emerged as a promising approach, using solar energy to convert water into vapor at the air-water interface.<sup>11</sup> This comes from the fact that water evaporation is inherently a surface-limited phenomenon, where only molecules at the air- water interface possess sufficient energy to escape into the vapor phase.<sup>12</sup> In conventional systems, heating the entire volume of water results in the unnecessary use of



energy on non-evaporative regions, significantly reducing efficiency. In contrast, interfacial solar heating concentrates energy exclusively at the evaporation zone, thereby enhancing localized temperature and reducing conductive losses to the bulk liquid.<sup>13</sup> Wang et al. used this interfacial heating method<sup>13</sup> with floating trifunctional membrane (MCE/HP/Au) to achieve a maximum evaporation rate of  $\sim 8.70 \text{ kg/m}^2\text{h}$  under 10 suns of solar intensity. An effective interfacial solar evaporation system need to fulfill three key criteria<sup>14</sup>: (i) the capacity to harness a broad spectrum of solar radiation while restricting heat generation to the surface layer, (ii) high photothermal conversion efficiency, and (iii) minimal heat transfer from the heated interface to the deeper, non-evaporative water. Such localized heat confinement improves energy utilization and accelerates evaporation under low solar flux conditions, making it an ideal strategy for sustainable water purification.

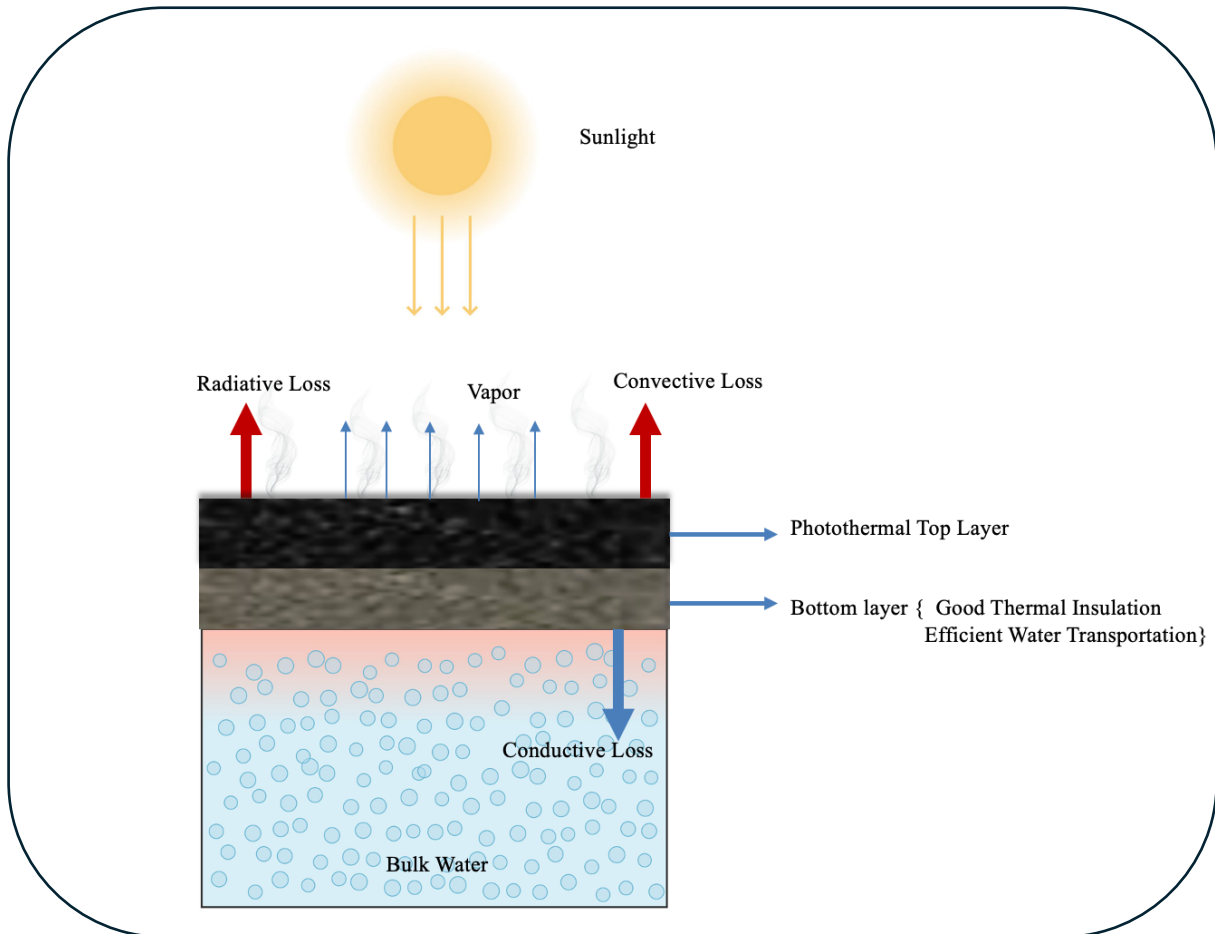


Figure 2: Schematic diagram of bilayer solar-driven interfacial evaporation (SDIE) principle.

Notably, optimizing evaporator design is essential to achieving efficient interfacial solar evaporation through heat localization. One of the successful implementations of localized heating employs bilayer photothermal structures. Figure 2 shows a schematic diagram of such structure. Typically, the top layer consists of a broadband light-absorbing material (e.g., carbon black, plasmonic nanoparticles, or 2D materials like graphene) which efficiently converts sunlight into heat.<sup>15</sup> This layer sits atop a thermally insulating substrate (e.g., cellulose foam, polyurethane, or aerogels) which serves two roles: it floats at the interface and thermally insulates the photothermal layer from the bulk liquid beneath, effectively minimizing downward heat losses.<sup>16</sup> The water supply mechanism in these bilayer systems is generally provided by capillary action or porous channels embedded within the insulating substrate. This ensures a continuous replenishment of water to the heated interface, supporting uninterrupted evaporation. Studies by Li et al. and Zhou et al. demonstrated that such designs not only enhance evaporation efficiency under 1-sun illumination but also maintain robust performance over extended periods, describing that high-efficiency evaporation (60–90%) is regularly achieved in the literature.<sup>17</sup>

## 1.2 Material Innovations for Solar-Driven Interfacial Evaporation (SDIE)

Recent advancements in SDIE have focused on the development of photothermal materials that exhibit high solar absorption, efficient heat localization, and rapid water transport. Table 1 shows a summary comparison between the traditional bulk evaporation and interfacial evaporation. The research work by Zhang et al.<sup>18</sup> demonstrated a self-healing, hydrophobic photothermal membrane achieving a solar-to-vapor conversion efficiency of ~58%, outperforming traditional bulk-heating systems and typical solar stills. This floating absorber membrane had low thermal conductivity which reduced the thermal loss efficiently. Liu et al.<sup>19</sup> developed a paper-based membrane embedded with  $\text{Fe}_3\text{O}_4$  nanoparticles, which served as efficient solar absorbers for wastewater treatment. The photothermal activity of the magnetic nanoparticles enhanced evaporation rates, offering a promising low-cost solution for solar-driven purification. The system showed high solar energy absorption (>95%) and solar-to-vapor conversion efficiency up to 79.91% under one sun solar illumination. Plasmonic materials such as gold and silver nanoparticles utilize localized surface plasmon resonance (LSPR) to achieve high photothermal conversion efficiency. Chen et al.<sup>20</sup> reported that integrating plasmonic nanostructures enhanced evaporation performance, they achieved solar-to-vapor efficiencies up to 95%, demonstrating the potential of nanostructured

metals like gold and silver for efficient photothermal water evaporation systems. Although their high cost and potential environmental impact pose challenges for large-scale application.

Table 1: Comparison of Traditional and Interfacial Solar Steam Generation.

| Feature                | Traditional Solar Still                  | SDIE (Interfacial Evaporation) |
|------------------------|------------------------------------------|--------------------------------|
| Heating Approach       | Bulk Heating                             | Surface Heating                |
| Energy Loss            | High (Reflection, Radiation, Conduction) | Low (Localized at Interface)   |
| Efficiency under 1 Sun | Low (~30–40%)                            | High (>80%)                    |
| Complexity             | Moderate                                 | Moderate to High               |
| Water Heating Zone     | Entire Water Volume                      | Top Layer Only                 |
| Thermal Confinement    | Low                                      | High                           |

Carbonaceous materials such as graphene, carbon nanotubes, and bio-derived carbon structures have dominated SDIE research due to their broadband light absorption and thermal stability. These materials can absorb solar radiation across the ultraviolet, visible, and near-infrared regions, converting it into heat with minimal energy loss. Wang et al.<sup>14</sup> used carbon nanotube along with silica membrane as bi-layered structure to improve the surface evaporation. Gong et al.<sup>21</sup> proposed a strategy for fabricating a multiscale roughness membrane by attaching a nanoparticle-assembled superstructure composed of CNTs onto a nanofibrous substrate. The engineered membrane exhibited less wettability, and under 1sun showed an evaporation rate of approximately 0.78 kg/m<sup>2</sup>h. Wang et al.<sup>22</sup> introduced a novel photothermal composite made from a combination of reduced graphene oxide (rGO) and multi-walled carbon nanotubes (MWCNTs). This mixture can be applied to various substrates and demonstrated a high-water evaporation rate of approximately 1.22 kg/m<sup>2</sup>h when coated onto a PVDF membrane. Compared to membranes coated with only rGO or only MWCNTs, which achieved 0.68 kg/m<sup>2</sup>h and 1.12 kg/m<sup>2</sup>h respectively. These findings emphasize the significant effect that material combinations can have on enhancing photothermal efficiency. Ghasemi et al.<sup>23</sup> designed a double-layered porous structure using carbon foam topped with exfoliated graphite, achieving solar-to-steam conversion efficiencies of up to 65% under 1

sun. This architecture localized heat at the air-water interface while keeping the bulk water cool, effectively minimizing thermal losses. Wang et al. reported that by optimizing the thickness of a carbon nanotube (CNT) coating combined with a microporous silica substrate, the system achieved and a solar-to-vapor energy conversion efficiency of 82%.<sup>14</sup>

The noncovalent functionalization of graphene derivatives has been explored to enhance its interaction with water, thereby improving its applicability in SDIE systems.<sup>24</sup> Unlike covalent modifications, noncovalent approaches preserve the intrinsic carbon network of graphene derivatives.<sup>25</sup> It is often preferred as it leads to less structural damage of graphene derivatives while improving properties such as hydrophilicity, wettability etc. <sup>26</sup> Zhang et al. reported that pyrene-end capped tetraphenylethene molecules could noncovalently interact with graphene sheets, enhancing their dispersion in aqueous solutions.<sup>27</sup>

Expanded graphite (EG), produced through the thermal expansion of graphite intercalation compounds(GIC) <sup>28</sup>, has emerged as a viable candidate for SDIE applications. Its unique porous structure with high surface area facilitates efficient light absorption and heat localization, while promoting rapid water transport to the evaporation interface.<sup>23</sup> Recent studies have shown that EG after expanding at high temperature has high potential in solar applications while having low optical concentrations.<sup>29</sup> EG also exhibits high thermal stability, chemical resistance, and mechanical flexibility, making it suitable for various applications, including energy storage, thermal management, and environmental remediation.<sup>30</sup>

EG has been effectively used in the bilayer SDIE structure as a top photothermal layer and achieved high solar to vapor efficiency.<sup>23</sup> Similarly, another study engineered a paraffin wax/expanded graphite composite with a yolk-shell bilayer structure, which exhibited a high evaporation rate under one sun.<sup>31</sup> These studies underscore the potential of EG-based bilayer structures in enhancing solar steam generation performance.

To further enhance the performance of EG in SDIE systems, functionalization strategies can be employed. Noncovalent functionalization methods, such as  $\pi$ - $\pi$  stacking interactions with aromatic molecules like pyrene derivatives, have been shown to improve the dispersion and stability of graphene-based materials. For example, the effect of 1-pyrene carboxylic acid

functionalization on graphene has been investigated, revealing improvements in its properties for various applications.<sup>32</sup> Non-covalent functionalization using surfactants like Triton X-100 has also been employed to modify EG, resulting in improved hydrophilicity.<sup>33</sup> Hinnemo et al. demonstrated that PBA molecules spontaneously form a self-limiting monolayer on graphene, driven by  $\pi$ - $\pi$  interactions. They suggest that at higher concentrations, PBA molecules tend to stand upright and stack laterally, leading to surfaces densely populated with carboxylic functional groups that enhance hydrophilicity.<sup>34</sup>

Oxidative treatments, including the use of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), have also been explored to introduce oxygen-containing functional groups onto the surface of carbon materials, thereby enhancing their hydrophilicity and facilitating better interaction with water molecules. The functionalization process leads to the incorporation of oxygen-containing groups such as hydroxyl (-OH), carbonyl ( $\text{C}=\text{O}$ ), and carboxyl (-COOH) onto the structure.<sup>35</sup> This oxidation primarily occurs at the edges and defect sites of the graphite layers, where the carbon atoms are more reactive. The introduction of these polar functional groups increases the surface energy of EG, thereby enhancing its affinity for water and improving its dispersibility in aqueous environments.<sup>36</sup> One research suggests that short-term  $\text{H}_2\text{O}_2$  treatments increase hydrophilicity, while long-term treatments have the opposite effect due to surface area reduction associated with the oxidation process.<sup>35</sup> These modifications aim to improve the overall efficiency of the SDIE process by optimizing the material's surface characteristics.

Graphene based aerogels have also emerged as effective photothermal evaporators for solar-driven interfacial evaporation due to their light-to-heat conversion and water evaporation performance.<sup>37</sup> Hu et al.<sup>38</sup> tailored a graphene oxide (GO) aerogel by incorporating carbon nanotubes and sodium alginate, enabling an 83% solar-to-vapor conversion efficiency under one sun. Graphene based aerogels are ultra-lightweight, highly porous 3D networks (often >90% porosity) with low thermal conductivity, which endow them with low density and excellent floatability on water.<sup>39</sup> This “thermal insulation plus water transport” function is a key advantage of aerogel evaporators, as noted by Hu et al.<sup>38</sup> Notably, partially reducing or doping GO based aerogels allows tuning of wettability and thermal conductivity: for example, appropriate nitrogen-doping improved graphene aerogel hydrophilicity while moderating its thermal conductivity, achieving an optimal balance that maximized evaporation performance.<sup>40</sup> It is anticipated that graphene oxide-graphene

nanoplatelet (GO-GnP) hybrid aerogels have good potential for SDIE system. GO can serve as both a dispersant and framework for GnPs, which provide broadband solar absorption and structural reinforcement.<sup>41</sup> Hybrid aerogels also demonstrate tunable wettability and reduced thermal conductivity<sup>42</sup>, which is key for confining heat at the interface while sustaining capillary-driven water replenishment.

To further enhance photothermal performance, defects in graphene-based nanostructures, including oxygen-containing functional groups, act as effective phonon scattering centers and electron traps, enabling the conversion of electronic energy into localized heat.<sup>43</sup> Allahbakhsh et al.<sup>44</sup> demonstrated that such defect-induced photothermal effects significantly enhance solar-driven interfacial evaporation (SDIE) efficiency by concentrating heat at the interface and reducing energy loss to the surrounding bulk water. In addition to defect engineering, structural modifications also play a vital role. While plain surfaces face inherent limitations in energy efficiency due to diffuse reflection and radiative losses, these limits can be reduced by introducing surface roughness. Textured or uneven surfaces create light-trapping geometries that facilitate multiple internal reflections of incident light<sup>43,45</sup>, thereby substantially increasing light absorption and thermal conversion efficiency.

### 1.3 Evaporation Rate and Efficiency:

Under one-sun illumination (1000 W/m<sup>2</sup>), a floating photothermal evaporator operates by converting absorbed solar energy into heat at the water-air interface. At steady state, an energy balance equates the incoming absorbed solar flux to the sum of heat sinks: latent heat of evaporation plus various losses. In general form:

$$q_{\text{solar}} \alpha_{\text{abs}} = q_{\text{evap}} + q_{\text{cond}} + q_{\text{conv}} + q_{\text{rad}} \quad (1)$$

where  $q_{\text{solar}} = 1000 \text{ W/m}^2$  is the incident solar flux for 1 sun,  $\alpha_{\text{abs}}$  is the absorptance of the photothermal layer (often 0.85~0.99) for black materials.<sup>46</sup> The terms on the right represent evaporative, conductive, convective, and radiative heat fluxes, respectively (all in W/m<sup>2</sup>). This equation formalizes the idea that at steady state all absorbed energy is either used to evaporate water or lost as heat. In practice, a well-designed interfacial evaporator maximizes the evaporative term,  $q_{\text{evap}}$  while minimizing heat loss.

$$q_{evap} = \frac{\dot{m} \times L_v}{A} \quad (2)$$

where  $\dot{m}$  is the evaporation rate in kg/s,  $L_v$  is water's latent and sensible heat, and  $A$  is the surface area. The latent heat term is substantial ( $\sim 2.26$  MJ/kg), so even small mass fluxes consume large energy; for instance, evaporating  $1.48 \text{ kg/m}^2 \cdot \text{h}$  of water (the theoretical maximum under  $1 \text{ kW/m}^2$  for a black material, if all energy went into phase change) requires  $\sim 1000 \text{ W/m}^2$  of continuous heat input.

If the evaporator surface temperature  $T_s$  rises above ambient  $T_\infty$ , heat will be lost by convection and radiation. Convective loss can be modeled by Newton's law:

$$q_{conv} = h (T_s - T_\infty) \quad (3)$$

where  $h$  is the convective coefficient ( $\sim 5\text{--}15 \text{ W/m}^2 \cdot \text{K}$  for free convection in indoor air).<sup>46</sup>

Radiative loss is given by the Stefan–Boltzmann law,

$$q_{rad} = \varepsilon \sigma (T_s^4 - T_\infty^4) \quad (4)$$

where  $\varepsilon$  emissivity (water and many blacks  $\approx 1$  in IR) and  $\sigma$  is the Stefan–Boltzmann constant.<sup>46</sup>

Conduction into the bulk water is another loss term:

$$q_{cond} = \frac{k_{eff}(T_s - T_w)}{\delta} \quad (5)$$

where  $T_w$  is the underlying water temperature,  $k_{eff}$  is the effective thermal conductivity of the float/wick below the interface, and  $\delta$  its thickness. For an ideal “perfect insulator” base,  $q_{cond} \rightarrow 0$ ; many designs use low thermal conductivity materials to approach this. For example, combining expanded graphite with a foamed support yields a high solar absorptance yet keeps thermal conduction low.<sup>47</sup> Insulating aerogels similarly have very low thermal conductivities (on the order of  $0.03\text{--}0.1 \text{ W/m} \cdot \text{K}$ ) which help confine heat near the top surface.<sup>48</sup> In fact, simulations confirm that under steady one-sun heating, the temperature profile decays within only a few millimeters of the evaporating surface, so most heat is consumed in evaporation rather than warming the bulk water.<sup>46</sup> This thermal localization is a key principle: by floating a thin absorber with poor thermal

contact to the reservoir, one can maintain a hot evaporating interface while the bulk fluid remains near ambient temperature.<sup>23</sup> As a result, the steady evaporation rate is maximized. Steady-state models typically assume: a uniform surface temperature, one-dimensional heat flow through the device, and negligible heat storage ( $dT/dt=0$ ), allowing the energy balance above to determine  $T_s$  and  $\dot{m}$  given environmental conditions and material properties.

The evaporation rate can be obtained from the latent heat term:

$$\dot{m} = \frac{q_{evap} \times A}{L_v} \quad (6)$$

To quantify steam generation performance, mass loss due to evaporation was continuously monitored using a precision analytical balance connected to a real-time data acquisition system (SPDC). The balance recorded the mass change ( $\Delta m$ ) of the water over time ( $\Delta t$ ), and data were logged throughout the duration of solar exposure. Once steady-state behavior was reached (after the initial transient period), the slope of the linear region of the mass-vs-time graph was calculated to obtain the evaporation rate.

Thermal efficiency,  $\eta_{th}$ , is defined as the ratio of the useful thermal energy captured by evaporation to the total incident solar energy. The equation is as follows,

$$\eta_{th} = \frac{\dot{m} \times h_{LV}}{C_{opt} * q_{solar}} \quad (7)$$

Where,  $\dot{m}$  is the evaporation rate flux ( $\text{kg/m}^2\text{s}$ )

$C_{opt}$  is the concentration Factor, (1 for one sun)

$h_{LV}$  is the enthalpy change of the water to vapor (including latent heat of vaporization,  $h_{vap}$  and the sensible heat). Typically, the  $h_{vap} \approx 2.26 \times 10^6 \text{J/kg}$ . We will ignore the sensible heat, as per assumption no major temperature rise should happen in a double layered system.

Often,  $q_{evap}$  itself is found by subtracting calculated losses from absorbed power. Well-designed interfacial evaporators can reach >80% efficiency (e.g. yielding  $\sim 1.2\text{-}1.3 \text{ kg/m}^2\text{h}$  under 1 sun).<sup>43</sup> Any efficiency >100% indicates that phenomena beyond simple bulk evaporation are at play. Steady-state modeling often assumes a stable ambient (e.g. fixed room temperature and humidity) to simplify calculations.



## 1.4 Research Objectives and Scope

In this study, our first research objective was to design and evaluate a bilayer solar steam generation device to achieve localized heat generation for efficient SDIE. The system features a photothermal top layer composed of either EG or graphene-based aerogels, and a bottom layer of porous carbon foam serving as a thermal insulator and water reservoir.

For our second objective, the top layer photothermal materials were engineered for enhanced performance: EG was functionalized using a dual approach, non-covalent surface functionalization with 1-pyrenebutyric acid (PBA) and oxidation via hydrogen peroxide ( $\text{H}_2\text{O}_2$ ); to increase surface hydrophilicity and water interaction without degrading its intrinsic photothermal properties. In parallel, graphene oxide (GO) aerogels and GO-graphene nanoplatelet (GnP) hybrid aerogels were synthesized through a reduction-based method to explore alternative photothermal materials with high porosity and water transport capacity. The carbon foam layer beneath acted as a thermally insulating support. By tuning the surface chemistry and structural properties of the top-layer materials, this bilayer configuration aims to enhance solar absorption, and water transport, thereby improving the overall evaporation rate under one-sun illumination. This research provides insights to the development of scalable and cost-effective materials for sustainable solar evaporation technologies.

## Chapter 2

### METHODOLOGY AND EXPERIMENT SETUP

#### 2.1 Solar Experimental Setup

To evaluate the photothermal performance of the fabricated structures, a controlled solar simulation setup was developed. Solar irradiation was simulated using a calibrated LED-based solar simulator capable of delivering intensities ranging from 1 to 3 kW m<sup>-2</sup>, representing both natural and concentrated sunlight conditions.

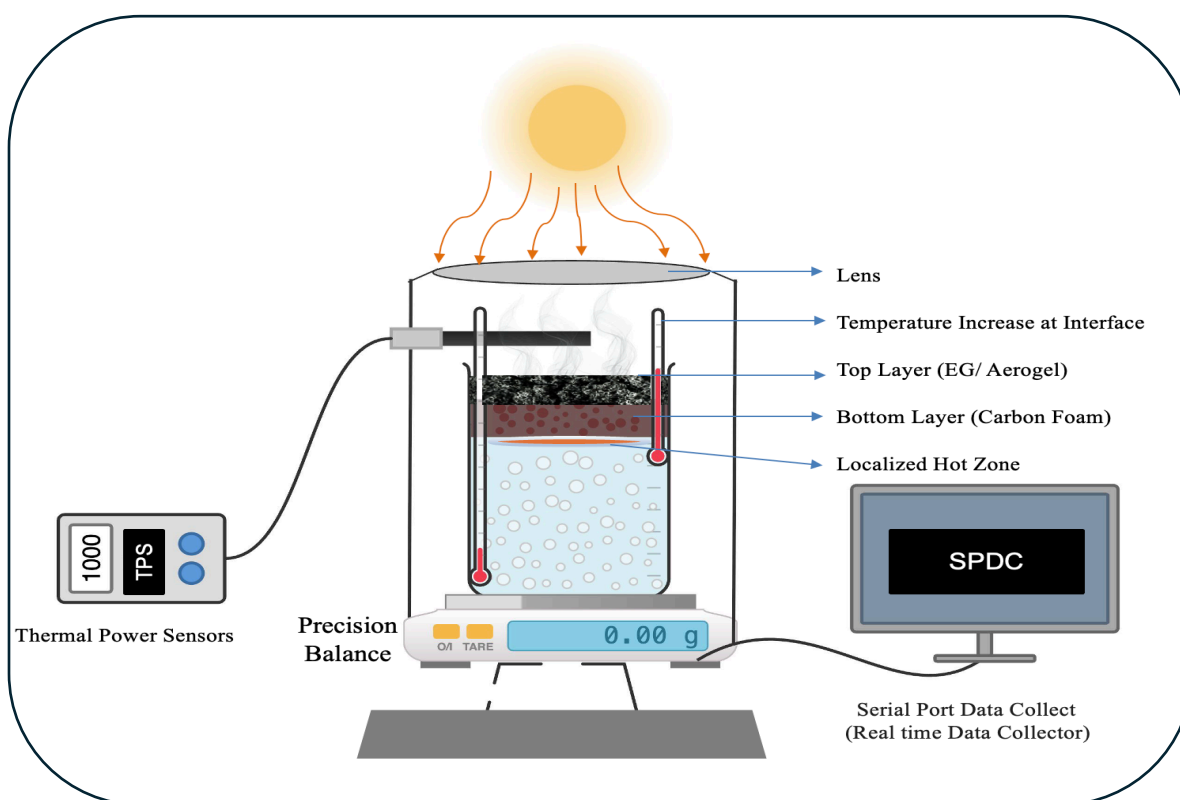


Figure 3: Schematic of the double-layer solar evaporation system. The setup features a top photothermal layer (EG or aerogel) supported by a 10 mm carbon foam substrate for thermal insulation and water transport. Under one-sun illumination, heat is localized at the interface to enhance evaporation. Mass loss is recorded in real time via a precision balance connected to SPDC software.

The irradiance was carefully measured and adjusted using a solar power meter (Thorlabs) to ensure consistent delivery of 1 sun ( $1000 \text{ W/m}^2$ ) or 2 suns, depending on the test condition. A Fresnel lens was employed to homogenize the light distribution across the test surface. The sample was floated in a beaker, which contained a fixed volume of deionized water.

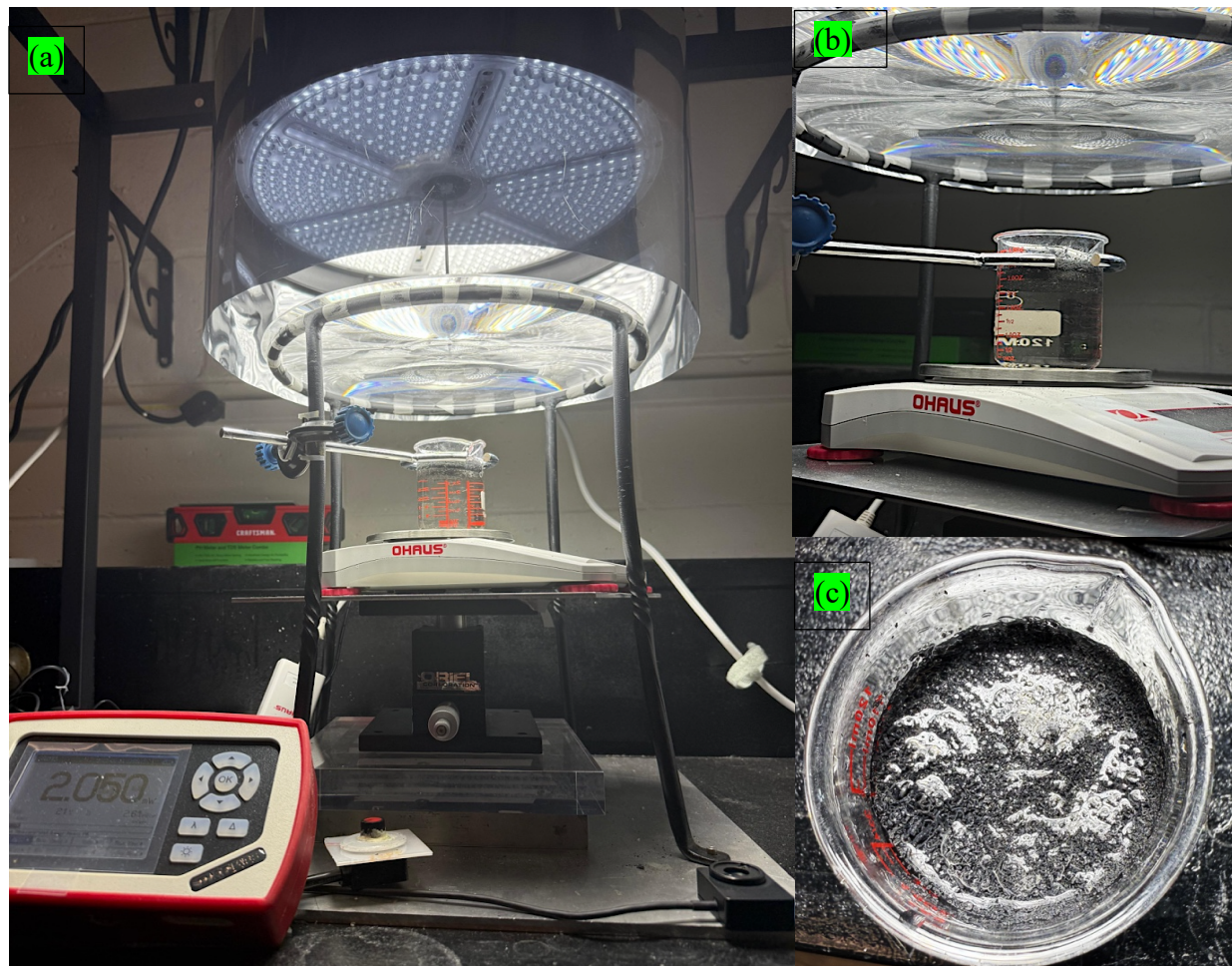


Figure 4: Solar evaporation experimental setup and material observations. (a) Full view of the solar-driven interfacial evaporation test setup under one-sun illumination, showing the LED-based simulator, precision balance, and sample alignment. (b) Closer view of the sample beaker placed on the OHAUS balance during testing. (c) Top-down image of EG in water, demonstrating its hydrophilicity and surface wettability behavior.

To precisely control the distance between the light source and the sample surface, the entire beaker was placed on a precision balance, and the balance could move with the help of a vertically adjustable lab lift. This allowed accurate alignment of the sample with the 1 sun intensity plane, ensuring uniform and reproducible exposure. The precision balance was connected to a SPDC (Serial Port Data Collect) software with a laptop, for the real-time data acquisition of the mass change over time. All experiments were conducted under controlled laboratory conditions (ambient temperature  $\sim 22^\circ\text{C}$ , relative humidity  $\sim 31\%$ ). The bulk water temperature was monitored using a digital thermocouple, to confirm that heat remained localized at the evaporation interface with minimal rise in the surrounding liquid, supporting the concept of thermal confinement.

## 2.2 Design of the Double-Layer Solar Interfacial Evaporator

### 2.2.1 Interfacial Heating Concept:

The solar-driven interfacial evaporation (SDIE) approach centers on localizing heat at the water-air interface, in contrast to traditional bulk heating. By confining solar energy absorption to a thin surface region where evaporation occurs, the system minimizes the heating of bulk water and thus reduces parasitic thermal losses.<sup>23</sup> In this work, we implement a double layer structure (DLS) that floats at the water surface, comprising a top photothermal absorber layer and an underlying thermal-insulation layer. This floating bilayer design allows the formation of a hot spot at the interface under solar illumination, which acts as thermal confinement. The bulk fluid remains at ambient or lower temperature throughout the process. The result shows enhancement of evaporation with lower energy input compared to volumetric or surface-heating methods. Notably, prior studies have demonstrated that such double-layer evaporators can more than double the evaporation rate of water under 1 sun compared to a bare water surface,<sup>23</sup> achieving solar thermal efficiencies far above those of conventional solar stills.

Based on theory and published studies, an effective interfacial evaporator should meet several key requirements:<sup>15,23</sup>

- Broadband Solar Absorption: The top layer should absorb most incident solar radiation ( $\lambda \approx 250\text{--}2500\text{ nm}$ ) with minimal reflection or transmission, converting sunlight to heat at the evaporative interface.
- Low Thermal Conductivity: To suppress heat leakage, the material system should impede thermal conduction from the hot interface down into the bulk liquid. An insulating layer (low  $k$ ) helps to maintain a steep temperature gradient and thermal localization at the surface.
- Hydrophilic Wettability: All interfacing surfaces should be water-loving to promote capillary action. Hydrophilic materials enable continuous wicking of liquid from the reservoir to the heated interface, sustaining evaporation and preventing dry-out.

Porous Structure: A porous architecture is necessary to allow fluid transport and vapor escape. The pore network should be tailored - smaller pores to enhance capillary pumping of water, and larger channels to expedite vapor flow and to mitigate flow resistances.

### 2.2.2 Double-Layer Configuration:

The SDIE device in this work is a bilayer assembly following the above criteria. The top layer is a porous, high-surface-area carbon-based absorber that provides efficient solar absorption and direct heating of the water at the interface. Two top-layer material variants were explored: (i) surface-treated expanded graphite (EG), and (ii) a graphene-based aerogel composed of graphene oxide and graphene nanoplatelets (GO/GnP). The bottom layer is a rigid Duocel® carbon foam substrate (100 pores per inch) that serves as a thermal insulator, floatation support, and water supply scaffold (wick). The schematic representations of the floating double-layer evaporator structure are shown in figure 2 and 3, highlighting the layered design and its operation. Both layers are engineered to be hydrophilic, ensuring water can rise from the bulk through the foam to the absorber, where it is heated and converted to vapor. The figure 2 represents a detailed schematic of the double layered solar evaporation lab setup.

The top layer, composed of EG or graphite oxide-based aerogels, exhibits good to moderate hydrophilicity. This is due to the presence of oxygen-containing functional groups that are

introduced during the surface treatment process of EG, or synthesis process of GO based aerogels. These oxygen groups enhance the material's affinity for water, enabling capillary flow across the porous matrix. The carbon foam used in the bottom insulating layer is naturally hydrophobic due to its chemically inert carbon surface. To make it suitable for this application, the foam was subjected to a chemical surface treatment using a mild oxidizing agent, - typically a 4% nitric acid ( $\text{HNO}_3$ ) solution. This treatment introduces polar functional groups onto the carbon surface. As a result, the treated foam retains its low thermal conductivity and mechanical strength and gains the ability to wick water through capillary action. Together, the characteristics of both layers ensure that water is efficiently transported to the interface, enabling consistent steam generation.

#### Top Photothermal Layer: Expanded Graphite vs. GO/GnP Aerogel:

The upper layer's role is to efficiently convert sunlight into heat right at the evaporation front. In one implementation, expanded graphite is used owing to its excellent solar absorptivity and thermal stability. Expandable graphite flakes with an average lateral particle size  $\geq 300 \mu\text{m}$  were expanded in a furnace at above  $900^\circ\text{C}$  for around 30 seconds. The expansion process creates a low-density, porous matrix of graphite worms, also the expansion process introduces oxygen which makes it hydrophilic to some extent. The surface treated EG layer exhibits a very low reflectance ( $<3\%$  across 250–2250 nm), meaning  $\sim 97\%$  of incident solar energy is absorbed in this top layer.<sup>23</sup> Such high absorptance is critical to maximize photothermal conversion. Moreover, the porous EG provides extensive solid- liquid interface area for effective heat transfer to the water, as well as fast water transport through its interconnected voids. The EG's in-plane graphitic domains also help spread heat laterally, promoting a more uniform temperature across the evaporating surface.

Alternatively, graphene oxide-based aerogel was developed by combining graphene oxide and graphene nanoplatelets. Their performances were compared with GO aerogels. From literature, by carefully tuning the composition and structure, graphene aerogels can reach near-unity solar absorptance while maintaining low thermal conductivity.<sup>43</sup> In our design, GO contributes oxygen-containing functional groups ( $-\text{OH}$ ,  $-\text{COOH}$ ) that improve hydrophilicity and dispersibility, whereas the GnPs (multi-layer graphene sheets) reinforce the carbon framework and enhance electrical/thermal connectivity. This GO/GnP aerogel is black in appearance and highly porous

(>90% porosity), providing active sites for water contact and evaporation. Notably, prior studies have achieved efficient one-sun steam generation using graphene-based aerogels as the photothermal medium.<sup>38</sup> While pure graphene can be hydrophobic when assembled in bulk, the inclusion of oxidized GO and the control of surface chemistry ensure that our aerogel's pore surfaces remain wetting to water. In practice, any slight hydrophobicity of graphene-based frameworks can be mitigated by incorporating hydrophilic binders.<sup>43</sup>

#### Bottom Wicking/Insulating Layer – Carbon Foam:

The supporting layer underneath the absorber is Duocel® carbon foam, a commercially available reticulated vitreous carbon foam. This material was chosen for its combination of high porosity, low thermal conductivity, and chemical/corrosion resistance. The foam (100 PPI) has an open-cell structure with cell diameters on the order of ~300–600  $\mu\text{m}$  and contains a fraction of closed pores that trap air, allowing the device to easily float at the water surface. We prepared the carbon foam by cutting to size (typically 1 cm thickness) and then acid-treating it to introduce hydrophilic surface functional groups. A 4% nitric acid bath for ~2 h was used to oxidize the internal surfaces of the foam, which greatly improves its wettability and wicking performance.<sup>23</sup> After this treatment, the foam readily soaks up water via capillarity. When the bottom of the foam is in contact with the reservoir, it continuously pumps water upward to replenish the evaporated liquid at the top interface. The relatively small pore size in the foam generates a capillary suction, ensuring water rises through the foam to feed the photothermal layer. At the same time, the foam's solid matrix is only a sparse carbon network, which means it is mostly air by volume and thus acts as a thermal insulator between the hot interface and the cooler bulk water.

## 2.3 Materials and Synthesis Techniques

### 2.3.1 Materials

Two grades of GIC compound (expandable graphite) were used, both purchased from GraphiteStore.com (USA). The primary material was ASB-3772, with an average lateral particle size  $\geq 300 \mu\text{m}$  (+50 mesh, ~92%) and an expansion ratio of 280:1 (cc/g). A lower-grade EG (old

EG) from the same supplier, with particle size  $<150\ \mu\text{m}$  and expansion ratio  $<200:1$ , was also used for supplementary purposes.

Industrial-grade graphene oxide ( $0.2\text{--}10\ \mu\text{m}$ , 50 g) was purchased from ACS Material.  $\gamma$ -Oxo-1-pyrenebutyric acid (PBA, 25 g, 95% purity) was obtained from AmBeed. A 1M  $\text{HNO}_3$  solution (4% v/v, 500 mL) was sourced from Carolina, and L-ascorbic acid was supplied by Alfa Aesar. Duocel® carbon foam (100 PPI,  $\leq 0.250$  in thickness) was acquired from Duocel® and served as the thermally insulating and water-transporting base layer.

### 2.3.2 Expanded Graphite Surface Treatment

Following thermal exfoliation, the expanded graphite (EG) was further functionalized through surface treatment processes designed to enhance its hydrophilicity and interfacial activity for solar steam generation. Two independent strategies were employed: chemical oxidation using hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), and non-covalent functionalization using 1-pyrenebutyric acid (PBA).

#### i. Hydrogen Peroxide ( $\text{H}_2\text{O}_2$ ) Treatment

Thermal exfoliation at  $<900^\circ\text{C}$  for 30 seconds led to partial oxidation of the graphite surface, imparting some hydrophilic character. To further increase oxygen-containing functional groups (e.g., hydroxyl and carboxyl), aqueous  $\text{H}_2\text{O}_2$  solutions of varying concentrations (5–30% v/v) were applied to the EG under controlled conditions.

- Reaction durations of 2, 5, 10, and 15 minutes were tested to identify the optimal exposure time.
- Post-treatment, samples were rinsed with deionized water ( $2\times$ , 5 minutes each) to remove residual oxidants and then oven-dried overnight at  $60^\circ\text{C}$ .
- The most effective treatment condition was determined to be 30%  $\text{H}_2\text{O}_2$  for 5 minutes, resulting in enhanced wettability without compromising structural integrity.



ii. 1-Pyrenebutyric Acid (PBA) Functionalization

To achieve stable and efficient surface modification through  $\pi$ - $\pi$  interactions, EG was functionalized with PBA, an aromatic molecule known to non-covalently bind carbon materials and present carboxylic groups for further interactions. The PBA modification protocol involved:

- Dispersing EG in ethanol, methanol, or DMF with dissolved PBA at various mass ratios (EG: PBA = 1:2, 1:1, 1:0.7, etc.).
- Reaction times from 10 to 48 hours were explored.
- A PTFE mesh support was used to stabilize the fragile EG structure and minimize collapse during stirring.
- Optimal performance (based on evaporation rate and integrity) was achieved at 1:1 mass ratio (EG: PBA), 600 mL ethanol, 24-hour reaction time.

Following reaction, the modified EG was rinsed twice with deionized water and dried in an oven overnight.

Table 2: Summary of Surface Treatment Parameters for the treatment of Expanded Graphite.

| Treatment Type                          | Variables Tested                                                                 | Optimal Conditions                        |
|-----------------------------------------|----------------------------------------------------------------------------------|-------------------------------------------|
| H <sub>2</sub> O <sub>2</sub> Oxidation | Concentration: 5%, 10%, 15%,<br>30%<br>Time: varying from 2–15 min               | 30% H <sub>2</sub> O <sub>2</sub> , 5 min |
| PBA<br>Functionalization                | Solvents: Ethanol, Methanol, DMF<br>Ratios: 1:2, 1:1, 2,1 etc.<br>Time: 12- 48 h | EG/ PBA(1g:1g), 600 mL ethanol,<br>24 h   |

The detailed description of the samples with varied parameters can be found in Appendices section, Table A1 and A2. All the mentioned samples in both tables are given separate names, for example EG/PBA-1, EG/PBA -2, EG/H<sub>2</sub>O<sub>2</sub>-1 etc. based on their parameters.

To assess the influence of absorber thickness on evaporation performance, treated EG samples with thicknesses of 0.5 cm, 1.0 cm, and 1.5 cm were also tested under 1 sun illumination. Mass loss data were collected and converted to evaporation rates.

### 2.3.3 Aerogel Preparation

To fabricate a porous, lightweight, and hydrophilic structure suitable for solar thermal applications, graphene oxide (GO) and graphene oxide–graphene nanoplatelet (GO–GnP) aerogels were synthesized via reduction using L-ascorbic acid as a reducing agent. The method uses the self-assembly behavior of GO during reduction and is followed by freeze-drying to yield aerogels with an interconnected, three-dimensional architecture. The schematic in the figure 4 shows the aerogel synthesis in detail, for both the GO aerogel and GO–GnP aerogel synthesis. The detailed process is described in the below sections.

#### i. GO Aerogel Synthesis

Initially, a homogeneous GO suspension was prepared by dispersing GO in 300 mL of deionized water, using a probe sonicator operating in a 3:1 pulse cycle for 45 minutes. To avoid unintended thermal reduction and possible damage to the graphene framework, the dispersion was maintained in an ice bath during sonication. Subsequently, L-ascorbic acid was added to the dispersion, pre-dissolved in an additional 50 mL of water. The mixture was subjected to a second round of sonication for 30 minutes to ensure even distribution of the reductant. Several GO-to-ascorbic acid weight ratios were trialed. Empirical optimization indicated that using less ascorbic acid than GO was essential, as excessive reduction disrupted hydrogel formation, likely due to premature crosslinking and incomplete network stabilization.

Following the mixing stage, the suspension was incubated in an oven at 70 °C for 8 hours to facilitate the redox-driven gelation process. During this stage, the ascorbic acid reduced the oxygen-containing functional groups on GO, forming reduced GO (rGO) sheets that self-assembled into a hydrogel framework via  $\pi$ – $\pi$  stacking and van der Waals interactions.

## ii. GO-GnP Aerogel Synthesis

For hybrid aerogels, graphene nanoplatelets (GnPs) were first sonicated independently in 300 mL deionized water for 1 hour under 3:1 pulse cycle, also using an ice bath to maintain structural integrity. After dispersion, GO was added and sonicated again for an additional 30 minutes to achieve a uniform mixture.

As with the GO-only system, 50 mL of water containing ascorbic acid was added, followed by a final 30-minute sonication. Various ratios of GO: GnP: ascorbic acid were evaluated to optimize gelation behavior and eliminate structural cracking during drying. For pure GO aerogels, a ratio of 1.0 g GO to 0.7 g ascorbic acid was found to yield the most stable, crack-free structure. In the case of the GO–GnP hybrid aerogels, the optimal composition was identified as 0.5 g GO: 0.25 g GnP : 0.5 g ascorbic acid. This formulation produced a robust and structurally uniform hydrogel that, after thermal incubation at 70 °C for 8 hours, formed a mechanically stable and crack-free aerogel network suitable for subsequent freeze-drying.



Figure 5: Photographs of synthesized aerogels.

- (a) GO-GnP hybrid aerogel exhibiting a crack-free cylindrical form.
- (b) Cross-sectional view of GO aerogel showing the characteristic porous, lamellar microstructure formed via freeze-drying.

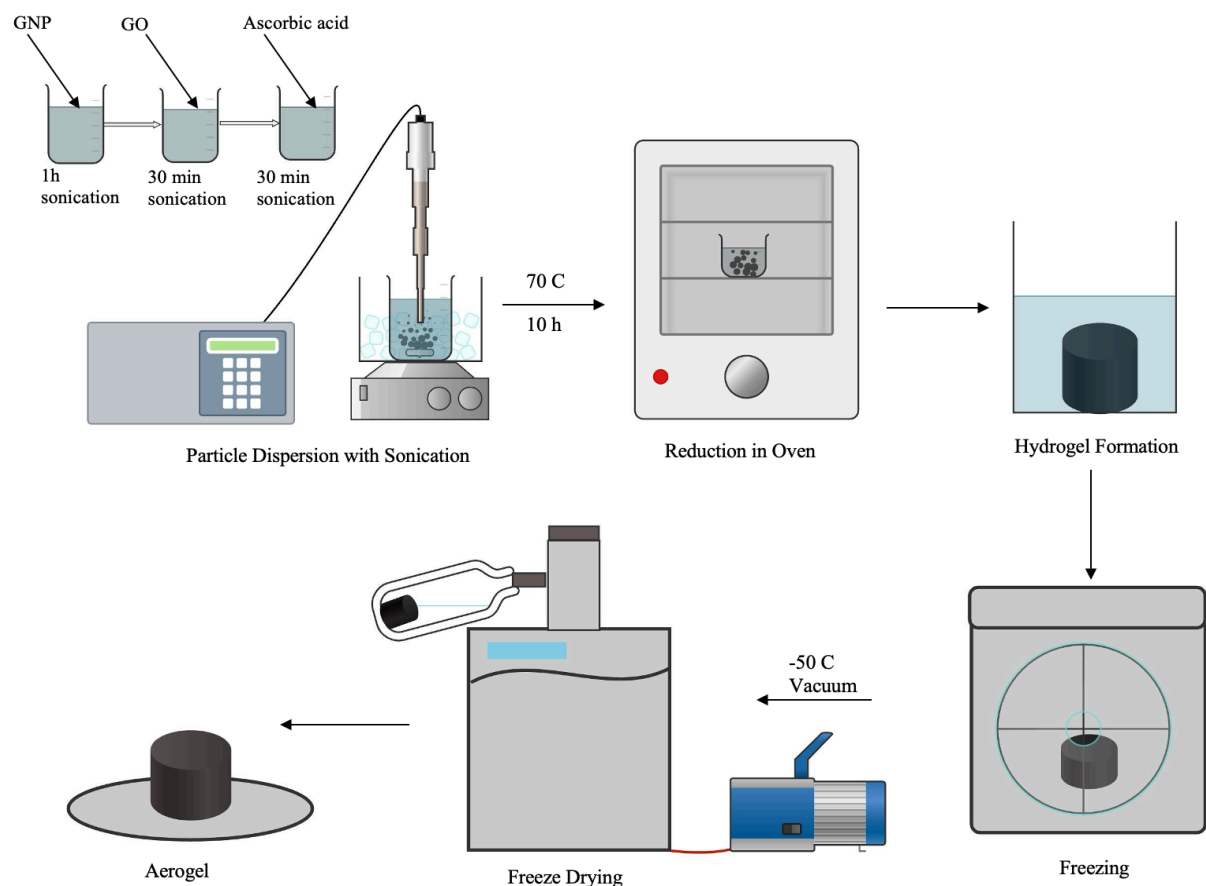


Figure 6: Schematic of the synthesis process for GO and GO-GnP aerogels. GO), GnP, and L-ascorbic acid are sequentially dispersed in deionized water. The resulting suspension is incubated at 70 °C to induce reduction and hydrogel formation. The hydrogel is then frozen at -50 °C and subjected to freeze-drying under vacuum, yielding lightweight, porous GO or GO-GnP aerogels suitable for photothermal applications.

### iii. Post-Processing and Drying

Post-reduction, the hydrogels were immersed in 20% ethanol for 2 hours to facilitate solvent exchange, improving pore preservation during freezing. The samples were then frozen at  $\sim -50$  °C overnight to solidify the network structure and freeze-dried for 24-48h in a VirTis freeze dryer in a vacuum chamber. Freeze-drying ensures sublimation of ice, preserving the high porosity and minimizing shrinkage, as supported by previous studies on step-freeze-drying methods. The

resulting aerogels exhibited a lightweight, foam-like structure suitable for photothermal applications.

#### iv. Physical properties of Aerogel

The graphene oxide (GO) aerogels synthesized in this study exhibit several notable physical properties that align with existing literature. These aerogels possess ultralow densities, typically ranging from 1.8 to 27.2 mg/cm<sup>3</sup>, and high porosities between 80% and 95%, contributing to their lightweight nature and extensive surface area.<sup>37</sup> The thermal conductivity of these materials is exceptionally low, often below 0.01 W·m<sup>-1</sup>·K<sup>-1</sup>, making them excellent thermal insulators. The GO-GnP aerogels synthesized in this study exhibit enhanced physical properties due to the synergistic integration of graphene oxide (GO) and graphene nanoplatelets (GnP). These hybrid aerogels maintain ultralow densities and high porosities, characteristic of GO aerogels, while the addition of GnP significantly improves mechanical strength and thermal conductivity. Specifically, the incorporation of GnP increases the compressive modulus and electrical conductivity of the aerogels, making them more robust and conductive compared to pure GO aerogels. The lamellar architecture formed through unidirectional freeze-casting contributes to these enhanced properties, resulting in materials suitable for applications in solar steam generation.

41,49

#### 2.3.4 Carbon Foam Treatment

As-received Duocel® carbon foam (100 PPI, ≤0.250" thickness) was used as the bottom layer of the double-layer structure due to its high porosity and low thermal conductivity. However, since untreated carbon foam is hydrophobic, surface treatment was necessary to improve water wettability. The foam was immersed in a 1 M nitric acid (4% v/v HNO<sub>3</sub>) solution at room temperature for 2h. This mild oxidative treatment introduced oxygen-containing functional groups (e.g., -OH, -COOH), enhancing hydrophilicity without compromising structural integrity.

After treatment, the foam was rinsed with deionized water and dried in room temperature. The resulting foam exhibited improved capillary action, making it suitable for continuous water transport in the solar steam generation system.

## RESULTS AND DISCUSSION

## 3.1 Evaporation Rate and Thermal Efficiency Calculation

Evaporation performance was evaluated under 1-sun solar simulation (1 kW/m<sup>2</sup>). A precision analytical balance logged the real-time mass loss of water, interfaced via Serial Port Data Collection (SPDC) software. After an initial transient warm-up period (typically 30-45 min), the system reached steady-state evaporation. Each experiment ran for ~3- 3.5 hours in total to ensure a stable linear evaporation regime. The evaporation rate was determined from the slope of the linear mass-loss vs. time curve, divided by the exposed water surface area, A (here A is the test beakers cross-sectional area).

$$\dot{m} = \frac{\Delta m}{A \times \Delta t} \quad (9)$$

Once the steady mass flux was obtained, the thermal efficiency was calculated using the equation (7). In applying this formula, sensible heat contributions were neglected, as the bulk water temperature rose only slightly under insulated, interfacial heating conditions. Any incident energy not converted to vapor is assumed lost via other pathways (conductive heat to the bulk water, convective and radiative losses to the surroundings). A thermocouple was periodically used to monitor the water temperature during illumination, to check that the temperature of bulk liquid to ensure interfacial thermal confinement.

Untreated expanded graphite (EG) showed moderate evaporation performance under 1-sun (1 kW/m<sup>2</sup>) illumination. The EG (ASB-3772) exhibited an evaporation rate of approximately 0.97 kg/m<sup>2</sup>h, while another kind of EG, old EG was also tested for comparison, which yielded 0.94 kg/m<sup>2</sup>h. Old EG refers to a lower-grade expandable graphite, with particle size <150 μm and expansion ratio <200:1. The reduced performance is attributed to lower internal porosity and decreased light scattering of old EG, which impedes capillary water transport and vapor escape. From literature, larger flake sizes in EG facilitate enhanced heat and water transport due to more efficient network formation.<sup>28</sup>

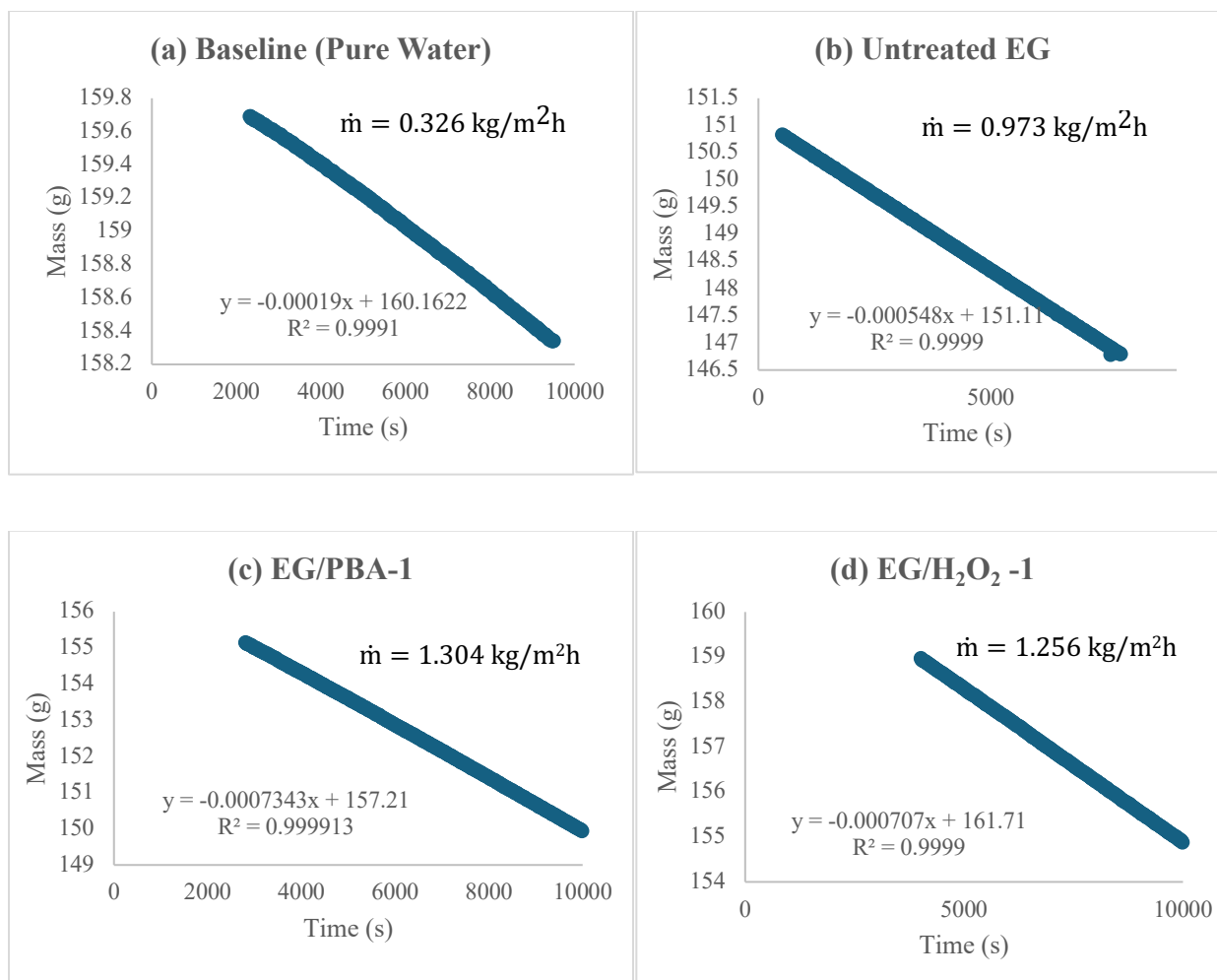


Figure 7: Evaporation performance of water and EG-based materials under 1-sun illumination. (a) Pure water baseline; (b) untreated EG; (c) EG/PBA-1; (d) EG/H<sub>2</sub>O<sub>2</sub>-1. Treated EG samples show significantly higher evaporation rates due to increased oxygen contents.

H<sub>2</sub>O<sub>2</sub>-treated new EG (EG/H<sub>2</sub>O<sub>2</sub> -1) exhibited a significantly improved performance. With 30% H<sub>2</sub>O<sub>2</sub> treatment for 5 minutes, the evaporation rate reached around 1.26 kg/m<sup>2</sup>h (Table A2), while without any H<sub>2</sub>O<sub>2</sub> treatment it was only 0.97 kg/m<sup>2</sup>h. The thermal efficiency was calculated to be 78.8%. This enhancement is primarily due to increased hydrophilicity resulting from the introduction of polar oxygen-containing functional groups (e.g., -OH) during oxidation. These groups reduce the water contact angle, promoting capillary-driven water transport to the evaporation interface. Studies have shown that such oxidative treatments significantly improve the hydrophilicity and surface energy of graphite-based materials, enabling efficient water

replenishment and better thermal localization near the surface.<sup>43,50</sup> Such oxidations also enhance heat transfer from graphene surfaces to water. Additionally, compared to aggressive oxidants like  $\text{KMnO}_4$ ,  $\text{H}_2\text{O}_2$  is environmentally safer and requires shorter treatment durations, making it a scalable and a green approach.

PBA-treated EG (e.g., EG/PBA -1) achieved the highest observed evaporation performance, with a rate of  $1.3 \text{ kg/m}^2\cdot\text{h}$  and a thermal efficiency of 81.61%. The enhanced performance stems from non-covalent  $\pi$ - $\pi$  stacking interactions between pyrenebutyric acid (PBA) and the  $\text{sp}^2$  carbon network in EG. This interaction decorates the graphite surface with hydrophilic  $-\text{COOH}$  groups from PBA without disrupting its porous morphology. Pyrene-functionalization is known to increase wettability and improve dispersibility while preserving the electrical and photothermal properties of the carbon backbone due to the presence of hydrophilic derivatives in the pyrene functional group.<sup>24,34</sup> The aromatic pyrene moiety strongly adsorbs onto graphite via  $\pi$ - $\pi$  interactions, while the butyric acid tail enhances water affinity, resulting in sustained water wicking and enhanced interfacial evaporation. Collectively, the evaporation rate results for pure water (baseline), untreated EG, PBA-treated EG, and  $\text{H}_2\text{O}_2$ -treated EG underscore the impact of material treatments on evaporation behavior and are summarized in Figure 7, which provides a comparative visualization of performance across the samples.

The GO aerogel structure showed comparatively less thermal evaporation rate,  $1.10 \text{ kg/m}^2\text{h}$  and a thermal efficiency of 69.06% under 1 sun. On the other hand, GO-GnP aerogel showed moderate evaporation rate of  $1.22 \text{ kg/m}^2\text{h}$  and a thermal efficiency of 76.5% under 1 sun illumination. The graphs in figure 8 presents their evaporation rate data over time.

The performance of GO-aerogel is likely hindered by weak capillary water transport through the aerogel matrix. If the pore network lacks directional alignment or hierarchical porosity, water cannot efficiently reach the heated surface, resulting in dry zones that suppress evaporation.<sup>51</sup> Surface chemistry also plays a critical role. Aerogels synthesized from GO and GO-GnP may have less oxygen-containing functional groups, which in turn lowers surface hydrophilicity and limits water spreading and retention at the interface.<sup>43</sup> Additionally, optical absorption by GO-based aerogels can be less effective across the full solar spectrum compared to more heavily reduced or



functionalized carbon materials. This results in less efficient solar-to-thermal conversion, which impacts the evaporation rate.<sup>43</sup>

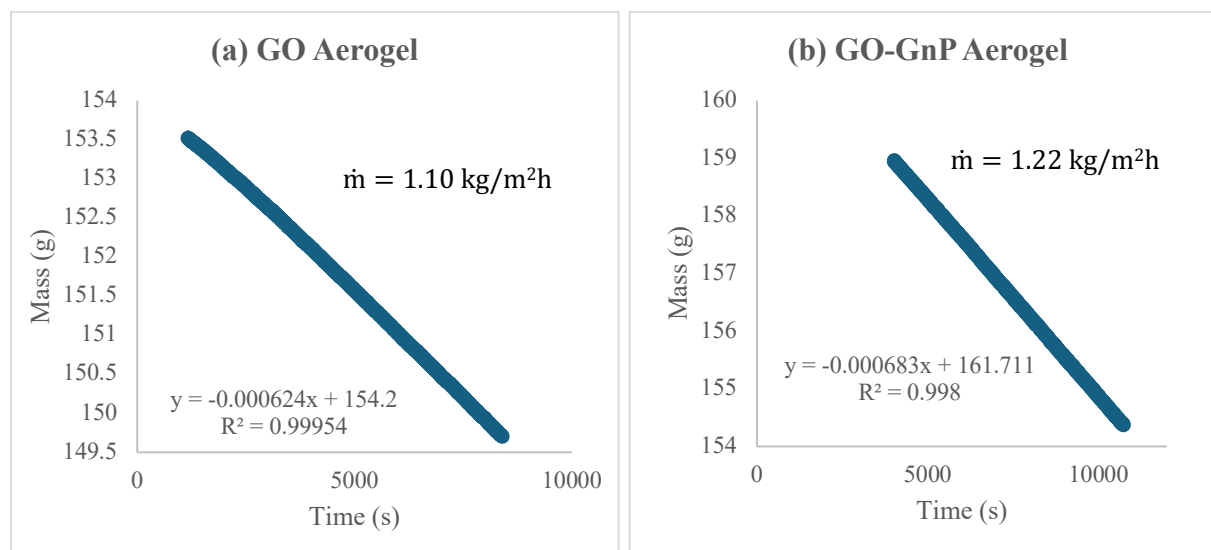


Figure 8: Evaporation performance of GO-based aerogels under 1-sun illumination. (a) GO aerogel and (b) GO-GnP aerogel. The addition of GnP enhances evaporation rate.

The graphs presented in appendix figure B1 demonstrate the role of thermal insulation in enhancing solar evaporation performance. The presence of a carbon foam base beneath the photothermal layer enhanced evaporation rates for both EG/PBA-1 and EG/H<sub>2</sub>O<sub>2</sub>-1. Specifically, the evaporation rate for EG/PBA-1 increased from 1.2081 kg/m<sup>2</sup>·h (without foam) to 1.304 kg/m<sup>2</sup>·h (with foam), corresponding to around 10% increase. Similarly, EG/H<sub>2</sub>O<sub>2</sub>-1 showed an improvement from 1.14 kg/m<sup>2</sup>·h to 1.26 kg/m<sup>2</sup>·h, equating to around 12% increase. These results signify the role of the carbon foam in reducing heat losses. With the foam present, a greater fraction of the absorbed solar energy is confined to the evaporative interface (instead of diffusing into the cooler bulk water), thus driving up the evaporation flux. Additionally, the foam's pore structure assists in capillary pumping of water upward to the EG layer.<sup>23</sup> The improvements observed (10-12% in our case) are notable, and better results can be expected with modification of the bottom layer.

The impact of absorber thickness is shown in appendix figure C1. Both EG/PBA-1 and EG/H<sub>2</sub>O<sub>2</sub>-1 exhibited their highest performance at a thickness of around 0.5 cm, with rates of 1.304 kg/m<sup>2</sup>·h

and  $1.26 \text{ kg/m}^2\cdot\text{h}$ , respectively. As the thickness increased to 1.0 cm and 1.5 cm, a decline in evaporation rates was observed. This trend can be attributed to two competing factors: although thicker layers may improve water retention and reduce rapid drying, they also introduce greater thermal resistance and hinder effective heat transfer to the water surface. Moreover, increased thickness can slow capillary water transport, limiting continuous hydration of the evaporative interface. Gong et al.<sup>21</sup> reported similar findings in graphite-derived composite aerogels, noting that beyond an optimal point, increased photothermal material concentration inhibited water escape and reduced overall efficiency. These insights suggest that optimizing the thickness of the photothermal absorber is essential for maximizing efficiency, as excessive material mass can counteract the benefits of enhanced surface area and porosity.

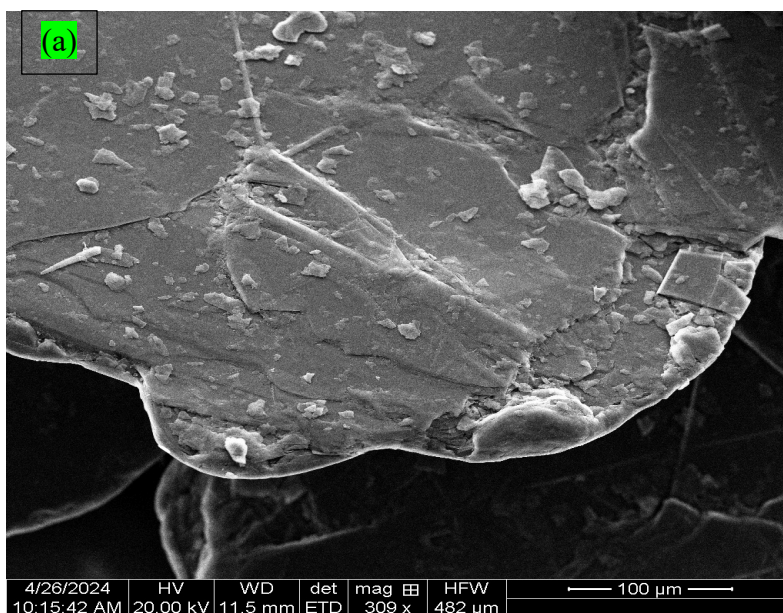
To evaluate the effectiveness of thermal confinement in the system, a thermocouple was employed to monitor bulk water temperature during solar illumination. With the carbon foam insulation in place, the temperature of the bulk water increased by approximately  $8\text{--}9^\circ\text{C}$ , rising from an ambient  $22^\circ\text{C}$  to around  $31\text{--}32^\circ\text{C}$ . In contrast, when the absorber was used without the insulating foam or any interfacial heat-localizing structure, the bulk temperature rose significantly higher, reaching  $40\text{--}42^\circ\text{C}$  under identical conditions. These results indicate that the system achieves partial thermal confinement, effectively restricting a portion of the absorbed solar energy to the evaporative interface. However, the observed temperature rise in the bulk suggests that some heat leakage persists, either through the foam or around the sides of the container. This residual heat loss represents a limitation of the current setup. To further enhance thermal localization and prevent environmental heat gain, future designs could incorporate external insulation around the beaker or test chamber. Such measures would help maintain the bulk water near ambient temperature and improve overall system efficiency.

### 3.2 Structural and Surface Characterization

#### 3.2.1 SEM Analysis

The SEM imaging was done in a Quattro SEM at a higher voltage of 20 kV and a spot size of 3.5. (figure 9). From SEM, the graphite layers (Figure 9-a) appear as flat sheets, resembling a honeycomb lattice, with a regular hexagonal pattern. SEM was used to examine the morphology

of expanded graphite (EG), EG/ H<sub>2</sub>O<sub>2</sub> -1 and pyrene butyric acid-functionalized EG (EG/PBA-1). All samples exhibit the characteristic “worm-like” expanded graphite structure, indicating significant expansion along the graphite c-axis. This worm-like, loosely folded morphology is typical for EG (figure 9-b,c) produced by thermal or chemical expansion<sup>28</sup>, as the graphite layers separate and form a porous, high-surface-area network. The H<sub>2</sub>O<sub>2</sub> treated EG (figure 9-f, g) shows a morphology like pristine EG, - large, worm-like graphite “worms” with no obvious new particulate phases; suggesting that the mild oxidative treatment with hydrogen peroxide did not markedly alter the layered structure at the microscale. Notably, EG/ PBA -1(d, e) in figure 9 also retained the expanded layered appearance, implying that the non-covalent functionalization did not collapse or heavily fragment the graphite framework. Any differences were subtle: the surface of EG/PBA -1 appeared slightly rougher or textured in SEM compared to unfunctionalized EG, consistent with literature reports that grafting aromatic molecules onto graphite can produce a less smooth surface due to the attached functional groups.<sup>52</sup> H<sub>2</sub>O<sub>2</sub>-treated EG maintains this porous architecture but shows increased surface roughness. The mild oxidation etches the graphite edges and introduces nano-scale pits, thereby increasing surface area and promoting capillary water transport. This roughening is attributed to the surface treatment process. Overall, the SEM analysis confirms that the introduction of oxygen preserves the expanded graphitic morphology, - all samples remain as expanded, worm-like graphite structures with only minor surface texture changes.



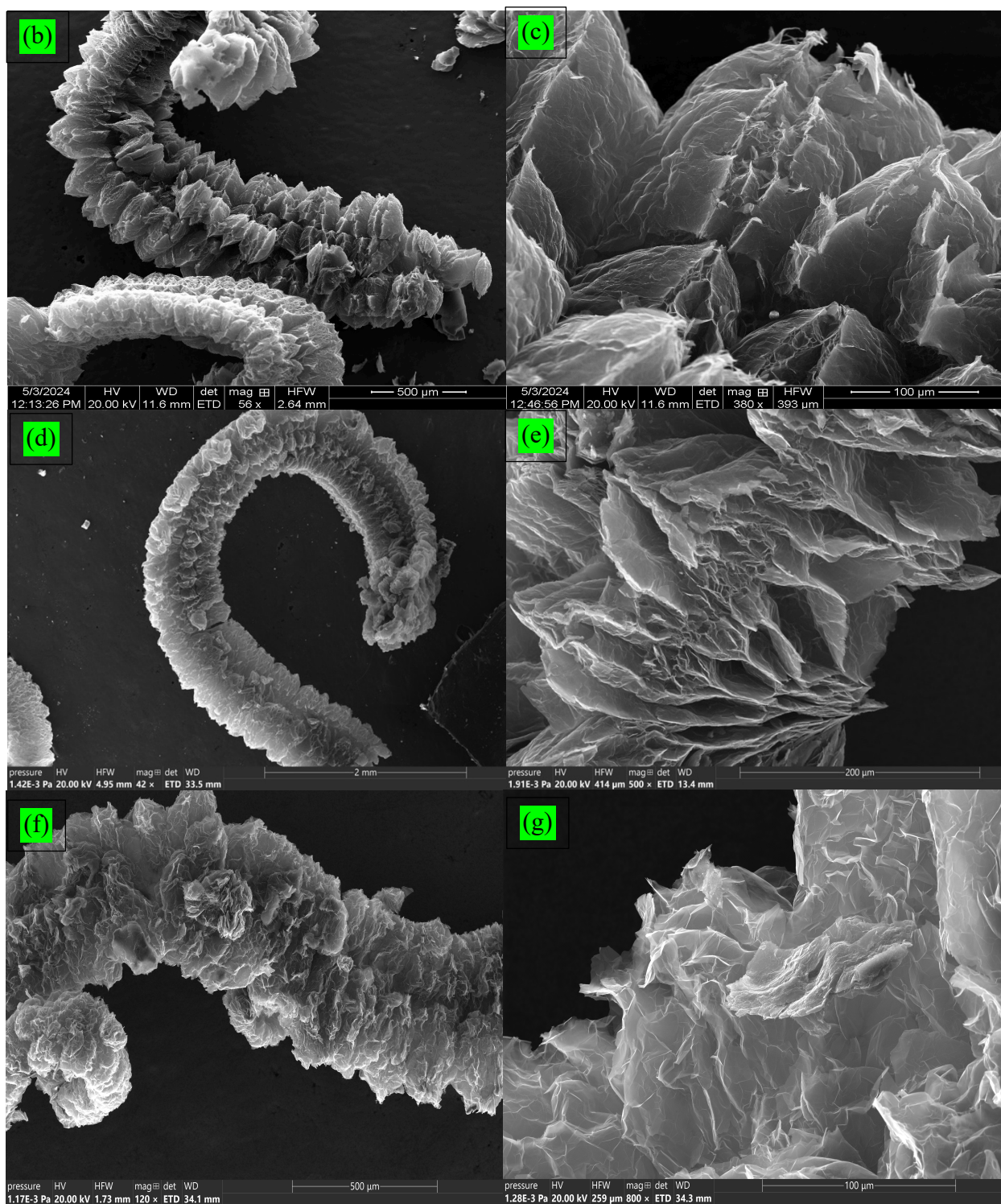


Figure 9: SEM images of graphite-based materials with and without surface treatments. (a) Graphene nanoplatelets (GnP); (b, c) untreated EG; (d, e) EG functionalized with PBA (EG/PBA-1); (f, g) EG treated with hydrogen peroxide (EG/H<sub>2</sub>O<sub>2</sub>-1). Functionalization preserves the porous morphology and wormlike structure while introducing minor surface roughness.

### 3.2.2 XRD Analysis

X-ray diffraction (XRD) analysis was conducted to investigate the structural modifications in expandable graphite (EG) following hydrogen peroxide treatment ( $\text{H}_2\text{O}_2$ -EG) and pyrene butyric acid functionalization (PBA-EG). (figure 10) The primary focus was on assessing changes in interlayer spacing and in-plane crystallinity.

The (002) diffraction peak, characteristic of the interlayer spacing in graphitic materials, was observed at  $2\theta \approx 26.42^\circ$  for untreated EG. Similar diffraction features are reported in thermal interface materials studied by Fatema et. al<sup>53</sup>, who emphasize that such sharp (002) reflections are characteristic of crystalline graphitic structures with preserved stacking order. This corresponds to an interlayer distance (d-spacing) of approximately 0.336 nm, as calculated using Bragg's Law:

$$n\lambda = 2d\sin\theta \quad (9)$$

where  $n=1$ ,  $\lambda=0.15406$  nm (Cu  $K\alpha$  radiation), and  $\theta$  is the Bragg angle, the interlayer spacing ( $d$ ) is calculated to be approximately 0.336 nm.<sup>28</sup> According to the relationship, if  $\theta$  increases, then  $d$  (interlayer spacing) must decrease, assuming constant  $\lambda$ .

In  $\text{H}_2\text{O}_2$ -EG and PBA-EG samples, the (002) peak exhibited a minor shift to lower angles (around  $2\theta \approx 26.2^\circ$ ), indicating slight increase in interlayer spacing to approximately 0.342 nm. This expansion suggests that the introduction of oxygen-containing functional groups in  $\text{H}_2\text{O}_2$ -EG and the non-covalent  $\pi$ - $\pi$  interactions in PBA-EG slightly disrupt the van der Waals forces between graphene layers, leading to a minor increase in the interlayer distance.

Beyond the (002) reflection, the XRD patterns revealed subtle variations in the  $2\theta = 43\sim 45^\circ$  region, corresponding to the (100) and (101) planes associated with in-plane periodicities of the graphite lattice. In untreated EG, these peaks are well-defined, indicative of high in-plane order. In contrast,  $\text{H}_2\text{O}_2$ -EG and PBA-EG samples displayed slight shifts and broadening of these peaks, suggesting minor disruptions in the in-plane crystallinity. These alterations are likely due to the incorporation of functional groups and molecular interactions that introduce strain or defects within the graphene planes.



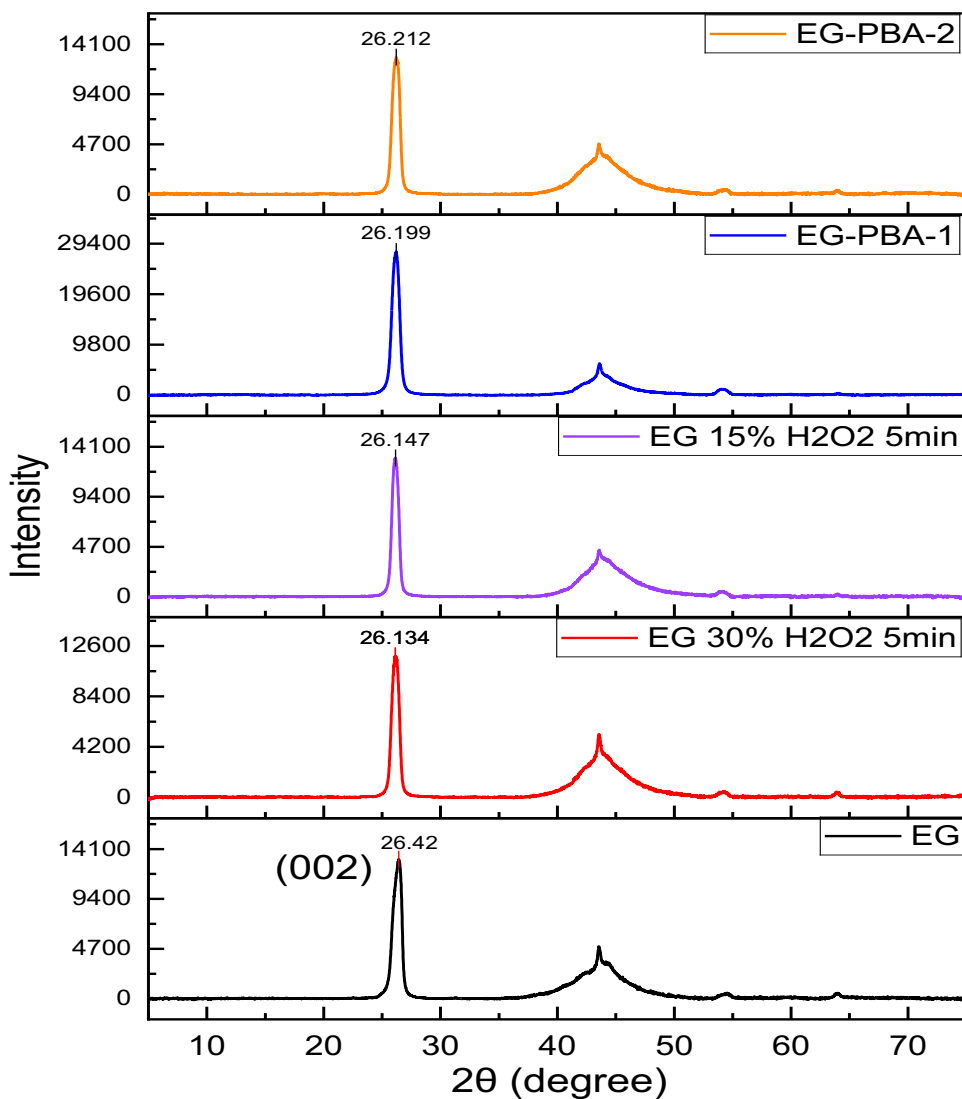


Figure 10: XRD patterns of untreated EG, H<sub>2</sub>O<sub>2</sub>-treated EG, and PBA-functionalized EG.

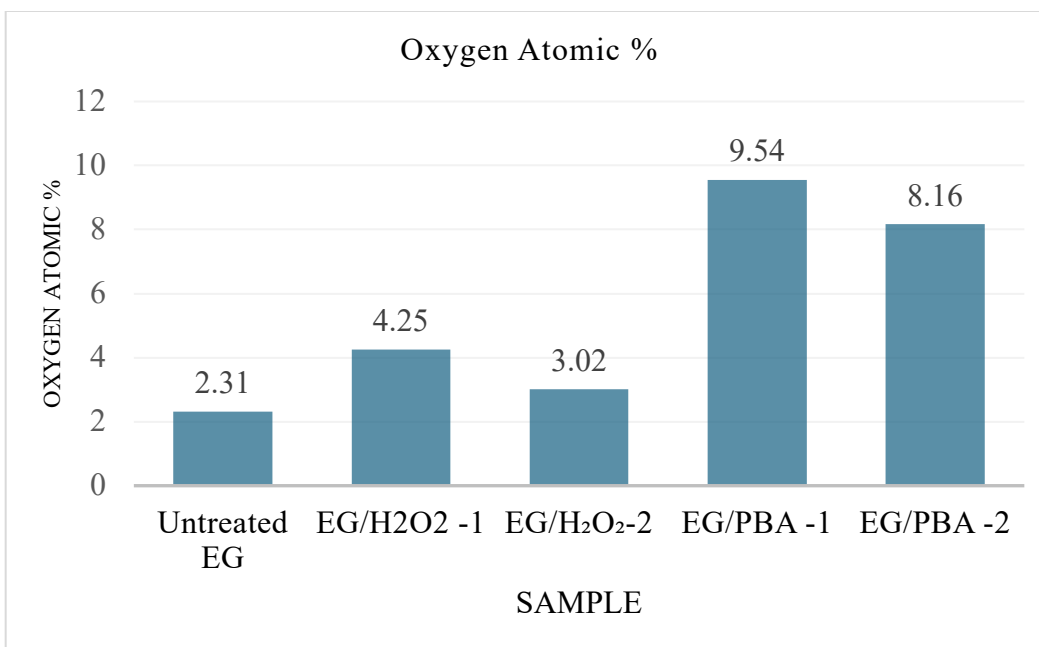
Beyond the (002) reflection, the XRD patterns revealed subtle variations in the  $2\theta = 43 \sim 45^\circ$  region, corresponding to the (100) and (101) planes associated with in-plane periodicities of the graphite lattice. In untreated EG, these peaks are well-defined, indicative of high in-plane order. In contrast, H<sub>2</sub>O<sub>2</sub>-EG and PBA-EG samples displayed slight shifts and broadening of these peaks, suggesting minor disruptions in the in-plane crystallinity. These alterations are likely due to the incorporation of functional groups and molecular interactions that introduce strain or defects within the graphene planes.

The XRD analysis confirms that while the fundamental graphitic structure is largely preserved in both H<sub>2</sub>O<sub>2</sub>-EG and PBA-EG, functionalization induces subtle changes. The observed shift in the (002) peak indicates a slight increase in interlayer spacing, and the modifications in the (100)/(101) reflections suggest minor perturbations in in-plane order. These structural changes are consistent with the expected effects of oxidative treatment and non-covalent functionalization on graphite materials.

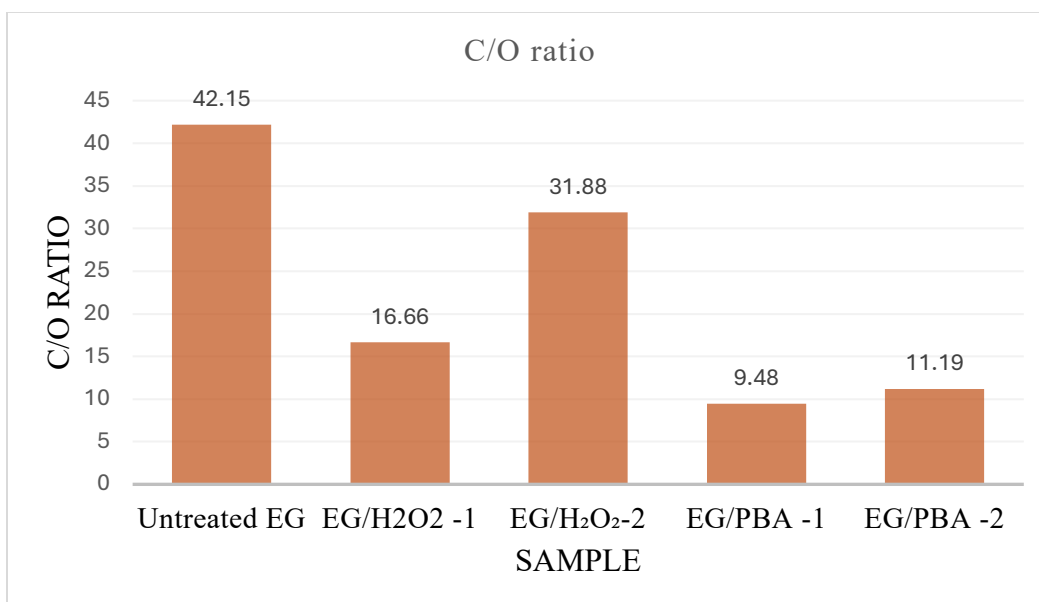
### 3.2.3 XPS Analysis

X-ray photoelectron spectroscopy (XPS) was employed to investigate the surface chemical composition and functionalization states of EG, hydrogen peroxide treated EG (15% and 30%), and PBA functionalized EG. The atomic percentages of key elements (C, O, S, and Ca) were extracted to understand the degree of surface oxidation and functional group incorporation. The untreated EG exhibited a dominant C 1s signal with minimal oxygen (2.31%) and sulfur content, indicating a highly graphitic and chemically inert surface. Upon treatment with hydrogen peroxide, an increase in oxygen content was observed (3.02% and 4.25% in EG/H<sub>2</sub>O<sub>2</sub>-2 and EG/H<sub>2</sub>O<sub>2</sub>-1 samples, respectively). This slight increase reflects the introduction of oxygen-containing functional groups, such as hydroxyl (-OH), epoxy (C-O-C), and carbonyl (C=O), through oxidative attack at defect sites.

PBA-functionalized samples (EG/PBA-1 and EG/PBA-2) displayed a substantial increase in surface oxygen content (up to 9.54% for EG/PBA-1), confirming oxygen increment. The oxygen levels in these samples likely result from the introduction of carboxylic acid or ester functionalities present in the pyrene butyric acid molecules onto the surface of EG. The C/O ratio is shown in Figure (8) where the optimal C/O ratio is for the sample EG/PBA-1, which also gives the best evaporation rate.



(a)



(b)

Figure 11: XPS analysis for comparison of untreated EG and surface treated EG. (a) Oxygen atomic % increment for all samples. (b) C/O ratio. The XPS shows highest oxygen increment, and lowest C/O ratio for EG/PBA-1 sample.



Despite the increase in surface oxygen content observed via XPS, X-ray diffraction (XRD) patterns reveal that the characteristic (002) peak position remains nearly unchanged, and higher-order reflections are only slightly broadened or shifted. This indicates that the graphitic lattice retains its overall crystalline ordering. This apparent discrepancy can be explained by the surface sensitivity of XPS versus the bulk-sensitive nature of XRD. XPS probes the top few nanometers of the sample surface and is thus highly sensitive to the presence of surface-bound functional groups. In contrast, XRD detects long-range periodicity and is less sensitive to such localized or low-density defects. Because the graphitic structure remains intact, - with only a slight increase in interlayer spacing; the functionalization appears to be limited to surface or near-surface regions, without significantly disrupting the overall graphitic stacking order. This is especially plausible for non-covalent interactions in PBA-EG, where  $\pi$ - $\pi$  stacking preserves the structural coherence, and even for mildly oxidized H<sub>2</sub>O<sub>2</sub>-EG, where oxidation is insufficiently aggressive to destroy graphitic domains.

#### 3.2.4 Raman Spectroscopy

To further analyze the crystal structures, a nondestructive Raman Spectroscopy analysis was performed. The result exhibited clear G band peaks for all the EG samples at  $\sim 1580\text{ cm}^{-1}$ . This signifies presence of defect-free  $\text{sp}^2$  hybridized carbon-carbon and high degree of graphitization. In comparison, the result shows a negligible presence of D-bands for all EG samples at  $\sim 1350\text{ cm}^{-1}$ . This signifies low structural defects or disorder. To explain this further, the significantly low  $I_d/I_g$  ratios in table 3 suggest low structural defects or disorder. The negligible peaks of D band also suggest that the oxidation from EG treatments is largely limited to the surface, which eventually resulted in making the EG hydrophilic.

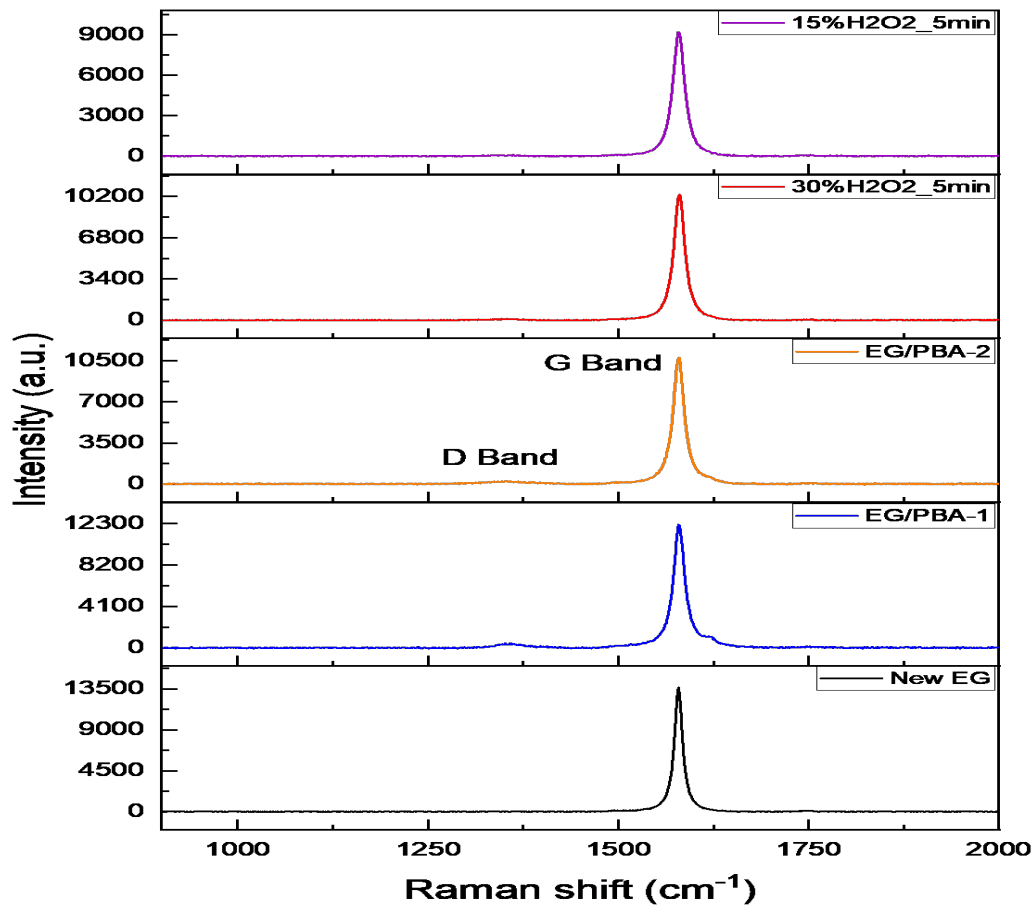


Figure 12: The Raman Spectrum of EG treated samples (EG, EG/H<sub>2</sub>O<sub>2</sub> -1, EG/H<sub>2</sub>O<sub>2</sub> -2, EG/PBA -1, EG/PBA-2) comparing with untreated EG.

Table 3: Raman characterization of the samples including G band, D band and I<sub>D</sub>/I<sub>G</sub> ratio

| Sample name                              | G band (cm <sup>-1</sup> ) | D band (cm <sup>-1</sup> ) | I <sub>D</sub> /I <sub>G</sub> ratio |
|------------------------------------------|----------------------------|----------------------------|--------------------------------------|
| New EG                                   | 1579                       | 1340                       | 0.003                                |
| EG/PBA-1                                 | 1579                       | 1351                       | 0.037                                |
| EG/PBA-2                                 | 1579                       | 1352                       | 0.023                                |
| 30% H <sub>2</sub> O <sub>2</sub> – 5min | 1580                       | 1347                       | 0.011                                |
| 15% H <sub>2</sub> O <sub>2</sub> – 5min | 1578                       | 1347                       | 0.009                                |

### CONCLUSIONS AND FUTURE WORK

This study presents a comparative exploration of expanded graphite (EG)-based materials; both untreated and surface-modified, and graphene-based aerogels for solar-driven interfacial evaporation (SDIE) under one-sun illumination. Among the tested materials, PBA-functionalized EG exhibited the highest evaporation performance at  $1.3 \text{ kg/m}^2\text{h}$  with a thermal efficiency of 81.61%, surpassing untreated EG ( $0.97 \text{ kg/m}^2\cdot\text{h}$ ) and even  $\text{H}_2\text{O}_2$ -treated EG ( $1.256 \text{ kg/m}^2\cdot\text{h}$ ,  $\sim 78.8\%$ ).

The enhancements are primarily attributed to surface functionalization strategies that increased hydrophilicity and preserved the structural integrity of EG. SEM and XRD analyses confirmed that non-covalent functionalization using PBA introduced carboxyl groups on to the surface without significantly disturbing the layered graphitic structure. Likewise,  $\text{H}_2\text{O}_2$  oxidation modestly increased surface oxygen content, improving wettability while maintaining morphology. Raman spectroscopy further showed low  $I_D/I_G$  ratios across all treated samples, confirming minimal structural disorder.

In contrast, graphene-based aerogels, while promising due to their high porosity and lightweight architecture, underperformed relative to surface-treated EG. The GO aerogel achieved only  $1.10 \text{ kg/m}^2\cdot\text{h}$  (69.06%), and the GO-GnP aerogel improved slightly to  $1.22 \text{ kg/m}^2\cdot\text{h}$  (76.5%). The reduced efficiency in aerogels stems from limitations in thermal conductivity management, suboptimal water transport, and potentially insufficient spectral absorption compared to EG.

The XRD, XPS, RAMAN, SEM characterizations suggest that the treated EG samples retained their structure while the attachment of oxygen groups only occurred on the surface. Another observation across material types was the importance of material thickness. For both EG and aerogels, optimal evaporation performance occurred at 0.5-0.6 cm thickness. Greater thickness led to thermal losses and inadequate water delivery. Moreover, thermocouple data indicated partial thermal confinement: the bulk water temperature increased by  $\sim 8\text{--}10^\circ\text{C}$  during operation, compared to  $\sim 20^\circ\text{C}$  without thermal insulation, suggesting room for improvement in heat localization.

This study advances the field of solar-driven interfacial evaporation by demonstrating that simple, low-cost surface functionalization of EG via surface treatment can significantly enhance evaporation performance while preserving structural integrity. Among all tested materials, PBA-treated EG performed the best, confirming the effectiveness of  $\pi$ - $\pi$  stacking in promoting hydrophilicity without disrupting the graphitic framework. The research provides a direct performance comparison between treated EG and graphene-based aerogels, revealing the superior thermal confinement and water transport of EG-based systems. Structural and spectroscopic analyses validated the functionalization strategies, linking improved efficiency to surface chemistry and minimal defect introduction. Additionally, the identification of optimal material thickness and the effect of thermal insulation contribute practical design insights. Overall, this work offers a scalable pathway for more efficient photothermal materials and informs the development of cost-effective, sustainable water purification systems.

Despite the promising results, this study has several limitations. Thermal confinement was not fully optimized, as indicated by the noticeable temperature rise in the bulk water, suggesting heat losses through the insulating layer, and through the test chamber to the environment. Optical absorption across the full solar spectrum was not directly measured, limiting precise correlation between material properties and photothermal performance. The aerogels, while structurally lightweight, lacked optimized pore architecture and exhibited suboptimal water transport and heat localization. Additionally, long-term stability and durability of the surface treated EG under continuous operation in real-world conditions were not assessed. Finally, the absence of Brunauer-Emmett-Teller (BET) surface area measurements limits understanding of the relationship between porosity and evaporation efficiency. Future work can focus on improving thermal confinement by exploring more effective insulating materials or multilayer structures to reduce heat loss to the bulk water. Direct measurement of spectral absorptance using a spectroradiometer would provide clearer insight into the photothermal efficiency of the materials. Optimization of aerogel structure through controlled porosity, doping, or surface functionalization could enhance both water transport and heat localization. Long-term stability tests under continuous operation and varying environmental conditions are essential to evaluate material durability. Additionally, measuring surface area via BET analysis would help correlate microstructure with evaporation performance,

while scaling up the system and integrating it into field-ready prototypes would move the technology closer to practical application.

## APPENDICES

### Appendix A: Supplementary Data Tables

This appendix contains detailed data on EG samples treated with pyrene butyric acid (PBA) and hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), including treatment conditions, solvent types, and corresponding evaporation rates under 1-sun illumination.

Table A1: Samples with PBA treated EG with EG:PBA ratio, solvent amount and treatment time parameters including the evaporation rate.

| Sample Name | EG/PBA ratio<br>(g/g) | Solvent name,<br>amount | Treatment time | Evaporation rate<br>with carbon foam<br>(kg/m <sup>2</sup> h) |
|-------------|-----------------------|-------------------------|----------------|---------------------------------------------------------------|
| EG          | None                  | None                    | None           | 1.12                                                          |
| EG/PBA-1    | 1:1                   | Ethanol,<br>600ml       | 24h            | 1.3                                                           |
| EG/PBA -2   | 1:2                   | Ethanol,<br>600ml       | 24h            | 1.21                                                          |
| EG/PBA-3    | 1:1                   | DMF,<br>600ml           | 24h            | 1.27                                                          |
| EG/PBA-4    | 1:1                   | Methanol,<br>600ml      | 24h            | 1.28                                                          |
| EG/PBA -5   | 1:1                   | Ethanol,<br>300ml       | 48h            | 1.28                                                          |
| EG/PBA -6   | 1: 0.7                | Ethanol,<br>600ml       | 24h            | 1.28                                                          |
| EG/PBA -7   | 1:0.7                 | Ethanol,<br>600ml       | 48h            | 1.24                                                          |
| EG/PBA -8   | 2:1                   | Ethanol, 600ml          | 24h            | 1.19                                                          |

|             |                       |                         |                |                                                               |
|-------------|-----------------------|-------------------------|----------------|---------------------------------------------------------------|
| EG/PBA -9   | 1: 0.3                | Ethanol,<br>600ml       | 24h            | 1.14                                                          |
| EG/PBA -10  | 1.5: 1.5              | Ethanol,<br>600ml       | 24h            | 1.24                                                          |
| Sample Name | EG/PBA ratio<br>(g/g) | Solvent name,<br>amount | Treatment time | Evaporation rate<br>with carbon foam<br>(kg/m <sup>2</sup> h) |
| EG/PBA-11   | 1: 1.5                | Ethanol,<br>600ml       | 24h            | 1.22                                                          |

Table A2: Samples with H<sub>2</sub>O<sub>2</sub> treated EG with various concentrations, treatment time, including the evaporation rate.

| Sample Name                         | H <sub>2</sub> O <sub>2</sub> Concentrations<br>(v/v) % | Treatment time | Evaporation rate<br>(kg/m <sup>2</sup> h) |
|-------------------------------------|---------------------------------------------------------|----------------|-------------------------------------------|
| EG/H <sub>2</sub> O <sub>2</sub> -1 | 30%                                                     | 5min           | 1.252                                     |
| EG/H <sub>2</sub> O <sub>2</sub> -2 | 15%                                                     | 5min           | 1.19                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -3 | 5%                                                      | 5min           | 1.08                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -4 | 5%                                                      | 10min          | 1.12                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -5 | 5%                                                      | 10min          | 1.13                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -6 | 10%                                                     | 5min           | 1.21                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -7 | 10%                                                     | 10 min         | 1.23                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -8 | 15%                                                     | 10min          | 1.20                                      |
| EG/H <sub>2</sub> O <sub>2</sub> -9 | 30%                                                     | 10min          | 1.251                                     |

## Appendix B: Effect of Carbon Foam Insulation on Evaporation Performance

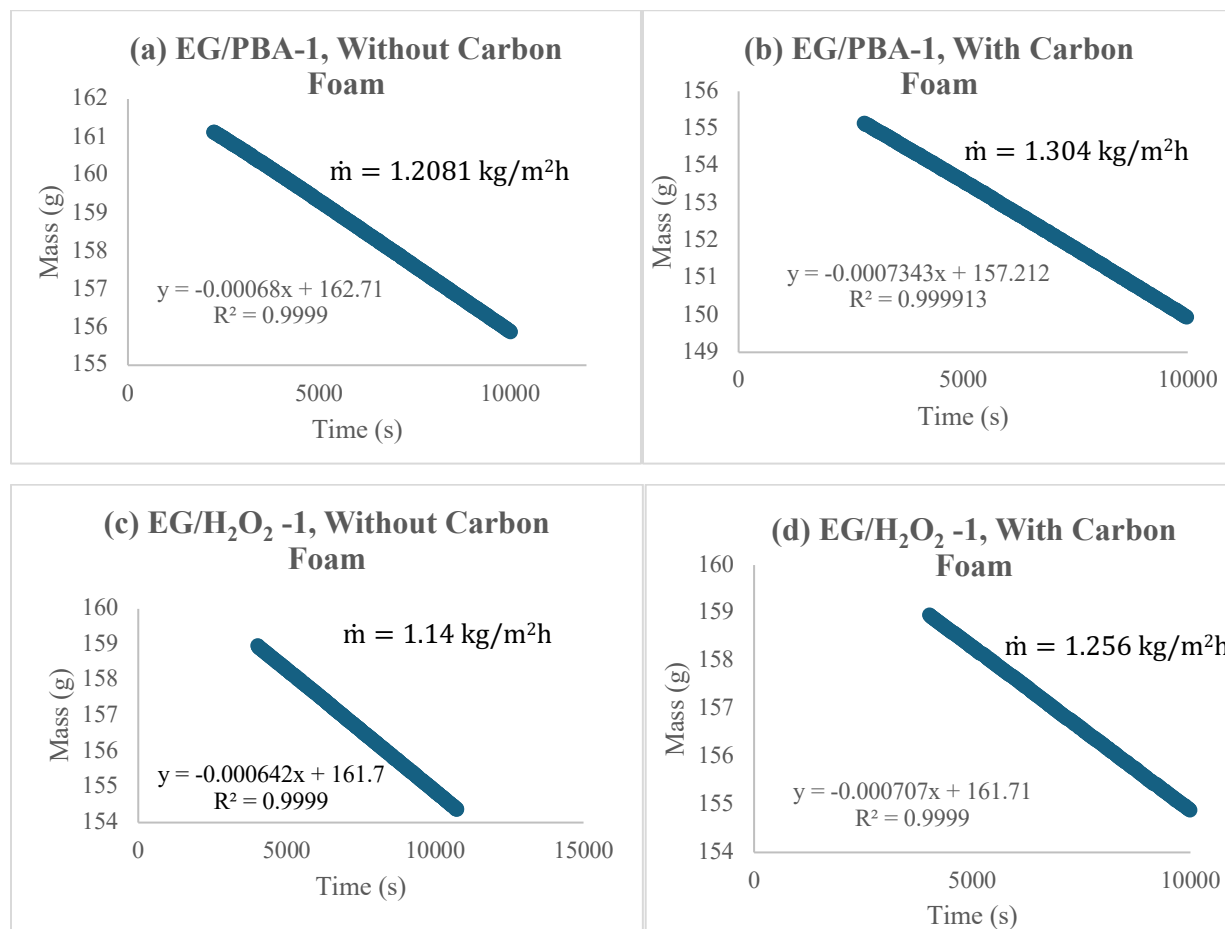


Figure B1: Effect of carbon foam insulation on water evaporation performance of functionalized expanded graphite. Mass loss versus time plots for (a) EG/PBA-1 without carbon foam, (b) EG/PBA-1 with carbon foam, (c) EG/H<sub>2</sub>O<sub>2</sub>-1 without carbon foam, and (d) EG/H<sub>2</sub>O<sub>2</sub>-1 with carbon foam. The addition of carbon foam improves thermal insulation, resulting in higher evaporation rates ( $\dot{m}$ ), as indicated by steeper slopes in the linear regression fits.



## Appendix C: Effect of Absorber Thickness on Water Evaporation Performance

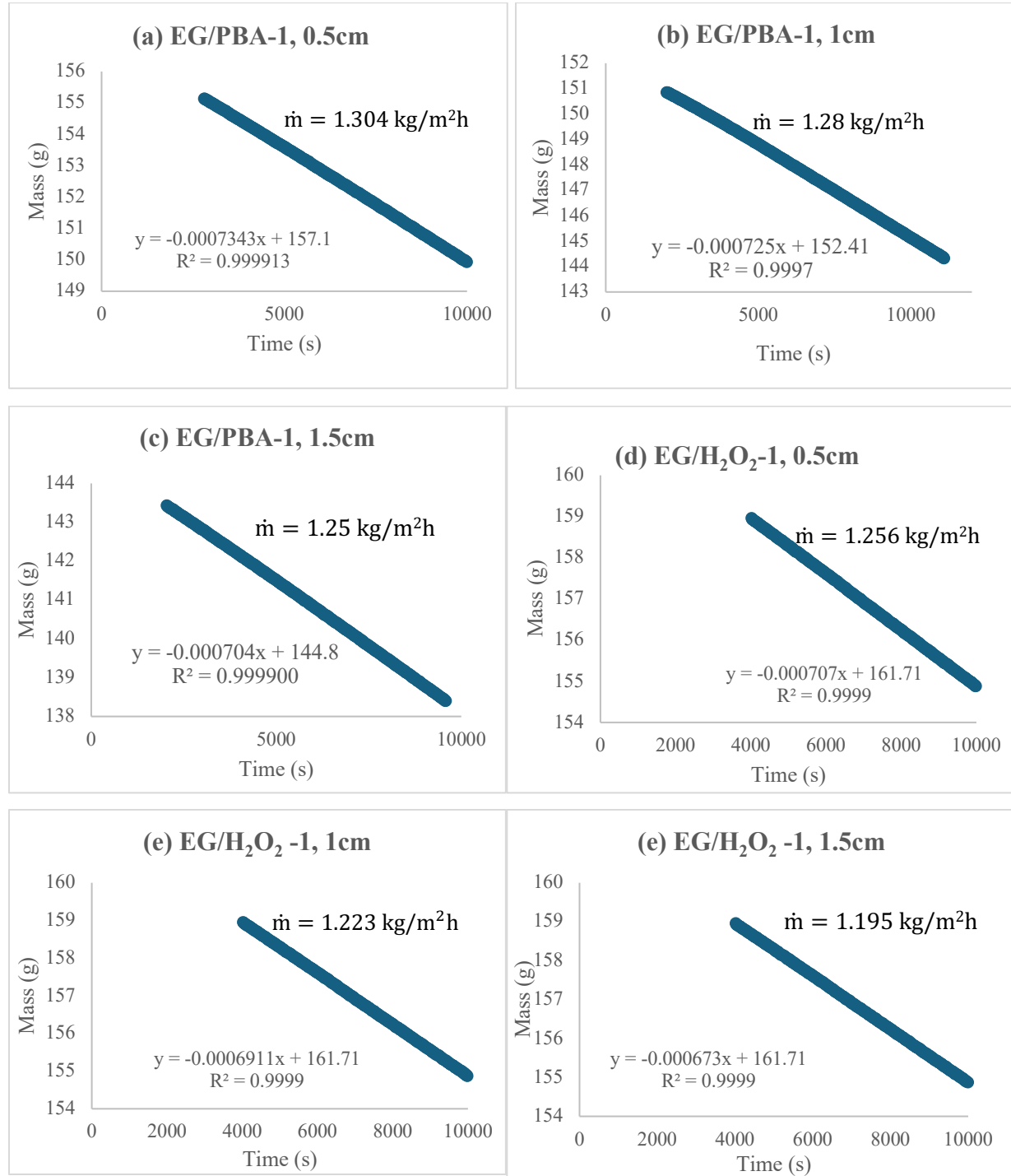
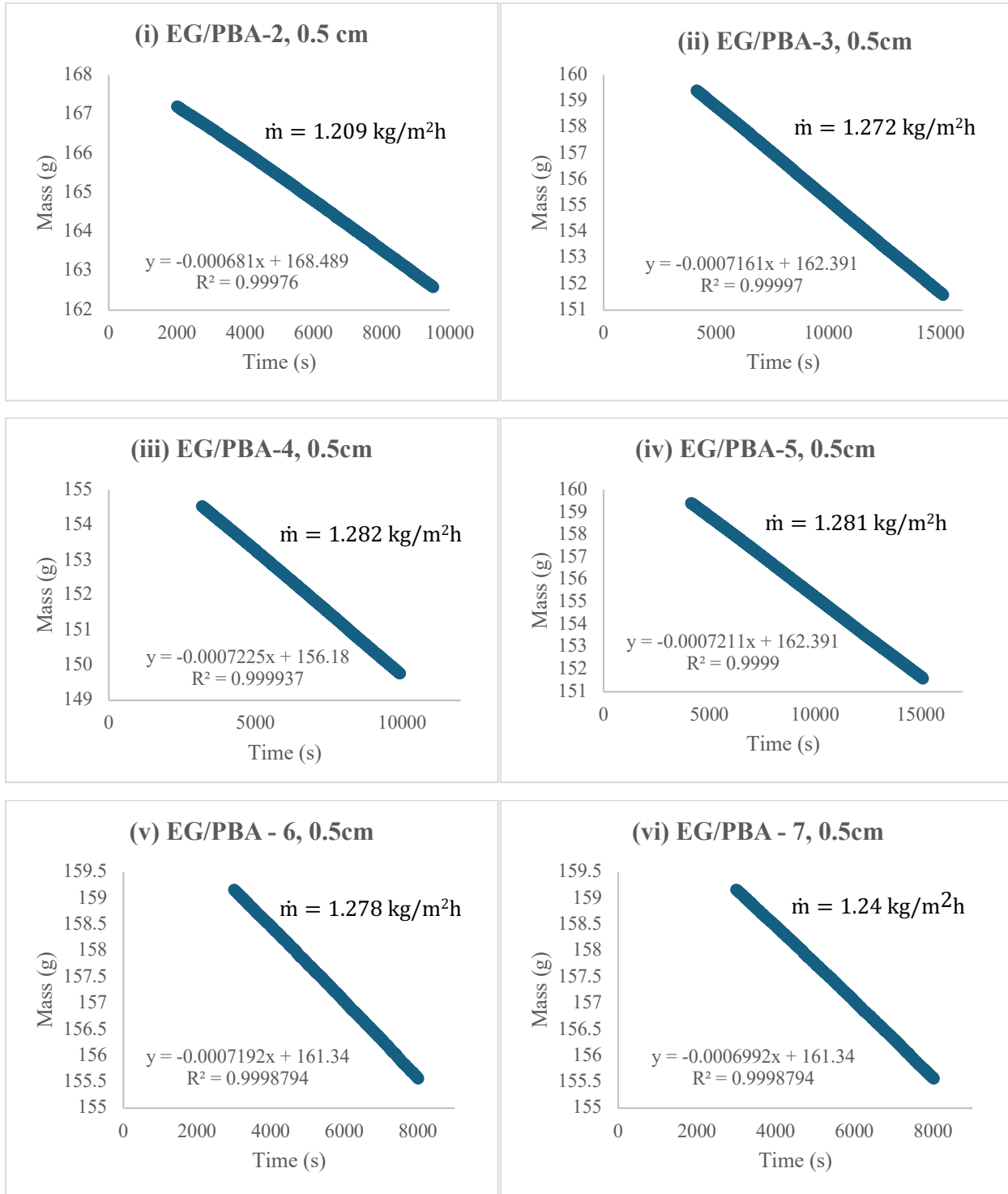


Figure C1: Effect of absorber thickness on water evaporation performance using EG/PBA-1 and EG/H<sub>2</sub>O<sub>2</sub>-1. Mass loss over time for varying absorber thicknesses: (a,b,c) EG/PBA-1 at 0.5 cm, 1.0 cm, and 1.5 cm; (d,e,f) EG/H<sub>2</sub>O<sub>2</sub>-1 at 0.5 cm, 1.0 cm, and 1.5 cm.

# Appendix D: Evaporate Rate Data of PBA treated EG Samples.

This appendix presents evaporation rate data for multiple EG/PBA samples tested under 1-sun illumination. All samples were 0.5 cm thick and tested under identical conditions. Variations reflect sample-to-sample differences due to treatment process.



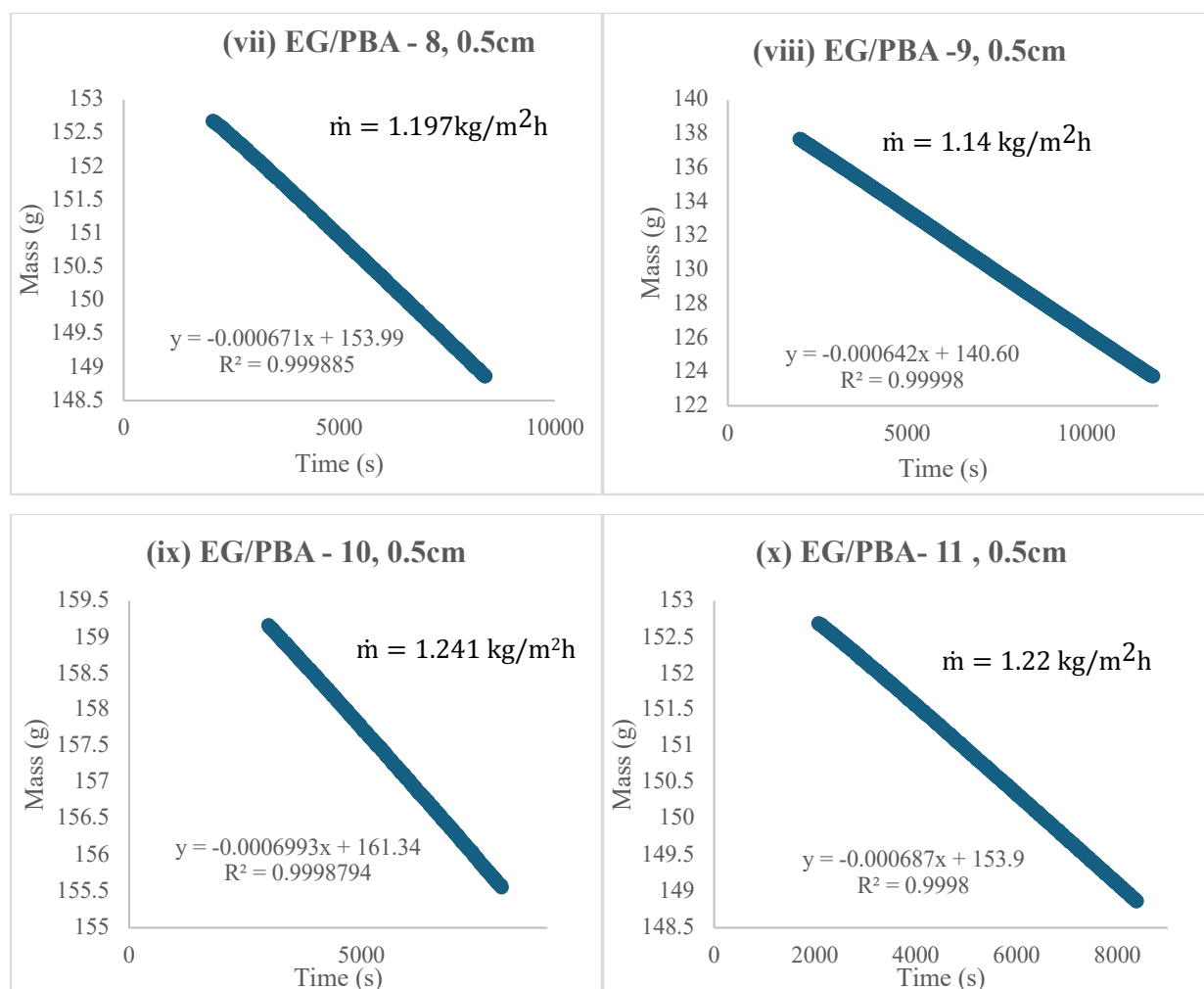


Figure D1: Evaporation performance of EG/PBA samples (0.5 cm thickness) under 1-sun illumination. The graphs show mass loss vs. time plots for ten EG/PBA samples with different treatment ratios or solvents.

# Appendix E: Evaporate Rate Data of H<sub>2</sub>O<sub>2</sub> Treated EG Samples.

This appendix presents evaporation rate data for multiple EG/ H<sub>2</sub>O<sub>2</sub> samples tested under 1-sun illumination. All samples were 0.5 cm thick and tested under identical conditions. Variations reflect sample-to-sample differences due to treatment process.

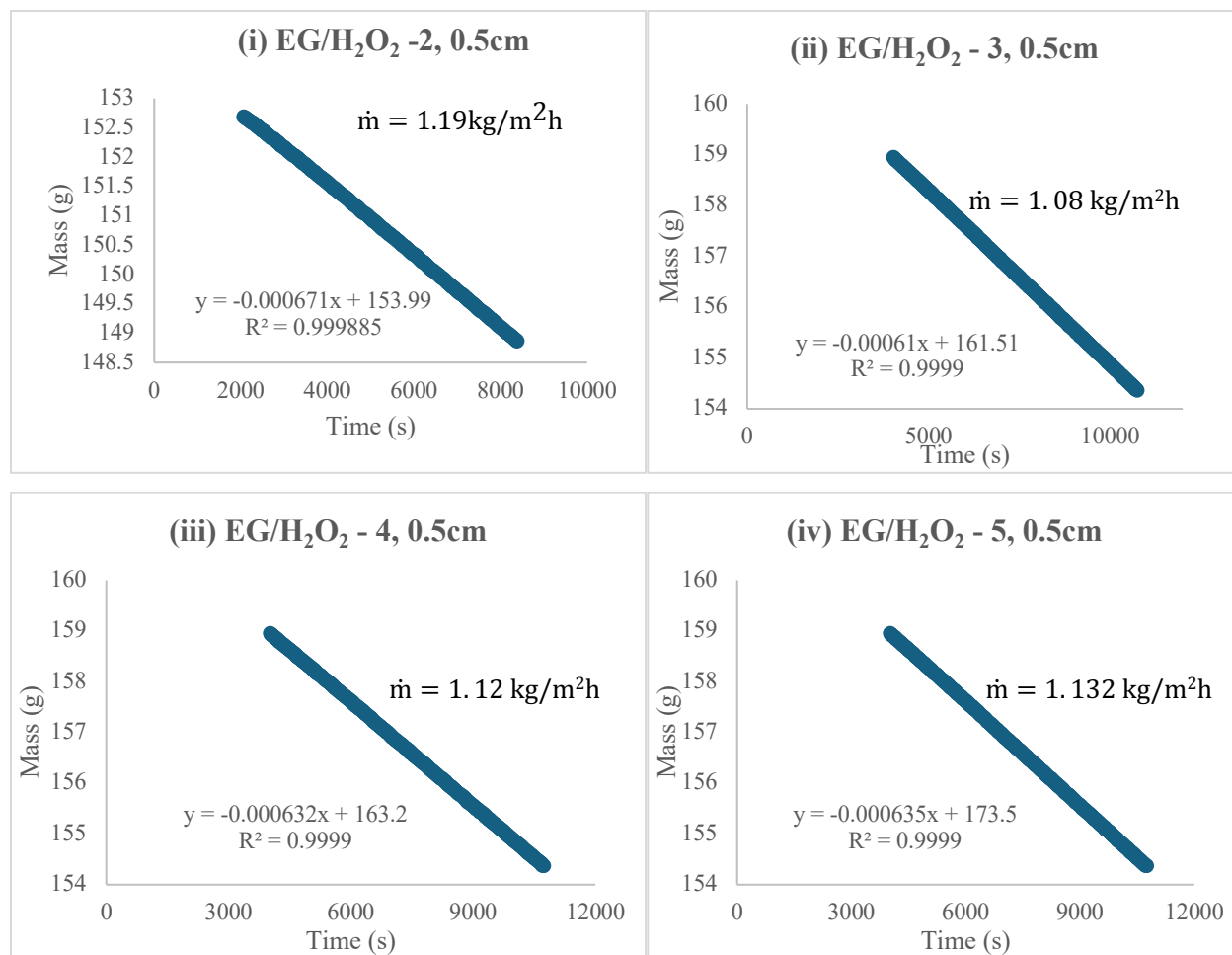


Figure E1: Evaporation performance of EG/H<sub>2</sub>O<sub>2</sub> samples (0.5 cm thickness) under 1-sun illumination. The graphs show mass loss vs. time plots for eight EG/H<sub>2</sub>O<sub>2</sub> samples with different treatment time or solvent concentrations.

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