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Carbonized mangrove wood as photothermal material for solar water desalination

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ABSTRACT

The investigation into the physical properties of carbonized mangrove wood (CMW) is essential for its development as an efficient solar heat absorber. This study explores the physical characteristics of CMW and its potential application in solar desalination. Initially, the mangrove wood was cleaned with running water, followed by ultrasonication at a frequency of 42 kHz in 96% ethanol for 5 minutes, and then heated at 125 °C for 2 hours. The carbonization process was conducted in a furnace for 1 hour at temperatures of 400, 500, and 600 °C. The physical properties of CMW were analyzed using an X-ray diffractometer (XRD), Fourier transform infrared spectroscopy (FTIR), energy dispersive spectroscopy, and scanning electron microscopy (SEM). The findings revealed the formation of a carbon structure at 2 theta angles of approximately 24.08, 23.26, and 23.16°, with carbon contents of 45.05, 36.86, and 39.37%, respectively. CMW was identified as a porous material, making it highly effective for sunlight absorption in seawater evaporation. The hydroxyl content within the CMW structure enhanced its water evaporation capabilities. In experimental investigations aimed at desalinating seawater, a 300-watt halogen lamp was positioned 15 centimeters above the CMW's surface, resulting in an evaporation rate of 5.33 $kg.m^{-2}.h^{-1}$. CMW shows significant promise as a solar evaporator.

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1. INTRODUCTION

The global demand for freshwater is projected to increase substantially in the coming decades, driven by factors such as population growth, urbanization, and industrial development. Seawater desalination offers a promising solution to this challenge; however, traditional methods like reverse osmosis and multi-stage flash distillation are associated with high energy consumption, costs, and environmental impact. Solar desalination, which harnesses solar energy to evaporate and condense water, provides a more sustainable alternative. Solar-powered seawater desalination is a strategic approach to addressing the scarcity of clean water in regions with limited water resources, such as small island areas in Indonesia [1]. However, the efficiency of solar desalination systems is often constrained by the performance of the photothermal materials used.

The photothermal material is a critical component of a solar-powered desalination system [2]. These materials absorb sunlight and convert it into thermal energy to evaporate seawater [3]. The efficiency of this conversion depends on the material's absorptivity and thermal conductivity [4]. High absorptivity enhances the material's ability to effectively utilize solar heat [5]. These properties are linked to molecular lattice vibrations, where electron transitions occur from conjugated pi to pi orbitals, facilitating the capture of thermal energy from solar rays [4]. Photothermal materials can be synthesized from carbonized wood, owing to the plentiful availability and economic viability of the raw materials [5]. Carbonized wood exhibits more abundant micro- and nano-channels, greater chemical stability, and superior light absorption compared to non-carbonized wood [6]. The advantage of carbonized wood lies in its ability to harvest environmental energy and reduce the enthalpy of water [7]. This characteristic is influenced by the structure of carbonized wood, including porosity, pore size distribution, and tortuosity [8]. The natural wood structure, with its numerous pore structures, supports high water storage capacity [9]. Chemically, natural wood contains abundant hydroxyl groups that can form hydrogen bonds with water, reducing the enthalpy of evaporation [10].

A diverse array of wood types has been employed as natural materials in photothermal applications to improve the evaporation efficiency of solar-driven desalination systems. Various wood species have been utilized as raw materials for photothermal materials, including balsa wood (*Ochroma pyramidale*), spruce wood (*Picea asperata Mast.*), poplar wood (*Populus tomentosa Carr.*), and beech wood (*Fagus sylvatica*). Gao *et al.* [11] conducted a comparative analysis of these four wood types and determined the evaporation rates from solar-driven interfacial desalination to be 1,635 $kg.m^{-2}.h^{-1}$ for balsa wood, 1,381 $kg.m^{-2}.h^{-1}$ for poplar wood, 1,476 $kg.m^{-2}.h^{-1}$ for spruce wood, and 1,368 $kg.m^{-2}.h^{-1}$ for beech wood. The application of carbonized balsa wood as a composite material for photothermal purposes has demonstrated enhanced evaporation rates, as documented by Hu *et al*. [12] at 1,7853 $kg.m^{-2}.h^{-1}$, and by Cheng *et al*. [13] at 4.39 $kg.m^{-2}.h^{-1}$. In addition to the four previously identified wood types for desalination purposes, research has investigated the use of carbonized mangrove roots [14]. Inspired by the functional properties of mangrove roots, a solar desalination evaporator has been developed, notable for its salt resistance and high efficiency [15]. While previous studies investigated the impact of several types of carbonized wood on evaporation rates as well as the effect of carbonized mangrove roots on capacitive deionization systems, they have not explicitly addressed the influence of carbonized mangrove wood on seawater evaporation rates.

In Indonesia, mangrove plants are predominantly located in coastal regions and on islands. However, there is a paucity of research regarding their application as photothermal materials. Drawing inspiration from natural processes that demonstrate the ability of mangrove plants to convert seawater and transport fresh water from roots to leaves, it is hypothesized that carbonized mangrove wood could be engineered as a photothermal material and also enhanced. Consequently, it is crucial to investigate the properties of carbonized mangrove wood and its viability as a photothermal material. To enhance our comprehension of the structure, composition, and morphology of carbonized mangrove wood, as well as its potential application as an evaporator in solar water desalination, this study has been undertaken.

2. RESEARCH METHOD

Mangrove wood was procured from the Bunaken National Park area, specifically from the *Avicennia alba* species, designated as the MW samples, as shown in Figure 1 [14], [15]. The wood was sectioned into pieces weighing between 30-50 grams, with dimensions of 2 cm in length and 3-5 cm in diameter [16]. It was initially rinsed with tap water. Subsequently, the wood underwent ultrasonication in 96% ethanol followed by distilled water, each for a duration of 5 minutes. The cleaned wood was then dried at 125 °C for 2 hours in an electric oven. The carbonization process of the mangrove wood samples was carried out in a muffle furnace at temperatures of 400 °C (sample 1), 500 °C (sample 2), and 600 °C (sample 3) for 1 hour [12]. Figure 2 illustrates the outcomes of the carbonization process applied to mangrove wood. Figure 2(a) shows the carbonized mangrove wood (CMW). Following this, the carbonized material was pulverized using a stainless-steel grinder. The resulting CMW powder, depicted in Figure 2(b), was then prepared for characterization.

To assess the structural characteristics, composition, compound classification, and surface morphology of CMW powder samples, we utilized a range of analytical techniques in the materials physics laboratory at Hasanuddin University, Makassar. These techniques comprised X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDX), Fourier transform infrared (FTIR) spectroscopy, and scanning electron microscopy (SEM) [17]. The XRD analysis was performed using a CuKα X-ray tube with a wavelength of 1.54060 angstroms, operating at a generator voltage of 40 kV and a current of 30 mA. Data were collected at a scanning rate of 2° per minute, spanning an angular range from 10° to 70°. For the chemical composition analysis, EDX was employed in conjunction with SEM to provide a semi-quantitative evaluation of the CMW samples. The chemical groups present in the samples were identified using a Shimadzu FTIR spectrometer. The surface morphology of the CMW samples was investigated using a JEOL

SEM, Model JCM 6000 plus, which operated at a generator voltage of 15 kV. The SEM provided detailed images at magnifications of 500, 1,000, and 3,000x. The flow diagram depicting the carbonization and characterization stages is presented in Figure 3.

Figure 1. Kind of samples of mangrove wood (MW *Avicennia alba*)

(a) (b)

Figure 2. CMW samples of (a) rigid cylinder of CMW and (b) powder of CMW

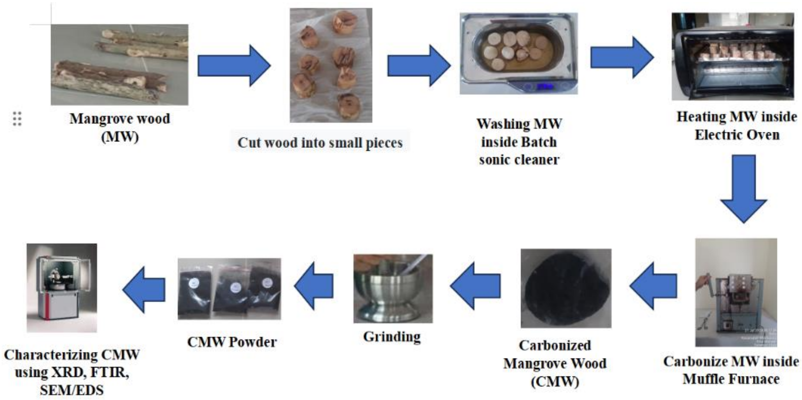


Figure 3. Scheme of MW carbonize and characterize

To evaluate the efficacy of CMW as a solar absorber, a 300 W halogen lamp was employed at varying distances of 15, 20, and 25 cm from the absorber. Seawater designated for desalination was transported to the CMW via a 30 cm-long stove wick, serving as a capillary conduit. The CMW harnessed the thermal energy from the halogen lamp to facilitate the evaporation of the seawater. The rate of evaporation and the corresponding efficiency were calculated using established formulas referenced as [16] and [17]. Figure 4 illustrates the experimental configuration of CMW as an absorber in the seawater desalination process. The CMW Figure 4(a) was constructed using polystyrene foam and affixed to the stove's axis to function as a light absorber in Figure 4(b). Subsequently, a halogen lamp was employed to illuminate the absorber, facilitating the conversion of seawater into water vapor in Figure 4(c). The surface temperature of the CMW was ascertained using a portable infrared thermometer, while the light intensity was gauged with a BH1750 sensor interfaced with an Arduino Uno microcontroller. The mass of the water was determined using a digital scale with a precision of 0.05 grams in Figure 4(d).

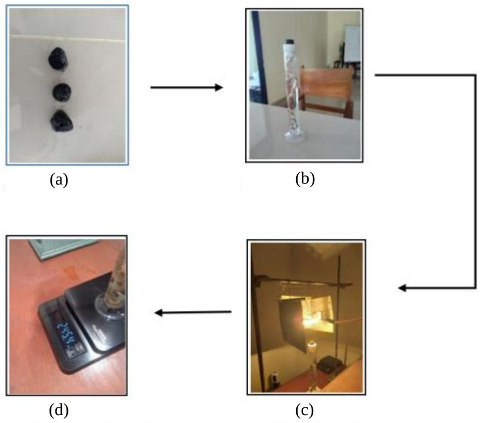


Figure 4. Experimental setup of seawater desalination of (a) CMW, (b) absorber preparation, (c) light illumination, and (d) water mass measurement

3. RESULTS AND DISCUSSION

3.1. Physical and chemical properties of CMW

Research has demonstrated that carbonized mangrove wood exhibits remarkable physical properties as a photothermal material. This conclusion is supported by analyses using XRD, FTIR, EDX, and SEM. The XRD results, illustrated in Figure 5, revealed that the most pronounced crystallization phases occur at 2 theta angles of 24.08, 23.26, and 23.16° for mangrove wood carbonized at temperatures of 400 °C in Figure 5(a), 500 °C in Figure 5(b), and 600 °C in Figure 5(c), respectively. These crystallization phases align with prior research [18], which identified the crystallization phase of mangrove wood charcoal within the 2-theta angle range of 20 to 24°. The emergence of these crystal phases verifies that the carbonization process was effectively conducted in the furnace at the specified temperatures of 400, 500, and 600 °C. Elevating the temperature beyond 400 °C results in diminished crystallinity, as evidenced by the reduced sharpness of the XRD spectral peaks and the shift in peak angles. At 600 °C, the spectral region between 2 theta angles of 10 and 20° displayed an amorphous pattern. Among the three samples, the highest degree of crystallization was observed in mangrove wood carbonized at 400 °C, with a spectral peak at 24.08°.

The FTIR spectroscopy analysis confirmed the presence of various functional groups in CMW, as depicted in Figure 6. The FTIR spectrum indicated that CMW exhibits O-H stretching vibrations attributable to hydroxyl groups and water molecules within the wavenumber range of 3,200-3,600 cm^{-1}. Aliphatic C-H bands from alkene groups were observed between 2,850-3,000 cm^{-1}. N-H stretching vibrations from amide groups appeared in the 1,550-1,640 cm^{-1} range, while C-C stretching vibrations from aromatic groups were detected in the 1,400-1,620 cm^{-1} range. C-O stretching vibrations from ether groups were identified in the 1,000-1,300 cm^{-1} range, C-H stretching vibrations from alkene groups were found in the 800-1,000 cm^{-1} range, and C-Cl stretching vibrations from alkyl halide groups were present in the 600-800 cm^{-1} range. The assignment of these functional groups to their respective wavenumber ranges is supported by prior research [19] and the interpretation of FTIR functional groups in organic materials [20]. This analysis highlighted the presence of hydroxyl groups, which play a role in enhancing the evaporation rate by lowering the enthalpy of water evaporation [10]. Photothermal materials containing hydroxyl functional groups demonstrated improved evaporation efficiency [21]. Increasing the pyrolysis temperature resulted in a reduction of hydroxyl content as it was released from the CMW. CMW carbonized at 400 °C exhibited a high hydroxyl content, which contributed to its enhanced light absorption capability.

The SEM analysis demonstrated that CMW is a carbon-based material distinguished by its rough and porous structure as shown in Figure 7. The SEM images depict the surface morphology of CMW, revealing pores of diverse shapes and sizes, with magnifications at 500x in Figure 7(a), 1,000x in Figure 7(b), and 3,000x in Figure 7(c). The irregular pore configuration is ascribed to the amorphous nature of CMW, indicating an absence of a defined crystalline structure. This irregularity significantly influences the interaction of light with the surface, thereby affecting its light absorption properties. The amorphous characteristic of CMW is beneficial for light absorption due to its extensive surface area and superior thermal conductivity [22]. As the pyrolysis temperature increases, the pores tend to become smaller and less abundant, which may diminish the material's efficacy in converting light to heat and its capacity for water absorption [17]. Sample 1, subjected to a temperature of 400 °C, exhibits a greater number of pores compared to samples 2 and 3, rendering it an optimal candidate for seawater desalination as a light absorber. This structural configuration facilitates efficient water evaporation.

EDX spectroscopy has identified the primary components of CMW as carbon, oxygen, sodium, chlorine, potassium, and calcium, as detailed in Table 1. The carbon content in the CMW samples was quantified at 45.05, 36.86, and 39.37% of the total composition. Notably, CMW subjected to pyrolysis at 400 °C demonstrated the highest carbon content, consistent with the XRD analysis, which indicated the most pronounced crystallization phase. The presence of carbon in CMW is essential for the photothermal process, wherein the material absorbs light, resulting in the excitation of electrons from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). These electrons subsequently relax without radiative emission, producing heat through lattice vibrations [20].

Our analysis of the physical properties revealed that mangrove wood carbonized at 400 °C exhibits high carbon content, numerous hydroxyl groups, and an irregular porous structure. These characteristics allow the CMW to efficiently absorb sunlight, convert it into thermal energy, and use that heat to evaporate saltwater.

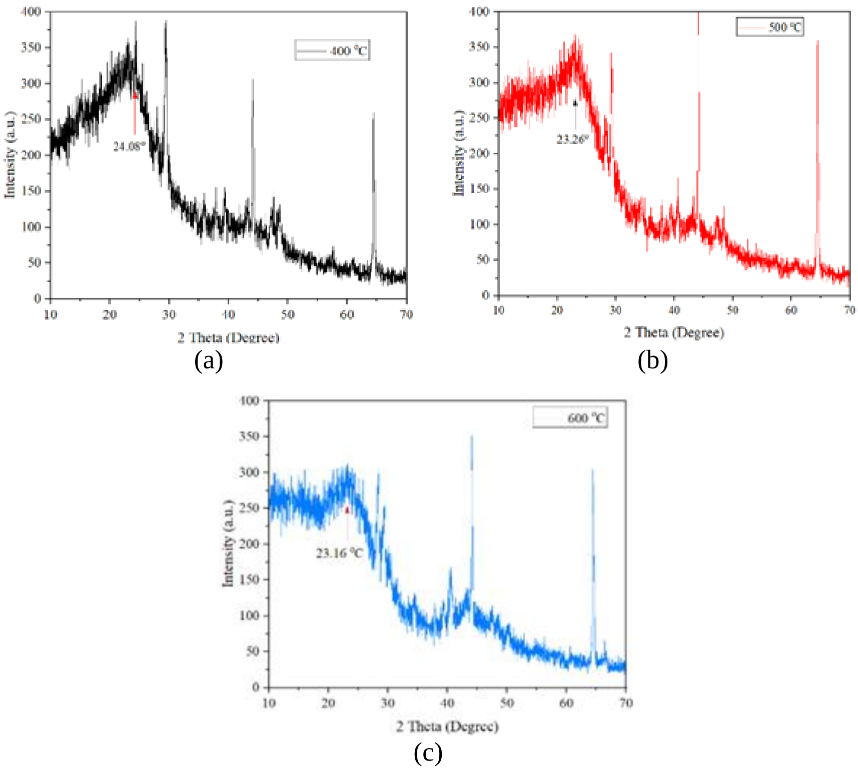


Figure 5. XRD spectra of CMW at (a) 400 °C, (b) 500 °C, and (c) 600 °C

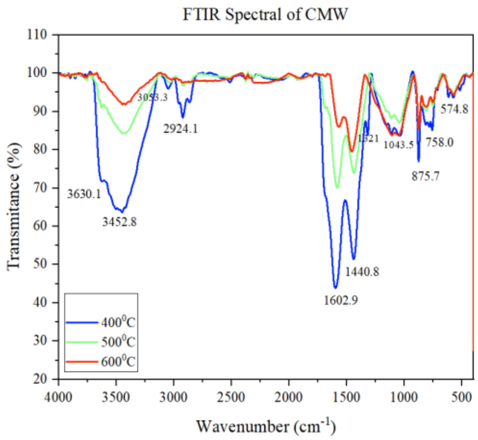
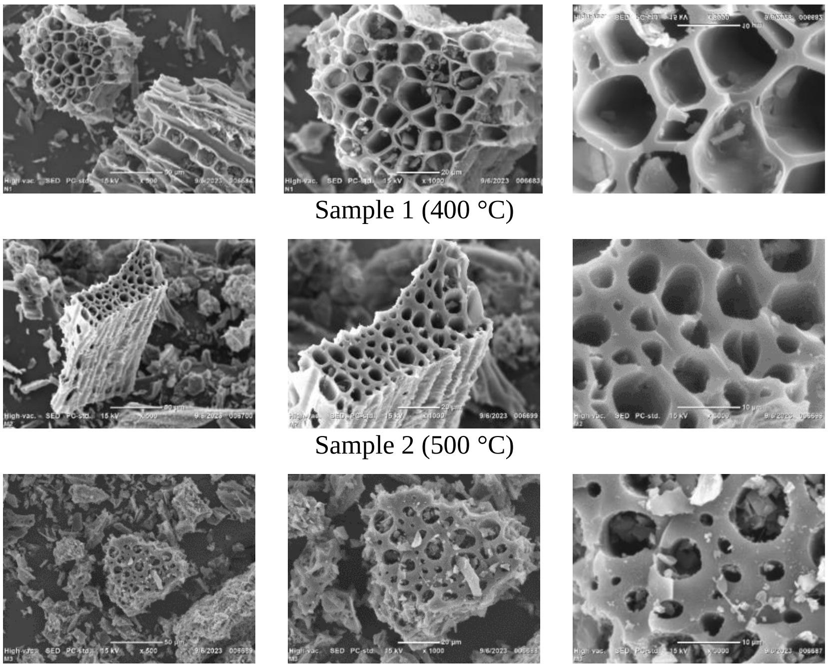


Figure 6. FTIR spectra of CMW



Sample 1 (400 °C)

Sample 2 (500 °C)

Sample 3 (600 °C)

(a) (b) (c)

Figure 7. SEM image of CMW (a) 500x, (b) 1,000x, and (c) 3,000x

Table 1. EDX results of CMW

No.	Element	Compound mass (%)			Type of compound
		Sample 1 (400 °C)	Sample 2 (500 °C)	Sample 3 (600 °C)	
1	C K	45.05	36.86	39.37	C
2	O K	4.15	3.92	3.23	-
3	Na K	1.35	2.46	3.58	Na_2O
4	Cl K	1.92	1.89	16.02	Cl
5	K K	20.08	22.96	33.19	K_2O
6	Ca K	27.46	31.90	4.61	CaO
	Total	100	100	100	

3.2. Implementation of CMW in solar thermal desalination

To evaluate the efficacy of CMW as an advanced photothermal material, its function in the seawater desalination process was meticulously analyzed. Experiments were conducted with CMW serving as a light absorber, illuminated by a 300 W halogen lamp, as depicted in Figure 8. The light was directed perpendicularly at varying distances of 15, 20, and 25 cm from the lamp to the CMW. Styrofoam was employed to insulate the CMW, thereby minimizing thermal dissipation, while a wool fiber wick facilitated water transport to the CMW. After 5 hours of exposure at a distance of 15 cm, the evaporation rate reached 5.33 $kg.m^{-2}.h^{-1}$ with an efficiency of 54%. At a distance of 20 cm, the evaporation rate was 3.66 $kg.m^{-2}.h^{-1}$ with an efficiency of 50%. At 25 cm, the rate was 2.54 kg.m $kg.m^{-2}.h^{-1}$ with an efficiency of 47%. The maximum evaporation rate was observed with a light intensity of 1.2 suns on the CMW surface. The results of the trials conducted in this study exceed those reported in previous research. Some studies have indicated that using carbonized wood in the desalination process leads to a high evaporation rate. Specifically, carbonized wood placed on the surface and floating in saline water achieved an evaporation rate of 6.89 $kg.m^{-2}.h^{-1}$ under the illumination of five suns [16]. In comparison, carbonized wood with 20% porosity in saline water under the illumination of one sun exhibited an evaporation rate of 1.28 $kg.m^{-2}.h^{-1}$ [17]. Carbonized cattail, when exposed to one sun intensity, evaporated water at a rate of 4.12 $kg.m^{-2}.h^{-1}$ [21]. Similarly, under one sun illumination, carbonized bamboo achieved an evaporation rate of 3.13 $kg.m^{-2}.h^{-1}$ [23].

Our research demonstrates that the application of halogen lamp irradiation on CMW leads to a significantly increased evaporation rate compared to the results obtained with carbonized balsa wood or other wood types exposed to standard solar intensity (1 sun). Assuming the desalination process operates for a duration of 10 hours daily, it is projected that 53 kg of potable water will be produced per square meter of

CMW. This yield is anticipated to adequately fulfill the daily drinking water requirements of 10 individuals, based on an estimated consumption of 5 liters per person [24]. If the electricity required for the halogen lamp is generated by converting sunlight into electricity via solar panels, this finding holds substantial promise for supplying fresh water to regions experiencing clean water shortages.

Achieving a high evaporation rate is a significant milestone; however, there remains room for enhancing the evaporation efficiency of CMW. It is imperative to research to understand how the thickness of CMW influences its capacity to evaporate saltwater, as this factor plays a crucial role in the process [15]. Investigating the application of nano-carbon materials, such as carbon dots (CDs), to coat CMW is essential, given that the integration of CDs into wood has been demonstrated to improve evaporation rates [25]–[28]. Moreover, the accumulation of salt on CMW can compromise its stability during water evaporation. Altering the configuration of CMW, for instance, by employing umbrella-shaped evaporators as developed by previous researchers [2], [29], is critical for optimizing its evaporative performance. Despite the promising outcomes, several challenges persist in the development and application of carbonized mangrove wood for solar desalination. The primary concerns are the durability and stability of the material when subjected to prolonged exposure to solar radiation and saline environments. Although preliminary studies suggest favorable performance, long-term stability assessments are essential to confirm the material's viability for practical applications. Additionally, addressing the scalability of the production process for carbonized mangrove wood is necessary. Current methodologies may not be economically feasible for large-scale applications, necessitating the innovation of more efficient and cost-effective production techniques. Furthermore, the environmental impact of sourcing mangrove wood must be taken into account. Mangroves are vital to coastal ecosystems, and unsustainable harvesting practices could have adverse effects.

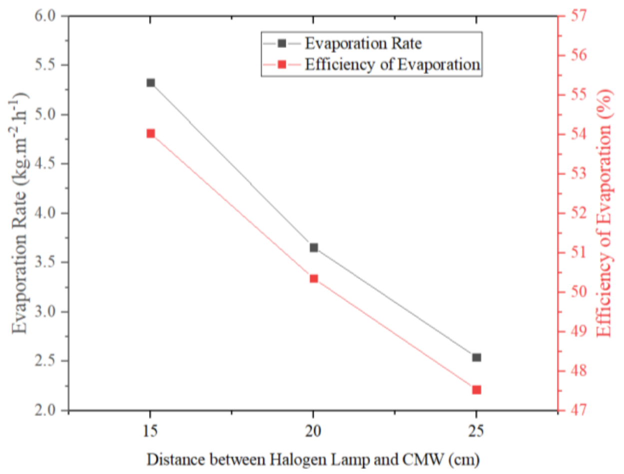


Figure 8. Evaporation rate and efficiency

4. CONCLUSION

Following a comprehensive analysis utilizing X-ray diffraction, Fourier-transform infrared spectroscopy, energy-dispersive X-ray spectroscopy, and scanning electron microscopy, it has been ascertained that CMW exhibits significant potential as a light absorber for solar thermal desalination applications. Under conditions of perpendicular illumination from a halogen lamp situated 15 cm away, CMW achieved an evaporation rate of 5.33 $kg.m^{-2}.h^{-1}$, corresponding to an efficiency of 54%. This remarkable evaporation rate can be attributed to CMW's proficiency in absorbing light and converting it into heat, coupled with its porous structure that facilitates water evaporation. Future investigations will aim to enhance evaporation efficiency by modifying the surface structure and integrating nano-carbon materials.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no financial or personal conflicts of interest that could have influenced the outcomes of this study.

DATA AVAILABILITY

Data will be made available on request. Supplementary data to this article can be found online at https://drive.google.com/file/d/15TBIGsVMiTWGc0AZ_nRmL5YDLOs8gIc1/view?usp=sharing.

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