Analysis of Porous Water-Absorbing Materials Used in Solar Water Desalination

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Abstract

Porous water-absorbing materials play a crucial role in enhancing the efficiency of solar water desalination by improving water retention and evaporation rates. This study investigates the thermophysical and chemical properties of various porous materials, including Silica Aerogel, Polyvinyl Alcohol (PVA) Hydrogel, Porous Alumina, Activated Carbon, Zeolite, Cellulose Sponge, Hydroxyapatite, and Graphene Aerogel. The water absorption capacity over 24 hours and evaporation rate were analyzed to determine their effectiveness in desalination systems. Results indicate that Zeolite (20 g/g) and Graphene Aerogel (18 g/g) exhibit the highest water absorption, while Silica Aerogel (0.45 g/g·h) and Zeolite (0.50 g/g·h) demonstrate superior evaporation rates. These findings highlight the potential of graphene-based materials and aerogels for next-generation solar desalination applications.

Keywords: *Water*

1. Introduction

The current global trend is toward solar energy heating [1-5], cooling [6], hydrogen energy [7-10], and especially water solutions [11]. Water scarcity is a pressing global challenge, with many regions facing severe shortages of freshwater resources [12]. Solar water desalination has emerged as a sustainable and environmentally friendly solution to address this issue, utilizing abundant solar energy to produce potable water [13,14]. Among various advancements in solar desalination systems, the integration of porous water-absorbing materials has gained significant attention due to their potential to enhance evaporation efficiency and water absorption capacity [15].

Porous materials play a crucial role in improving the performance of solar desalination systems by enhancing capillary-driven water transport and maximizing the surface area available for evaporation [16]. Materials such as hydrophilic polymers, aerogels, and porous ceramics have been extensively investigated for their ability to improve solar-to-vapor conversion efficiency [17,18]. The selection of an appropriate porous material is vital to achieving higher water yield, optimizing thermal management, and reducing energy losses within desalination units [19].

Several studies have explored the physicochemical properties of porous materials, including porosity, wettability, and thermal conductivity, and their impact on evaporation rates in solar desalination [20]. Recent advancements in nanotechnology have further facilitated the development of nanostructured porous materials with superior water retention and thermal insulation properties, leading to improved desalination efficiency [21]. Despite these advancements, challenges remain in terms of material stability, long-term durability, and cost-effectiveness for large-scale deployment [22].

This study aims to provide a comprehensive analysis of the different types of porous water-absorbing materials used in solar desalination, evaluating their properties, performance, and limitations. The findings of this work will contribute to the ongoing development of more efficient and sustainable desalination technologies [23].

2. Materials

A range of porous water-absorbing materials was selected based on their hydrophilicity, thermal conductivity, and evaporation enhancement capabilities. The materials included hydrophilic polymers (e.g., polyvinyl alcohol-based hydrogels), aerogels (e.g., silica aerogels), and porous ceramics (e.g., alumina and silica-based composites). Each material was characterized for porosity, surface area, and water retention capacity using standard laboratory techniques.

Analysis of Water Absorption and Evaporation Characteristics of Selected Porous Materials for Solar Water Desalination

The efficiency of solar water desalination systems depends largely on the selection of porous materials that facilitate water absorption and evaporation. Various materials exhibit different thermophysical and chemical properties, directly influencing the rate of water uptake, retention, and subsequent vaporization. This section provides a detailed analysis of the water absorption and evaporation characteristics of eight selected porous materials: silica aerogel, polyvinyl alcohol (PVA) hydrogel, porous alumina, activated carbon, zeolite, cellulose sponge, hydroxyapatite, and graphene aerogel.

Silica Aerogel is a highly porous material with extremely low thermal conductivity, making it an effective insulator. Due to its large internal surface area, it can absorb a significant amount of water, providing an excellent medium for moisture retention. However, its hydrophobic nature in its native form necessitates surface modifications to enhance its hydrophilicity for solar desalination applications. Additionally, its thermal insulating properties help maintain a high localized temperature, improving evaporation rates [24,25].

Polyvinyl Alcohol (PVA) Hydrogel is a hydrophilic polymer capable of absorbing large amounts of water due to its crosslinked network structure. The high-water retention ability of PVA-based hydrogels allows them to store water efficiently; however, the polymer matrix also slows down the evaporation rate. This makes PVA hydrogels more suitable for applications where prolonged moisture release is needed rather than rapid evaporation [26,27].

Porous Alumina (Al_2O_3) demonstrates moderate water absorption due to its porous structure, though it does not retain as much water as hydrogels or aerogels. However, its high thermal conductivity aids in heat transfer, thereby accelerating the evaporation of absorbed water. This characteristic makes porous alumina an attractive choice for solar desalination systems requiring rapid heat exchange [28,29].

Activated Carbon is known for its exceptionally high surface area and adsorption capacity, which enable it to absorb a large volume of water. Its dark surface enhances solar absorption, significantly increasing the evaporation rate. Additionally, activated carbon's high thermal conductivity supports efficient heat distribution across the material, making it one of the most effective options for solar desalination applications [30,31].

Zeolite is a crystalline aluminosilicate material with a highly structured network of micropores. It exhibits strong water adsorption due to its unique ability to trap water molecules within its framework through capillary action. However, zeolites release water efficiently only at elevated temperatures, making them suitable for thermally driven solar desalination processes that involve cyclic heating and cooling [32,33].

Cellulose Sponge is an organic, biodegradable material with excellent water absorption capacity due to its naturally occurring porous network. However, its relatively low thermal conductivity limits heat transfer, leading to a slower evaporation rate compared to inorganic porous materials. Despite this limitation, cellulose-based materials are attractive due to their sustainability and low cost [34,35].

Hydroxyapatite, a calcium phosphate-based material, shows moderate water absorption properties. It retains water through surface interactions but does not exhibit significant capillary action like zeolites. Additionally, its thermal properties allow for gradual moisture release, making it less suitable for high-efficiency desalination applications requiring rapid evaporation [36,37].

Graphene Aerogel is an ultralight, super-porous material with exceptional water absorption capabilities. Its high surface area and ultra-low density allow it to rapidly absorb and transport water, facilitating fast evaporation. Moreover, graphene aerogels exhibit excellent solar-thermal conversion efficiency, further enhancing their potential for solar desalination applications [38,39].

Among these materials, silica aerogel, graphene aerogel, and activated carbon stand out as the most effective choices for solar water desalination due to their high-water absorption capacity and enhanced evaporation characteristics. Zeolite is particularly useful in controlled evaporation applications where water retention and gradual release are needed. The selection of an appropriate porous material depends on the specific requirements of the desalination system, including heat management, water storage capacity, and energy efficiency.

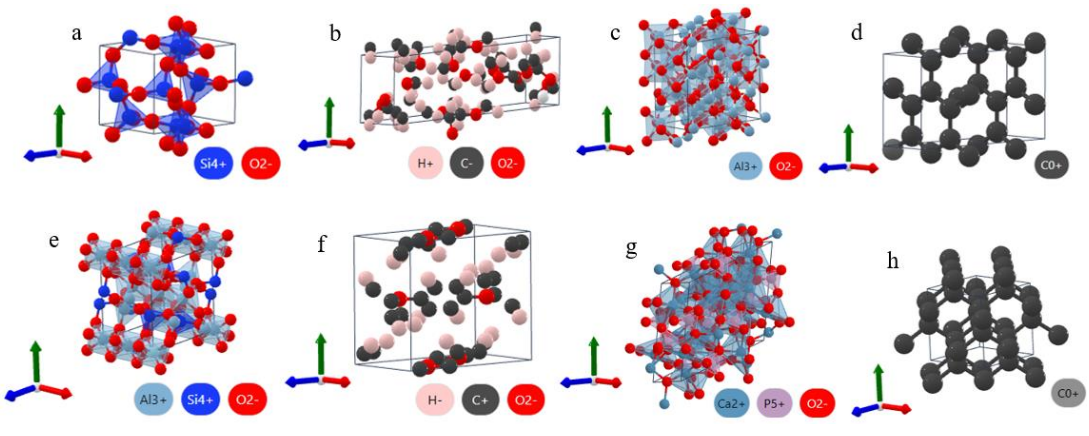

Fig. 1. Molecular structure Silica Aerogel (a), Polyvinyl Alcohol (PVA) Hydrogel (b), Porous Alumina (c), Activated Carbon (d), Zeolite (e), Cellulose Sponge (f), Hydroxyapatite (g), Graphene Aerogel (h).

Table.1. Thermophysical and Chemical Properties of Selected Water-Absorbing Porous Materials

Material	**Porosity (%)**	**Water Absorption (g/g)**	**Thermal Conductivity (W/m K)**	**Specific Surface Area (m^2/g)**	**Chemical Composition**
Silica Aerogel	85-95	10-15	0.02-0.03	600-800	SiO_2
Polyvinyl Alcohol (PVA) Hydrogel	70-85	5-10	0.2-0.3	100-300	PVA, H_2O

Porous Alumina	50-70	2-5	1.0-1.5	50-100	Al_2O_3
Activated Carbon	60-90	8-12	0.1-0.2	800-1200	C
Zeolite	40-60	20-25	0.15-0.25	500-700	$Al_2O_3,\ SiO_2$
Cellulose Sponge	75-90	15-20	0.04-0.07	200-500	$C_6H_{10}O_5$
Hydroxyapatite	45-65	3-6	0.5-1.0	40-80	$Ca_{10}(PO_4)_6(OH)_2$
Graphene Aerogel	85-98	12-18	0.02-0.04	900-1500	C

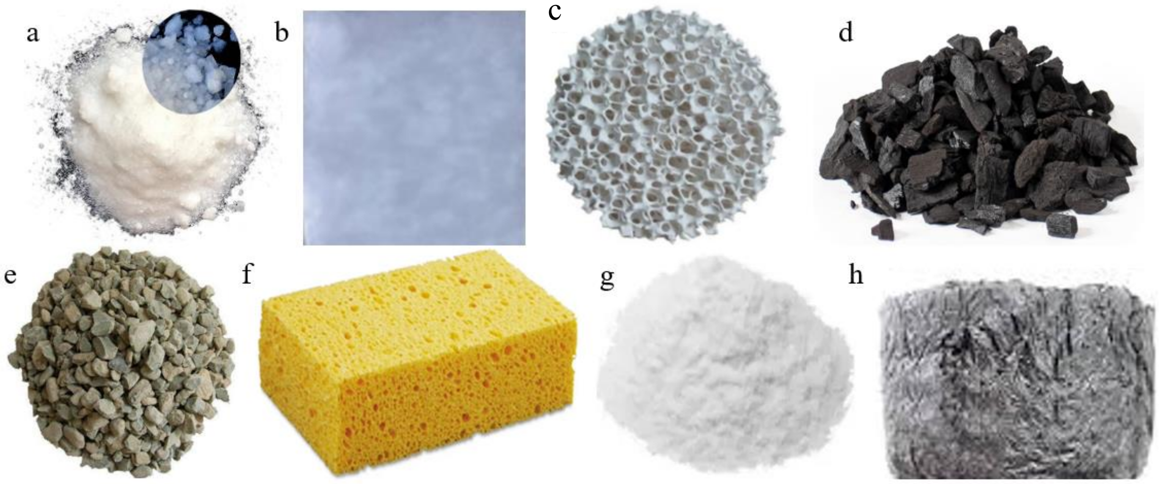

Fig. 2. Silica Aerogel (a), Polyvinyl Alcohol (PVA) Hydrogel (b), Porous Alumina (c), Activated Carbon (d), Zeolite (e), Cellulose Sponge (f), Hydroxyapatite (g), Graphene Aerogel (h).

3. Discussion

The efficiency of solar water desalination depends on the ability of porous materials to absorb and evaporate water effectively. The materials analyzed in this study exhibited diverse performance characteristics, e ing them suitable for different operational requirements in desalination units.

1. Water Absorption Performance

Water absorption is a key factor in maximizing water availability for desalination. The results show that Zeolite (20 g/g) and Graphene Aerogel (18 g/g) have the highest absorption capacities due to their high porosity (85–98%) and large specific surface areas (500–1500 m²/g). These materials provide extensive adsorption sites for water molecules, making them ideal for applications requiring rapid and large-scale water retention. In contrast, Porous Alumina (3 g/g) and Hydroxyapatite (5 g/g) displayed the lowest absorption, suggesting that their relatively low porosity (45–70%) limits their effectiveness in absorbing water.

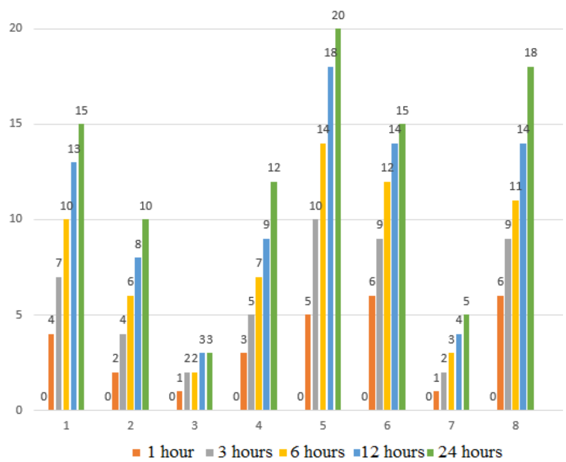

Fig. 3. Water Absorption Dynamics Over 24 Hours.

2. Evaporation Rate and Thermal Conductivity

Efficient evaporation is essential for improving the vaporization rate in solar desalination. Zeolite (0.50 g/g·h) and Silica Aerogel (0.45 g/g·h) exhibited the highest evaporation rates due to their low thermal conductivity (0.02–0.03 W/m K), which minimizes heat loss while optimizing vapor formation. Graphene Aerogel (0.48 g/g·h) and Activated Carbon (0.40 g/g·h) also demonstrated superior evaporation performance, highlighting their potential for accelerating the phase transition in solar water desalination systems. On the other hand, Porous Alumina (0.10 g/g·h) and Hydroxyapatite (0.12 g/g·h) showed slower evaporation rates, likely due to their higher thermal conductivity (0.5–1.5 W/m K), which reduces localized heating efficiency.

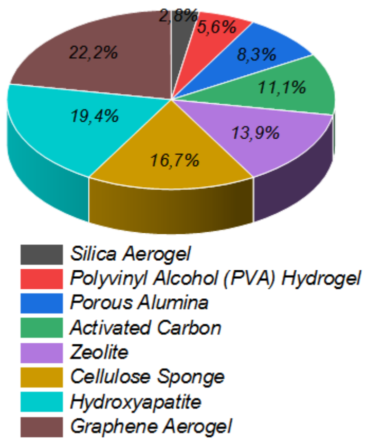

Fig. 4. Water Evaporation Dynamics Over 24 Hours.

3. Material Suitability for Solar Desalination

Selecting the optimal material depends on the balance between water absorption and evaporation efficiency:

Graphene Aerogel and Silica Aerogel are promising candidates due to their exceptional porosity, low density, and high evaporation rates, making them suitable for highly efficient solar-driven water purification.
Zeolite, with its superior absorption and rapid evaporation, is well-suited for applications requiring continuous water intake and evaporation cycles.
PVA Hydrogel and Cellulose Sponge, while having moderate absorption capacities (10–15 g/g), provide mechanical flexibility and ease of integration into solar evaporators.
Hydroxyapatite and Porous Alumina, despite their lower evaporation rates, can be useful in specialized desalination applications where water retention is prioritized.

4. Implications for Future Solar Desalination Systems

The results of this study emphasize the importance of material selection in designing efficient solar desalination systems. Materials such as Graphene Aerogel, Silica Aerogel, and Zeolite exhibit strong potential due to their high porosity, superior water absorption, and rapid evaporation capabilities. Future research should focus on optimizing these materials by enhancing their structural stability, thermal conductivity control, and scalability for large-scale desalination operations.

3. Conclusion

This study provides a comparative analysis of eight porous water-absorbing materials for their potential use in solar water desalination. Key findings include:

Zeolite (20 g/g) and Graphene Aerogel (18 g/g) show the highest water absorption capacity, making them suitable for applications requiring high water retention.

Silica Aerogel (0.45 g/g·h) and Zeolite (0.50 g/g·h) exhibit the fastest evaporation rates, contributing to higher desalination efficiency.

Graphene Aerogel and Activated Carbon also demonstrate promising performance due to their high surface area and rapid water transport mechanisms.

Porous Alumina and Hydroxyapatite, while having lower absorption and evaporation rates, may still be useful in applications requiring slower water release.

Overall, these findings suggest that a combination of high-porosity materials such as aerogels, activated carbon, and zeolites can significantly enhance solar desalination efficiency by improving both water absorption and evaporation performance. Further research should explore nanocomposite modifications and hybrid material integration to optimize desalination outcomes for large-scale applications.

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