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Solar evaporation and clean water

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Despite significant advancements in fundamental understanding and technical applications, much remains to be explored to fully harness solar energy for addressing water, energy, and resource challenges. We asked experts in the field to share their insights on opportunities and challenges in pushing solar technology to better serve society's increasing demands for water and achieve sustainability in water-related domains.

Ghim Wei Ho: System integration for boosting solar technologies

The adverse environmental impacts of CO_2 emissions and persistent pollution from fossil fuels usage are intensifying the demand for sustainable technologies in clean energy, waste remediation and recycling. Solar evaporation and related technologies have gained widespread adoption as clean and renewable technologies to address the pressing energy crisis and environmental challenges. Unlike conventional water and energy systems, which often require large-scale facilities, high energy inputs, and produce secondary pollution, solar evaporation offers a transformative approach that can redefine water and energy accessibility in rural and underserved regions, with resilience across diverse terrain.

Solar technologies can be broadly classified into two main categories based on their underlying mechanisms: thermodynamic systems and electrochemical systems. In traditional solar thermodynamic systems, like solar water and mineral mining, photothermal and auxiliary capillary effects drive the phase transition of water from liquid to gas, effectively separating water molecules from pollutants or salts to yield purified water and minerals[1,2]. In contrast, solar electrochemical systems harness sunlight to initiate chemical reactions to generate pure water, electricity or chemical fuels through processes such as photocatalysis, solar water dynamics systems (hydrovoltaic/moisture devices)[3] and solar electronics. However, the efficiency of individual solar technologies remains suboptimal, typically below 50%, with a significant portion of energy dissipating as heat.

Given the distinct yet compatible mechanisms of these solar systems, integrating different solar thermodynamic evaporation and electrochemical technologies into a unified system is feasible. This integration enables graded energy utilization across multiple systems, enhancing energy efficiency and cost-efficiency beyond single solar systems and offering a revolutionary solution with environmental, operational, and economic benefits. Additionally, integrated solar technologies create a sustainable framework by repurposing inefficiencies from one system to benefit another, upcycling unwanted outputs into valuable assets for enhanced system performance. For example, waste heat from solar cells, typically viewed as an efficiency loss, can be harnessed by solar thermoelectric devices to generate additional electricity, reducing thermal accumulation and boosting solar-electric efficiency to 20.06% (ref. 4), which can be further enhanced by utilizing latent heat in solar water systems. Similarly, combining photocatalysis within a solar water system allows for concurrent water purification, pollutant removal in flowing water, and water splitting through scalar energy harvesting and collection. These integrations mitigate localized heat build-up and energy dissipation, resulting in higher energy conversion efficiency and additional products, like water and electricity. By pushing the boundaries of efficiency, durability, and adaptability, integrated solar evaporation can lead to a paradigm shift to a future where high-efficiency, environmentally friendly solar systems are harmoniously integrated to address the specific challenges of various practical applications, paving a sustainable path to meet global water and energy needs.

Yusuke Yamauchi: Carbon-based materials for solar evaporation

Solar-powered water evaporation technology is emerging as a sustainable method for generating clean water directly from untreated sources. The materials used in this process must efficiently absorb sunlight, convert it into heat, and promote water evaporation[5,6]. Black materials, renowned for their ability to absorb a broad range of light wavelengths, are particularly effective in solar distillation. Recent research has highlighted the advantages of carbon-based materials, such as activated carbon, carbon nanotubes, and graphene, due to their excellent light absorption properties, chemical stability, mechanical strength, and low manufacturing costs. Among these, nanoporous carbon is noteworthy for its large specific surface area, which enhances water evaporation while optimizing heat absorption and dissipation. Surface modifications, including oxidation treatments and the introduction of functional groups, can significantly improve hydrophilicity, leading to better water interaction and increased evaporation efficiency.

An exciting development in this field is the creation of hybrid materials that integrate carbon with plasmonic nanoparticles like gold, silver, and copper. These nanoparticles selectively absorb light at specific wavelengths, enhancing localized heat generation through the localized surface plasmon resonance effect. While metal nanoparticles can be expensive when used alone, their combination with carbon materials offers both cost reduction and performance enhancement. Hybridization with porous materials such as metal–organic frameworks (MOFs), zeolites, and silica is also gaining attention. Some MOFs are designed to efficiently absorb specific light wavelengths, allowing for new solar distillation technologies that maximize sunlight utilization. The synergy of MOFs with plasmonic nanoparticles and carbon materials results in hybrid systems that leverage multiple mechanisms, leading to exceptionally high light-to-heat conversion efficiency.

The use of nanoporous carbon is essential in solar distillation efficiency. Microporous materials (<2 nm) effectively capture water molecules through capillary action and enhance heat absorption. However, small pores can impede water molecule diffusion. Macroporous materials (>50 nm) facilitate fluid movement but may suffer from low surface area, reducing water retention. Mesoporous materials (2–50 nm) offer a balance, enhancing water movement and evaporation rates. Hierarchical pore structures are particularly effective, where micropores

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retain water, mesopores facilitate evaporation, and macropores assist vapour transfer. Additionally, the orientation of nanopores relative to the water surface significantly impacts heat absorption and evaporation efficiency. Properly designed pore openings facing the water surface, that is, anisotropic pore structures, can enhance evaporation by allowing efficient heat absorption and vapour escape. However, salt resistance is sometimes crucial for photothermal water evaporation, especially in desalination. Employing surface treatments to enhance hydrophilicity and designing hierarchical pore structures can facilitate salt drainage and maintain high evaporation rates. By addressing these factors, the advancement of solar-powered water purification technologies can become more effective and sustainable in the future.

Liangbing Hu: Plant-inspired solar evaporator

For meaningful deployment of solar evaporation to address the global water shortage challenge, the systems must be low-cost and scalable, with the capability for long-term operation, as well as demonstrating low environmental impacts. Natural materials, especially their nanoscale building blocks (for example, cellulose nanofibres), have been widely explored as high-performance solar evaporators through bottom-up assembly approaches. Multilayer structures with precision control of each layer's property have been demonstrated with excellent solar steam performance, even under one-sun solar radiation. But the high cost associated with the extraction of nanoscale building blocks and the energy and/or water use in their fabrication most likely will prevent their use in practical applications[7].

Many plants (for example, a living tree) are constantly circulating water from the ground system by relying on the unique mesostructures evolved from nature. We can take advantage of such natural plant nanostructures using top-down fabrication approaches to potentially achieve solar evaporation with both high performance and low cost. For example, a tree-inspired design was proposed using natural wood with a bilayer structure for solar steam generation[8]. Thanks to the unique open-channel structure, a carbonized surface layer of the natural wood functions as an almost perfect solar energy absorber (super black surface, ~99%). The low thermal conductivity of the natural wood layer just below the carbonized surface enabled local heat concentration toward a high temperature, which leads to a highly efficient water evaporator. The natural wood layer can also continuously pump wastewater upstream, as a natural tree does. To further increase the water transport of a plant-based solar evaporator, lignin modification (for example, delignification) of the natural plant layer can be used to create nanochannels among the cellulose fibres. Such plant-inspired design and top-down manufacturing offers inexpensive and scalable solar energy harvesting and steam generation technology.

In addition to the high steam generation rate under solar radiation, preventing salt accumulation during operation while maintaining long-term stability and a rapid evaporation rate is a critical challenge. Plants with unique interconnected macrostructures (for example, balsa wood with a bimodal porous structure with both large vessel channels ~200–400 μm and small tracheid channels ~20 μm) were demonstrated to solve this salt accumulating issue effectively by providing sufficient brine replenishment at the top surface during clean water vapour generation and effective transverse brine diffusion through the wood pits and ray cells[9].

Beyond clean water generation, plant-based solar evaporators can also be further nano-engineered with controlled surface charge and nanoscale transport for fluids and ions, which can function as unique ionic membranes for other emerging technologies (for example, energy harvesting, the extraction of useful materials from water, such as Li salt, and environmental treatment).

Baoxia Mi: Critical research gaps in mineral recovery from brine

Interfacial solar evaporation technology has great potential in mineral recovery from industrial or natural brine waters. For example, as a retrofit of existing solar evaporation ponds that are being used for mineral (such as lithium) production from natural brine lakes, interfacial solar evaporation, especially with a three-dimensional (3D) design, can significantly increase the water evaporation rate. At the same time, managing salt transport within a 3D interfacial solar evaporator has the potential to enable salt separation for targeted mineral recovery. Effective mineral recovery can be achieved by engineering the evaporation material, optimizing the 3D structure design, and developing an integrated system.

However, there are great challenges we need to address for brine water applications, among which the most prominent one is the effect of multivalent cations. Multivalent cations, such as calcium and magnesium, are often found with high concentrations in either industrial or natural brine waters. These cations will most likely have more negative impacts on the evaporation process than anions[10], due to their stronger interactions with material surfaces within the evaporator. However, such effects have not been sufficiently investigated by the research community and remain as a critical research gap that we need to fill.

In addition, it is critical to understand the transport and separation of different ions in complex water chemistry. Many studies on interfacial solar evaporation report excellent performance, but they often only use very simple sodium chloride (NaCl) solutions and ignore the fact that brine water has high concentrations of other ions as well. These ions will not only affect water transport and evaporation, but also interfere with each other during transport and crystallization. For example, many researchers in this field target at achieving mineral (such as lithium) recovery by separating minerals at different locations in the evaporator. In this case, it is extremely important to characterize the separation performance in the presence of a complex ion composition instead of simply adding the targeted minerals in NaCl solutions.

Finally, mineral crystallization on the evaporator surface is much more complicated than the typical scaling in membrane separation. Scaling on the membrane surface only involves precipitation of ions at the liquid–solid interface, while the crystallization in a solar evaporator involves air–liquid–solid interfaces and thermal effects, that is, elevated temperature due to solar heating. Therefore, the behaviour of mineral crystallization in the solar evaporator is extremely challenging to predict using existing literature. Systematic investigation of mineral scaling is thus urgently needed for better utilizing this technology for mineral recovery from brine.

Ning Xu and Jia Zhu: Challenges in scaling up solar evaporation technologies

Interfacial solar evaporation, which harnesses solar energy at the air–liquid interface to enhance water evaporation, is regarded as an emerging solar water technology[11]. It has garnered significant research interest due to its promising applications in desalination, wastewater treatment, and so on. The past decade has witnessed remarkable progress in numerous designs of materials and devices for solar evaporators, pushing the solar-to-vapour efficiency close to the thermodynamic limit. However, significant challenges remain when advancing this technology from laboratory settings to industrial applications.

First, while laboratory research encourages a variety of material categories, when transitioning to industrial applications, the abundance, non-toxicity, and eco-friendliness of the materials, as well as the scalability of the material fabrication process, need to be considered. The abundance of materials and the scalability of fabrication processes are key determinants of the cost and production efficiency of solar evaporators, thereby significantly affect the industrialization prospects of solar evaporation technology. Material toxicity and eco-friendliness are crucial for both their impact on aquatic ecosystems and the safety of collected water in practical water purification processes. However, thorough assessments of these factors are scarce at this stage.

Moreover, maintaining high evaporation efficiency as the evaporator scales up to practical applications remains challenging. Many studies have reported high evaporation rates for laboratory-scale solar evaporators with elaborately designed three-dimensional structures that utilize environmental energy. However, performance tends to decay when scaling up either by enlarging the horizontal size or constructing arrays. This is because increasing the horizontal size reduces the proportion of side areas of the absorbers, which primarily contributes to the evaporation enhancement by environmental energy utilization. Additionally, adjacent evaporation increases the ambient humidity, which in turn suppresses the evaporation rate as solar evaporators scale up.

Furthermore, real-world water sources often contain a variety of ions and contaminants, making them more complex than laboratory conditions. This complexity necessitates the development of more thoughtful material and device designs to ensure stability during solar evaporation. For different water bodies, these designs must take into account factors such as various types of salts, salinity, the presence of organic matter, and the potential for biological fouling. For example, seawater contains calcium and magnesium ions in addition to sodium ions, which can lead to the formation of more compact precipitates. Resisting or removing precipitates out of real seawater is more challenging than performing these processes with NaCl solution-based simulated seawater.

Despite these challenges, it is optimistic that continuous and collaborative efforts will lead to further progress towards this goal. More importantly, in addition to water purification, initial trials have also demonstrated promising applications of solar evaporation in electricity generation and resource recovery[12]. These achievements highlight the broader potential of this technology. We believe that, with ongoing innovations and advancements, solar evaporation technology is poised to become an effective solution for addressing the global crises involving water, energy, and resource scarcity.

Peng Wang: Thinking outside the box of solar evaporation

The abundant and sustainable nature of solar energy positions it as a promising solution to pressing global challenges, such as, most notably, freshwater scarcity, clean energy shortages, and our joint pursuit of carbon neutrality.

Over the past decade, solar-driven evaporation processes have been gaining increased attention, which is evident in the growing depth of research and the expanding range of applications. However, the field now stands at a pivotal juncture, where innovative approaches and fresh perspectives are essential to sustain growth and facilitate tangible societal impacts in the next decade. From my past experiences in the field, I have the following humble points to share.

First, we should not constrain ourselves only to solar thermal energy; as a matter of fact, there is always a high abundance of ambient low-grade heat produced by industrial, commercial, and/or residential processes. The efficient utilization of this heat will certainly broaden the practical application horizon and expand the impact of evaporation-based processes.

Second, as the phase change of water is an energy-laden process, water evaporation and condensation are both mass-transfer and energy-transfer processes. The water–energy nexus mindset can help in the design of better and more efficient systems. As such, metrics other than evaporation rate and freshwater production rate – for example, energy recovery, electricity generation, and cooling power – should be considered as key parameters that directly influence the efficiency of these processes.

Third, dissolved salts in wastewater, seawater, and brines offer significant opportunities for resource recovery. For example, extracting lithium from seawater (and other relevant high-saline waters) by evaporation processes is a hot topic nowadays. However, achieving direct production of high-purity minerals from these source waters is still elusive and thus calls for innovative approaches. A breakthrough in this area would make a significant contribution to the circular economy as it would ensure valuable resources being reintegrated into the production cycle rather than being discarded as waste.

Last but not the least, (solar-driven) evaporation is never the ultimate purpose of any practical application, so system-integration is key to demonstrating the performance of proclaimed application scenarios. Interdisciplinary thinking and approaches are always needed to come up with new applications (for example, solar evaporation with thermoregulatory clothing) and broaden the existing application windows (for example, sorption-based atmospheric water harvesting) and, more broadly, to drive innovation and the sustainability of the field.

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Competing interests

The authors declare no competing interests.