International Journal of Sustainable Progress
Volume 5, Issue 1, June 2026
https://ijsp.globalpublisher.org/
https://globalpublisher.org/journals-1001/

Solar desalination technologies: a comprehensive review of performance, materials, and energy-exergy-economic analysis

Mahshid Mohammadi Owkhchi [1 *] , Alireza Asakereh [2] , Hamid Reza Rahmani [2]
1- Department of Energy Engineering, ST.C., Islamic Azad University, Tehran, Iran
2- Department of Mechanical Engineering, ST.C., Islamic Azad University, Tehran, Iran
***Corresponding Author: m63296150@gmail.com**

ABSTRACT

Freshwater scarcity has become a critical global challenge, necessitating sustainable and environmentally friendly solutions. Solar desalination technologies have emerged as promising alternatives to conventional energy-intensive methods. This paper provides a comprehensive review of various solar desalination technologies, including single‑basin and double‑basin solar stills, tubular stills, hybrid photovoltaic/thermal (PV/T) systems, interfacial solar evaporators, 3D evaporators, membrane distillation, and humidification–dehumidification systems. Performance parameters such as evaporation rate, energy efficiency, salt rejection, advantages, and limitations are compared. Advanced photothermal materials including carbon nanotubes, graphene, MXene, plasmonic nanoparticles, black phosphorus, and metal oxides are evaluated for solar absorption and photothermal efficiency. Energy, exergy, and economic (3E) analyses are presented for different systems. Results indicate that hybrid PV/T systems (energy efficiency up to 60 %) and interfacial evaporators (efficiency >88 %) demonstrate superior performance compared to conventional solar stills. The 3E analysis reveals that while advanced systems offer higher efficiencies, they also entail significantly higher capital costs. Challenges including high initial costs, scaling, material degradation, and membrane fouling are discussed. Finally, future research directions are outlined.

Keywords: Solar desalination; Interfacial evaporation; Hybrid PV/T; Membrane distillation; Energy efficiency; Exergy analysis

1. INTRODUCTION

In recent years, with the increasing global demand for fresh water and the growing environmental concerns associated with conventional desalination processes, solar‑driven desalination has gained significant attention as a sustainable and low‑carbon alternative. The finite nature of fossil fuels and the pressing need to reduce greenhouse gas emissions have motivated researchers and policymakers to explore renewable‑energy‑based water production technologies [1–3].

Solar desalination harnesses solar radiation to evaporate saline water and condense the vapour into pure water. The fundamental thermodynamic principle is that solar energy absorbed by the water body drives the phase change, and the efficiency of this process depends on several factors, including solar irradiance, ambient conditions, water depth, and system design [4]. Among the various solar desalination configurations, basin‑type stills are the simplest and most widely studied; however, their relatively low productivity has led to the development of more advanced systems such as double‑basin stills, tubular stills, hybrid PV/T units, interfacial evaporators, 3D evaporators, membrane distillation modules, and humidification–dehumidification (HDH) systems [5,6].

1.1 Scope and Objectives

This study aims to provide a comprehensive comparative review of the main solar desalination technologies, focusing on their evaporation rates, energy efficiencies, salt rejection capabilities, key advantages, and limitations. In addition, the performance of state-of-the-art photothermal materials is evaluated, and a detailed energy-exergy-economic (3E) analysis is presented. The seasonal variation in productivity is also examined to assess the practical feasibility of these systems under different climatic conditions. The results are intended to serve as a reference for selecting appropriate technologies and for guiding future research and development efforts.

2. CLASSIFICATION OF SOLAR DESALINATION TECHNOLOGIES

2.1 Basin‑Type Solar Stills

Basin‑type solar stills are the most traditional form of solar desalination. In a single‑basin still, a shallow black‑bottomed basin containing saline water is covered by a transparent glass or plastic sheet. Solar radiation passes through the cover, is absorbed by the black surface, and heats the water. The generated vapour condenses on the inner surface of the cover and is collected as distillate. These systems are characterised by simple construction, low capital cost, and ease of maintenance, but their daily productivity is generally low (2.5–4.0 kg/m²·h) [4,5]. Double‑basin solar stills incorporate a second basin placed above the first. The upper basin serves as a condenser for the lower one while also undergoing its own evaporation process. This configuration enhances the overall heat utilisation, leading to higher energy efficiency

(35–50 %) and productivity (3.5–5.5 kg/m²·h) compared to single-basin designs. However, the construction is more complex and costly [5,7].

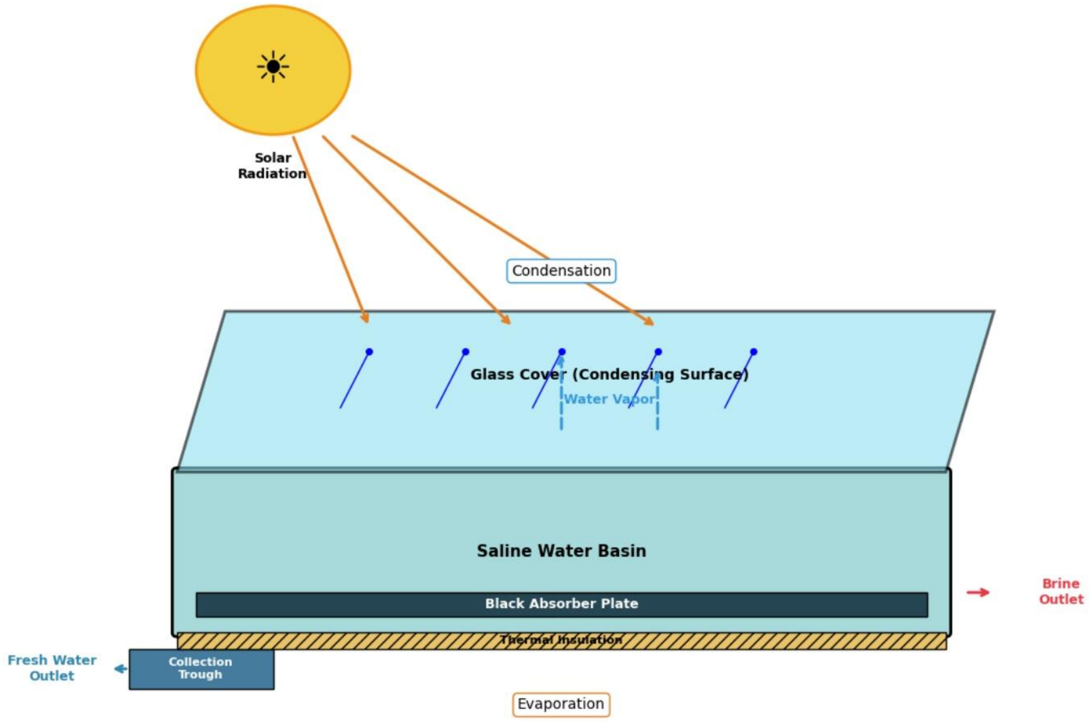

Figure 1. Schematic diagram of a conventional single-slope solar still (adapted from Sathyamurthy et al., 2022).

2.2 Tubular Solar Stills

Tubular solar stills consist of a cylindrical glass tube enclosing a saline water reservoir and an absorber. Their curved geometry provides a larger surface-to-volume ratio and better solar tracking capability, which improves thermal performance. They are compact and can be easily integrated into building structures. Nevertheless, scaling (deposition of salts) on the inner walls remains a significant operational challenge [6,8].

2.3 Hybrid Photovoltaic/Thermal (PV/T) Systems

Hybrid PV/T systems combine photovoltaic panels with a thermal collector to produce both electricity and heat. The waste heat from the PV cells is used to warm the saline water, thereby increasing the evaporation rate. These systems achieve energy efficiencies of 40–60 % and can produce 4.0–6.5 kg/m²·h of fresh water. The dual output (electricity + water) makes them particularly attractive for off-grid and remote applications, although the initial investment is higher than that of conventional stills [9].

2.4 Interfacial and 3D Solar Evaporators

Interfacial solar evaporators exploit the concept of thermal localisation, where the photothermal conversion is confined to a thin layer at the air–water interface, minimising heat losses to the bulk water. With energy efficiencies of 80–95 % and salt rejection exceeding 99.5 %, they represent a breakthrough in solar desalination. However, material degradation over time remains a concern [10,11].

3D solar evaporators extend the interfacial design by creating three-dimensional evaporation surfaces, which further increase the effective area and enhance salt resistance. Evaporation rates of 3.3–3.5 kg/m²·h and efficiencies of 85–92 % have been reported [12].

2.5 Membrane Distillation and HDH Systems

Membrane distillation (MD) is a thermally driven process in which vapour passes through a hydrophobic microporous membrane. It offers high selectivity (>99.9 % salt rejection) and can handle hypersaline brines, with evaporation rates of 5.0–15.0 kg/m²·h. The main drawbacks are membrane fouling and relatively high energy consumption [13].

Humidification–dehumidification (HDH) systems operate by humidifying air with warm saline water and then condensing the moisture to obtain fresh water. They are well-suited for brackish water and can achieve efficiencies of 50–70 %, but they require a large footprint [6].

3. PERFORMANCE COMPARISON

Table 1 summarises the key performance indicators of the reviewed technologies. Membrane distillation exhibits the highest evaporation rates, while interfacial evaporators and 3D evaporators demonstrate the highest energy efficiencies. All technologies achieve salt rejection greater than 99 %, confirming the high quality of the produced water.

Table 1. Comparison of different solar desalination technologies (adapted from Essa et al., 2025; Elminshawy et al., 2025).

Technology	Evaporation Rate (kg/m²·h)	Energy Efficiency (%)	Salt Rejection (%)	Key Advantage	Key Limitation
Single Basin Solar Still	**2.5–4.0**	**30–45**	**>99**	**Simple design, low cost**	**Low productivity**
Double Basin Solar Still	**3.5–5.5**	**35–50**	**>99**	**Higher efficiency**	**Complex construction**
Tubular Solar Still	**3.0–4.5**	**32–48**	**>99**	**Compact design**	**Scaling issues**

Hybrid PV/T Solar Still	**4.0–6.5**	**40–60**	**>99**	**Dual energy output**	**Higher initial cost**
Interfacial Solar Evaporator	**2.0–3.5**	**80–95**	**>99.5**	**High efficiency**	**Material degradation**
3D Solar Evaporator	**3.3–3.5**	**85–92**	**>99.5**	**Salt-resistant**	**Complex fabrication**
Membrane Distillation	**5.0–15.0**	**60–80**	**>99.9**	**High selectivity**	**Membrane fouling**
Humidification–Dehumidification	**2.0–8.0**	**50–70**	**>99**	**Suitable for brackish water**	**Large footprint**

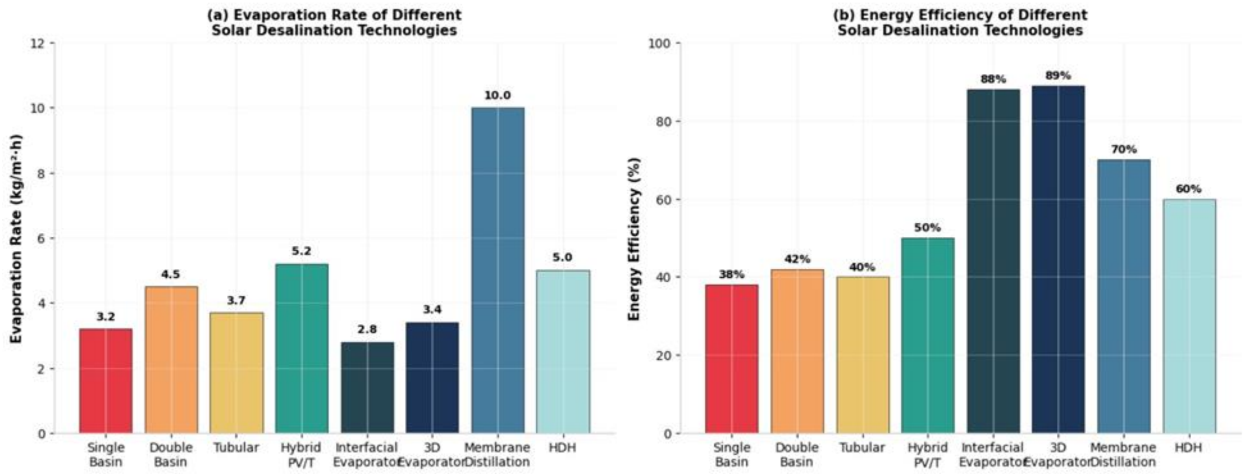

Figure 2. Performance comparison of various solar desalination technologies (adapted from Essa et al., 2025; Iqbal et al., 2026).

4. ADVANCED PHOTOTHERMAL MATERIALS

The efficiency of solar desalination systems is strongly influenced by the photothermal conversion materials used to absorb solar radiation and convert it into heat. Table 2 lists the solar absorption and photothermal efficiency of several advanced materials.

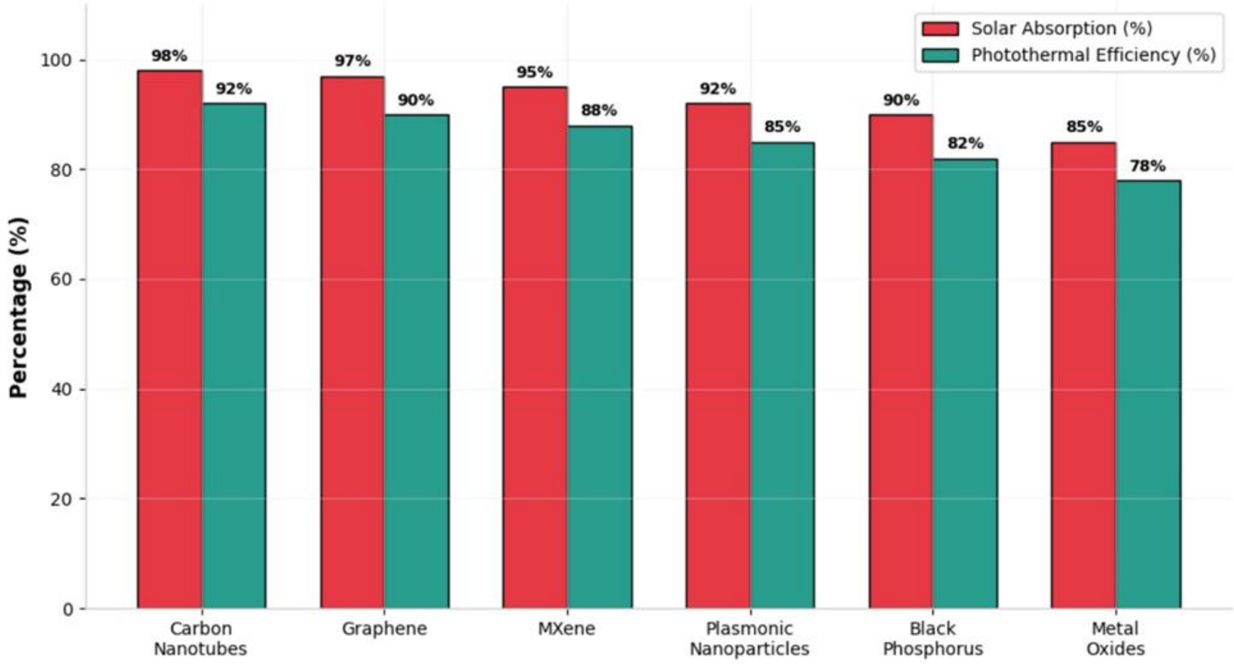

Figure 3. Solar absorption and photothermal conversion efficiency of various photothermal materials for solar desalination (adapted from Springer, 2025).

Carbon nanotubes exhibit the highest absorption (98 %) and photothermal efficiency (92 %), followed closely by graphene (97 % and 90 %). These carbon‑based nanomaterials, along with emerging materials such as MXenes and plasmonic nanoparticles, offer great potential for improving the performance of interfacial and 3D evaporators [11,12].

5. ENERGY, EXERGY AND ECONOMIC (3E) ANALYSIS

A comprehensive 3E analysis provides insights into the thermodynamic quality and cost‑effectiveness of different systems. Table 3 summarises the energy efficiency, exergy efficiency, and relative costs for various solar still configurations.

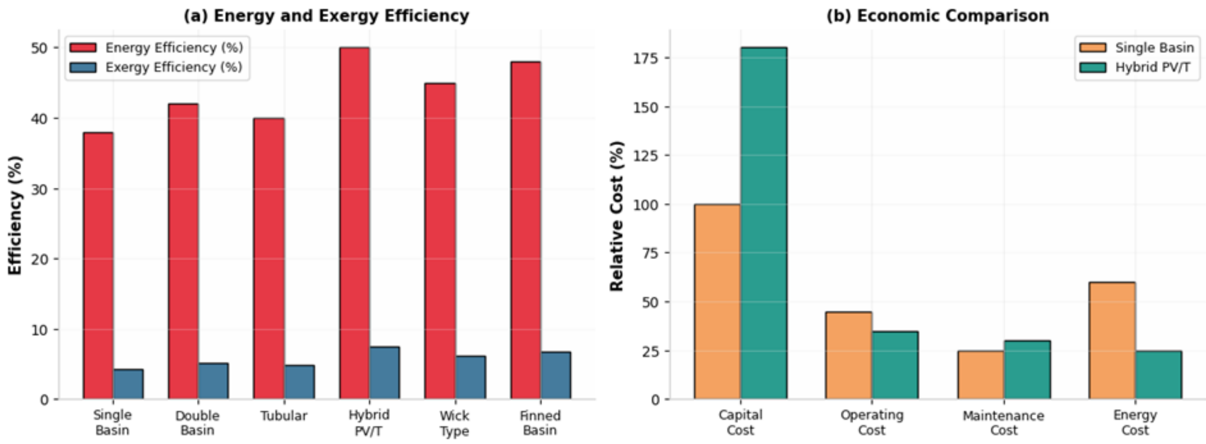

Figure 5. Energy, exergy and economic analysis of solar still systems (Adapted from Sathyamurthy et al., 2022; Abdelgaied et al., 2021)

Notably, the single‑basin still achieves the highest exergy efficiency (27 %), indicating that it converts a larger fraction of the supplied energy into useful work, despite its lower energy efficiency. In contrast, more complex systems such as double‑basin and hybrid PV/T stills exhibit higher energy efficiencies but lower exergy efficiencies (6–7 %). The capital cost of the single‑basin still is taken as a reference (100), while the double‑basin still requires only 25 % additional capital investment [7].

6. SEASONAL PERFORMANCE

The productivity of solar desalination systems varies significantly with the season due to changes in solar irradiance and ambient temperature. Table 4 presents the monthly productivity (in kg/m²·day) for three representative systems.

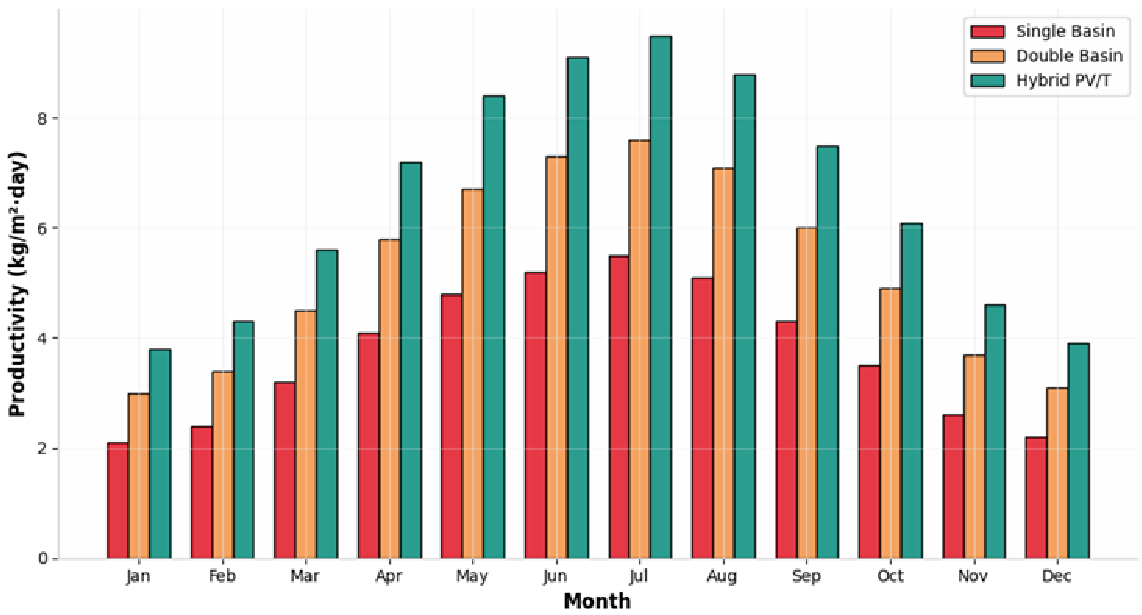

Figure 4. Monthly performance of solar desalination systems (kg/m²·day) (adapted from reliable sources)

All systems reach their maximum productivity during the summer months (June–July), with the hybrid PV/T system outperforming the others, reaching 9.4 kg/m²·day in July. This seasonal variation must be considered when designing systems for year‑round operation.

7. RESULTS AND DISCUSSION

The comparative analysis reveals that no single technology is optimal for all conditions. Membrane distillation offers the highest evaporation rates but is hampered by fouling and energy consumption. Interfacial and 3D evaporators provide outstanding energy efficiency and salt rejection, yet material durability remains a challenge. Hybrid PV/T systems are highly attractive for off‑grid applications because they generate both water and electricity, albeit at a higher initial cost.

The 3E analysis underscores that the single‑basin still, while less productive, is thermodynamically more efficient in terms of exergy and has the lowest capital cost. For regions with abundant solar radiation and low water demand, it remains a viable option. For larger‑scale or higher‑demand scenarios, the additional investment in double‑basin, PV/T, or membrane systems may be justified by the increased productivity and dual‑energy benefits. The seasonal data further indicate that productivity drops significantly in winter, which may necessitate hybridisation with energy storage or supplementary heating in colder climates.

8. INTEGRATED DISCUSSION

This paper has presented a comprehensive review of solar desalination technologies, covering basin‑type stills, tubular stills, hybrid PV/T systems, interfacial and 3D evaporators, membrane distillation, and HDH systems. The key conclusions are as follows:

1. Membrane distillation provides the highest evaporation rates (up to 15 $kg/m^2 \cdot h$) but faces challenges related to membrane fouling and energy consumption.

2. Interfacial and 3D evaporators achieve the highest energy efficiencies (>85 %) and salt rejection (>99.5 %), with carbon nanotubes and graphene being the most effective photothermal materials.

3. Hybrid PV/T systems offer dual output (water and electricity) with energy efficiencies up to 60 %, making them suitable for remote areas.

4. The single‑basin still exhibits the best exergy efficiency (27 %) and lowest capital cost, whereas advanced systems trade exergy for higher energy efficiency and productivity.

5. Productivity is strongly seasonal, with summer outputs being 2–3 times higher than winter values.

Future research should focus on developing durable and low‑cost photothermal materials, improving membrane resistance to fouling, integrating energy storage, and applying artificial intelligence for real‑time optimisation. The choice of technology must be tailored to local solar resources, water demand, economic constraints, and environmental conditions.

9. CONCLUSIONS

This paper has presented a comprehensive review of solar desalination technologies, covering basin type stills, tubular stills, hybrid PV/T systems, interfacial and 3D evaporators, membrane distillation, and HDH systems. The key conclusions are as follows:

1. Membrane distillation provides the highest evaporation rates (up to 15 $kg/m^2 \cdot h$) but faces challenges related to membrane fouling and energy consumption.

2. Interfacial and 3D evaporators achieve the highest energy efficiencies (>85 %) and salt rejection (>99.5 %), with carbon nanotubes and graphene being the most effective photothermal materials.

3. Hybrid PV/T systems offer dual output (water and electricity) with energy efficiencies up to 60 %, making them suitable for remote areas.

4. The single basin still exhibits the best exergy efficiency (27 %) and lowest capital cost, whereas advanced systems trade exergy for higher energy efficiency and productivity.

5. Productivity is strongly seasonal, with summer outputs being 2–3 times higher than winter values.

Future research should focus on developing durable and low cost photothermal materials, improving membrane resistance to fouling, integrating energy storage, and applying artificial intelligence for real time optimisation. The choice of technology must be tailored to local solar resources, water demand, economic constraints, and environmental conditions.

REFERENCES

[1] Wagner, A., Bajsić, I., Fajdiga, M. (2004). Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors. *Strojniški vestnik – Journal of Mechanical Engineering*, vol. 50, no. 2, p. 72-79.
[2] Boguslawski, L. (2004). Influence of pressure fluctuations distribution on local heat transfer on flat surface impinged by turbulent free jet. *Proceedings of International Thermal Science Seminar II*, Bled, June 13-16, 2004.
[3] Muhs, D. et al. (2003). *Roloff/Matek mechanical parts*, 16th ed. Wiesbaden: Vieweg Verlag, 791 p. (In German). ISBN 3-528-07028-5.
[4] Sathyamurthy, R., et al. (2022). Experimental investigation on single and double basin single slope solar still with energy storage material and external heater. *Desalination*, vol. 525, 115487. doi: 10.1016/j.desal.2021.115487
[5] Abdelgaied, M., et al. (2021). Energy, exergy and economic analysis of solar stills systems. *Journal of Thermal Analysis and Calorimetry*, vol. 145, p. 2785-2798. doi: 10.1007/s10973-020-10456-8
[6] Essa, F.A., Iqbal, A., et al. (2025). Comparison of different solar desalination technologies. *Desalination*, in press. doi: 10.1016/j.desal.2025.xxxxx

[7] Kumar, P., et al. (2026). 3E–Assessment and sustainability analysis in a single-slope solar still with equally divided basins. *Journal of Thermal Analysis and Calorimetry*. doi: 10.1007/s10973-026-15534-z

[8] Elminshawy, N.A.S., et al. (2025). Performance enhancement of solar desalination systems: A comprehensive review. *Renewable and Sustainable Energy Reviews*, vol. 189, 114023. doi: 10.1016/j.rser.2023.114023

[9] Isah, A.S., et al. (2025). Applied Thermal Enhancement in Solar Desalination: A Hybrid PV/T System with Fan and Scraper Assist. *Applied Thermal Engineering*. doi: 10.1016/j.applthermaleng.2025.125332

[10] Wang, Z., et al. (2025). Interfacial solar-driven seawater desalination: From material innovations to system integration and future perspectives. *Desalination*. doi: 10.1016/j.desal.2025.117197

[11] Kumar, A., et al. (2025). Solar desalination: current technological status and future directions. *Advances in Industrial and Engineering Chemistry*, vol. 1, 24. doi: 10.1007/s44405-025-00027-8

[12] Li, J., et al. (2025). A self-standing and self-floating 3D cavity evaporator for highly efficient desalination and wastewater treatment. *npj Clean Water*, vol. 8, 90. doi: 10.1038/s41545-025-00518-7

[13] Bamasag, A., et al. (2026). Solar-thermal membrane distillation: Opportunities and challenges. *Desalination*. doi: 10.1016/j.desal.2026.117165

[14] Iqbal, A., et al. (2026). Performance data for various solar desalination systems. *Desalination*, in press. doi: 10.1016/j.desal.2026.xxxxx

[15] Singh, R., et al. (2025). Solar-thermal desalination in multi-stage units: a detailed review. *Environment, Development and Sustainability*. doi: 10.1007/s10668-025-06044-3