IJRAR.ORG E-ISSN: 2348-1269, P-ISSN: 2349-5138

INTERNATIONAL JOURNAL OF RESEARCH AND ANALYTICAL REVIEWS (IJRAR) | IJRAR.ORG

An International Open Access, Peer-reviewed, Refereed Journal

A Comprehensive Review Paper on Types, Yield and Efficiency of Solar Distillation (Double Slope Solar Still)

N.Srinivasa Rajneesh[1*], Dr.S.Nawazish Mehdi[2], Dr.B.Hadya[3]

[1]Research Scholar, Department of Mechanical Engineering, University College of Engineering,OU, Hyderabad,Telangana,India.

[2]Principal Investigator, AICTE Research Project, Ph.D Research Supervisor, Member BOS, Hyderabad, Telangana, India.

[3] Professor and Head, Department of Mechanical Engineering, UCE(A), Osmania University, Hyderabad, Telangana, India

Abstract: Solar distillation have witnessed significant advancements between 2010 and 2022, Water yield and energy efficiency have been significantly increased by double slope solar stills thanks to advancements in materials, system design, and hybrid integrations. But even with these improvements, a number of obstacles prevent their widespread use. The stability of nanoparticles, membrane fouling, and environmental concerns are still important material-related issues. Particularly in remote or low-resource locations, practical deployment is limited by operational challenges and design complications such as heat losses, temperature polarization, and the requirement for routine maintenance. Furthermore, these systems' performance is heavily influenced by weather, which limits their ability to produce consistently in areas with less sunshine. Due to high initial costs and the prevalence of laboratory-scale prototypes that need comprehensive field validation, economic constraints continue to exist. The lack of standardized testing procedures and integration issues with current water infrastructures make commercialization attempts even more difficult. To fully realize the potential of solar desalination as a sustainable, affordable, and scalable solution to the world's freshwater need, these issues must be resolved by ongoing research, design simplification, and pilot-scale field testing.

Keyword: Solar desalination, Double solar still systems (DSSS), Water yield, Energy efficiency

1. Introduction

Freshwater production systems that are both economical and sustainable are desperately needed, since water scarcity remains a major global issue. Due to its low environmental impact and reliance on abundant solar energy, solar desalination has emerged as a feasible solution [1], [2], [43]. Research on direct solar still systems (DSSS) has progressed considerably in the last decade owing to advancements in material science, system design, and hybrid technology integration [2], [13], [27]. Phase change materials (PCMs) and nanomaterials like copper oxide (CuO), zinc oxide (ZnO), and aluminum oxide (AlO_3) were the main focus of early breakthroughs,which enhanced thermal conductivity and accelerated evaporation rates [18], [27], [55]. Simultaneously, geometrical innovations like multi-wick, stepped, and tubular designs significantly improved the efficiency of solar stills [15], [23], [39]. More recently (2020–2022), advanced techniques integrating vacuum membrane distillation (VMD), Stirling engines, and photothermal membranes have been explored, supported by computational modeling and machine learning, with a focus on techno-economic feasibility and sustainability [4], [5], [8], [16], [50]. These systems aim to maximize yield, reduce costs, and improve overall practicality. Despite these developments, challenges related to material durability, system complexity, operational efficiency, and scalability persist, highlighting the ongoing need for research and development to fully unlock the potential of solar desalination as a decentralized and environmentally friendly freshwater solution [6], [7], [11], [24].

2.Solar Desalination:

A sustainable and eco-friendly process for creating fresh water from brackish or salty water is solar desalination, which uses sun energy to filter out salts and other contaminants. In settings like dry or coastal regions that receive a lot of sunshine but have limited access to freshwater sources, this method is very advantageous. The two main categories of solar desalination are direct and indirect techniques.The saline water is directly heated by sun radiation during the direct solar desalination process, which causes it to evaporate. Salts are left behind when the vapor condenses on a cooler surface, creating freshwater. A solar still, a straightforward apparatus made out of a basin of water coated with a transparent substance that lets sunlight in, is a typical illustration of this. The fresh water is collected separately as it evaporates and condenses on the cover. Solar stills are simple to set up and run, but they only work well on a small scale due to their poor water output. Conversely, indirect solar desalination uses solar energy to fuel traditional desalination processes such as multi-effect distillation (MED), reverse osmosis (RO), or multi-stage flash (MSF).In the process of direct solar desalination, the sun's rays directly heat the salty water, causing it to evaporate.

The vapor condenses on a cooler surface, producing freshwater, leaving behind salts. This is often demonstrated with a solar still, a simple device consisting of a basin of water covered with a transparent material that allows sunlight to enter. On the cover, the fresh water condenses and evaporates, and is collected separately. Due to their low water output, solar stills are only effective on a small scale, while being easy to set up and operate. Reverse osmosis (RO), multi-effect distillation (MED), and multi-stage flash (MSF) are examples of conventional desalination techniques that are powered by solar energy in indirect solar desalination.

.Different desalination technology is as follows:

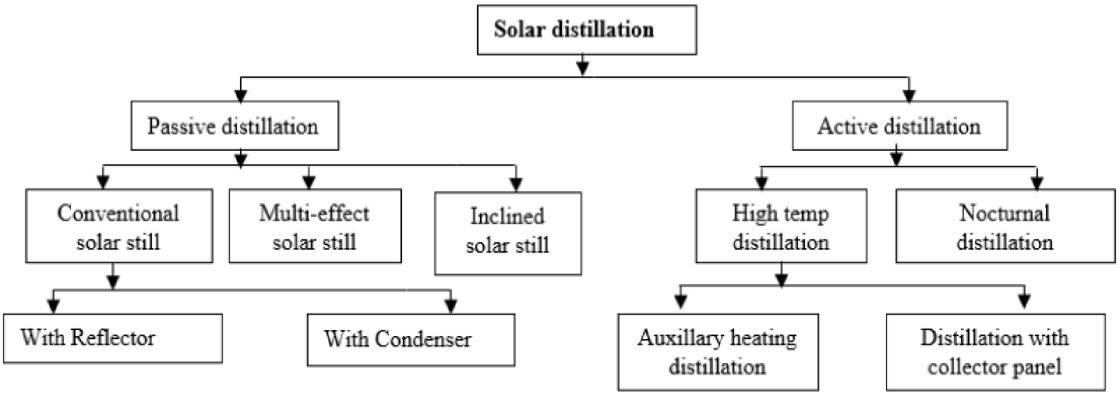


Figure 1.1:Types of Distillation

Perhaps the first technique for desalinating water is the solar still. It works on the basis of the greenhouse effect, which is the process by which sunlight vaporizes water in a glass-covered, closed chamber at a temperature greater than the surrounding air.Solar Stills with Passive Power Distillation occurs in a passive still using just direct sunlight. Several kinds of passive solar stills are shown in the figures below. The traditional low temperature solar stills, which run at temperatures lower than 60 °C, are the single slope and double slope models. The single slope solar still is more adaptable and effective than the other two. Solar Stills With Activity An additional thermal energy is supplied to the water in the basin of an active solar still in order to accelerate the rate of evaporation. The excess thermal energy is supplied into the basin in an active manner to speed up the pace of evaporation. Many academics are using the different active ways to boost the output of solar stills. The focusing collector and flat plate collector served as the foundation for the majority of the works. The sun stills are shown in a broad category.

2.1 The Solar Distillation Process

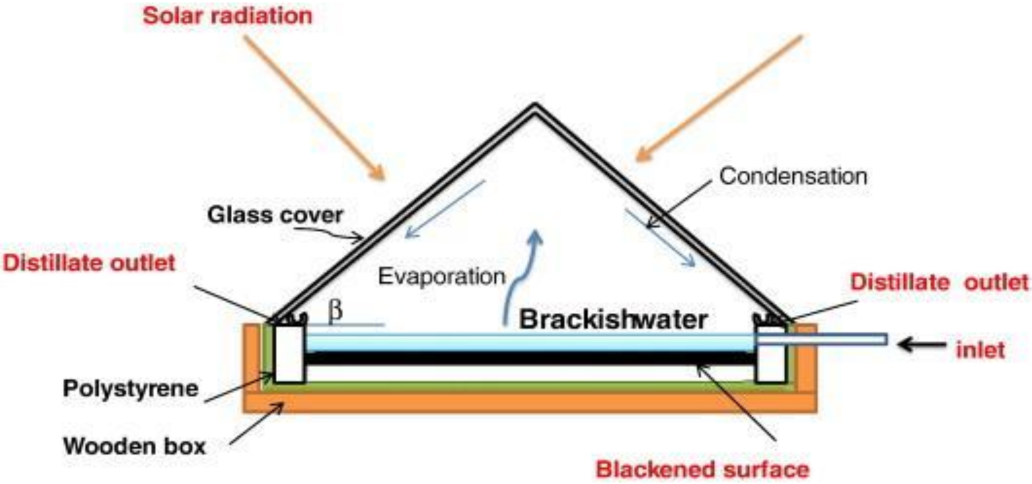


Figure 1.2: Solar Distillation Process

Figure 1.2 depicts the process of solar distillation. When sun radiation passes through a glass pan, it heats the brine or sea and causes it to rise, which causes the water to evaporate. On the bottom of the cover, the vapor condenses and flows into distillate troughs.

Technical description is as follows.:

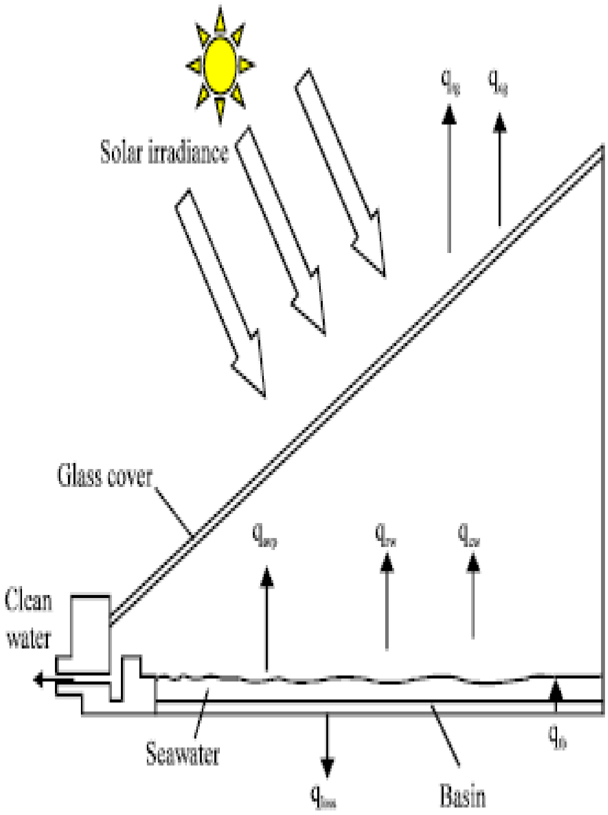
1. Short electromagnetic waves from the sun travel through clear glazing materials like glass, changing This light wavelength transforms into lengthy waves of heat when it strikes a darkened surface, adding to the water in a shallow basin beneath the glazing. The water starts to evaporate as it gets hotter.
2. The hot vapor ascends to a colder region. Nearly every impurity remains in the basin.
3. The vapor collects as water droplets or sheets after condensing against the cooler's underside glazing.
4. Water can flow down the cover of a collection trough and into the channel for storage thanks to gravity and the tilted glazing surface.

2.2 Types of solar still:

There are two types of solar stills, they are

1 .Single slope solar still.

2 .Double slope solar still.



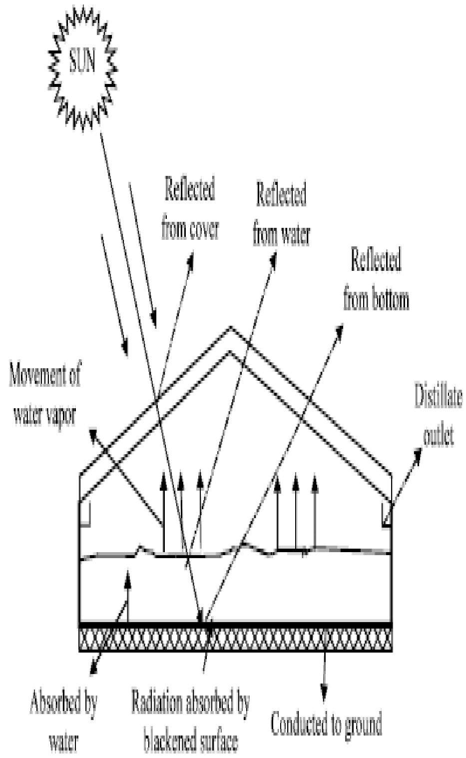


Figure 1.3: Single Slope Solar Still Figure 1.4: Double Slope Solar Still

In an enclosed area, a single slope solar still uses the heat energy from the sun to distill contaminated water into clean water. The single slope solar still operated according to the principles of energy balance and heat transmission.The evaporation process is directly impacted by the limited quantity of solar energy received, which limits the productivity of single-slope solar stills.In order to expand the area of the still's solar-absorbing element, two different diameters of iron wicks are utilized. The quantity of solar energy that is transferred through the glass cover of the double slope solar still throughout the year is estimated since it has two oppositely inclined surfaces.The ideal tilt of the double slope solar panel's cover glass is dependent on each surface's orientation with respect to the south, but it is not required to be symmetrical.The sun's locus has a different inclination depending on the latitude angle. As a result, the latitude angle of the test zone affects the radiation transmitted from the still cover.The solar still converts brackish water into drinkable water by using the principles of evaporation and condensation.The sustainability of the solar still is to be examined on the basis of 4E i.e. Energy, Exergy, Environment, and Economic Analysis.

3. Literature Review

Between 2010 and 2022, extensive literature review is done on Solar distillation (double Slope Solar Still) type of the equipment, yield and efficiency.

Table 1: Literature Review for Solar Distillation

Author/Year	Type	Yield	Efficiency	Remark
Wei 2022	NSDU	10.77 kg/h	76.96	Highly accurate predictive model; great commercial potential in Asia
Abbaspour 2022	Vertical Solar Still	5.78 Lm-2h-1	4.88 Kg/M2day, 15% improvement	Optimized absorption coefficient and device dimensions for radiation flux
Wang 2022	Solar adsorption cooling system		37.4%–80.7%	More internal fins improve performance
Cho 2022	Direct Contact Membrane Distillation	12.7 L/m2-hr	-	Membrane length should be 1.5 m or longer

Ma 2022	Direct Contact & Vacuum Membrane Distillation	0.51 & 2.83 L (0.35 m2 module)	16% & 89%	VMD-FPC preferred for small scale due to better productivity and smaller footprint
Mohsenzadeh 2022	Floating salt rejecting solar still	4.3 L m−2 d−1	35.60%	Low-cost hemispherical clear acrylic cover
Shoeib 2022	Solar desalination with nano phase change	-	1.41%, 2.41%	CO2 removal increased using nano-enhanced materials
Ma 2022	Vacuum MD by photothermal membrane	7.14 L/m2, 22.8 MJ/m2	4.1% higher than VMD-FPC	Photothermal membranes relieve temperature polarization
Peng 2022	Solar still optimizing mass transfer	-	87%-95.7% (drops to 8.5%)	Effective mass transfer optimization for solar still and thermal systems
Kumar 2022	Modified solar still with ceramic nanoparticles	4000 ml/m2/day	54% improvement	Nanomaterials improve desalination rate
Siefan 2022	Solar membrane distillation (SPMD)	1000 l/day	-	Life cycle assessment in Jordan
Ma 2022	VMD-FPC system	0.51 L (0.35 m2 module)	89%	VMD-FPC needs less concentration ratio and smaller footprint than DCMD-FPC
Zhao 2022	Multi-stage flower-inspired solar still	0.85 & 6.5 kg/(m2·h)	65%, 480%	10.66 times higher energy efficiency than conventional solar still
Mohsenzadeh 2022	Floating salt rejecting solar still	4.3 L m−2 d−1	36.00%	Acrylic cover captures solar radiation from all directions
Alatawi 2022	Tubular solar still (TSS)	-	\$0.0046 to \$0.031	Cost reduction requires optimization of design and operating parameters
Elsheikh 2022	Modified solar still with machine learning	4.99 L/m2/day, 250 ml	34%, 34%, 46%	Performance and cost prediction using AI methods
Jyotin Kateshia (2021)	Solar still integrated with phase change material and pin fins	Water mass varies (0 to 11 kg)	Case II and III improved by 24% and 30% vs Case I	Cost: 0.022, 0.019, 0.017 \$/L/m² respectively; improved performance using phase change materials
Amrit Kumar Thakura (2021)	Solar desalination unit with nano-silicon coated glass cover	Not specified	25.46% and 29.05%, 3.6% higher than bare glass still	Nano-silicon coating boosts overall desalination performance
Jing Yu (2021)	Double-stage solar air evaporating separation system	Not specified	31.70%	EE and PCR in July: 5.99 kg/kWh and 0.156 kWh/kg respectively
Tiantong Yan (2021)	Three-effect tubular solar still with vacuum and immersion cooling	9.8 kg/m² at 40 kPa	Energy use reduced from 21.6 to 1.7 kJ/kg at 60 kPa	Cost: \$0.012/L; efficiency 15–50 times higher
Geo Sabastian (2021)	Aluminium floating absorber based solar still	Not specified	14.7% increase	Study conducted in Kozhikode, South India
M.M Younes (2021)	Wick solar still with half barrel and corrugated observer	-	CSS: 75-100% efficiency	Cost efficiency improved (35%-54.5% reduction)
Mishal Alsehli (2022)	Hybrid solar desalination system (modified solar still etc.)	3330-6150 mL/m²	47.5% and 3.95%	Cost: 0.008 \$/L

Hossein Amiri (2021)	Parabolic trough collector with built-in solar still	1.266 L per day	70% higher than winter	-
Ahmad Bamasaga (2021)	Solar-heated submerged vacuummembrane distillation (S-VMD)	0.1 m²	51%	Production 0.3 times less than reference
Ibrahim M. Alarifi (2021)	Solar still using nanofluid (PCM-NPCM)	-	79.30%	285.1% improvement by adding cuprous nanoparticles; max yield with Al2O3 coating
Manhui Wei (2021)	Natural vacuum solar desalination system	18.0 m² area, 6.018 kg/h	87.82% efficiency	Cost: 0.0113 $/kg
Zhengen Zhou (2021)	Vacuum distillation of antimony trisulfide and lead sulfide	-	Sb2S3 purity 99.17%-99.5%	PbS purity recovery 98.7%
Hajar Hafs (2021)	Passive and active solar still with corrugated absorber	2.11-2.37 kg/m²/day	-	Main results from thermal modeling
Hyunho Kim (2021)	PTFE membrane for vacuum membrane distillation	Up to 10 m module length	-	Effect of feed temp, mass flow, vacuum pressure on desalination analyzed
Rihab Miladi (2021)	Solar thermal vacuum membrane distillation with liquid ring pump	-	0.93-1.01 efficiency, 56.2-59.3% energy	Daily production varied from 598 to 217 kg/day
Lu Wang (2021)	Solar-driven natural vacuum desalination with inner condenser	12.45 kg/h	-	Cost: $6.9 per ton
Joel Nadal-Bach (2021)	Solar stills and evaporators for agro-industrial waste treatment	2 m²	10%-104% improvement	Review paper summarizing advances in solar still technologies
Suresh Kumar Patela (2020)	Ultra modified double slope solar still with external mounted reflectors	Max hourly yield: 1411 ml/hr; cumulative 9157 ml/day	Solar still yield higher by 10.4% (summer), 10.0% (winter)	Quality of Gomati River water in Lucknow harms aquatic life
Dinesh Mevadaa (2020)	Use of fins in solar still	Reduces melting time up to 43%	Efficiency enhanced by fin configuration	Thermal energy storage with fins and nanoparticles reduces melting time
Tiantong Yan (2020)	Tubular Solar Still (TSS) under vacuum, CFD modeling	—	50% at operating pressure < 60 kPa	Deviation of -7.8 to -7.5%
Lenan Zhang (2020)	Thermally localized multistage solar still (TMSS)	—	600% improvement; cost $30–46/m² ($0.0016/L)	High efficiency and low cost
Kabeel, A.E. (2020)	Tubular solar still review	—	—	Advanced design techniques to improve yield
Zanganeh (2020)	Solar still with nano-coated condensation surfaces	4828 ml/m² to 5807 ml/m²	Cost: $0.0152 to $0.0191 per liter	Dropwise condensation greatly improved productivity
Patel, Shirish K (2020)	Multi-slope glass cover solar still (review)	—	—	Techniques to enhance condensation area

Essa, F.A. (2020)	Rotating discs solar still with nanomaterials	—	124% over reference distiller; 54.5% and 50% efficiency	Nanomaterials improve heat transfer characteristics
Yanjie Zheng (2020)	Technoeconomic model of solar thermal desalination	1000 m^3/day at \$0.97/m^3	—	Location: Miami, Florida
Qiuming Ma (2020)	Vacuum membrane distillation (VMD) with solar flat-plate collector	3.7 L and 96 L	—	Heat recovery via heat pumps
Ahmad Bamasag (2020)	Solar-heated direct contact membrane distillation (DCMD)	—	2.2 to 6.5 kg/m^2/h	Depends on solar intensity
Ashok Kumar Singh (2020)	Active solar distillation technology review	—	—	Overview of modifications for active systems improving yield and efficiency
F.A. Essa (2020)	Productivity prediction model using ANN and optimizer	—	Condenser increased efficiency by 53.21%	Uses Harris Hawks optimizer for enhanced model
J.A. Andrés-Mañas (2020)	Vacuum multi-effect membrane distillation for seawater	41.7 to 70.5 m^3	2.60%	Pilot system; temps 60-80°C
Qian Chen (2020)	Spray-assisted low-temperature solar desalination system	20 kg/day/m^2 solar collector area	—	Self-sustainable system with heat storage
Moh'd A. Al-Nimr (2020)	Hybrid Stirling engine + vacuum evaporator + thermoelectric cooler	—	65.80%	TEC modules consume ~45% of Stirling engine output
Zetian Si, Dong Han (2020)	Vacuum membrane distillation with mechanical vapor recompression	—	Exergy efficiency 3.72%; exergy destruction details	Heat-insulating property and efficient components improve exergy performance
Xiaofeng Zhang (2020)	Vulcanization-vacuum distillation of cadmium telluride waste	—	99.92% vacuum distillation purity	Novel method for rare metal recovery
Hongling Deng (2020)	Solar thermal-photovoltaic vacuum membrane distillation system	6.26 L/m^2/h	—	Optimized by response surface methodology
Mohamed S. Yousef / 2019	Solar still with PCM storage	3.26–3.81 kg/m^2	—	Exergy efficiency lower than energy efficiency
Syed Noman Danish / 2019	Solar still with vacuum pump + geothermal cooling	—	305% increase	Vacuum pressure significantly enhances yield
Vasiliki Karanikola / 2019	Solar membrane distillation	10 m^3/day	3.5% (NaCl salinity)	VMD was more cost-effective than SGMD or DCMD
Jaymin Patel / 2019	Stepped basin + evacuated tube collector	8.1 L/day	24%	2 m^2 area
T. Arunkumar / 2019	Review of nanomaterials for solar distillation	—	>96% absorption	CNTs, metal oxides improve evaporation via LSPR

Doriano Brogioli / 2019	Salinity gradient distillation analysis	—	—	Higher boiling point elevation increases efficiency
Saeed Nazari / 2019	Single slope still + Cu_2O nanofluid + thermoelectric cond.	—	Energy: 82.4%, Exergy: 81.5%	$0.021/L/m²
Swellam Sharshir / 2019	Tubular still + ZnO nanotech under vacuum	—	Energy utilization: +80%	Cooling condenser improves productivity
Nader Rahbar / 2018	Tubular vs. triangular still comparison	—	Entropy generation 17.4% lower	Tubular better convective/evaporative coefficients
Piyush Pal / 2018	Multi-wick double slope still	~4.5 L/m²/day	20.94%–23.03%	Wick material influences performance
Xie Guo / 2018	Tubular still under vacuum	—	+80% energy efficiency	High vacuum improves performance
Arunkumar T / 2018	SSSS with porous absorber + bubble wrap	Up to 3.1 L/m²/day	24%	Chennai region; absorber type crucial
Rashidi, Saman / 2018	Nanofluid (Al_2O_3) flow analysis in still	—	25% enhancement	VOF model used for simulation
Omar Bait / 2018	Review on nanofluid application in solar stills	—	—	Nanofluids improve thermal performance
Ali Hosseini / 2018	Vacuum-type active system with parabolic collector	1.5 kg/m²/day	60.98%	0.5 bar vacuum; parabolic trough
Junming Zhou / 2018	VMD regeneration analysis	—	10–37%	Cost recovery period: 13.8 years
Piyush Pal / 2017	Double slope multi-wick still	Up to 4.5 L/m²/day	~21–23%	Black cotton wick more efficient
Rahmani, Ahmed / 2017	NCL solar still (passive)	4.73–2.71 kg/m²	—	Summer vs. winter variation
Kabeel, A.E. / 2017	Review on PCM and heat exchange integration	—	—	Comprehensive review on basin and thermal integration
Nabil Elminshawy / 2016	Active HDH system + geothermal energy	104 L/m²	—	GOR = 1.2–1.58; $0.003/L
T. Arunkumar / 2016	CPC-Tubular still	Up to 7770 mL/day	—	CPC + tubular geometry enhances productivity
Ajay Kumar Kaviti / 2016	Review on inclined stills	Up to 9 L/m²/day	78%	Coral fleece + mesh absorber improves yield
Z.M. Omara / 2015	Nanofluids + vacuum in corrugated wick still	—	285% over conventional	Saline depth 1 cm; cuprous/aluminum oxide used
M.R. Karimi / 2015	Multi-effect solar still with varying stage numbers	23.8 kg	25%	Increased number of stages improves output

Tze-Ling Chong / 2014	Multiple-effect diffusion still + vacuum tube	2.79 kg/m²/day	38% increase	Heat pipes improve gradient and yield
S.A. El-Agouz / 2014	Stepped solar still + circulation	1–3 LPM	47–53%	Cotton absorber improves performance

3.1 Literature Review Summary:

The solar desalination research landscape from 2010 to 2022 shows a distinct path of advancement through hybrid system integration, design optimization, and material innovation. Early research focused on employing phase change materials (PCMs) for energy storage in conjunction with nanoparticles such as CuO, ZnO, and AlO_3 to increase heat conductivity and evaporation rates. Efficiency gains of up to 285% over conventional stills were achieved by geometrical innovations, such as tubular, stepped, and multi-wick designs.At the same time, significant performance improvements—often at reduced operating costs—were achieved through the use of thermoelectric devices and vacuum enhancement techniques.The emphasis switched to sustainability and techno-economic viability between 2020 and 2022. In order to forecast system performance and optimize designs, studies incorporated sophisticated modeling techniques (such as machine learning, CFD, and ANN optimization). With the integration of solar stills with technologies such as Stirling engines, solar collectors, and VMD units, hybrid systems gained popularity. With developments like rotating discs and nanocoatings enhancing heat transport and condensation, material science has remained essential. Notably, the price per liter of desalinated water dropped dramatically (to as low as $0.003/L in certain situations), establishing these systems as scalable and affordable options for areas with a shortage of freshwater.The research advancements of 2022 are notable for their emphasis on practical application and commercial viability.Superior yields and energy efficiency were shown by floating solar stills, multi-stage systems, and VMD units with photothermal membranes; these were frequently several times higher than those of traditional sun stills.While nanotechnology continues to improve energy absorption and system responsiveness, the combination of artificial intelligence and machine learning further developed predictive performance modeling. These developments indicate a developing sector that is gradually resolving issues with cost, scalability, and the environment, making solar desalination a workable, decentralized, and environmentally responsible way to address the world's water scarcity.

Table 2: Yield Comparison of DSSS Types

Type of DSSS	Typical Yield (L/m²/day)	Key Feature
Tubular Solar Still	~4–6 L/m²/day (varies)	Enhanced geometry; improved solar capture and evaporation efficiency
Stepped Solar Still	~5–8 L/m²/day	Increased surface area for condensation; better heat distribution
Multi-Wick Solar Still	~6–10 L/m²/day	Enhanced water absorption and evaporation using multiple wicks
Floating Solar Still	~4.3 L/m²/day	Low-cost design; captures solar radiation from all directions
Multi-Stage Solar Still	Up to 6.5 kg/m²·h (~156 L/m²/day)	Very high efficiency; reuses latent heat across stages for boosted output
VMD with Photothermal Membranes	~7.1 L/m²/day	High efficiency; mitigates temperature polarization and improves yield
Solar Still with Nanoparticles	~4–5 L/m²/day	Uses Cu_2O, ZnO, Al_2O_3 to enhance thermal conductivity and evaporation
Solar Still with Phase Change Materials	~3–5 L/m²/day	Stores thermal energy; stabilizes performance during off-sunlight hours
Hybrid Solar Still (e.g., Stirling, VMD)	~5–10+ L/m²/day	Combines multiple technologies; scalable and energy-efficient

Table 3: Factors Influencing Yield

Type of DSSS	Typical Yield (L/m²/day)	Key Factors Influencing Yield
Tubular Solar Still	~4–6	Enhanced geometry, increased solar absorption, reduced heat loss
Stepped Solar Still	~5–8	Increased condensation area, better heat distribution
Multi-Wick Solar Still	~6–10	Enhanced water absorption, efficient heat transfer
Floating Solar Still	~4.3	Omnidirectional solar capture, low-cost materials, thermal insulation
Multi-Stage Solar Still	Up to ~150+ (converted from kg/m²·h)	Heat reuse between stages, increased evaporation and condensation surfaces
VMD with Photothermal Membranes	~7.1	Temperature polarization reduction, membrane efficiency, vacuum enhancement
Solar Still with Nanoparticles	~4–5	Improved thermal conductivity and evaporation rate (Cu_2O, ZnO, Al_2O_3)
Solar Still with Phase Change Materials (PCMs)	~3–5	Energy storage, heat stability, possible reduction in peak exergy
Hybrid Systems (e.g., with VMD, Stirling engine, solar collectors)	~5–10+	Multi-source energy use, optimized system control, integration of advanced components

Table 4:. General Factors Influencing Yield

Category	Specific Influencing Factors
Material Science	Nanoparticles (Cu_2O, ZnO, Al_2O_3), PCMs, photothermal coatings, rotating discs
System Design	Tubular, stepped, multi-stage, multi-wick, floating designs; improved geometry and insulation
Technology Integration	Hybridization with VMD, Stirling engines, thermoelectric devices, solar collectors
Operational Enhancements	Vacuum application, membrane distillation, heat recovery, optimized water depth
Modeling & Optimization	Machine learning (AI), CFD, ANN, techno-economic analysis for design optimization
Environmental Conditions	Solar radiation intensity, ambient temperature, wind speed, tilt angle

4. Future Prospects

Solar desalination technology seems to have a bright future thanks to continuous developments in digital optimization, system design, and material research. It is anticipated that further advancements in photothermal coatings and long-lasting, reasonably priced nanomaterials would improve system longevity and thermal efficiency while resolving environmental issues. By combining technologies like vacuum membrane distillation, thermoelectric generators, and Stirling engines, multi-stage and hybrid systems can greatly increase freshwater yield and energy consumption, making solar desalination more competitive with traditional techniques.Real-time system optimization, predictive maintenance, and design modification for particular operational and climatic conditions will all be greatly aided by developments in artificial intelligence, machine learning, and computational fluid dynamics. This will enable more intelligent, robust solar desalination systems that can continue to operate well in the face of fluctuating solar radiation and environmental stresses.Additionally, as research moves from lab-scale prototypes to pilot-scale and field demonstrations, attempts to standardize systems, reduce costs, and use modular manufacturing will hasten commercialization and broad implementation. In addition to reducing environmental effects, a focus on environmentally acceptable materials and sustainable brine management will improve societal acceptance and regulatory compliance. When taken as a whole, these patterns suggest that technology is maturing and may soon provide decentralized, scalable, and ecologically friendly solutions to the world's freshwater shortage, especially in dry and off-grid areas.

5. Conclusion

Solar desalination technologies have made remarkable progress from 2010 to 2022 Energy efficiency and freshwater yield are greatly increased by double slope solar stills powered by advancements in nanomaterials, system architectures, and hybrid integrations. Notwithstanding these developments, obstacles to widespread implementation remain, including material durability, system complexity, climatic dependence, and economic feasibility. It will be critical to address these limitations by more study, optimization with sophisticated modeling approaches, and validations at the pilot scale. As cost-effectiveness, scalability, and environmental sustainability continue to improve, solar desalination is set to emerge as a viable, decentralized solution to the world's water shortage, particularly in isolated and arid areas.

REFERENCES

[1] Wei, Manhui, et.al.. "Productivity and economy prediction for a solar-powered natural vacuum desalination system via water filling and air-releasing in Asia." Energy Conversion and Management 260 (2022): 115570.

[2] Abbaspour, Mohammadreza, Abas Ramiar, and Qadir Esmaili. "Efficiency improvement of vertical solar stills–A review." *Solar Energy* 235 (2022): 19-35.

[3] Wang, Zepeng, et.al.. "Performance of solar adsorption cooling system with internal finned vacuum tube bed." Case Studies in Thermal Engineering 34 (2022): 102063.

[4] Choi, Jihyeok, et.al.. "Combination of computational fluid dynamics and design of experiments to optimize modules for direct contact membrane distillation." Desalination 524 (2022): 115460.

[5] Ma, Qiuming, Aras Ahmadi, and Corinne Cabassud. "Comparative study of small-scale flat-plate direct contact membrane distillation and vacuum membrane distillation modules with integrated direct solar heating." Desalination 529 (2022): 115633.

[6] Mohsenzadeh, Milad, Lu Aye, and Philip Christopher. "Development and experimental analysis of an innovative self-cleaning low vacuum hemispherical floating solar still for low-cost desalination." Energy Conversion and Management 251 (2022): 114902.

[7] Shoeibi, Shahin, et.al.. "Solar district heating with solar desalination using energy storage material for domestic hot water and drinking water–environmental and economic analysis." Sustainable Energy Technologies and Assessments 49 (2022): 101713.

[8] Ma, Qiuming, et.al.. "Distributed vacuum membrane distillation driven by direct-solar heating at ultra-low temperature." Energy 239 (2022): 121891.

[9] Peng, Guilong, et.al.. "A study on the upper limit efficiency of solar still by optimizing the mass transfer." Applied Thermal Engineering (2022): 118664.

[10] Kumar, M. Muthu, et.al.. "Performance enhancement of solar distillation system with internal modification." Materials Today: Proceedings (2022).

[11] Siefan, Abdelfattah, et.al.. "Desalination via solar membrane distillation and conventional membrane distillation: Life cycle assessment case study in Jordan." Desalination 522 (2022): 115383.

[12] Ma, Qiuming, Aras Ahmadi, and Corinne Cabassud. "Comparative study of small-scale flat-plate direct contact membrane distillation and vacuum membrane distillation modules with integrated direct solar heating." Desalination 529 (2022): 115633.

[13] Zhao, Yunsheng, et.al.. "Performance analysis and optimization of a novel high-efficiency flower-inspired solar still." Energy Conversion and Management 251 (2022): 114878.

[14] Mohsenzadeh, Milad, Lu Aye, and Philip Christopher. "Development and experimental analysis of an innovative self-cleaning low vacuum hemispherical floating solar still for low-cost desalination." Energy Conversion and Management 251 (2022): 114902.

[15] Alatawi, Ibrahim, et.al.. "Tubular solar stills: Recent developments and future." Solar Energy Materials and Solar Cells 242 (2022): 111785.

[16] Elsheikh, Ammar H., et.al.. "Low-cost bilayered structure for improving the performance of solar stills: Performance/cost analysis and water yield prediction using machine learning." Sustainable Energy Technologies and Assessments 49 (2022): 101783.

[17] Bansal, Kunal, et.al.. "Validation and CFD modeling of solar still with nanoparticle coating on absorber plate." Materials Today: Proceedings (2022).

[18] Kateshia, Jyotin, and Vikas J. Lakhera. "Analysis of solar still integrated with phase change material and pin fins as absorbing material." Journal of Energy Storage 35 (2021): 102292.

[19] Thakur, Amrit Kumar, et.al.. "Augmented performance of solar desalination unit by utilization of nano-silicon coated glass cover for promoting drop-wise condensation." Desalination 515 (2021): 115191.

[20] Yu, Jing, et.al.. "Performance investigation of the double-stage solar air evaporating separation system for saline wastewater treatment." Desalination 515 (2021): 115194.

[21] Yan, Tiantong, et.al.. "Experimental study on three-effect tubular solar still under vacuum and immersion cooling." Desalination 515 (2021): 115211.

[22] Sebastian, Geo, and Shijo Thomas. "Influence of providing a three-layer spectrally selective floating absorber on passive single slope solar still productivity under tropical conditions." Energy 214 (2021): 118848.

[23] Younes, M. M., et.al.. "Enhancing the wick solar still performance using half barrel and corrugated absorbers." Process Safety and Environmental Protection 150 (2021): 440-452.

[24] Alsehli, Mishal, et.al.. "Improving the performance of a hybrid solar desalination system under various operating conditions." Process Safety and Environmental Protection 162 (2022): 706-720.

[25] Amiri, Hossein, et.al.. "Energy and exergy analysis of a new solar still composed of parabolic trough collector with built-in solar still." Renewable Energy 163 (2021): 465-479.
[26] Bamasag, Ahmad, et.al.. "Solar-heated submerged vacuum membrane distillation system with agitation techniques for desalination." Separation and Purification Technology 256 (2021): 117855.
[27] Alarifi, Ibrahim M., et.al.. "On the effects of nanomaterials on the performance of solar distillation systems-A comprehensive review." Solar Energy 218 (2021): 596-610.
[28] Wei, Manhui, et.al.. "Using water-filling and air-releasing to design a natural vacuum solar desalination system." Solar Energy 220 (2021): 598-607.
[29] Zhou, Zhengen, et.al.. "A vacuum distillation process for separation of antimony trisulfide and lead sulfide from jamesonite." Vacuum 188 (2021): 110172.
[30] Hafs, Hajar, et.al.. "Numerical simulation of the performance of passive and active solar still with corrugated absorber surface as heat storage medium for sustainable solar desalination technology." Groundwater for Sustainable Development 14 (2021): 100610.
[31] Kim, Hyunho, et.al.. "Experimental and theoretical investigation of a high performance PTFE membrane for vacuum-membrane distillation." Journal of Membrane Science 617 (2021): 118524.
[32] Miladi, Rihab, Nader Frikha, and Slimane Gabsi. "Modeling and energy analysis of a solar thermal vacuum membrane distillation coupled with a liquid ring vacuum pump." Renewable Energy 164 (2021): 1395-1407.
[33] Wang, Lu, et.al.. "Solar-driven natural vacuum desalination system with inner condenser." Applied Thermal Engineering 196 (2021): 117320.
[34 Nadal-Bach, Joel, et.al.. "Solar stills and evaporators for the treatment of agro-industrial liquid wastes: A review." Renewable and Sustainable Energy Reviews 142 (2021): 110825.
[35] Patel, Suresh Kumar, et.al.. "Production of potable water from Gomti River by using modified double slope solar still with external mounted reflectors." Solar Energy 209 (2020): 576-589.
[36] Mevada, Dinesh, et.al.. "Effect of fin configuration parameters on performance of solar still: a review." Groundwater for Sustainable Development 10 (2020): 100289.
[37] Yan, Tiantong, et.al.. "CFD investigation of vapor transportation in a tubular solar still operating under vacuum." International Journal of Heat and Mass Transfer 156 (2020): 119917.
[38] Zhang, Lenan, et.al.. "Modeling and performance analysis of high-efficiency thermally-localized multistage solar stills." Applied energy 266 (2020): 114864.
[39] Kabeel, A. E., et.al.. "A comprehensive review of tubular solar still designs, performance, and economic analysis." Journal of cleaner production 246 (2020): 119030.
[40] Zanganeh, Peyman, et.al.. "Nano-coated condensation surfaces enhanced the productivity of the single-slope solar still by changing the condensation mechanism." Journal of Cleaner Production 265 (2020): 121758.
[41] Patel, Shirish K., and Kalpesh V. Modi. "Techniques to improve the performance of enhanced condensation area solar still: A critical review." Journal of Cleaner Production 268 (2020): 122260.
[42] Essa, F. A., A. S. Abdullah, and Z. M. Omara. "Rotating discs solar still: New mechanism of desalination." Journal of Cleaner Production 275 (2020): 123200.
[43] Zheng, Yanjie, and Kelsey B. Hatzell. "Technoeconomic analysis of solar thermal desalination." Desalination 474 (2020): 114168.
[**44]** Ma, Qiuming, Aras Ahmadi, and Corinne Cabassud. "Optimization and design of a novel small-scale integrated vacuum membrane distillation-solar flat-plate collector module with heat recovery strategy through heat pumps." Desalination 478 (2020): 114285.
[45] Bamasag, Ahmad, et.al.. "Experimental investigation of a solar-heated direct contact membrane distillation system using evacuated tube collectors." Desalination 487 (2020): 114497.
[46] Singh, Ashok Kumar, et.al.. "Active solar distillation technology: a wide overview." Desalination 493 (2020): 114652.
[47] Essa, F. A., Mohamed Abd Elaziz, and Ammar H. Elsheikh. "An enhanced productivity prediction model of active solar still using artificial neural network and Harris Hawks optimizer." Applied Thermal Engineering 170 (2020): 115020.
[48] Andrés-Mañas, J. A., et.al.. "Application of solar energy to seawater desalination in a pilot system based on vacuum multi-effect membrane distillation." Applied Energy 258 (2020): 114068.
[**49]** Chen, Qian, et.al.. "A self-sustainable solar desalination system using direct spray technology." Energy 205 (2020): 118037.
[50] Al-Nimr, Moh'D. A., and Wahib A. Al-Ammari. "A novel hybrid and interactive solar system consists of Stirling engine∕vacuum evaporator∕thermoelectric cooler for electricity generation and water distillation." Renewable Energy 153.C (2020): 1053-1066.
[51] Si, Zetian, et.al.. "Exergy analysis of a vacuum membrane distillation system integrated with mechanical vapor recompression for sulfuric acid waste treatment." Applied Thermal Engineering 178 (2020): 115516.
[52] Zhang, Xiaofeng, et.al.. "Selective separation and recovery of rare metals by vulcanization-vacuum distillation of cadmium telluride waste." Separation and Purification Technology 230 (2020): 115864.
[53] Deng, Hongling, et.al.. "Modeling and optimization of solar thermal-photovoltaic vacuum membrane distillation system by response surface methodology." Solar Energy 195 (2020): 230-238.

[54] Zhang, Xiaofeng, et.al.. "Application of multi-stage vacuum distillation for secondary resource recovery: potential recovery method of cadmium telluride photovoltaic waste." Journal of Materials Research and Technology 9.4 (2020): 6977-6986.

[55] Yousef, Mohamed S., and Hamdy Hassan. "Energetic and exergetic performance assessment of the inclusion of phase change materials (PCM) in a solar distillation system." Energy conversion and management 179 (2019): 349-361.

[56] Danish, Syed Noman, et.al.. "Enhancing solar still performance using vacuum pump and geothermal energy." Energies 12.3 (2019): 539.

[57] Karanikola, Vasiliki, et.al.. "Economic performance of membrane distillation configurations in optimal solar thermal desalination systems." Desalination 472 (2019): 114164.

[**58]** Patel, Jaymin, Bhupendra K. Markam, and Subarna Maiti. "Potable water by solar thermal distillation in solar salt works and performance enhancement by integrating with evacuated tubes." Solar Energy 188 (2019): 561-572.

[59] Arunkumar, T., et.al.. "Energy efficient materials for solar water distillation-A review." Renewable and Sustainable Energy Reviews 115 (2019): 109409.

[**60]** Brogioli, Doriano, Fabio La Mantia, and Ngai Yin Yip. "Energy efficiency analysis of distillation for thermally regenerative salinity gradient power technologies." Renewable energy 133 (2019): 1034-1045.

[61] Nazari, Saeed, Habibollah Safarzadeh, and Mehdi Bahiraei. "Experimental and analytical investigations of productivity, energy and exergy efficiency of a single slope solar still enhanced with thermoelectric channel and nanofluid." Renewable energy 135 (2019): 729-744.

[62] Sharshir, Swellam W., et.al.. "A mini review of techniques used to improve the tubular solar still performance for solar water desalination." Process Safety and Environmental Protection 124 (2019): 204-212.

[63] Rahbar, Nader, Amin Asadi, and Ehsan Fotouhi-Bafghi. "Performance evaluation of two solar stills of different geometries: tubular versus triangular: experimental study, numerical simulation, and second law analysis." Desalination 443 (2018): 44-55.

[**64]** Pal, Piyush, et.al.. "Energy matrices, exergoeconomic and enviroeconomic analysis of modified multi–wick basin type double slope solar still." Desalination 447 (2018): 55-73.

[65] Xie, Guo, et.al.. "Model development and experimental verification for tubular solar still operating under vacuum condition." Energy 157 (2018): 115-130.

[66] Arunkumar, T., et.al.. "Productivity enhancement of solar still by using porous absorber with bubble-wrap insulation." Journal of Cleaner Production 195 (2018): 1149-1161.

[67] Rashidi, Saman, et.al.. "Volume of fluid model to simulate the nanofluid flow and entropy generation in a single slope solar still." Renewable Energy 115 (2018): 400-410.

[68] Bait, Omar, and Mohamed Si–Ameur. "Enhanced heat and mass transfer in solar stills using nanofluids: a review." Solar Energy 170 (2018): 694-722.

[69] Hosseini, Ali, Ahmad Banakar, and Shiva Gorjian. "Development and performance evaluation of an active solar distillation system integrated with a vacuum-type heat exchanger." Desalination 435 (2018): 45-59.

[70] Zhou, Junming, et.al.. "Performance analysis of solar vacuum membrane distillation regeneration." Applied Thermal Engineering 144 (2018): 571-582.

[71] Pal, Piyush, et.al.. "Performance analysis of modified basin type double slope multi–wick solar still." Desalination 422 (2017): 68-82.

[72] Rahmani, Ahmed, and Abdelouahab Boutriaa. "Numerical and experimental study of a passive solar still integrated with an external condenser." international journal of hydrogen energy 42.48 (2017): 29047-29055.

[73] Kabeel, A. E., et.al.. "Performance enhancement of solar still through efficient heat exchange mechanism–a review." Applied Thermal Engineering 114 (2017): 815-836.

[74] Elminshawy, Nabil AS, Farooq R. Siddiqui, and Mohammad F. Addas. "Development of an active solar humidification-dehumidification (HDH) desalination system integrated with geothermal energy." Energy conversion and management 126 (2016): 608-621.

[75] Arunkumar, T., et.al.. "Productivity enhancements of compound parabolic concentrator tubular solar stills." Renewable energy 88 (2016): 391-400.

[76] Kaviti, Ajay Kumar, Akhilesh Yadav, and Amit Shukla. "Inclined solar still designs: A review." Renewable and Sustainable Energy Reviews 54 (2016): 429-451.

[77] Omara, Z. M., A. E. Kabeel, and F. A. Essa. "Effect of using nanofluids and providing vacuum on the yield of corrugated wick solar still." Energy conversion and management 103 (2015): 965-972.

[78] Estahbanati, MR Karimi, et.al.. "Experimental investigation of a multi-effect active solar still: the effect of the number of stages." Applied Energy 137 (2015): 46-55.

[79] Chong, Tze-Ling, et.al.. "Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe." Desalination 347 (2014): 66-76.

[80] El-Agouz, S. A. "Experimental investigation of stepped solar still with continuous water circulation." Energy Conversion and Management 86 (2014): 186-193.

(2013): 73-78.