Cihan University-Erbil Scientific Journal (CUESJ)

REVIEW ARTICLE

Performance Enhancement of Solar Stills: A Comprehensive Review of Methods and Technologies

Dlair A. Baban

Department of Mechanical Engineering, College of Engineering, Salahaddin University-Erbil, Kurdistan Region, Iraq

ABSTRACT

Access to safely managed drinking water services has become a serious issue for 2.2 billion people worldwide. As is known, traditional stilling designs suffer from low quality and production. Therefore, solar stills offer an eco-friendly solution. This review study provides the first comprehensive cross-comparison of enhancement technologies for solar stills developed between 2020 and 2025. This work rigorously analyzes 121 peer-reviewed articles, comparing 11 different enhancement methods based on technical performance, economic viability, and practical implementation challenges, unlike previous reviews focusing on limited improvements. An innovative combined deductive–inductive taxonomy was developed and validated, providing a rationale-based technology selection framework. Results show productivity improvements ranging from 4.2% to 748%, with costs between \$0.0014 and \$0.29/L. Low-cost technologies (thermal storage, fins, stepped designs: \$0.005–0.035/L) are ideal for resource-limited settings, offering payback periods under 2 years. Moderate-cost options (\$0.018–0.060/L), including phase change materials and pyramidal designs, show promise for community-scale applications, though they face short- to medium-term economic barriers. Enhancements are categorized using a four-stage technology readiness scale: deployment-ready, community-scale ready, pilot-scale, and research stage. Key research gaps include insufficient long-term performance data and unsystematic evaluation of hybrid enhancement approaches. This study uniquely provides a systematic, evidence-based framework integrating technical performance with economic feasibility and practical viability, enabling informed decision-making for expanding safe drinking water access through solar desalination technology.

Keywords: Solar distillation, Performance enhancement, Economic feasibility, Technology assessment, Sustainable desalination

INTRODUCTION

Water scarcity is among the most challenging global problems in the 21st century, and about 2.2 billion people on the planet have no access to safely managed drinking water services.[1] Safe drinking water is in ever-increasing demand as populations grow, industrial activities expand, and climate impacts are felt;[2,3] thus, sustainable, effective, and economical water treatment technologies have to be established.

Solar distillation systems have gained considerable interest, especially in the case of rural and underprivileged communities where access to conventional energy resources is scarce or non-existent. Solar still systems purify non-potable water by natural evaporation and condensation with solar energy only, consuming neither electricity nor intricate mechanical construction.[4,5] However, traditional solar stills inherently have low daily productivity, which has conventionally impeded their use for large-scale implementation.

Various approaches have led to numerous efforts recently to enhance the performance of solar stills. Enhancement methods can be generally divided into passive (improving the design configuration and selection of materials) and active (external sources or mechanical approaches). Some of the passive enhancement techniques include adding nanomaterials to improve thermal and optical properties, using phase change materials (PCMs) to ensure functionality during non-sunshine hours, and implementing geometrical modifications such as pyramidal, stepped, and corrugated designs. Solar concentrators, rotating techniques, and external condensers or thermoelectric systems are all examples of active cooling methods.

Recent technological advances have demonstrated that these augmentation techniques can significantly increase the productivity of solar stills. Studies have investigated

Corresponding Author:
Dlair A. Baban, College of Engineering, Salahaddin University-Erbil, Kurdistan Region, Iraq.
E-mail: dlair.hassan@su.edu.krd

Received: September 03, 2025
Accepted: October 18, 2025
Published: December 1, 2025

DOI: 10.24086/cuesj.v9n2y2025.pp100-110

nanomaterial coatings, high-performance integration with PCM, innovative geometry configurations, solar concentration methods, and hybrid multi-technology solutions. These developments have demonstrated excellent results in laboratory and field tests, offering significant performance enhancements under varying operating conditions.

Research Gap Identification. However, the scale-up and performance optimization of solar augmentation technologies still face many challenges. Most previous reviews are mainly focused on a certain kind of enhancing category (e.g., only nanomaterials or PCMs), which introduces the challenges of very limited cross-comparison among different enhancement strategies.[2-4] Most studies do not holistically assess performance enhancements, economic feasibility, and practical barriers of major enhancement approaches. Moreover, both researchers and practitioners are faced with the absence of well-defined evidence-based guidelines on how technologies should be chosen and tuned to respond to given functional needs and constraints in their deployment contexts. Such a fragmented knowledge base of the existing knowledge makes it difficult for people to make informed choices and greatly reduces the effective translation of research results into practice.

Furthermore, many studies indicate performance improvements without comparing the cost-effectiveness, scalability, maintenance costs, and long-term reliability between various approaches of enhancement. The field would be well served by a unifying framework that brings together technical performance measures on the one hand with economic and practical considerations in implementation on the other.

The current review covers the existing research gap and fills it by systematically examining enhancement technologies for solar stills. The aims for this study are as follows:
1. To classify and categorize solar still improvement technologies systematically.
2. To quantitatively assess performance gains for different enhancement methods.
3. To evaluate the economic feasibility and cost–benefit ratio.
4. To examine practical implementation feasibility.
5. To uncover missing critical research and future research directions.
6. To develop an integrative, evidence-based approach for selecting technologies.

METHODOLOGY

This rigorous, systematic study was on the enhancement technologies of solar stills, published from January 2020 to December 2025. The process included five critical stages: identification and selection of the literature, data extraction and assessment of quality, development of taxonomies, analytical synthesis, and assessment.

Literature Search and Selection of Studies

A comprehensive electronic search was performed using five well-known academic databases (Scopus, Web of Science, SpringerLink, Science Direct, and IEEE Xplore). Key words were combined, primary keywords (solar still, solar distillation, desalination) with enhancement-specific terms (nanomaterials, PCMs, rotating design, solar concentrator, and enhancement efficiency). Search terms used Boolean operators for comprehensive coverage with high specificity.

The first search identified 347 articles, which were potentially relevant. A total of 198 articles were included for full-text screening after title and abstract selection. Studies were incorporated if they (1) were published in peer-reviewed journals, (2) had reported original experimental or theoretical research of quantitative data, (3) showed quantifiable enhancements in performance due to some specific enhancement methods used, and (4) included a clear methodological description and were written in English. The exclusion criteria were conference papers, studies that were entirely based on hypotheses without experimentation, no quantitative results, duplicate articles, and reviews without original data. One hundred and twenty-one articles fulfilled all inclusion criteria and were included in the final analysis.

Data Extraction and Quality Appraisal

A standardized extraction was employed to extract technical, economic, and practical operation data from all of the studies. This technical content encompassed descriptions of the enhancement method used, experimental setups, baseline and enhanced performance measurements, productivity enhancement (percentage and absolute values), and efficiency gain. Economic indicators were cost per liter, capital cost, and payback period (where available). The pragmatic parameters concerned system complexity, material availability, maintenance requirements, scalability potential, and operational constraints.

The included studies were quality-assessed on methodological rigor (experimental design, control of variables or dosages, statistical treatment), data completeness and reporting clarity, reproducibility based on methodological detail reported, validity assessment based on statistical evaluation (correct use of statistics, confidence intervals, significance tests), as well as quality of publication venue. Studies were included only if they satisfied minimum quality requirements on these dimensions, thereby ensuring that the synthesis is informed by methodologically rigorous scholarship.

Classification Taxonomy Development

The eleven-category classification system was developed through a systematic, combined deductive-inductive approach. The deductive phase began with previous review studies that identified major enhancement categories such as nanomaterials, PCMs, and solar concentrators. However, these prior reviews typically covered only two to four categories and had a limited temporal scope.

The inductive stage was an iterative thematic analysis of the full set of 121 studies to determine unique enhancement techniques that required their own category. Additional categories had arisen or developed during 2020–2025 according to the outcome of a data-driven approach that encompassed rotating parts, pyramid and stepped shapes, external condensers, materials for storage heat (not PCM), fin and corrugated surface systems, advanced hybrid systems, computational methods to model optimizing strategies, and economic-environmental analysis studies.

Four explicit criteria were used to validate each category: (1) A distinct operational principle with a fundamentally different enhancement mechanism; (2) sufficient study volume with a minimum of 6–7 studies for meaningful analysis; (3) practical differentiation of implementation requirements and performance characteristics; and (4) technological independence, so that the category can be a standalone or a hybrid. The taxonomy was tested for inter-rater reliability (94% agreement between two independent evaluators) and assessed for mutual exclusiveness, exhaustiveness, and practical usefulness as a basis to support the choice of technologies.

This eleven-class categorization is a substantial improvement over previous classification systems, embracing the complete variety of modern solar still enhancement research and providing strong categories for comparative study.

Analytical Methods and Synthesis

Several complementary techniques have been used to guarantee a complete assessment. Descriptive statistics were computed for each of the categories (minimum, maximum, average performance, and performance range). Comparative analysis included relative performance between categories, consistency of performances, outlying cases, and change over time.

Based on a systematic thematic review, information content analysis identified operational principles applied, technical challenges continually faced, implementation impediments met, and success edge factors in both categories as well as emerging trends. This qualitative synthesis set quantitative performance measures in a contextual frame and identified elements influencing the practical use.

A multi-dimensional synthesis structure structured the literature findings through four interrelated dimensions: (1) Technical, including productivity gains, efficiency improvements and performance consistency; (2) economic in terms of cost per liter, investment demand and payback period; (3) implementation feasibility in relation to complexity, scalability and maintenance or material availability; and (4) impact on the environment from an energy consumption perspective as well as considering carbon footprint and material aspects. It allows for the integration of all real-world deployment-relevant influences, making it applicable to a comprehensive, end-to-end analysis.

Synthesis comparatively analyzed performance-cost trade-offs, complexity-effectiveness balance, scalability potential, and context fit for various deployment scenarios (rural/remote vis-à-vis industrial/utility-scale applications). This novel multi-criteria assessment helps in technology selection that is evidence-based and appropriate to particular operational needs, but also to available facilities.

Performance Evaluation Framework

All enhancement methods were methodically assessed through a standardized, multicriteria-based analysis. Performance metrics were scaling factors, water production as a percentage of improvement rates, absolute water yields ($L/m^2/h$ or $kg/m^2/h$), efficiency increments, and performance robustness for different conditions. Economic indexes included the liter purchasing cost, capital investment, and payback period. The feasibility of implementation was rated in terms of technical complexity (low/medium/high), availability of materials (local/regional/specialized) and scalability potential (lab/pilot/commercial scale), and maintenance. Energy and material performance were measured using environmental metrics such as energy utilization, carbon footprint, and material sustainability.

The foundation provided can support informed choices by exemplifying the complete set of drivers influencing technology choice, not limited to performance metrics, but also economic, practical, and environmental issues that play a significant role in creating an environment for successful deployment.

Study Rationale and Scope

With this purpose in mind, the present review systematically explores 121 peer-reviewed studies published from 2020 to 2025 to report up-to-date advancements in solar still improvement measures. In this study, we present a complete cross-comparison of 11 different enhancement strategies, as shown in Table 1, unlike prior reviews that focused on a single

Table 1: Summary of solar still enhancement strategies, reported performance improvements, and representative references (2020–2025)

Category	Performance improvement	Representative references
Nanomaterials	19.5–300%	[2,4,5,32,62,84,88,91,96,98,101,104]
Phase change materials	10.6–675%	[3,10,14,16,30,52,55,57,59,109,112-114,119,120]
Rotating configurations	37–300%	[6,13,17,18,41-43,51,82]
Solar concentrator systems	14.18–216.6%	[12,19,20,29,31,54,60,65,69,70,74]
Fins and corrugated surfaces	24–128%	[21,23,38,46,53,61,72,79,83,90,97]
Pyramid and stepped designs	60–675%	[9,14-16,44,45,58,63,64,73,80,101]
External condensers	32.46–469.48%	[27,34,35,40,87,112-114]
Thermal storage materials	4.21–85.86%	[22,25,26,67,71,76,93,110]
Advanced/Innovative Technologies	33.26–748%	[11,28,36,37,47,48,49,50,56,68,78,85,95,100,103,105,107,115,117,118,121]
Modeling and Prediction Methods	Forecast accuracy (<5% error)	[24,38,40,66,77,92,99,116]
Economic and Environmental Analysis	\$0.0014–0.29/L; CO_2 reduction	[33,86,94,102,106,108,111,120]

class of technology. This systematic classification provides a structured analysis of the performance, economics, and implementation advantages of each enhancement method to pursue informed technology development and optimization strategy selection.

RESULTS AND DISCUSSION

In this section, an extensive review of a set of 11 categories of solar still enhancement is provided by considering a structured data analysis based on 121 reviewed articles. Technical, economic feasibility, and implementation resistance are evaluated for each of the categories.

Nanomaterial Enhancements

The use of nanomaterials was the focus of 15 studies[2,4,7,32,62,84,88,91,96,98,101,104] reporting productivity gains ranging from 19.5 to 300%. Maximum enhancement (300%) in case rotating wick systems employing nanofluids[5] has been reported, and for conventional ones CuO nanofluids with PCM (80.2%),[2] graphene oxide (116.5%),[62] and silver nanoparticles (106–218%).[91] Augmentation mechanisms include increased solar absorption, raised thermal conductivity, and elevated evaporation due to nucleation sites for nanoparticles.[32,84,96]

Economic-Nano materials increase capital costs by 40–60% because they are very complex to synthesize, and the cost per liter is observed between $0.015 and 0.045.[86,108] There is a particularly narrow range of highly technical applications where commercial feasibility exists.

Long-term stability remains a critical constraint in practical implementations, as numerous nanoparticle synthesis routes tend to induce particle aggregation and system fouling after prolonged operation, typically within six to twelve months.[32,91] Such progressive performance degradation has hindered the realization of any notable commercial deployment, while the scaling-up of solar still systems beyond the laboratory scale (<1 m²) continues to be limited by significant technical and economic challenges.[2,4,91] Health and safety conditions restrict access in rural areas.[89,106] Better applied in research installations, short of widespread use.[17,108]

PCMs

Eighteen studies considered running PCM,[3,10,14,16,30,52,55,57,59,109,112,114,119,120] reporting Improvements of 10.6–675%. Single PCMs were used with step pyramids embedded with PVs to reach the extraordinary thermal performance of 675%.[14] Common applications demonstrated an improvement from 90% to 230%, while Nano-enhanced PCMs showed enhancements of 180–245%.[10,55] PCMs make 24-h operation possible by storing hot-day heat and releasing it during the night.[57,81]

Economic: PCMs contribute 20–35% to the construction cost, at $0.018–0.080/L.[86,108,120] 2–4 years payback periods render them economically attractive in community-based supplies.[120]

Practical Limits: Climate matching is necessary for the selection of PCM.[55,57] The thermal cycling degradation (15–25% after 1000 cycles) requires replacement every 2–3 years.[52,109] Threat of leakage is a motivation for sound encapsulation.[30,59] Pilot-scale demonstrations (5–10 m²) are feasible[14,55] but scale-dependent weight and volume increases. Most appropriate for systematic community interventions, agency-based settings.[17,108]

Rotating Configurations

Eight studies investigated spinning designs,[6,13,17,18,41-43,51,82] demonstrating enhances by 37–300%. Four-cylinder systems 214%,[13] rotating drums between 200–300%[43] and rotating disks at 124%[42] were obtained. Enhancement happens by continuous renewal of the surface and better mass transfer.[41,43]

Economic Viability: Mechanical complexity leads to 60–100% with estimated cost per liter of $0.05–0.15/L.[86,108] The payback period of 8–15 years is uncertain from an economic standpoint.[108]

Practical Issues: The primary limitation is mechanical reliability, with bearings, seals, and motors that need to be serviced on a regular basis.[17,41,43] When using in solutions, for example, saline media component damage is intensified.[6,43] Energy demand presumes a reliable electrical power supply.[41] There are no long-term reliability data available, and all the implementations are still confined to the laboratory scale (< 2 m²).[6,13,41-43] Most appropriate for research settings.[17,108]

Solar Concentrator Systems

Concentrators were explored in eleven studies[12,19,20,29,31,54,60,65,69,70,74] with an increase of 14.2–216%. Parabolic troughs had the highest gains (216%),[54] while CPCs had a 65%.[20] Concentration: Enhancing the concentration of solar radiation increases the effective thermal energy absorbed by the distillation unit, leading to higher evaporation rates and improved freshwater yield.[19,24,75]

Economic Feasibility: Concentrators add 100–200% cost that drives the total price per liter between $0.03–0.12.[54,86,108] The economic feasibility relies on high direct normal irradiance (DNI) sites.[54,75] Tracking the sun introduces 22% cost reduction potential but incurs maintenance.[54]

Practical Limitation: Need high-quality direct sunlight, i.e., can only be deployed in clear-sky areas.[19,54,75] Tracking mechanisms have mechanical reliability issues.[54] Every 2–7 days cleaning the surfaces results in the water use paradox.[54] Installing a lid is technically demanding and precise work.[17] Owing to geographic limitation, viability to 20–30% of water-scarce regions. Best applications using technical support large-scale in high DNI locations.[17,54,108]

Fins and Corrugated Surfaces

Fins were studied in eleven studies,[21,23,38,46,53,61,72,79,83,90,97] exhibiting improvements for (24–128%]). Meanwhile, 128%[38,39] were obtained by corrugated plates, 77%[61] V-corrugated fins with PCM and 24–46% for simple fins.[72,83] Increasing the area of attachment and better convection aiding enhancement.[61,72]

Economy: Adds only 5–15% at minimal cost,

Table 2: Performance and economic comparison

Category	Improvement range (%)	Cost/L	Complexity	Scalability	Studies
Thermal storage	4.2–85.9	$0.005–0.018	Very low	Excellent	7
Fins and corrugated	24–128	$0.008–0.025	Very low	Excellent	11
Pyramid systems	60–675	$0.020–0.060	Moderate	Moderate	10
PCMs	10.6–675	$0.018–0.080	Moderate	Moderate	18
External condensers	32.5–469.5	$0.025–0.100	Low-moderate	Good	7
Concentrators	14.2–216.6	$0.030–0.120	High	Moderate	11
Nanomaterials	19.5–300	$0.015–0.045	High	Poor	15
Rotating Designs	37–300	$0.05–0.15*	High	Poor	8
Advanced Tech	33.3–748	$0.08–0.29	Very high	Poor	11

*Estimated; limited data available

$0.008–0.025/l.[86,108] Return on investment of 1–2 years indicates very high cost-effectiveness.[61,72,108]

Practical considerations: No significant obstacles – rudimentary construction, simple upkeep, corrosion can be controlled by choice of materials (aluminum or stainless steel).[72,83] Great scalability from homes to businesses.[17,72] Limitation: relatively modest performance (24–46% for simple fins) but suitable to combine with other low-cost methods.[61,72] Most extensive grass-roots use.[17,72,108]

Pyramid and Stepped Designs

Pyramids (ten studies,[14-16,45,58,59,63,64,73,80,101] showed benefits of 60–675%. Combination of PCM and PV: The maximum 675% combined stepped pyramids with PCM and PV.[14] Pyramidal-wick devices realized 195%,[45] while simple step concepts reached in the range of 60–90%.[15,58] Multi-level evaporation surfaces.[15,45]

Economic Feasibility: Complexity of construction raises prices by 30–50%, cost/L $0.02–0.06.[14,86,108] Positive performance-to-investment ratio with 2–4 year payback times.[15,108]

Practical bounds: Building the plumes needs more precision for watertight seals and multilevel assembly.[15,58] DC access is difficult to clean.[58] As the glass area increases, cost and fragility are raised.[15] Medium scalability up to 2–3 m^2 per unit[14,15] and[58] most appropriate in community initiatives with minimal technical support.[17,108]

External Condenser Systems

Seven studies were conducted on the use of external condensers[27,34,35,87,112-114] and observed an increase in efficiency ranging between 32.5 = 469%. The highest 469% beam for the Fresnel lens with a submerging condenser.[35] Conventional systems resulted in 80–150%.[27,112-114] Augmentation by decoupling and optimizing condensation.[34,112]

- Economic Potential: Design 10–20% more expensive, sophisticated systems 60–90% greater per L of $0.025–0.10.[86,108] 2–4-year payback from basic passive systems.[112,113]
- Practical Constraints: The complexity range is extremely broad, for example passive air-cooled systems are simple,[27] though water-cooled or active designs typically require pumps and heat exchangers.[34] Climate sensitive efficacy; least effective in hot humid climates.[27,112] Immersion condensers are subjected to biofouling and corrosion.[35] Ideal for maritime or cool, well-ventilated climate/habitat.[27,34,108]

Thermal Storage Materials

Non-PCM storage materials were explored in 7 publications,[25,26,67,71,76,93] and[110] which indicated reductions/enhancements of values from 4.2% to 86%. The removal rates for carbonaceous materials were reported as 76–86%,[76] iron chips and cement 50%,[67] shells 11–26%[26] and sand/gravel of 4–15%.[25,71] Improvement by sensible heat storage.[25,26]

Economic viability: Most economically affordable class – for many materials, all or only 3–8% cost increase; and the price per liter of $0.005–0.018.[86,108] Payback times <1 year are indicative of high value.[26,76,108]

Practical Limitations: Low barriers–No specific expertise, easy to maintain, long life span.[25,26,76] Superior scalability at all system sizes.[17,26] Primary restriction is limited speed (4–15% for common materials), but suitable to compound with other extensions.[26,76] The most democratically deployable enhancement is its universal accessibility.[17,25,108]

Advanced and Innovative Technologies

Eleven studies evaluated novel technologies[11,28,36,100,103,105,107,115,117,118,121] and revealed an increase of 33.3–748%. PV-thermal units were as high as 748–1162 mL/m^2, the rate of thermoelectric generators was 232% and thermally localized multistage purifiers delivered 5.78 L/m^2 h with an efficiency of 385%.

Economic Feasibility: Highest at prices of 100–375% premiums, cost per liter ranging from $0.08 to $0.29.[86,108] Such payback periods, 8–25 years, far exceed normal system lives.[108]

Constraints in Practice: Technological complexity requires domain experts.[105,118] Installation has professional needs that are not available in rural areas.[17] Component outages leave systems offline, and there are unreliable supply chains for replacement parts.[17,108] Energy needs require large-scale electrical infrastructure.[105,107] Scalability is technology-dependent.[17,118]

No long-term reliability information.[105,107] Most appropriate for research tasks and custom high-value deployments.[17,108]

Performance Prediction and Modeling

Seven studies employed machine learning and statistical methods[24,38,40,77,92,99,116] (prediction error $<5\%$). Production was predicted by LSTM networks using time-series data,[38] 5.21% error was obtained by Random Forest[116] and yields were estimated across modes of operation with Artificial Neural Networks ANN.[24,40]

Practical Relevance: Useful for prediction of performance, design optimization, and operational control.[38,40,116] Yet, model performance can be limited by the quality and quantity of training data.[38] Accessibility is restricted due to computational competency.[17,38] Models can support experimental validation rather than replace it.[17,40] The greatest impact for research institutions, broader deployment will come once tooling is accessible.[17,92,108]

Economic and Environmental Analysis

In total, six studies presented an in-depth techno-economic and environmental evaluation.[86,94,106,108,111,120] Prices varied up to 200-fold (comparable price range: USD/liter from $0.0014–0.29);[86,108] cost per liter was calculated using the entire document. Some simple improvements were found to be the least expensive solar thermal storage 0.005–0.018 fins 0.008–0.025.[86,108] Reasonable techniques: PCMs 0.018–0.080, pyramids 0.020–0.060.[86,108,120] Expensive materials: new $0.015–0.045, concentrators $0.030–0.120, and advanced cells 0.080–$0.290.[86,108]

Environmental-related benefits sustainability profiles are positive for all themes + [94,106] and categories +.[111] The solar stills save 0.5–2.5 kg CO_2/m^3 compared to the fossil fuel desalination (2.5–8 kg CO_2/m^3).[106] Passive methods are best for net environmental profiles because they are least manufacturing dependent.[106] Economic and environmental incentives converge to promote simple low-cost techniques for organizing a distributed use.[17,106,108]

COMPARATIVE ANALYSIS

Technology Selection Framework

1. Tier 1 - Deployment-Ready (Widespread Adoption):
    - Thermal storage materials[25,26,76]
    - Fins and corrugated surfaces[61,72,97]
    - Simple stepped designs[15,58]
2. Tier 2 - Community-Scale Ready:
    - Pyramid designs[14,15,45]
    - Common PCMs[10,55,57]
    - Simple external condensers[27,112]
3. Tier 3 - Pilot-Scale:
    - Nano-enhanced PCMs[8,104]
    - Fixed concentrators[20,60]
    - Sophisticated hybrids[14,16]
4. Tier 4 - Research Stage:
    - Nanomaterials[2,91]
    - Rotating systems[13,41]
    - Advanced technologies[105,118]

CHALLENGES AND LIMITATIONS

Technical Challenges

Material degradation in saline environments affects all categories through corrosion, fouling, and stability issues.[53,72,91] Seasonal performance variation with climate conditions.[17,27] Maintenance requirements range from minimal (thermal storage, fins) to substantial (rotating systems, advanced technologies).[17,72]

Economic Challenges

High initial costs for advanced methods limit accessibility.[105,108] Scale-up challenges from laboratory to commercial deployment.[17,108] Market competition with established desalination technologies.[108]

Implementation Barriers

Technical expertise requirements vary from minimal (thermal storage, fins) to specialized (advanced technologies).[17,72,105] Material availability constraints in remote regions.[17] Long-term reliability data gap across most categories.[17,108]

CONCLUSION

This review of 121 peer-reviewed papers (2020–2025) offers a thorough assessment of solar still enhancement technologies in terms of performance, economics, and implementation feasibility.

Key Findings

Table 2 summarizes the key findings from the systematic review and provides essential data for decision-making regarding technology selection. It integrates performance metrics, cost analysis, complexity assessment, and scalability evaluation across all 11 enhancement categories analyzed in this study. On enhancement technologies demonstrated improvements ranged from 4.2% to 748% in eleven categories. High performance techniques such as PCMs (10.6–675%), pyramid patterns (60–675%), and sophisticated hybrid schemes have been recommended (33.3–748%). Economical choices are thermal storage (4.2–85.9%), Fins (24–128%), and stepped configurations (60–675%). Economic evaluation showed the cost per liter ranging from $0.0014 to $0.29, simple improvements ($0.005–0.025/L) representing an exceptional cost–benefit while advanced system technologies ($0.08–0.29/L) face economic limitations.

Technology Readiness Assessment

Technologies are organized into four readiness levels: (1) Deployment-ready with low barriers to large-scale adoption (e.g., direct storage, fins, and simple stepped structures), (2) Community-ready for public projects with moderate resources (pyramid-shaped designs, common PCMs, simple condensers), (3) Pilot scale that require further validation before deployment; examples include Nano-enhanced PCMs and fixed concentrators. […] These four levels span the range from technologies with high deployability and low cost to those that are in a preliminary stage needing deeper scoping and research investment before being ready for full deployment.

Critical Research Gaps

Longer-term performance data (>1 year) are still scarce in all categories. It is important to conduct a full-life-cycle cost analysis for economic assessment. There is a great lack of information on the scaling-up of this transformation from lab to industrial scale. Common history effects from mixing multiple enhancement methods have not been well examined. Research is also needed regarding the adaptation of technologies to different water qualities, climate types, and application contexts.

Practical Recommendations

For resource-limited settings: Introduce phase-change materials and fins (15–85% savings, <\$0.025/L, <1-year payback). For community: Use pyramid designs with common PCMs (100–250%, \$0.020–0.050/L, 2–4 years payback). For niche applications: Central receivers (solar concentrators); High-DNI areas with technical assistance of special systems. Hybrid approaches: Use combinations of complementary solutions (thermal storage + fins, pyramids + PCM) for performance/cost tradeoffs.

Environmental Impact

A positive environmental profile is demonstrated for all categories of the enhancements. Solar stills save 0.5–2.5 kg of CO_2/m^3 compared to desalination by fossil fuels (2.5–8 kg of CO_2/m^3). Simple passive approaches are ideal for sustainability in minimum manufacturing cost and zero operational energy.

Future Directions

Priority research needs are long-term field testing to demonstrate operational reliability; systematic optimization of hybrid-enhancement methods combinations; cost-reduction avenues, including design simplification and manufacturing innovation; easily accessible technology selection decision tools. Progressive development of established technologies alongside the implementation of demonstrated accessible solutions represents the best approach to use solar still enhancement as a sustainable solution against water stress.

Contribution and Significance

The present review supplies the first ever complete cross-comparison between all existing solar still enhancement types of current research, linking technical utility with economic provability and practical facility. The evidence technology selection process allows enhancement methods to be matched against settings of deployment and resources available for implementation, assisting researchers, practitioners, and policymakers in making informed decisions. The development of multiple options at various economic and technology capacity levels opens opportunities for different actors to facilitate wider delivery of safe drinking water through better solar distillation.

Limitations and Considerations

Several limitations must be acknowledged. The review was restricted to articles published in peer-reviewed journals and did not include conference papers or gray literature. Differences in performance data between the studies reflect different experimental settings, and the contextual factors should be considered when making comparisons. Most of the studies have not been long-term, and there are few data about the performance and reliability over time. There was heterogeneity in the economic data reported in studies, and cost estimates should be checked against local data for particular circumstances. Use of more than one single technique in a study was considered in categorizing, but the actual decision was based on the dominant primary developmental focus with a degree of interpretive judgment.

Limitations notwithstanding, this systematic review represents the most exhaustive synthesis of established enhancement criteria for enhancing contemporary solar stills (2020–2025) and has adopted a meticulous report approach based on systematized search protocols, explicit selection criteria, a standardized data extraction technique, quality assessment methods, and multi-dimensional utilization. The results provide a strong basis to understand the present trends of investigation as well as to act in future technological developments and deployments.

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