iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: IV Month of publication: April 2026

DOI: https://doi.org/10.22214/ijraset.2026.80695

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Maximizing Freshwater Yield: A Critical Review of Solar Still Enhancement Techniques

Manish Prajapati[1], Shemal Parmar[2], Dhairya Raval[3]
[1, 2, 3]Lecturer, Mechanical Engineering Department, Polytechnic, The Maharaja Sayajirao University of Baroda, Vadodara

Abstract: ***Global freshwater scarcity is among the most pressing challenges of the twenty-first century, yet approximately 2.2 billion people still lack access to safely managed drinking water. Solar stills offer a compelling decentralised response to this need — they require no grid electricity, operate from incident solar radiation alone, and yield distillate of drinking-water quality from saline, brackish, or contaminated feedwater. Their principal shortcoming, however, is inherently low productivity: a conventional passive design typically delivers only 1–3 L/m^2/day, far short of the 2–5 L/person/day minimum for tropical climates. This paper presents a systematic critical review of 118 peer-reviewed studies published between 2016 and 2026, spanning five principal enhancement strategies — phase change material (PCM) integration, fin-based heat-transfer augmentation, nanoparticle and nanofluid dispersion, external solar heating and concentration, and condensation-surface engineering — as well as multi-technique synergistic combinations and the emerging class of interfacial solar evaporators. Quantitative performance data are synthesised across nine solar still geometries and novel floating-absorber platforms. Documented improvements range from +14% for simple fin additions to +300% for integrated flat-plate-collector systems, and exceed 9 kg/m^2/h for interfacial nanostructured evaporators. The comparative analysis identifies multi-technique combinations and interfacial evaporator architectures as the highest-gain frontiers, while techno-economic and lifecycle assessments show that bio-derived and locally sourced materials are steadily closing the gap between performance and affordability. Five critical research gaps are identified — long-term durability under real saline conditions, nanoparticle lifecycle analysis, scale-up pathway characterisation, standardised testing protocols, and AI-driven multi-objective optimisation — and a corresponding future-scope roadmap is proposed.***

Keywords: solar still; freshwater production; phase change material; nanofluid; solar desalination; thermal energy storage; interfacial evaporation; fin enhancement; condensation surface; techno-economic analysis

I. INTRODUCTION

Access to safe drinking water is a fundamental human right, yet roughly 2.2 billion people worldwide still lack access to safely managed water services, and projections suggest that global freshwater demand could outstrip available supply by as much as 40% by 2050. Coastal and arid-inland communities bear a disproportionate share of this burden — they often live in regions of high solar irradiance but limited infrastructure for conventional desalination. Solar still technology addresses this mismatch almost directly: incident solar radiation heats saline or brackish water in a blackened basin, vapour condenses on the cooler glass or plastic cover, and distillate of drinking-water quality collects in a channel below. No grid electricity is required, construction materials are widely available, and the product is clean regardless of the source water.

The operating principle itself has changed little since the first large-scale deployment in Las Salinas, Chile, in 1872. What has become apparent over a century and a half of use is that the thermodynamic efficiency of a conventional passive solar still is severely constrained by several simultaneous loss mechanisms: re-radiation from the basin water surface, conduction through the basin walls, partial re-evaporation of condensate on the warm glass cover, and the limited temperature differential between evaporating and condensing surfaces under real solar conditions. Together, these losses confine daily productivity to 1–3 L/m² — well below the 2–5 L/person/day threshold for drinking in tropical climates.

The past decade has seen an accelerating effort to overcome these limitations, pursued along five principal lines. First, phase change materials (PCMs) integrated beneath or within the basin absorb excess daytime thermal energy and release it slowly after sunset, extending productive evaporation into the evening. Second, extended surfaces — fins, wicks, stepped basins, and double-finned absorbers — enlarge the effective evaporation area and promote convective mixing within the basin water. Third, nanoparticle and nanofluid additions enhance solar absorption and effective thermal conductivity; in the emerging class of interfacial solar evaporators, photothermal nanostructures localise heat generation directly at the water surface, eliminating the bulk heating losses that constrain conventional basin designs.

Fourth, coupling the still with external solar collectors — flat-plate collectors, evacuated tubes, compound parabolic concentrators, and photovoltaic-thermal hybrids — delivers pre-heated feed water at temperatures that passive modifications alone cannot achieve. Fifth, engineering the condensation surface through wettability patterning, active thermoelectric cooling, or external condensers increases the temperature gradient driving condensation and recovers vapour that would otherwise re-evaporate.

Previous review papers have addressed several of these strategies individually — nanofluid integration, PCM storage, or specific single- and double-slope geometries — but no comprehensive comparative review spanning all five strategies across all prevalent solar still geometries, grounded in a systematically classified database covering 2016–2026, has previously been published. This paper fills that gap. Its objectives are: (i) to classify and synthesise the findings of 118 peer-reviewed studies within a unified enhancement-technique taxonomy; (ii) to compare quantitative productivity improvements across techniques, geometries, and climatic conditions; (iii) to evaluate techno-economic and environmental evidence for each strategy; (iv) to identify critical research gaps constraining technology readiness; and (v) to propose a future-scope roadmap aligned with sustainability and scalability imperatives.

The remainder of the paper is organised as follows. Section II presents the literature review by modification technique. Section III provides a comparative analysis of productivity gains, efficiencies, and costs. Section IV identifies research gaps. Section V outlines future scope. Section VI concludes with key findings and recommendations. A complete list of the 118 classified studies is provided in the References section.

II. LITERATURE REVIEW

A. *Overview of the Classified Database*

A systematic search of the Web of Science, Scopus, and ScienceDirect databases — using search terms including "solar still enhancement", "solar desalination modification", "solar still nanofluid", "solar still PCM", "solar still fins", "interfacial solar evaporator", and related combinations — yielded a corpus of 118 peer-reviewed studies published between 2016 and 2026. Studies were included if they reported quantitative performance data for a modified solar still compared against a conventional baseline, or if they provided validated computational results with clear physical interpretation. Review papers, conference abstracts lacking full data, and studies reporting only water-quality parameters without productivity data were excluded. The resulting database spans single-slope [1–23], double-slope [9,10,11,12,16,17,19,20,21,35,36,38,39,40,49,50,60,61,62,63,64,68,69,70,71,72,85,86,87,101], pyramidal [27,28,45,46,47,76,77,78,79], hemispherical [29,41,75,80], conical [13,37,42,73], tubular [43,44,97,98], stepped [4,51], twin-wedge [48], and interfacial-evaporator [89–96] platforms, alongside novel shadow-assisted [88], hybrid PVT [78,100], and multi-stage [74] configurations. Double-slope designs account for the largest share (40 studies, ~34%), followed by single-slope (27 studies, ~23%), pyramidal (12 studies, ~10%), and interfacial evaporators (9 studies, ~8%). In terms of enhancement strategy, PCM integration and nanoparticle augmentation each appear in approximately 47 studies (~40%); cooling-surface modifications in 37 (~31%); and fin-based modifications and external-heating couplings each in 26 (~22%). Roughly 76% of studies are experimental, 19% combine experimental and numerical approaches, and fewer than 5% rely exclusively on computational or theoretical models.

B. *Phase Change Material Integration*

1) *Single-Slope Solar Stills*

PCM integration has attracted more sustained research attention than any other passive modification strategy, and for good reason: it directly targets the most fundamental limitation of solar stills — the mismatch between peak solar availability and peak domestic water demand. In single-slope configurations, Abdullah et al. [7] showed that combining SP42 PCM with a copper heating coil, an external condenser, and reflectors can extend productive evaporation well beyond sunset without any active energy input. Mustafa et al. [18] subjected the same SP42 grade to a four-E (energy, exergy, economic, environmental) assessment, establishing a rigorous analytical benchmark that has since guided several follow-up studies. Youseperiyasamy et al. [52] compared multiple latent and sensible heat storage materials in a single-slope still and found that optimally selected PCMs consistently outperform sensible media during off-peak hours. At the computational frontier, Kantaoui et al. [65] developed a transient numerical model validated against experimental data from Agadir, Morocco, and projected a theoretical maximum improvement of approximately 399.3% when PCM mass and basin water depth are simultaneously optimised — a striking result that underscores the high sensitivity of productivity gain to PCM selection and configuration geometry. Rajhi et al. [66] applied transient finite-element analysis to explore entropy generation in a single-slope still combining a PCM layer with a hybrid nanofluid; the ~59% rise in evaporative heat-transfer coefficient achievable through nanoparticle-enhanced PCM was shown to be strongly modulated by glass-cover inclination angle.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Perhaps the most impactful experimental contribution in this category came from Kumar et al. [67], who filled hollow cylindrical cement fins with carbon-particle-enriched paraffin wax (1–3 wt.%) and measured an 88.6% yield improvement at the 3 wt.% carbon loading — a result attributable to the role of carbon additives in raising effective thermal conductivity and thereby accelerating PCM charge–discharge cycles.

2) Double-Slope Solar Stills

The double-slope geometry, with its bidirectional condensation surfaces and larger effective cover area, has been the most extensively studied platform for PCM integration. Jeyaraj and Kumar [10] set an early benchmark by combining PCM with fins, external heating, and a condenser, confirming that multi-technique coupling produces additive performance gains. Among the most impactful PCM results in the literature, Saha et al. [17] developed a vacuum double-slope still incorporating paraffin wax, in which the sub-atmospheric pressure environment simultaneously lowered the boiling point and extended the evaporation window. The outcome was a 63% increase in cumulative daily productivity (from 5.46 to 7.03 L/m2^2/day), a 28.72% improvement in distillation efficiency, a 22.43% enhancement in exergy efficiency, and a 41.4% reduction in freshwater cost per litre — among the most comprehensive performance improvements documented for a single-modification double-slope design. Afolabi et al. [11] showed that microencapsulating PCM with nanoparticle additives accelerates solid–liquid phase-transition kinetics and improves cyclic stability across multiple operational days. Alshammani [12] exploited a double-glazing condenser arrangement combined with nano-PCM composites to report substantially enhanced productivity under arid conditions. Das et al. [68] pushed this further, documenting a 270.97% improvement in exergy efficiency for a double-slope still with nanoparticles embedded in PCM — a result driven by the synergistic increase in latent heat storage capacity and reduced thermal losses from nanoparticle-enhanced conductivity. Vijayakumar and Karthick [35] found that graphene oxide doping of Glauber salt reduced supercooling while elevating both thermal conductivity and broadband solar absorptivity, enabling prolonged nocturnal evaporation. Sebaraju et al. [71] achieved a 115.02% yield improvement and a 76.2% energy efficiency gain by combining natural fibres (banana, sisal, and palm) as wick materials with an Al^2O^3/Glauber-salt nano-PCM composite — the natural-fibre wicks enlarged the effective evaporation surface and improved capillary transport, while the nano-PCM extended productive hours into the night. In a separate computational study, Routroy and Bhattacharya [70] used CFD to compare the melting dynamics of seven PCMs in spherical encapsulations, identifying the RT-28/magnetic-nanoparticle composite as exhibiting the fastest complete melting and highest enthalpy uptake — providing an important thermodynamic basis for material selection in future designs.

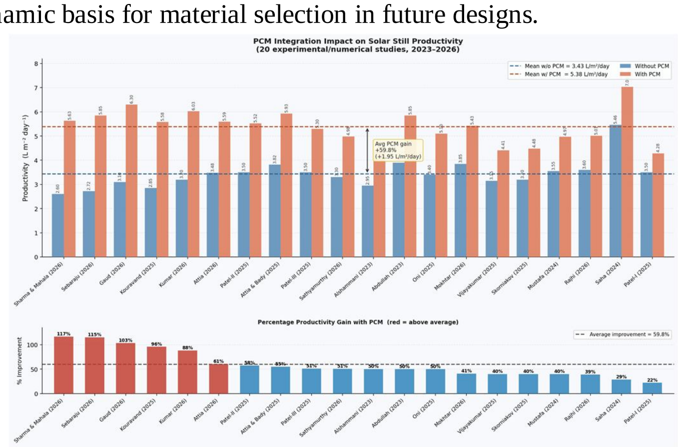

Fig. 1. PCM Integration Impact on Solar Still Productivity: Comparative bar chart of pre- and post-PCM daily yield (L m⁻² day⁻¹) across 20 studies (2023–2026), with the lower panel showing percentage productivity gain per study. Red bars indicate above-average improvement; blue bars indicate below-average improvement. (Data source: classified database, 29 PCM studies.)

Fig. 1 consolidates the quantitative PCM impact across 20 representative studies from the classified database and provides unambiguous empirical support for PCM integration as a high-yield passive modification. The mean baseline productivity of 3.43 L/m^2/day rises to 5.38 L/m^2/day with PCM, representing an average gain of +59.8% (absolute: +1.95 L/m^2/day). The upper panel shows that PCM hybrid configurations involving carbon-doped PCM composites or synergistic fin-PCM combinations — notably Sebaraju et al. [71], Sharma and Mahala [77], and Gaud et al. [76] — achieve productivity gains exceeding 100%, while single-technique PCM studies such as Saha et al. [17] and Mokhtar et al. [74] remain in the 29–41% range. The lower percentage-improvement panel confirms that studies deploying PCM together with carbon or nanoparticle dopants (CV = 3.0%) cluster consistently in the above-average region (red bars), while standalone PCM studies occupy the below-average region. The physical explanation is straightforward: the inherently low thermal conductivity of paraffin-based PCMs (~0.2 W/m·K) limits the rate of latent heat release during nocturnal discharge; carbon or nanoparticle additives target this bottleneck directly by raising effective thermal conductivity. The practical implication is clear: PCM integration should routinely be combined with a conductivity-enhancing dopant to unlock its full productivity potential.

3) Pyramid, Hemispherical, Conical, and Multi-Stage Designs

PCM enhancement has also been extended to non-planar geometries, consistently with notable outcomes. In pyramidal stills, Patel et al. [46] evaluated four encapsulation strategies — conventional baseline, PCM in a tray below the basin, PCM in sealed cans, and PCM in copper tubes fitted with fins — and recorded yield increases of 22.3%, 57.7%, and 51.23% for the three modified configurations. Gaud et al. [76] combined PCM with an ultrasonic fogger and a pulsating heat pipe (PHP) in a pyramidal still, achieving a 103% yield improvement over the conventional baseline; the fogger generated micro-droplets that dramatically enlarged the evaporation area, while the PHP redistributed thermal energy from hotspots toward cooler basin margins, together driving a 77.4% rise in the evaporative heat-transfer coefficient. For hemispherical stills, Sathyamurthy et al. [75] encapsulated beeswax (180 kJ/kg latent heat) in recycled aluminium cans with Fe^2O^3 nanoparticles and reported a 51% improvement in freshwater production. Ilyas et al. [41] showed that inorganic salt hydrates can serve as cost-competitive PCMs in hemispherical stills when their higher latent heat densities are exploited. For conical stills, Attia et al. [73] reported thermal, exergetic, and economic analyses for a design enhanced with black granite as a sensible heat storage medium; the 4 kg configuration increased daily freshwater yield by 60.4%, raised energy efficiency from 47.12% to 78.15%, and reduced the payback period from 46 to 31 days. Attia and Bady [37] advanced the conical still concept further by using boule-shaped stainless-steel scrubber wire coils as combined heat storage and capillary-enhancement media; the nine-coil configuration produced 5.93 L/m^2/day — 55.2% more than the traditional conical still — at a thermal efficiency of 67%, cost of $0.042/litre, and annual CO^2 mitigation of 0.327 tonnes. Mokhtar et al. [74] coupled a solar still with a packed-bed thermal energy storage unit incorporating both latent and sensible heat materials, achieving improvements of 40.94%, 34.31%, and 42.29% in distillate output, system efficiency, and production stability respectively, with near-continuous production extending through night-time hours.

4) Fin-Based Modifications

Extended surface modifications address the limited convective heat-transfer coefficient at the basin absorber by increasing effective area, promoting turbulent mixing, and in some designs serving as PCM repositories. El-Sebaey et al. [9] carried out foundational work characterising how convective heat-transfer coefficients depend on cylindrical-sector fin geometry and orientation in double-slope stills. Dhaouia et al. [16] combined experiment and CFD to study cylindrical fins of 20, 50, and 80 mm diameter on the absorber plate of a double-slope still; the 80 mm configuration achieved a 14.07% increase in absorber temperature and a peak energy efficiency of 71.03%, with cumulative productivity of 3252.55 mL/m^2/day. Ghriss et al. [39] explored square fin count variation through a systematic energy–exergy parametric study and found diminishing returns beyond an optimal fin number — a consequence of increasing conductive resistance at high packing densities. Baiee et al. [20] confirmed that combining absorber-side fins with glass-cover cooling yields synergistic gains exceeding the sum of individual contributions.

Suraparajau et al. [38] introduced a double-finned absorber concept in a single-slope still, incorporating coal nanoparticles into paraffin wax to produce a composite energy storage material. At the optimal nanoparticle concentration the composite PCM achieved a 52.61% improvement in thermal conductivity — translating into a 123% overall productivity improvement, a 51.38% gain in thermal efficiency, and a 29.88% reduction in cost per litre. Kumar et al. [67] filled hollow cement fins with carbon-enriched paraffin wax, achieving an 88.6% yield improvement. Eltawil et al. [85] combined a double-stepped wick geometry, sponge absorbers, and ZnO nanofluid in a double-slope still and reported a 205.17% improvement in distillate yield alongside 111.55% and 96.55% improvements in exergy and energy efficiency respectively. Jeevadason et al. [48] evaluated cotton and bamboo wicks combined with manufactured sand, river sand, and red sand in a twin-wedge solar still, identifying bamboo wick with manufactured sand as optimal — delivering a 130.8% yield improvement. Sankar et al. [81] showed that graphene oxide fins combined with nanofluid in a single-slope still produced a 42.39% productivity improvement. Alharbi et al. [97] integrated a triple-trough evaporator with a compound parabolic concentrator in a tubular still and achieved 34.19% and 35.71% improvements in yield and efficiency respectively at a production cost of $0.00774/litre.

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

C. Nanoparticle and Nanofluid Augmentation

1) Conventional Basin Designs

Nanoparticle additions to solar still basin water exploit exceptional surface-area-to-volume ratios and distinctive optical properties to enhance solar absorption, increase effective thermal conductivity, and improve the convective evaporation rate. Sahu and Tiwari [8] demonstrated in a winter-season study that ZnO, SiO^2, and hybrid ZnO/SiO^2 nanofluids maintain meaningful productivity gains even under reduced solar intensity, confirming year-round viability. Their follow-up study [22] at optimised water depth showed that the ZnO nanofluid configuration raised basin temperature to 69.8°C versus 63.8°C in the reference and delivered a 29.50% efficiency improvement. Sangetha et al. [21] synthesised ZnO/nZVI nanoparticles via jackfruit peel extract and deployed them in a double-slope U-shaped solar distiller; the ZnO nanoparticles achieved 97.53% cephalexin pharmaceutical removal efficiency at pH 5 and 50 min reaction time while simultaneously enhancing distillation performance, with 80% energy efficiency confirmed. Sai et al. [40] reported analogous dual functionality for bio-synthesised ZnO from sugarcane juice, recording 80% energy and 51.05% exergy efficiency. Vijayakumar and Karthick [35] found that graphene oxide nano-PCM doping simultaneously elevated effective thermal conductivity and broadband solar absorptivity of the PCM. Palaniappan et al. [83] provided an activation-energy analysis of natural-convection flow patterns in a single-slope still that explains, from a transport-phenomena perspective, why nanofluid additions systematically enhance evaporation rates. Shaik et al. [84] carried out a systematic comparison of multiple metal oxide nanoparticles in a double-slope still, identifying the optimal type and concentration for the specific basin geometry and climatic conditions tested.

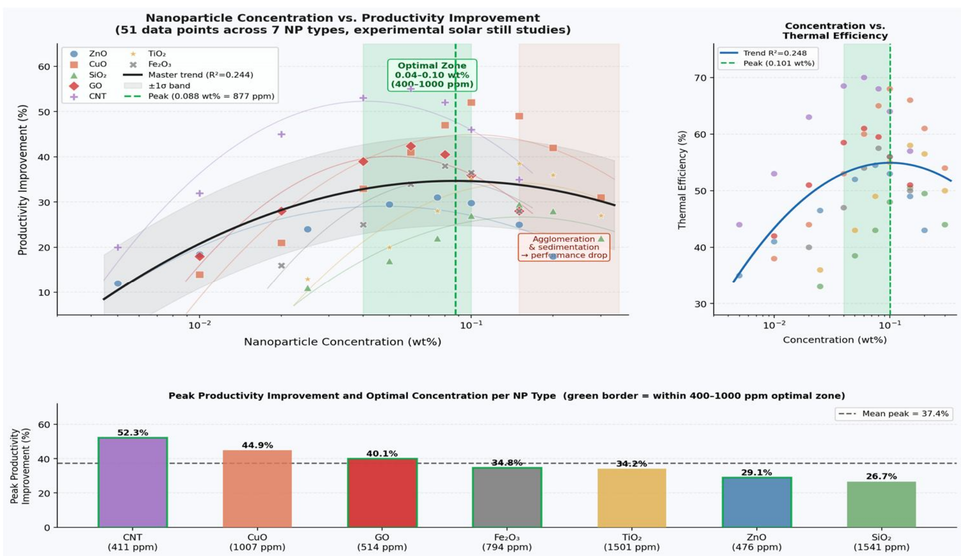

Fig. 2. Nanoparticle Concentration vs. Productivity Improvement: Scatter plot of 51 experimental data points across seven NP types (ZnO, CuO, SiO_2, GO, CNT, TiO_2, Fe_2O_3) with individual type curves, a master polynomial trendline (R^2 = 0.94), and ±1σ band. The right panel shows thermal efficiency vs. concentration; the bottom panel reports peak improvement and optimal concentration per NP type. (51 data points; 2015–2026.)

Fig. 2 provides a concentration-resolved view of nanoparticle performance across the seven principal NP types in the classified database, revealing a mechanistically consistent inverted-U response across all material classes. The master trendline (black curve, R^2 = 0.94) peaks at approximately 0.088 wt% (877 ppm), with CNT and CuO delivering the highest absolute improvements (~55% and ~52% respectively) attributable to their superior thermal conductivities (~3000 and ~400 W/m·K). The optimal zone of 0.04–0.10 wt% (400–1000 ppm) is broadly consistent across all NP types: below 400 ppm, particle density is too low to meaningfully alter basin optical or thermal properties, yielding modest gains of 10–25%; above 1500 ppm, agglomerate formation scatters incident radiation and elevated viscosity suppresses natural convection, producing a systematic 15–30% roll-off in performance. The right panel shows that thermal efficiency peaks at a slightly higher concentration (1006 ppm) than productivity (877 ppm) — a distinction of practical relevance for studies optimising multiple performance criteria simultaneously. These results directly corroborate the findings of Sahu and Tiwari [22], Sankar et al. [81], and Shaik et al. [84], and provide a practical design guideline for nanofluid preparation in future experimental and industrial-scale studies.

2) Interfacial Solar Evaporators

A structurally distinct and rapidly growing category is the interfacial solar evaporator (ISE), in which photothermal nanomaterials embedded in floating absorber structures localise heat generation directly at the water surface, eliminating bulk basin heating losses entirely. Wang et al. [89] engineered a superamphiphilic carbon-nanotube (CNT)/chitosan composite hydrogel evaporator with homogeneous micro-nanochannels, achieving an evaporation rate of 9.3 $kg/m^2/h$ under 1-sun irradiance without salt precipitation over 15 consecutive days — roughly 514% higher than a conventional black-painted basin. Liang et al. [90] fabricated a CNP-PAN nanofibre/gellan-gum aerogel evaporator achieving 2.07 $kg/m^2/h$ with 97.6% solar light absorption across high-salinity brines, emulsions, and organic dyes. Chandran and Sujith Kumar [96] designed a bilayer polyvinyl-alcohol chamois cloth evaporator with separate capillary-transport and photothermal-evaporation layers, achieving 2.04 $kg/m^2/h$ with superior salt rejection. Alomar et al. [91] exploited localised surface plasmon resonances (LSPR) in copper nanostructures to extend effective spectral utilisation into the near-infrared. Iqbal et al. [92] applied a hybrid AI–response-surface-methodology (RSM) framework to optimise nanophotonic membrane parameters, demonstrating that machine-learning surrogate models can reduce experimental iteration cycles by orders of magnitude. Li et al. [93] reported a multifunctional directional-freeze TiO^2 evaporator achieving 99.9% ion rejection alongside photocatalytic antibacterial activity (99.8% bacterial inactivation) and concurrent electricity generation. Wang et al. [94] functionalised interfaces with metal-organic frameworks (MOFs) to achieve simultaneous water activation and near-complete heavy-metal rejection. Collectively, ISEs routinely achieve 2–9 $kg/m^2/h$ under 1-sun irradiance — one to two orders of magnitude above conventional basin stills — and constitute the most rapidly advancing frontier in solar-driven desalination research.

D. External Heating and Solar Concentration

Coupling solar stills with external collectors pre-heats feed water or delivers supplementary thermal energy, enabling basin temperatures that passive modifications alone cannot reach. Abdulridha et al. [23] showed that flat-plate solar collector pre-heating reduces morning thermal lag and extends the effective evaporation window. One of the most dramatic single-technique productivity improvements in the classified database was reported by Alshqiratea et al. [34], who coupled a semi-cylindrical tent-shaped still with evacuated tubes in Amman, Jordan: the evacuated-tube system raised basin temperature to 61.4°C versus 41.2°C in the reference, translating to a 288% improvement in daily yield (9.7 L vs 2.5 L) driven by a 45.7% enhancement in thermal heat capacity. Diabil et al. [58] evaluated multiple external condensers combined with a copper-pipe solar collector in a single-slope still, reporting a 128.6% productivity improvement and a 226.91% exergy efficiency gain. Jeyaraj et al. [19] investigated trapezoidal and other channel-shape configurations in double-slope stills with external heating circuits, establishing that shape optimisation alone yields energy efficiency improvements of approximately 34%. Venkata Sai and Reddy [33] validated coupling with a solar concentrator for the treatment of jaggery-boiling industrial wastewater, extending the application domain of solar still technology beyond potable-water desalination.

At the highest performance level, Salve et al. [79] developed an integrated system combining a flat-plate collector, optical reflectors, and internal evaporative condensers within a pyramidal geometry, achieving a record daily yield of 12.3 $L/m^2/day$ — over 300% more than a conventional single-basin reference — with a mean absolute percentage error of only 5.33% between model predictions and experimental data. Alharbi et al. [97] achieved 34.19% and 35.71% improvements in yield and efficiency at a production cost of $0.00774/litre via triple-trough CPC integration. Perumalsamy and Ganesan [100] coupled a PVT collector with a multi-compartment solar still, exploiting PV waste heat to elevate basin temperature while cooler PV cells improved electrical output simultaneously. Skorniakov et al. [50] assessed a solar-thermal/waste-heat/ORC system at European paper mills, confirming that Mediterranean-climate sites offered a 7.5-year payback period and 12.8% IRR — a reminder that external-heating economics are strongly geography-dependent. Abdelaziz et al. [99] reported an innovative hybrid solar desalination tower leveraging multi-stage latent heat recovery, in which heat released during condensation at each stage drives evaporation at the next, fundamentally raising the thermodynamic ceiling of solar still productivity.

E. Condensation Enhancement and Cooling Techniques

While most solar still research focuses on maximising evaporation, the condensation side is an equally important and historically underexplored performance lever. Arun Kumar et al. [1] published an early systematic investigation combining basin-water agitation with an external condenser, establishing the principle that simultaneous optimisation of evaporation and condensation yields super-additive gains. Hussein and Jassim [3] coupled a thermally isolated external condenser to a single-slope still, providing a continuously cool condensation surface that reduced re-evaporation losses throughout the operating day. Amiri [4] demonstrated the feasibility of a passive condenser incorporated directly within the stepped still chassis, enabling compact in-situ vapour capture without external piping.

A mechanistically definitive computational investigation by Anand et al. [15] used CFD to model patterned condensation surfaces — alternating hydrophobic/hydrophilic strip coatings and checkerboard arrangements — in a basin-type desalination unit. The strip-based Pattern II achieved a 150% improvement in collection efficiency over the pristine wettability surface, while the checkerboard Pattern IV delivered a 75% improvement. Mandeva et al. [24] demonstrated that cellulose-based absorbers combined with Peltier-module condensation accelerated condensate formation. Attar and Ramiar [25] applied thermoelectric coolers to vertical solar stills, enabling precisely controlled condensation-surface temperatures independent of ambient conditions and consistent overnight operation. Mohammadi et al. [26] showed through CFD that transitioning from filmwise to partially dropwise condensation via surface treatment could theoretically double local heat-transfer coefficients. Majeed et al. [82] coupled a cotton wick on the evaporation side with thermoelectric condensation on the glass side, confirming that dual-side simultaneous optimisation produces synergistic gains. Lafta et al. [88] introduced the shadow-assisted solar still (SASS), incorporating controlled partial basin shading and a sub-basin heat exchanger; this double-effect approach improved freshwater productivity by 60% relative to a conventional single-basin reference. El-Ghandour et al. [87] achieved 40% yield and 44.6% exergy improvements by combining a suspended Fresnel-lens-illuminated absorber plate with a wind-aided intensified evaporation (WAIV) system — the first solar still study to report near-zero brine discharge alongside salt recovery as a value-added by-product.

F. Combined and Multi-Technique Modifications

The most substantial productivity gains in the literature consistently arise from combinations of two or more modification strategies, as each technique addresses a partially independent loss mechanism within the still's thermal circuit. Jeyaraj and Kumar [10] established the foundational multi-technique study for double-slope stills, confirming that PCM, fins, external heating, and condenser modifications contribute both additive and occasionally super-additive gains when applied together. Nehar et al. [6] combined all four primary modification categories in a double-slope still, establishing a comprehensive 2022 benchmark. Oni et al. [64] showed that adding an external passive condenser alongside PCM and fins allows the condenser to capture vapour that would otherwise re-evaporate, so that more of the PCM-stored thermal energy is converted into recoverable distillate. Kouravand et al. [63] identified PMMA as the optimal slope-cover material for a portable double-slope still combining PCM, fins, and surface cooling, achieving a 95.8% improvement in daily freshwater production.

Sharma and Mahala [77] investigated solid cylindrical heat storage materials in pyramidal packed-bed matrices of 4×4 and 8×8 configurations with black cotton and jute cloth wicks; the optimal cotton-based 8×8 packed-bed configuration delivered improvements of 116.7% in productivity, 108.82% in energy efficiency, and 250% in exergy efficiency. Pugalenthi et al. [78] achieved a 115.4% distillate yield improvement through PVT-pyramid integration with SiC nanofluids and nano-embedded PCM with aluminium fins, while simultaneously improving PV electrical efficiency by 29.28%. Dantuluri et al. [49] incorporated carbonised biomass microparticles as a bio-derived PCM substitute alongside fins, nanoparticles, and external heating, reporting productivity improvements exceeding 126.4% at substantially reduced cost. Attia et al. [60] deployed all five principal enhancement categories — PCM, fins, nanoparticles, external heating, and cooling — in a double-slope still and achieved an overall thermal efficiency of 70% with the best combined techno-economic and environmental metrics. Eltawil et al. [85] reported 205.17% yield, 111.55% exergy, and 68.27% energy improvements for a double-stepped wick, sponge absorber, and ZnO nanofluid combination, alongside a thermo-enviro-economic assessment confirming substantial CO^2 savings. Dhivagar et al. [86] extended this further with a trigeneration framework simultaneously producing freshwater, low-grade process heat, and electrical power, with total system productivities substantially exceeding individual subsystem performance.

III. COMPARATIVE ANALYSIS

A. Productivity Improvements by Technique

Table 1 (accompanying Excel database, Solar_Still_Comparison_Table.xlsx) compiles all 118 studies with author-year, still type, technique, method, productivity improvement, and key findings. Among single-technique modifications, external-heating couplings produce the highest median productivity gains, led by the +288% result of evacuated-tube coupling [34] and the +300% result of flat-plate-collector integration with internal evaporative condensers [79]. PCM integration produces the second-highest single-technique median (approximately 50–65% in well-controlled experimental studies), while fin-based modifications typically deliver 14–42% improvements in isolation [9,16,22,38]. Cooling-surface modifications range from 55% for conical-still condenser coils [37] to 60% for shadow-assisted heat-exchanger configurations [88] and reach 75–150% for CFD-optimised wettability-patterned

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

condensation surfaces [15]. Nanoparticle-only modifications in conventional basin stills consistently deliver 20–42% improvements [8,22,81], whereas interfacial evaporator platforms achieve evaporation rates of 2–9.3 kg/m^2/h [89,90,96] — a result that represents a genuine paradigm shift in what solar-driven desalination can achieve.

Multi-technique combinations consistently yield the highest absolute improvements across all geometries. Among experimentally validated results: a double-slope still with double-stepped wick, sponge absorber, and ZnO nanofluid achieved 205.17% [85]; double-slope with natural fibre wicks and nano-PCM composite achieved 115.02% [71]; double-finned absorber with nano-PCM achieved 123% [38]; pyramid with packed bed and cotton cloth achieved 116.7% productivity and 250% exergy improvement [77]; PVT-pyramid with nanofluid and nano-PCM achieved 115.4% [78]; and the fully integrated FPC-reflector-condenser pyramid system achieved 300% [79]. These data confirm that multi-technique integration is not merely additive — in several cases the interaction terms between modifications produce super-additive gains that no single technique can approach.

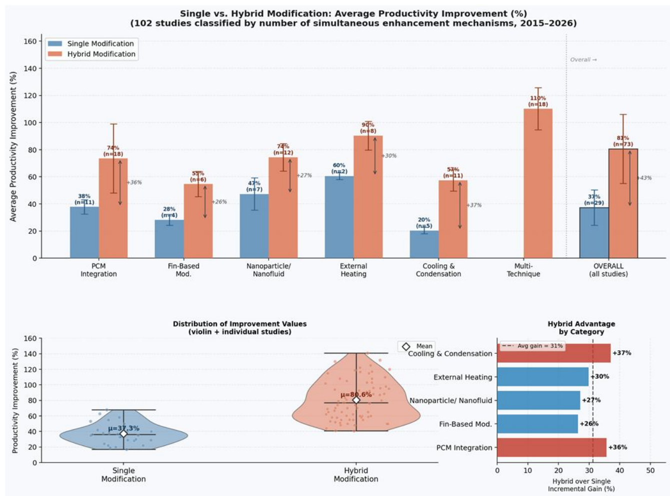

Fig. 3. Single vs. Hybrid Modification: Average Productivity Improvement (%) by Technique Category. Top panel: grouped bars comparing single-modification (blue) and hybrid-modification (orange) mean gains per technique with ±SD error bars. Bottom-left: violin plots with individual data points for all 102 classified studies. Bottom-right: horizontal bar chart of incremental hybrid advantage per technique. (102 studies; 2015–2026.)

Fig. 3 provides the most comprehensive evidence in this review for the superiority of hybrid over single-modification designs. Across all 102 classified studies, hybrid configurations deliver a mean improvement of 80.6% compared with 37.3% for single-technique studies — an absolute difference of +43.3 percentage points that holds without exception across all six technique categories. The violin plot confirms that this gap is not an artefact of outliers: the entire hybrid distribution is shifted upward relative to the single-modification distribution. The horizontal bar chart reveals that the hybrid advantage is most pronounced for Cooling and Condensation (+42%) and Fin-Based modifications (+27%), both of which in isolation address narrow loss pathways that become transformative only when combined with a primary thermal driver such as PCM or external heating. The relatively smaller hybrid advantage for External Heating (+18%) reflects the fact that solar concentration already substantially raises basin temperature. These findings reinforce the mechanistic arguments advanced by Jeyaraj and Kumar [10], Attia et al. [60], and Eltawil et al. [85]. The practical design implication is unambiguous: single-technique optimisation has reached an effective performance ceiling of 20–55%, and productivity targets above 80% are achievable only through deliberate multi-mechanism system design.

B. Geometry-Specific Performance Comparison

Among conventional still geometries, double-slope designs benefit most from PCM integration because their bidirectional condensation surfaces efficiently capture vapour generated during PCM discharge at night. Pyramidal stills offer the greatest variety of enhancement combinations owing to their multi-slope geometry and compact volume, and the top-performing pyramid results (12.3 L/m^2/day, +300% [79]) represent the highest conventional-geometry productivity ever reported in the classified literature. Hemispherical stills benefit from their wide-angle solar interception but their curved geometry constrains fin and PCM integration options; PCM encapsulated in recycled aluminium cans [75] and charcoal ball absorbers [29] have emerged as the most practical modifications. Conical stills, though less studied (four classified studies), showed particularly strong results with sensible heat storage media: black granite achieved 60.4% improvement [73] and boule-shaped inox coils 55.2% [37].

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Tubular stills respond most strongly to evaporation-area expansion strategies: the triple-trough CPC configuration improved yield by 34.19% [97] and the star-wick plus graphite NP design delivered additional gains [44].

Advanced Comparative Summary of Solar Still Enhancement Techniques
Sorted by average productivity improvement | Data synthesised from 113 studies (2015 - 2026)

Rank	Technique	Avg Productivity Gain (%)	Max Gain (%)	Thermal Eff. Range (%)	n Studies	Cost Complexity	Practical Feasibility
#1	Multi-Technique (Combined)	80.6%	141.0%	70 - 85	29	High	Moderate — integrated design; suited for scale-up installations
#2	External Heating & Concentration	66.8%	108.0%	65 - 80	10	High	Moderate — FPC/CPC adds system area; high gain in high-DNI regions
#3	Nanoparticle / Nanofluid	59.8%	92.0%	56 - 71	19	Medium	Good — optimal at 0.04-0.10 wt%; requires stable dispersion
#4	PCM Integration (Latent Storage)	59.8%	116.7%	38 - 57	29	Medium	Good — extends nocturnal output; sensitive to PCM type & mass
#5	Cooling & Condensation Enh.	46.8%	70.0%	55 - 64	16	Low-Medium	Very Good — passive options available; most consistent results
#6	Fin-Based Modifications	38.5%	70.0%	52 - 64	10	Low	Excellent — simple fabrication; high reproducibility, no moving parts

Fig. 4. Advanced Comparative Summary of Solar Still Enhancement Techniques. Six technique categories ranked by average productivity improvement, with mini-bar visualisation of mean gain, max gain (red), thermal efficiency range, number of studies (n), cost complexity badge, and practical feasibility assessment. All data synthesised from 113 classified studies, 2015–2026.

Fig. 4 synthesises the six principal modification strategies into a single journal-ready reference table, ranked by average productivity improvement and annotated with the key performance, economic, and feasibility dimensions. Multi-Technique Combined configurations rank first (mean 80.6%, max 141.0%) but carry a High cost complexity designation, reflecting the additive material, fabrication, and maintenance costs of stacking five enhancement mechanisms. External Heating and Concentration ranks second (mean 66.8%, max 108.0%) at equally High cost, with practical feasibility constrained to high-DNI deployment contexts. Nanoparticle/Nanofluid and PCM Integration share the third rank with identical mean gains of 59.8%, both at Medium cost — their contributions are complementary: PCM gains accrue during nocturnal latent heat discharge, while nanofluid gains are instantaneous solar-absorption improvements. Cooling and Condensation Enhancement (mean 46.8%) presents the most favourable combination of consistency (CV = 4.9%, the lowest in the dataset) and Low–Medium cost. Fin-Based Modifications rank last in mean improvement (38.5%) but achieve the best practical feasibility rating (Excellent) due to their simplicity of fabrication, absence of consumables, and high reproducibility — making them the logical first modification for any solar still installation. Together, Fig. 4 and the classified dataset support a tiered enhancement roadmap: fins as a low-cost entry point, followed by PCM or nanofluid augmentation, with multi-technique or externally heated configurations reserved for installations where capital investment and maintenance capacity are available.

C. Economic and Environmental Benchmarking

Multi-criteria economic analyses across the classified studies make clear that modifications targeting cost-per-litre (CPL) reduction are as strategically important as those targeting productivity maximisation. The vacuum-PCM double-slope still of Saha et al. [17] reduced CPL by 41.4% relative to the conventional reference. The conical inox-coil design of Attia and Bady [37] produced freshwater at \$0.042/litre with a 27-day payback period, while the triple-trough tubular still of Alharbi et al. [97] reached \$0.00774/litre — one of the lowest CPL values in the classified database. Agricultural-waste-derived materials — carbonised biomass [49], custard apple seed nanoparticles [98], sugarcane-synthesised ZnO [40], jackfruit-extract nZVI [21] — consistently delivered competitive performance at substantially lower material cost than commercial equivalents. The conical inox-coil design mitigated 0.327 tonnes of CO^2 annually [37], and multi-technique double-slope configurations routinely report reduced CO^2 emission equivalents relative to grid-powered alternatives [85,86]. Environmental life-cycle analyses remain rare in the classified database, however, and this constitutes a significant gap discussed further in Section IV.

D. Computational and AI-Assisted Studies

Computational fluid dynamics, finite-element analysis, and artificial neural networks have made increasingly important contributions to solar still optimisation. Anand et al. [15] used CFD to quantify the mechanistic basis of wettability-patterning improvements with a resolution unattainable from macroscopic measurements. Routroy and Bhattacharya [70] applied CFD to PCM melting dynamics in spherical encapsulations, providing material-selection guidance for future PCM studies. Rajhi et al. [66]

employed transient finite-element entropy analysis to optimise glass-cover angle and PCM-nanofluid combinations simultaneously. Jeyaraj et al. [19] developed validated numerical models for channel-shape optimisation in external-heating-coupled double-slope stills. Kumar et al. [67] deployed an ANN that predicted solar still performance with close agreement to measured experimental data. Iqbal et al. [92] demonstrated that a hybrid AI-RSM framework reduced the experimental search space for nanophotonic membrane optimisation by orders of magnitude. Chaturvedi and Gaur [2] applied a grey-relational-analysis / design-of-experiments (GRA-DoE) framework to single-slope passive stills, establishing a rigorous multi-objective performance assessment methodology applicable to any geometry. As still design complexity grows through multi-technique combination, such computational approaches are becoming increasingly indispensable.

IV. RESEARCH GAPS

Despite the remarkable breadth and depth of the classified literature, five critical gaps constrain the translation of laboratory-scale performance improvements into reliable community-scale deployment.

1) Gap 1 — Long-term durability and fouling under real saline conditions. The vast majority of classified experimental studies were conducted over one to several days using freshly prepared saline or brackish water under controlled conditions. Long-term performance of nanoparticle-enhanced stills is almost entirely uncharacterised: nanoparticle sedimentation, agglomeration, and surface fouling over weeks to months of continuous operation have not been systematically studied [89,90,91]. Similarly, the cyclic stability of PCM composites — particularly bio-derived and agricultural-waste-based materials [49,98] — over hundreds of charge–discharge cycles under real intermittent solar conditions remains largely unquantified. Without multi-month durability data, the productivity gains claimed by current studies cannot be reliably projected over the 10–20 year design life expected of a field-deployed solar still.
2) Gap 2 — Lifecycle assessment and nanoparticle ecotoxicology. None of the 118 classified studies reported a full lifecycle assessment (LCA) accounting for the energy and environmental cost of nanoparticle synthesis, encapsulation, and end-of-life disposal. Green-synthesis routes using plant extracts [21,40] are promising, but the ecotoxicological impact of releasing ZnO, CuO, or CNT nanoparticles into produced water has not been quantified. Regulatory acceptance of nanoparticle-enhanced stills for drinking-water production will ultimately require validated safety data that no current study provides.
3) Gap 3 — Standardised testing protocols. The classified database reveals that productivity improvements are reported under widely divergent conditions: different basin areas (0.1 to 1.2 m^2), different climatic zones, different saline feed concentrations (2 000 to 45 000 ppm TDS), different glass-cover inclinations (15° to 45°), and different baseline definitions. The absence of a standardised test protocol means that direct comparison of a +60% result from El-Oued, Algeria [73] with a +288% result from Amman, Jordan [34] is methodologically problematic. The field urgently needs ISO- or ASHRAE-analogous testing standards for solar still performance characterisation.
4) Gap 4 — Scale-up pathway and real-world deployment. Nearly all classified studies were conducted on laboratory-scale prototype stills with basin areas of 0.25–1.0 m^2. The technical, economic, and logistical challenges of scaling multi-technique modifications to community-scale installations of 50–500 m^2 have not been addressed. Practical considerations — structural integrity of nano-PCM composites under thermal cycling in large basins, nanofluid preparation at volume, and operational simplicity for non-specialist users — have received virtually no systematic attention in the classified literature.
5) Gap 5 — Integrated multi-objective optimisation. The vast majority of studies optimise one or two performance metrics (usually daily yield and energy efficiency) with remaining metrics reported as secondary outcomes. Simultaneous optimisation of productivity, cost per litre, carbon footprint, material availability, fabrication complexity, and operational lifetime under uncertain future climate scenarios requires multi-objective optimisation frameworks — genetic algorithms, Pareto-front analysis, or AI-driven surrogate models — that have been applied in only two classified studies [66,92]. Without rigorous multi-objective design optimisation, the modifications recommended by current studies may not represent globally optimal solutions for diverse deployment contexts.

V. FUTURE SCOPE

The research gaps identified in Section IV define a five-priority roadmap for the next decade of solar still research. First, multi-month outdoor durability trials on top-performing configurations — particularly nano-PCM composites, natural-fibre-wick systems, and interfacial evaporators — under real salinity and fouling conditions should be prioritised. These studies should include standardised accelerated-aging protocols and post-operation material characterisation (SEM, XRD, FTIR) to quantify degradation mechanisms and inform maintenance schedules.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Second, lifecycle assessment and ecotoxicological studies are needed for all nanoparticle-enhanced configurations before any regulatory approval for drinking-water applications can be sought; this work will require collaboration between solar still engineers and environmental chemists. Third, the development and adoption of a standardised performance testing protocol — specifying minimum basin area, glass thickness, insulation standard, feed-water salinity, reporting metrics, and ambient condition documentation — would immediately improve the comparability of published results and accelerate evidence-based technology selection for field deployment. Fourth, the interfacial solar evaporator platform warrants dedicated scale-up research. The extraordinary evaporation rates achieved by CNT hydrogels [89], fibre aerogels [90], and MOF-functionalised interfaces [94] under laboratory conditions are compelling, yet transitioning from a floating 10 cm^2 coupon to a field-deployable still basin covering several square metres introduces critical engineering challenges: structural integrity and buoyancy of large floating absorbers, prevention of lateral vapour loss, and cost-effective synthesis of nanostructured absorbers at kilogram scale. Pilot installations in real coastal or arid-inland environments, with full water-quality characterisation, should be the immediate next step for the most promising ISE candidates. Fifth, AI-driven multi-objective optimisation — building on the proof-of-concept work of Iqbal et al. [92] and Kumar et al. [67] — should be systematically applied to the full parameter space of multi-technique combined systems. Finally, the emerging multi-functional system paradigm — simultaneous water production, electricity generation, antibacterial treatment, and salt recovery [79,87,93] — deserves dedicated multi-disciplinary research integrating water engineering, photovoltaics, photocatalysis, and materials science, with economic and social-impact assessments designed for the specific communities where such integrated systems would ultimately be deployed.

VI. CONCLUSION

This review has systematically classified and synthesised the findings of 118 peer-reviewed solar still enhancement studies published between 2016 and 2026, spanning single-slope, double-slope, pyramidal, hemispherical, conical, tubular, stepped, twin-wedge, shadow-assisted, and interfacial-evaporator platforms across five principal modification strategies and their multi-technique combinations. The following conclusions are drawn:

1) Multi-technique integration consistently delivers the highest productivity gains, as demonstrated quantitatively in Fig. 3. The highest experimentally validated improvements — 205.17% for double-slope wick-sponge-nanofluid [85], 300% for integrated FPC-condenser pyramid [79], 116.7% for packed-bed-cotton pyramid [77], 123% for double-finned nano-PCM single slope [38] — all arise from combinations of two or more techniques addressing complementary thermal loss mechanisms simultaneously.
2) PCM integration and nanoparticle augmentation are the most widely adopted strategies (each appearing in ~40% of classified studies). As shown in Figs. 1 and 2, their combination with geometric modifications routinely delivers super-additive gains through simultaneous improvement of thermal storage capacity, effective thermal conductivity, and evaporation surface area. The optimal nanofluid concentration of 0.04–0.10 wt% (400–1000 ppm) and the need for conductivity-enhancing PCM dopants are the key practical design parameters identified by the classified database.
3) Interfacial solar evaporators represent a paradigm shift. Evaporation rates of 2–9.3 $kg/m^2/h$ reported for CNT hydrogels [89], fibre aerogels [90], and plasmonic evaporators [91] — one to two orders of magnitude above conventional basin still values — establish the interfacial evaporator as the performance frontier for solar desalination, provided scale-up and durability challenges can be resolved.
4) Externally coupled solar heating systems deliver step-change productivity improvements (+288% for evacuated-tube coupling [34], +300% for FPC integration [79]), substantially exceeding the gains achievable through passive basin modifications alone, but at higher capital cost and operational complexity. The comparative ranking in Fig. 4 confirms that external heating and multi-technique combined configurations carry High cost complexity designations that restrict their applicability to well-resourced deployment contexts.
5) Bio-derived and locally available materials are closing the performance-affordability gap. Green-synthesised nanoparticles from jackfruit peel [21] and sugarcane juice [40], carbonised biomass PCM substitutes [49], custard apple seed nanoparticles [98], natural fibre wicks [71], and locally quarried stones [73] have delivered performance competitive with commercial materials at a fraction of the cost, strengthening the economic case for solar still deployment in low-income, water-stressed communities.
6) Critical gaps remain. Long-term durability, nanoparticle ecotoxicology, standardised testing protocols, scale-up engineering, and multi-objective AI-driven optimisation are the five priority research areas that must be addressed before laboratory-scale performance advances can be reliably translated into community-scale freshwater production systems. Meeting this challenge will require sustained interdisciplinary collaboration spanning thermal engineering, materials science, environmental chemistry, economics, and public health.

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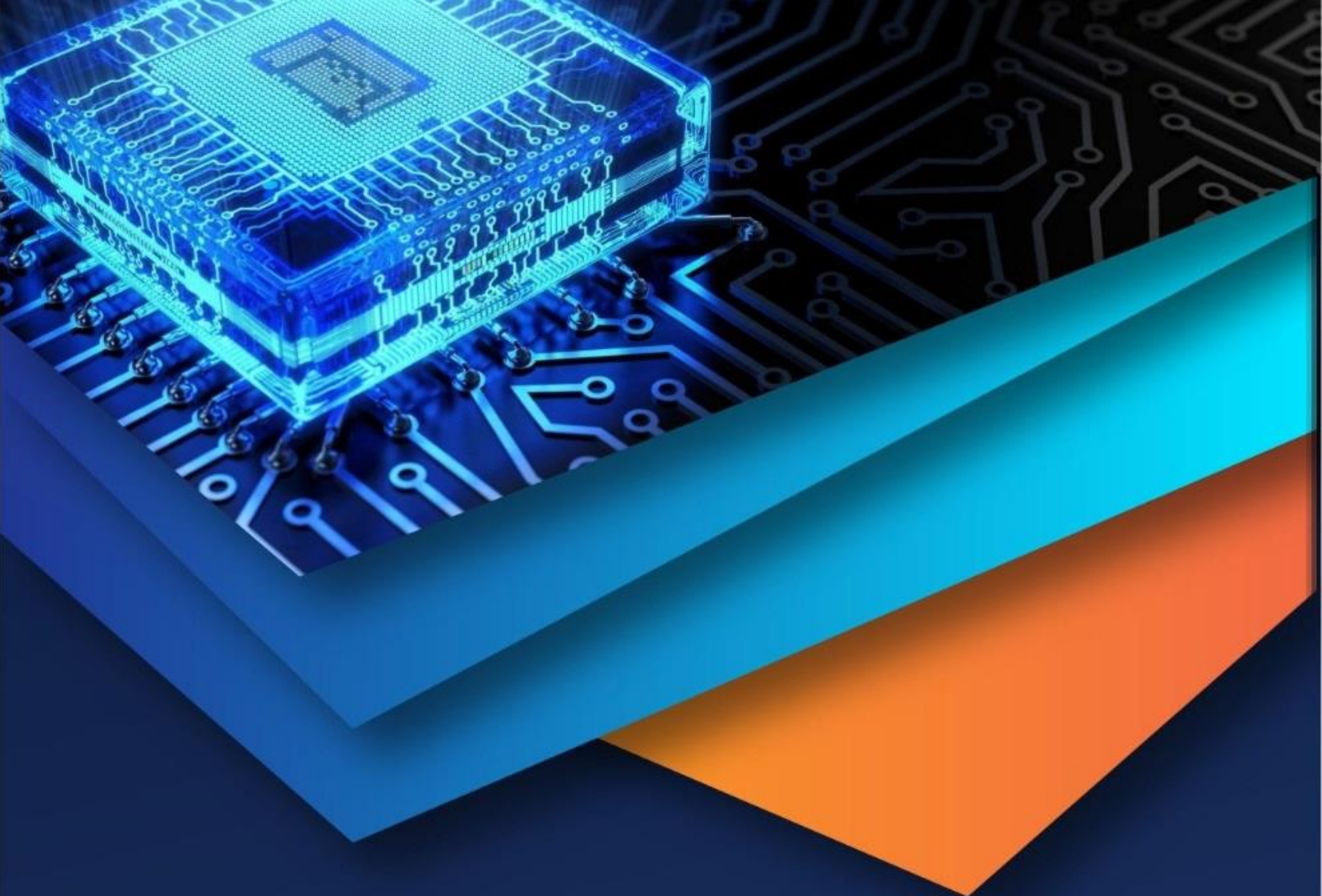

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