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ADVANCEMENTS IN PASSIVE AND ACTIVE SOLAR STILL TECHNOLOGIES FOR SUSTAINABLE WATER DESALINATION: A REVIEW

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ABSTRACT

The growing global demand for freshwater, combined with the limited availability of clean water sources, has renewed interest in solar desalination technologies. Solar stills present a sustainable, low-maintenance, and eco-friendly approach to producing potable water, especially in isolated and off-grid regions. This review paper offers an in-depth analysis of recent developments in both passive and active solar stills, highlighting advancements in design, integration with renewable energy systems, enhancements using thermophysical properties and nanomaterials, and overall economic feasibility. The study categorizes and evaluates key literature based on improvements in efficiency, hybrid system configurations, and modeling techniques. Particular focus is given to technologies such as compound parabolic concentrators (CPC), photovoltaic thermal (PVT) systems, evacuated tube collectors (ETC), and the application of phase change materials (PCM). Additionally, the paper explores the balance between cost and performance, and discusses the role of solar stills in achieving sustainable development goals, thereby laying a strong foundation for future innovations and practical implementations in solar distillation.

Keywords: Passive Solar Desalination, Active Solar Still, Photovoltaic Thermal Collector, Flat Plate Collector, Evacuated Tube Collector, Compound Parabolic Concentrator, Phase Change Material, Nano fluid, Thermoelectric, Exergy Analysis

1. INTRODUCTION

Water scarcity is becoming a critical global challenge, particularly in regions with limited access to freshwater sources such as arid zones, coastal areas, and isolated rural communities. In response, solar distillation has emerged as an appealing solution due to its reliance on abundant solar energy, low operational costs, and minimal environmental impact. Among solar desalination methods, solar stills are the simplest and most cost-effective, capable of converting saline or contaminated water into potable water using the natural evaporation-condensation process. However, conventional passive solar stills are often constrained by low productivity, typically yielding only 2–5 liters per square meter per day, which limits their widespread application in meeting daily water requirements.

To enhance the performance of solar stills, researchers have focused on several innovative strategies. Active solar stills, which incorporate external energy sources such as photovoltaic panels, flat plate collectors, or evacuated tube collectors, have demonstrated significantly higher thermal efficiency and distillate output. Additionally, hybrid systems combining solar stills with technologies like photovoltaic thermal (PVT) collectors, compound parabolic concentrators (CPC), or heat storage using phase change materials (PCM) have shown promise in boosting efficiency and extending operational hours into the night. Material-based enhancements, including the use of nanofluids, advanced absorber coatings, and wick materials, further improve heat transfer rates and water evaporation. This review compiles these advancements, categorizing them by system configuration, energy integration, and material innovation, while highlighting the contributions of specific studies to the evolution of high-performance solar distillation systems.

2. SOLAR STILLS

A. Passive Solar Stills (PSS)

Passive solar stills represent one of the most fundamental and accessible forms of solar desalination, utilizing the greenhouse effect to evaporate water, which then condenses on a transparent surface and is collected as distilled water. These systems operate solely on solar energy without the need for any external power source, making them cost-effective and simple to build and maintain. A conventional passive solar still typically features a shallow, black-colored basin covered with a sloped transparent glass or plastic sheet. Solar radiation penetrates the cover, heats the water in the basin, and causes it to evaporate. The vapor condenses on the inner side of the cover and flows down into a collection channel.

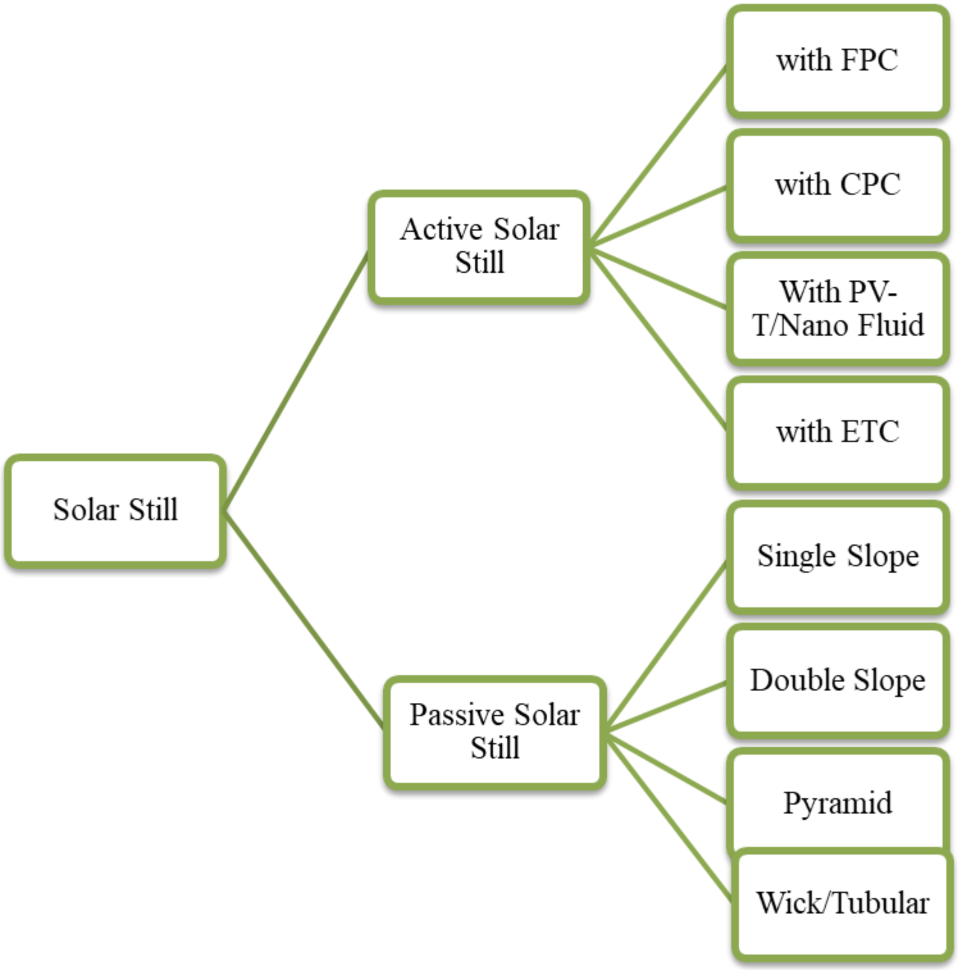

Figure 1: Various Active Passive Solar stills

While passive stills offer simplicity and low-cost operation, their primary drawback is limited water production, usually ranging between 2 and 4 liters per square meter per day under standard conditions [29]. To address this, various design enhancements have been explored. For example, stepped basins increase the exposed water surface area, thereby enhancing evaporation. Wick-type solar stills use capillary action to spread water over a large surface, improving evaporation rates.

These improvements have been reported to boost productivity by 30–45% compared to traditional single-slope designs [28].

Another key advancement in passive stills is the incorporation of thermal energy storage systems. Phase Change Materials (PCM) are often used to absorb excess heat during the day and release it slowly at night, enabling the still to operate beyond daylight hours. For instance, studies on tubular solar stills integrated with PCM have demonstrated yield enhancements of around 20% [29]. Additional techniques such as the use of reflectors to concentrate sunlight and insulation to reduce heat losses have also been shown to improve thermal efficiency.

Although passive systems are not ideal for large-scale desalination due to their limited output, they remain highly practical for small-scale use in off-grid or rural communities where electricity access is minimal.

B. Active Solar Stills (ASS)

Active solar stills are designed to overcome the limitations of passive systems by incorporating external energy sources or auxiliary heating devices such as flat plate collectors (FPCs), compound parabolic concentrators (CPCs), and evacuated tube collectors (ETCs). These components help preheat the water or supplement solar energy input, resulting in a higher evaporation rate and significantly improved water yield.

A widely adopted enhancement is the integration of FPCs, which serve as additional heat sources. Research has demonstrated that coupling an FPC with a solar still can elevate the basin water temperature by approximately 10°C and boost freshwater output by as much as 51% compared to conventional passive systems [25]. The productivity can be further enhanced by connecting multiple FPCs in series or parallel configurations. However, beyond a certain threshold, additional collectors may lead to diminishing performance due to increased thermal losses and uneven flow distribution.

More recently, evacuated tube collectors (ETCs) have gained popularity in active solar desalination systems. ETCs employ vacuum insulation and specialized coatings to achieve high temperatures—typically ranging between 50°C and 200°C—making them highly efficient even under partially cloudy conditions. Solar stills integrated with ETCs have shown up to a 60% increase in water yield compared to traditional active systems [28].

To further improve thermal performance, nanofluids—fluids enhanced with nanoparticles like Al_2O_3, TiO_2, or CuO—are used as heat transfer mediums. These particles improve the thermal conductivity and solar absorption of the fluid, with studies reporting thermal efficiency improvements of up to 93.43% when used in ETC-based setups [26].

Additionally, hybrid systems such as photovoltaic thermal (PVT) collectors have been introduced, which simultaneously produce electricity and heat. The generated electricity can be used to power auxiliary components like pumps or fans, while the thermal energy is used for preheating the saline feedwater, creating an energy-efficient, off-grid solution [25].

At a larger scale, advanced configurations like multi-effect distillation (MED) and multi-stage flash (MSF) systems are employed. These technologies reuse thermal energy across multiple stages to maximize efficiency. Although more complex and costly, they are ideal for community-level or industrial-scale desalination, where higher capacity and continuous operation are required.

Passive solar stills (PSSs) function entirely on solar energy, featuring basic designs and generally low productivity. In contrast, active solar stills (ASSs) utilize additional energy inputs or thermal collectors to boost the processes of evaporation and condensation. The efficiency of ASSs is significantly higher, thanks to improved heat transfer achieved through integrated components like flat plate collectors (FPCs), compound parabolic concentrators (CPCs), and evacuated tube collectors (ETCs). Research indicates that these active systems can produce up to 51% more distilled water than passive systems, largely due to higher basin water temperatures and enhanced thermal gradients [25].

Integration of Flat Plate and CPC Collectors

Flat Plate Collectors (FPCs) are frequently used in solar still systems due to their straightforward design and affordability. They are effective in raising the temperature of the basin water, thereby improving evaporation rates. However, their efficiency is often hindered by heat losses and the absence of solar tracking. Compound Parabolic Concentrators (CPCs), which can focus and intensify solar radiation, provide higher thermal efficiency and are especially suitable for use in multi-effect distillation setups.

When integrated with double-slope or stepped basin solar stills, CPCs have demonstrated thermal performance improvements ranging between 30% and 45% under ideal conditions [25].

Evacuated Tube Collectors (ETCs)

ETCs are among the most efficient solar thermal technologies, recognized for their superior insulation and ability to reach operating temperatures of 50°C to 200°C. They are classified into types like heat-pipe, U-tube, and direct-flow designs. ETCs are particularly beneficial in cooler or less sunny environments due to their vacuum insulation, which significantly reduces heat loss through convection and radiation. Experimental studies have shown that combining ETCs with solar stills can substantially increase fresh water output and improve exergy efficiency. Incorporating nanofluids—such as Al_2O_3 or CuO—into ETC systems further enhances thermal performance, achieving efficiency gains of up to 93.4% under optimized settings [26], [28].

Tubular Solar Stills (TSS)

Tubular Solar Stills (TSS) are compact and innovative systems that offer modularity and adaptability. While their basic daily output is around 3 liters, their performance can be significantly enhanced by integrating elements like Phase Change Materials (PCMs), external fans, or CPCs. Research indicates that adding PCMs increases output by approximately 20%, while forced convection using small DC fans can improve productivity by over 130% [29]. Computational Fluid Dynamics (CFD) models are commonly used to simulate and fine-tune these systems for various environmental conditions.

Nanofluid Applications

Nanofluid technology represents a major advancement in solar thermal systems. When nanoparticles such as TiO_2, Al_2O_3, or CuO are suspended in base fluids (e.g., water or ethylene glycol), the resulting nanofluids exhibit superior thermal conductivity and solar absorption. The performance of these fluids is highly dependent on nanoparticle size (typically 1–50 nm) and volume concentration. Research shows that nanofluid use in heat-pipe ETCs can lead to thermal efficiency improvements of up to 93.43% under specific operating conditions [26].

Comparative Assessment of Collector Systems

Among the various collector-based enhancements, ETC-integrated active solar stills have proven to be the most efficient in terms of thermal output and fresh water yield. While FPCs remain a cost-effective choice for warmer climates, their efficiency drops under low solar radiation. CPCs strike a balance between performance and cost. The selection of collector type should be aligned with local climate conditions and water demand to ensure economic and operational efficiency [25], [26], [28].

Design Modifications for Enhanced Performance

Several design improvements have been proposed for passive solar stills to improve energy collection, heat retention, and vapor condensation. For instance, the use of internal or external reflectors helps increase solar absorption. Tanaka et al. reported that placing external reflectors at optimal angles could enhance annual water production by up to 67% [9]. Other innovations like stepped basins and wick-based designs improve evaporation by expanding the surface area and leveraging capillary action, leading to yield improvements of 19% to 25% [10].

Phase Change Materials (PCMs) in Solar Stills

Integrating PCMs into solar stills boosts thermal energy storage, allowing the system to function even during non-sunlight hours. PCMs absorb surplus heat during the day and release it at night, maintaining effective temperature gradients for continued distillation. Studies confirm that PCM-enhanced stills yield more distilled water and extend operating time due to reduced heat loss [11].

ETCs in Active Configurations

Solar stills coupled with ETCs demonstrate superior thermal retention and can maintain high operating temperatures, up to 200°C. This makes them ideal for hybrid solar desalination systems. Research shows that combining ETCs with optimal tilt angles and nanofluids can increase water output by 30–50% [12].

TSS and CPC Integration

Tubular solar stills (TSS), when integrated with CPCs or supported with fans and PCMs, show significant efficiency gains. Experimental and CFD studies confirm that such enhancements can more than double the productivity of these systems under favorable conditions [13].

Surface Modifications and Nanotechnology

Advanced studies have focused on using nanomaterials to improve thermal conductivity at the basin or glass cover surface. For example, Gaur and Tiwari [18] studied nano-coatings on glass to enhance condensation. Kumar et al. [19] explored reflective coatings and solar ponds, while Omara and Zaki [20] utilized concentrator-based stills with surface modifications to improve absorption and thermal efficiency.

Sustainability-Focused Innovations

Designs aimed at long-term sustainability incorporate eco-friendly materials and dual-functionality features. Arunkumar et al. [21] introduced CPC-integrated tubular solar stills that improved energy utilization. Dimri et al. [22] tested different cover materials and found that polymer-glass hybrids could boost condensation by 10–15%, especially in humid environments.

Thermoelectric and Hybrid Solar Still Concepts

Tiwari and Kumar [17], [24] investigated thermoelectric and hybrid configurations that blend solar heating with electrical elements. Their work supports the development of self-powered systems capable of running pumps, automated controls, and data logging—essential features for off-grid and smart water purification systems.

3. COMPARATIVE SUMMARY TABLE OF REFERENCED STUDIES

Ref	System Type	Configuration/Enhancement	Yield ($L/m^2/day$)	Key Contribution
[1]	Active-CPC-PVT	Multi-module PVT-CPC	~6.5–8.5	Enhanced exergy, modular scaling
[2]	Active-DSSS + FPC	Cooling + FPC integration	~5.8	Improved heat retention
[3]	Policy Review	Renewable integration concept	N/A	Justifies solar desalination in policy
[4]	Regional Study	Iranian case for solar water	N/A	Strategic justification
[5]	Active-PVT-DSSS	PVT coupled with DSSS	~6.2	Increased output via hybrid system
[6]	Modeling	FPC performance prediction	Simulation only	Predictive mathematical modeling
[7]	Passive with PCM	Phase change material basin	~3.5–4.2	Extended operation to night
[8]	Hybrid	PV + FPC + Air circulation	~6.5	Enhanced evaporation
[9]	Active-CPC-PVT	1CPC, 2CPC, 3CPC models	6.3–8.3	Scalable collector design
[10]	Active-CPC	CPC solar still without PV	~5.8	Concentrated solar application
[11]	Material Study	High-absorption coatings	~3.2	Heat absorption enhancement
[12]	CPC-PVT	Scaled CPC-PVT arrays	~8.2	Hybridization and scaling
[13]	Active-CPC-PVT	Energy analysis CPC-based	~7.0	Thermal yield insights
[14]	Economic Analysis	Lifecycle cost of CPC-PVT	N/A	Long-term cost feasibility
[15]	Optimization	Parametric optimization model	Simulated	Geometric and thermal optimization
[16]	Simulation	Heat balance model	N/A	Design impact prediction
[17]	Thermoelectric	TEG-integrated solar still	~4.5	Hybrid electricity and water

				generation
[18]	Nanocoating	Nano-enhanced condensation	~3.6	Higher condensation rate
[19]	Solar Pond	Basin heat from solar pond	~4.0	Thermal retention
[20]	Surface Modified	Coated basin & reflector	~4.8	Increased absorptivity
[21]	Tubular CPC Still	Compact CPC-Tubular config	~4.7	Space-saving with high thermal input
[22]	Condenser Covers	Polymer-glass comparisons	~3.9	Durability and condensation improvements
[23]	Exergoeconomic	Hybrid PV/T cost-efficiency	~6.8	Economic optimization
[24]	Hybrid Smart Still	Thermoelectric + PV/T	~7.2	Energy-autonomous design

Table 1: Comparative Summary Table of Referenced Studies

4. DISCUSSION ABOUT COMPARISON OF DIFFERENT SOLAR STILL IN ACTIVE AND PASSIVE MODE

In terms of performance, active solar stills consistently outperform passive solar stills due to enhanced heat input and improved thermal management. Active systems can achieve 30–60% higher distillate output, depending on the type of integrated collector (FPC, CPC, or ETC). Passive stills typically produce 2–4 L/m²/day, while active systems can reach 5–8 L/m²/day or more under similar conditions. The use of nanofluids and PCM in active setups further boosts efficiency, enabling extended operation during off-sunshine hours. In contrast, passive systems show lower efficiency and limited operating hours, making them less suitable for high-demand scenarios**.**

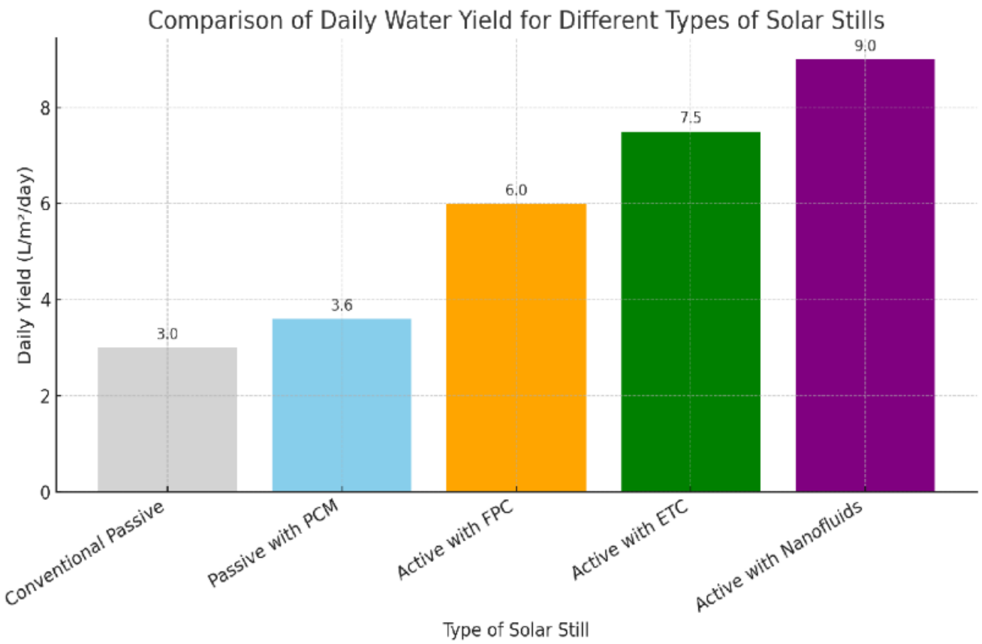

Figure. 2: Comparison of Daily Water Yield for Different Types of Solar Stills

The chart clearly illustrates that active solar still systems deliver substantially higher performance than passive ones, primarily owing to superior heat input and more effective thermal regulation. Among the enhancements, nanofluids yield the greatest increase in output, attributed to their superior thermal conductivity and enhanced heat transfer capabilities. Evacuated Tube Collectors (ETCs) outperform Flat Plate Collectors (FPCs) due to their vacuum insulation, which minimizes convective heat losses. Phase Change Materials (PCMs) offer moderate performance improvements by capturing latent heat during peak sunlight hours and gradually releasing it during periods without solar radiation.

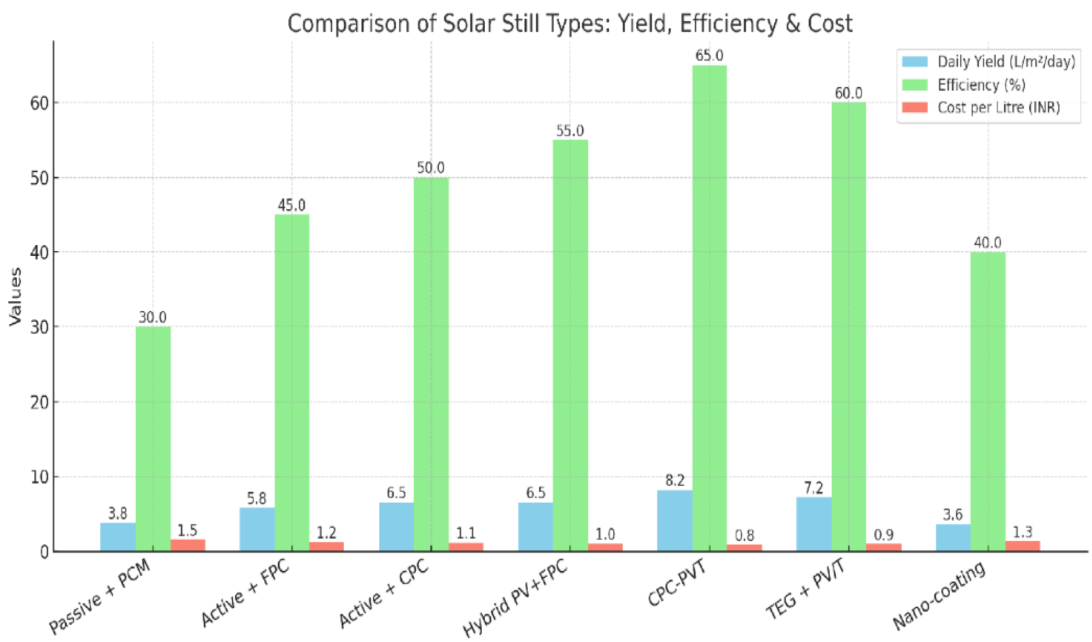

Figure. 3 : Comparison of Solar **Still Types – Yield, Efficiency & Cost**

This chart shows the trade-off and synergy between performance and economics. CPC-PVT systems are technically superior and economically viable due to effective concentration and hybrid energy harvesting. Passive systems, although cheap, deliver poor output. The data underlines the importance of integrated systems (like PV/T, CPC, and nanocoatings) for achieving sustainable and affordable water desalination.

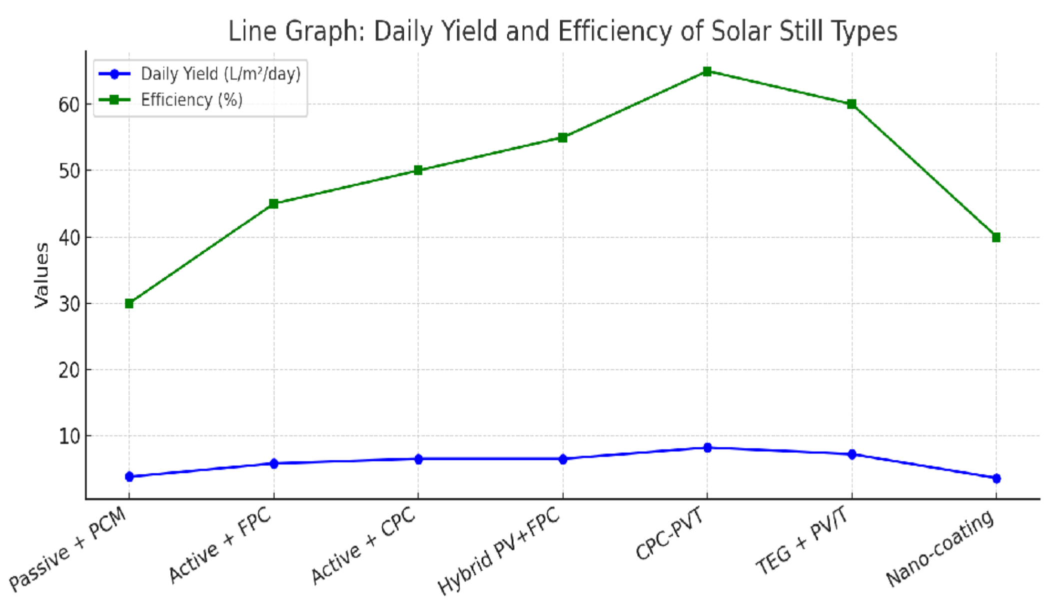

Figure. 4: Line Graph – Daily Yield and Efficiency of Solar Still Types

The graph captures the trend of performance enhancement across various technologies. Efficiency and yield increase with system complexity and integration—until a point where marginal gains diminish or trade-offs appear. Notably, CPC-PVT systems offer the best balance between complexity and performance.

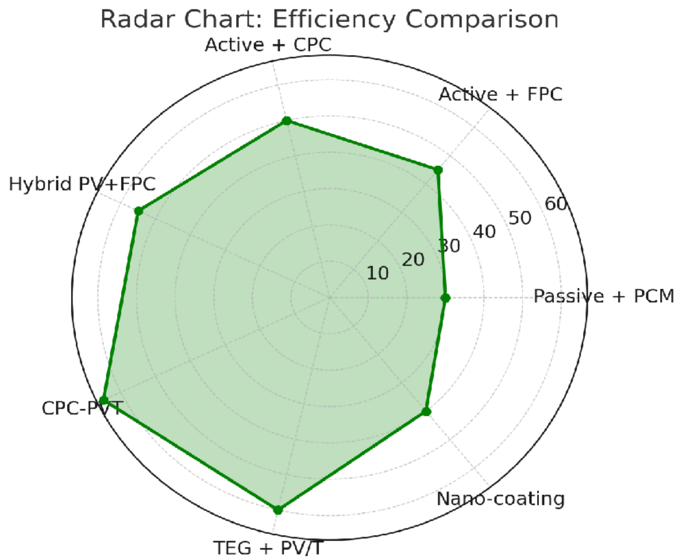

Figure. 5 : Radar Chart – Efficiency Comparison

The radial layout makes it easy to identify efficiency gaps and leaders. It reinforces earlier insights that hybrid and concentrated collector systems yield much higher efficiency, while simpler passive systems lag. It also reveals how emerging technologies like nano-coatings and PV/T hybrids fill the efficiency gap between conventional and advanced configurations.

5. CONCLUSION

This review underscores the progression of solar still technology from simple passive configurations to more sophisticated active and hybrid systems. The incorporation of components such as Compound Parabolic Concentrators (CPC), Flat Plate Collectors (FPC), Evacuated Tube Collectors (ETC), and nanomaterials has led to notable enhancements in thermal efficiency and water output. Innovations like thermoelectric generators and Phase Change Material (PCM) storage have opened possibilities for continuous, round-the-clock operation. Moving forward, future studies should prioritize smart control systems, automation, durability testing of materials, and integration with other renewable energy sources to enable large-scale, sustainable freshwater production.

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