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"PERFORMANCE ENHANCEMENT STRATEGIES AND MODERN TRENDS IN SINGLE SLOPE SOLAR STILLS: A SYSTEMATIC REVIEW"

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ABSTRACT

Freshwater scarcity represents one of the most critical socio-economic and public health crises across arid, semi-arid, and remote coastal territories. Solar distillation using Single Slope Solar Stills (SSSS) offers a thermodynamically sustainable, low-carbon, decentralized water purification solution characterized by low capital expenditure and operational simplicity. Nevertheless, conventional passive SSSS units suffer from inherently low daily distillate yields (typically 2.0 to 3.5 L/m²· day) and modest thermal conversion efficiencies (25% to 35%), hindered by large basin water thermal inertia, sluggish natural convection mass transfer rates, and condensation film thermal resistance. This systematic review presents an exhaustive state-of-the-art appraisal of SSSS thermal augmentation techniques. Fundamental governing energy balances, internal heat and mass transfer correlations (Dunkle, Clark, Kumar-Tiwari), and exergy-exergoeconomic metrics are critically examined. Augmentation paradigms are methodically evaluated, including: (i) absorber surface engineering (corrugated, stepped, and porous wick materials), (ii) thermal energy storage (sensible and latent heat phase change materials, PCMs/ nano-PCMs), (iii) optical enhancement (internal/external flat and parabolic reflectors), (iv) hybrid nanofluids and photothermal interfacial evaporators, and (v) active external condensing systems. Furthermore, an extensive literature survey synthesizing recent breakthroughs from 2024 to 2026 highlights innovations in 3D-printed biomimetic evaporators, machine-learning-driven predictive yield modeling, and circular enviroeconomic life cycle analyses, concluding with design guidelines for commercial-scale deployment.

Key Words: *Single Slope Solar Still; Solar Desalination, Distillate Yield, Energy and Exergy Analysis, Phase Change Materials, Nanofluids, Interfacial Solar Evaporation, Cost per Liter (CPL).*

I. INTRODUCTION

Access to potable drinking water is a fundamental human right recognized by the United Nations Sustainable Development Goal 6 (SDG 6). Despite oceans covering over 71 % of the Earth's surface, more than 97.5% of total global water inventory exists as saline seawater, and roughly 1 .75% is locked within polar ice caps and glaciers. Consequently, less than 0.75% of global fresh water is available for agricultural, municipal, and industrial consumption. Escalating climate fluctuations, exponential population growth, over-extraction of inland aquifers, and industrial effluent contamination have driven severe water stress across arid and coastal regions.

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Fig.1 Single slope solar still

Conventional large-scale desalination technologies—such as Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Reverse Osmosis (RO)—dominate commercial utility installations. However, these centralized industrial plants rely on grid electricity or fossil fuel combustion, demanding intense specific energy inputs (3 to 6 kWh/m³ for RO, 10 to 15 kWh/m³ equivalent for MSF), accompanied by severe greenhouse gas emissions and environmental brine disposal challenges. In decentralized, off-grid rural communities, isolated islands, and desert settlements, centralized desalination is logistically and economically non-viable.

In this context, direct solar thermal desalination utilizing Single Slope Solar Stills (SSSS) provides an attractive alternative [Tiwari et al., 2015]. Operating on direct evaporation and condensation inspired by the natural hydrologic cycle, an SSSS purges total dissolved solids (TDS), bacteria, heavy metals, and suspended matter using free solar irradiance. Despite these advantages, standard baseline passive SSSS installations exhibit modest daily distillate productivity, motivating extensive engineering research into thermo-fluid and optical enhancements.

II. Working Principle & Governing Thermodynamic Formulations

A conventional Single Slope Solar Still comprises an insulated, leak-proof basin lined with a solar-absorptive black coating, containing a shallow saline water layer (typically 1 to 5 cm depth). The basin is enclosed by an inclined transparent glass cover (tilt angle β typically matched to local geographic latitude to maximize annual insolation). Incoming shortwave solar irradiance ($I(t)$) traverses the high-transmissivity cover and impinges upon the blackened absorber plate, converting optical photons into sensible thermal energy.

This thermal energy conducts into the adjacent water mass, raising its bulk temperature (Tw) and elevating the vapor pressure at the water-air interface. Water evaporates, and buoyant, moisture-saturated air rises via natural convection toward the cooler glass cover (Tg). Upon contacting the inner glass surface, water vapor condenses into thin liquid films or discrete droplets, releasing its latent heat of vaporization (hfg). Gravitational force drives the condensate film down the inclined glass underside into an insulated collection channel, leaving salts and non-volatile impurities in the basin.

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2.1 Differential Energy Balance Formulations

The transient thermal performance of the three core domains—glass cover (g), water mass (w), and absorber basin liner (b)—is modeled via coupled differential energy balances:

Glass Cover Energy Balance:

$$m_g \cdot C_{pg} \cdot (dT_g/dt) = \alpha_g \cdot I(t) \cdot A_g + q_{t,w\text{-}g} \cdot A_b - q_{t,g\text{-}a} \cdot A_g$$

Saline Water Layer Energy Balance:

$$m_w \cdot C_{pw} \cdot (dT_w/dt) = \alpha_w \cdot \tau_g \cdot I(t) \cdot A_w + q_{c,b\text{-}w} \cdot A_b - q_{t,w\text{-}g} \cdot A_b$$

Basin Absorber Liner Energy Balance:

$$m_b \cdot C_{pb} \cdot (dT_b/dt) = \alpha_b \cdot \tau_g \cdot \tau_w \cdot I(t) \cdot A_b - q_{c,b\text{-}w} \cdot A_b - q_{loss,b\text{-}a} \cdot A_b$$

2.2 Internal Heat and Mass Transfer Mechanisms

Internal heat transfer from the saline water surface to the glass cover ($q_{t,w\text{-}g}$) occurs simultaneously through three parallel pathways: radiation ($q_{r,w\text{-}g}$), convection ($q_{c,w\text{-}g}$), and evaporation ($q_{e,w\text{-}g}$):

$$q_{t,w\text{-}g} = q_{r,w\text{-}g} + q_{c,w\text{-}g} + q_{e,w\text{-}g} = (h_{r,w\text{-}g} + h_{c,w\text{-}g} + h_{e,w\text{-}g}) \cdot (T_w - T_g)$$

The evaporative heat transfer mode represents the productive distillation driver, governed by the mass flux equation:

$$\dot{m} = q / h = [h \cdot A \cdot (T - T)] / h$$

$$ew \quad e,w\text{-}g \quad fg \quad e,w\text{-}g \quad b \quad w \quad g \quad fg$$

In 1961, Dunkle proposed the foundational semi-empirical correlation for enclosed cavity natural convection:

$$h_{c,w\text{-}g} = 0.884 \cdot [(T_w - T_g) + \{(P_w - P_g) \cdot (T_w + 273.15)\} / \{268.9 \times 10^3 - P_w\}]^{1/3}$$

$$h_{e,w\text{-}g} = 16.273 \times 10^{-3} \cdot h_{c,w\text{-}g} \cdot [(P_w - P_g) / (T_w - T_g)]$$

where P_W and P_g are saturated partial vapor pressures evaluated at T_W and T_g (N/m²). While Dunkle's model remains widespread, it assumes pure air-water vapor behavior and small operating cavity heights (<0.05 m). At higher operating temperatures ($T_W > 60°C$), modified formulations by Clark and Kumar-Tiwari provide superior agreement with empirical measurements by correcting for temperature-dependent Rayleigh and Nusselt numbers [Tiwari et al., 2015].

III. Thermal Performance Augmentation Methodologies

The modest daily distillate output of simple passive solar stills stems from three fundamental bottlenecks: excessive water thermal mass, low solar absorption, and thermal condensation resistance on the glass cover. Systematic engineering interventions focus on overcoming these limitations:

1.1 Basin Absorber Geometrical Modifications

Replacing flat rectangular absorber liners with modified surface geometries alters fluid-thermal behavior:

- **Corrugated and V-Grooved Basins:** Corrugated troughs expand the effective solar absorption area by 30% to 50% without altering the external physical footprint. Triangular and sinusoidal ridges trap reflected incident rays, reducing optical reflection losses.
- **Stepped / Cascading Solar Stills:** Stepped trays subdivide the basin liquid into shallow cascades. This minimizes thermal inertia, enabling water to heat rapidly during morning hours and boosting peak evaporative flux.
- **Porous and Capillary Wicking Materials:** Introducing porous matrices (jute cloth, blackened cotton wicks,

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porous carbon foam) draws water continuously via capillary action. This maintains an ultra-thin evaporating film, virtually eliminating bulk water thermal mass and delivering yield improvements of 35% to 55% **[Kabeel et al., 2020]**.

1.2 Thermal Energy Storage: PCMs and Nano-PCMs

Solar stills suffer from sharp productivity declines during cloudy spells and zero output during nighttime. Integrating Phase Change Materials (PCMs) beneath the basin liner mitigates this intermittency. During peak daylight hours, the PCM absorbs excess thermal energy and melts isothermally (charging phase). During sunset and nighttime hours, as ambient temperatures drop, the PCM solidifies (discharging phase), continuously releasing its latent heat of fusion into the basin water.

Because pure organic paraffin waxes possess low thermal conductivity ($k \approx 0.2\ W/m{\cdot}K$), modern systems disperse high-conductivity nanoparticles (such as Al_2O_3, CuO, graphene, and multi-walled carbon nanotubes) into the wax matrix, creating nano-enhanced PCMs (NePCMs). Studies demonstrate that NePCMs accelerate phase transition kinetics and raise overnight distillate production by up to 85% compared to baseline units **[Sarhaddi et al., 2023]**.

1.3 Nanofluids & Photothermal Interfacial Solar Evaporators

Direct volumetric absorption solar desalination replaces traditional bottom-heated basins with nanofluid suspensions or floating photothermal evaporators. Dispersing plasmonic metallic or carbonaceous nanoparticles (e.g., $Ti_3C_2T_X$ MXenes, reduced graphene oxide, Biochar) directly into saline water localizes heat generation at the liquid-vapor interface. This interfacial localization minimizes parasitic heat conduction into the bulk water substrate, achieving solar-to-vapor conversion efficiencies exceeding 85% **[Alvarez et al., 2024]**.

1.4 External Condensers and Glass Cooling Techniques

Distillate production is directly proportional to the temperature differential ($T_w - T_g$). However, latent heat released during vapor condensation gradually heats the glass cover, lowering ($T_w - T_g$) and stalling condensation. Countermeasures include:

- **External Glass Water Film Cooling:** Distributing a uniform water film across the glass outer surface enhances evaporative and convective cooling, sustaining a steep temperature gradient and increasing yield by 20% to 30%.
- **Active External Condensers:** Connecting the still cavity to a separate shaded or fan-cooled condensing chamber prevents latent heat buildup beneath the glass, avoiding film-boiling resistance.

IV. Comparative Performance Synthesis Across SSSS Modifications

Table 1 compiles a comprehensive comparative synthesis of performance benchmarks, energy/exergy efficiencies, and economic indicators across key SSSS configurations evaluated in recent literature.

Still Configuration & Modification Category	Thermal Mass Reduction Technique	Daily Yield ($L/m^2 \cdot day$)	Yield Gain vs. Conventional	Daily Thermal Efficiency (η_{th})	Exergy Efficiency (η_{ex})	Cost per Liter (CPL, USD/L)
Conventional Passive SSSS (Flat Basin Baseline)	None (Bulk 3.0 cm Water Layer)	2.20 – 3.20	Reference Baseline (0%)	26.5% – 32.0%	1.8% – 2.8%	$0.028 – $0.035

Still Configuration & Modification Category	Thermal Mass Reduction Technique	Daily Yield (L/m²· day)	Yield Gain vs. Conventional	Daily Thermal Efficiency (η_{th})	Exergy Efficiency (η_{ex})	Cost per Liter (CPL, USD/L)
Corrugated Absorber with Internal Mirrors	V-Ridge Geometrical Trapping	4.45 – 5.10	+58% to +65%	39.2% – 44.5%	3.4% – 4.2%	$0.024 – $0.029
Floating Blackened Jute Wick Matrix	Continuous Capillary Thin-Film	5.20 – 5.85	+82% to +95%	46.0% – 51.5%	4.5% – 5.1%	$0.019 – $0.022
Paraffin Wax PCM Sub-Basin Storage	Latent Heat Thermal Storage Core	4.80 – 5.40	+68% to +78%	42.5% – 48.0%	3.8% – 4.6%	$0.025 – $0.031
Nano-PCM (Paraffin + 1.5 wt% CuO Nanoparticles)	Enhanced Conductivity Nano-Dispersoid	5.90 – 6.60	+105% to +125%	52.0% – 57.8%	5.2% – 6.4%	$0.022 – $0.027
Interfacial Evaporator (3D MXene/Porous Wood)	Localized Surface Photothermal Layer	7.10 – 8.20	+155% to +185%	64.5% – 72.0%	7.1% – 8.5%	$0.016 – $0.020
Hybrid Active SSSS (PV-Powered Fan + Condenser)	Forced Vapor Extraction & Glass Cooling	7.80 – 9.10	+180% to +215%	68.0% – 76.5%	8.0% – 9.8%	$0.021 – $0.026

V. Energy, Exergy, Enviroeconomic, And Exergoeconomic (4E) Frameworks

Assessing solar stills purely on daily volume output (L/day) masks fundamental thermodynamic irreversibilities and economic practicalities. Modern analyses employ a comprehensive 4E assessment framework:

5.1 Energy and Exergy Evaluation

The daily thermal energy efficiency (η_{th}) measures overall heat utilization:

$$\eta_{th} = [\sum (\dot{m}_{ew} \cdot h_{fg})] / [A_b \sum I(t) \cdot \Delta t]$$

In contrast, exergy efficiency (η_{ex}) assesses thermodynamic quality by accounting for entropy generation during conversion ofhigh-temperature solar radiation ($T_{sun} \approx 5778\ K$) into low-grade heat:

$$\eta_{ex} = Ex_{evap} / Ex_{solar} = [\sum \dot{m}_{ew} \cdot h_{fg} \cdot (1 - T_a/T_w)] / [A_b \cdot \sum I(t) \cdot \{1 - (4/3) \cdot (T_a/T_{sun}) + (1/3) \cdot (T_a/T_{sun})^4\} \cdot \Delta t]$$

Conventional stills rarely exceed 3% exergy efficiency due to large internal temperature drops and irreversible heat rejection through the base and insulation.

5.2 Exergoeconomic and Enviroeconomic (CO_2 Mitigation) Metrics

The Cost per Liter (CPL) is calculated via uniform annual cost methods accounting for capital cost (P), sinking fund factor (SFF), annual maintenance (M), salvage value (S), and design life ($n \approx 10–20\ years$):

CPL = [Total Annualized Cost (TAC)] /[Annual Distillate Production (Mannual)]

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Enviroeconomic analysis quantifies the carbon dioxide emissions mitigated by substituting fossil-fueled electric or thermal water purification with solar stills. Over a 20-year lifespan, a single 1 m² solar still offsets between 15 and 32 metric tons of embodied CO_2, generating environmental carbon credit returns that improve overall economic feasibility [Tiwari et al., 2025].

VI. Literature Survey & Emerging Horizons

Recent literature spanning 2024 to 2026 reflects significant advances in material science, automated monitoring, and circular manufacturing:

- **Additively Manufactured and Biomimetic Evaporators (2025–2026):** Researchers have leveraged 3D printing to create biomimetic vascular channels mimicking transpiration in plant leaves. Utilizing hydrogel-coated porous carbon lattices, these evaporators supply water continuously to the evaporation front while preventing salt crystallization and fouling through reverse salt-drainage pathways **[Wang & Chen, 2025]**.
- **Machine Learning & Real-Time Hybrid Digital Twins (2025–2026):** Integration ofArtificial Neural Networks (ANN), Long Short-Term Memory (LSTM) models, and Random Forest algorithms enables real-time forecasting ofdistillate output with coefficients ofdetermination exceeding $R^2 > 0.98$. These models dynamically modulate active cooling flow rates and reflector tracking angles based on ambient wind and irradiance variations **[Sharma & Das, 2025]**.
- **Sustainable and Biochar-Based Absorbers (2026):** In response to environmental concerns surrounding synthetic polymers and nanoparticles, recent studies utilize agricultural waste pyrolyzed into activated biochar matrices. These sustainable absorbers achieve high solar absorption (>94%) and robust capillary pumping at low material cost **[Zhang et al., 2026]**.
- **Standardization and Water Quality Compliance:** Contemporary investigations report that distillate produced by advanced SSSS configurations conforms to both World Health Organization (WHO) and Bureau of Indian Standards (BIS 10500:2012) drinking water metrics. Saline feedstock with TDS levels exceeding 35,000 ppm is consistently reduced to potable levels under 150 ppm, with zero detectable pathogens.

VII. Concluding Remarks & Strategic Recommendations

Single Slope Solar Stills represent an adaptable, environmentally benign solution to global potable water shortages. While conventional flat-basin stills are limited by low thermal efficiency, recent engineering interventions have demonstrated substantial performance improvements:

1. **Water Layer Minimization:** Maintaining a shallow water depth (1 .0 to 1 .5 cm) or deploying porous capillary wicks is the most cost-effective method to reduce basin thermal mass and enhance instantaneous evaporation.
2. **Composite PCM Implementation:** Incorporating nano-enhanced PCMs effectively addresses nocturnal productivity loss, enabling round-the-clock water generation and boosting cumulative daily yields by over 100%.
3. **Selective Condensation Management:** Active cooling ofthe transparent cover combined with external condensing chambers

   preserves the essential vapor-glass driving potential ($T_w - T_g$).
4. **Path Toward Commercialization:** Future research must prioritize scalable, low-cost biochar interfacial absorbers, anti-scaling/self-cleaning mechanisms to handle long-term brine deposition, and standardized life-cycle 4E benchmarks to support deployment in remote communities.

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