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Sustainable Solar Desalination Utilizing Wood Waste-Based Phase Change Materials: Performance Enhancement and Comparative Analysis

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Abstract: Addressing global freshwater scarcity requires innovative, sustainable technologies. Solar desalination, a renewable and eco-friendly process, converts saline water into potable water using solar energy. Nonetheless, its productivity is often limited by the intermittent nature of solar radiation. The integration of phase change materials (PCMs) enhances thermal energy storage, enabling distillation beyond daylight hours. This paper presents a detailed analysis of wood waste-based PCM composites in solar desalination systems and provides a comparative assessment against conventional PCMs such as paraffin wax, stearic acid, and lauric acid.
The study highlights improvements in freshwater yield, economic viability, and sustainability, demonstrating the potential of harnessing biomass residues to advance energy-efficient water purification technologies.
Keywords: Solar desalination, phase change material, wood waste, latent heat storage, thermal energy storage, freshwater production, sustainability, renewable energy.

I. INTRODUCTION

Freshwater demand is surging globally owing to population growth, industrialization, and climate change impacts, making conventional freshwater sources inadequate in many regions. Desalination has become indispensable for augmenting potable water supply.

However, widely used desalination methods such as reverse osmosis impose high energy and environmental costs. Solar desalination, driven by free solar radiation, offers an environmentally sustainable alternative by converting seawater or brackish water into freshwater with low greenhouse gas emissions.

Traditional solar stills, often the simplest form of solar desalination devices, suffer from productivity limitations tied to the diurnal cycle of solar intensity — producing water mainly during peak sunlight hours and ceasing operation at night [1]. This cyclical nature restricts daily output and efficiency.

Incorporating phase change materials (PCMs) into solar stills as thermal energy storage components has emerged as an effective strategy to alleviate this limitation. PCMs absorb solar heat during the day by melting, storing latent heat, and subsequently releasing stored energy gradually when ambient temperature declines. This thermal buffering extends evaporation time into evening and early night, significantly increasing freshwater output.

Recently, extensive research attention has been drawn to the valorization of wood waste—a renewable and abundant biomass residue—as a matrix for embedding PCMs [2]. Such wood waste-based PCM composites simultaneously provide thermal energy storage, mechanical stability, and insulation, while promoting waste utilization and circular economy principles.

This paper reviews the current state of solar desalination employing wood waste-based PCMs, evaluates their performance relative to conventional PCMs, and discusses materials, fabrication, experimental outcomes, sustainability, and future research needs.

II. FUNDAMENTALS OF SOLAR DESALINATION SYSTEMS

Solar stills function by harnessing solar radiation to evaporate saline water contained within an insulated basin covered by transparent material (glass or plastic). The vapor condenses on the cooler surface of the cover and is collected as purified water. The overall system efficiency depends on solar irradiance, ambient temperature, basin temperature, and heat losses.

Key performance indicators include:

1) Distillate yield – Volume of freshwater produced per square meter area per day.
2) Thermal efficiency – Energy conversion effectiveness.
3) Duration of operation – How long evaporation sustains daily.

A critical challenge arises from solar dependency, where production falls sharply after sunset, limiting total daily yields.

III. PHASE CHANGE MATERIALS (PCMS) IN SOLAR DESALINATION

PCMs are substances that absorb or release large quantities of latent heat during phase transitions (typically melting/freezing), allowing storage and controlled release of thermal energy.

In solar desalination:

1) PCMs melt when temperatures rise due to solar input, absorbing heat without large temperature increases.
2) Later, during cooling periods, they solidify releasing latent heat, maintaining higher basin temperatures and supporting evaporation.
3) The choice of PCM is influenced by melting temperature, latent heat capacity, thermal conductivity, chemical stability, cost, and environmental impacts.

Common PCMs for solar desalination include paraffin wax (organic, petroleum-derived), fatty acids like stearic and lauric acid, and salt hydrates (inorganic) [3]. Organic PCMs generally offer moderate latent heat values, are chemically stable, but may have leakage and flammability concerns.

Composite PCMs incorporate supporting materials to improve shape stability and thermal reliability.

IV. WOOD WASTE-BASED PCM COMPOSITES: MATERIALS AND FABRICATION

Wood waste—sawdust, wood shavings, or forestry residues—is a porous biomass rich in lignocellulosic components ideal for PCM encapsulation [4].

Its natural porosity allows PCM impregnation, while providing:

1) Encapsulation and leakage reduction: Wood fibers physically hold PCM, minimizing fluid seepage.
2) Thermal insulation: Low thermal conductivity reduces heat dissipation, sustaining temperature maintenance.
3) Mechanical robustness: Wood structure buffers against deformation during phase transitions, extending thermal cycling durability.

Composite fabrication commonly involves:

- Cleaning and drying wood waste to remove impurities.
- Melting PCM (e.g., paraffin wax) and vacuum or pressure impregnation of wood matrix.
- Cooling to solidify PCM within pores.
- Optional surface sealing to prevent PCM loss and environmental ingress.

This method yields eco-friendly, cost-effective PCMs integrating thermal storage and insulation.

V. EXPERIMENTAL PERFORMANCE AND COMPARATIVE RESULTS

Multiple studies [5] show solar stills employing wood waste-based PCM composites exhibit:

1) Daily freshwater yields of approximately 2.0 to 2.2 liters per 0.54 m^2 surface area.
2) Yield improvements of 30% to 80% compared to traditional solar stills without PCM.
3) Sustained basin temperatures several hours post-sunset (up to 7 hours), extending operational duration.
4) Thermal cycling stability over more than 50 melt-freeze cycles, ensuring longevity.

When benchmarked against conventional PCMs:

TABLE I
WOOD WASTE PCM COMPOSITES OUTPERFORM

PCM Type	Approx. Daily Yield	Latent Heat (kJ/kg)	Sustainability	Cost	Thermal Retention
Paraffin Wax	~1.2 L/m²-day	150–200	Moderate (petrochemical)	Low	Good
Stearic Acid	~1.0 L/m²-day	~200	Moderate (biodegradable)	Moderate	Moderate
Lauric Acid	~0.93 L/m²-day	~170	Good (organic)	Moderate	Moderate
Wood Waste Composite	~2.0-2.2 L/0.54 m²	Composite dependent	Excellent (biomass reuse)	Very Low	Extended due to insulation

Wood waste PCM composites outperform or match traditional PCMs in freshwater yield, with additional advantages in sustainability and cost-efficiency.

VI. SUSTAINABILITY AND ECONOMIC IMPACT

Utilizing wood waste addresses two challenges simultaneously: freshwater scarcity and biomass waste management. This approach:

1) Supports circular economy models converting waste into valuable TES materials.
2) Lowers raw material and processing costs relative to commercial PCMs.
3) Reduces environmental impacts associated with petroleum-based PCM production and disposal.
4) Enhances feasibility for low-income, off-grid, or rural communities abundant in biomass residues and solar resources.

VII. CHALLENGES AND FUTURE DIRECTIONS

While promising, wood waste-based PCM solar desalination requires further development:

1) Optimization of PCM loading capacity and composite fabrication to maximize thermal storage without compromising mechanical strength.
2) Long-term field testing in diverse climatic conditions to validate durability and performance consistency.
3) Integration with multi-stage or hybrid desalination techniques for enhanced yield.
4) Exploration of alternative biomass matrices and bio-based PCMs tailored to specific thermal and environmental requirements.
5) Lifecycle and environmental impact assessments for widespread deployment.

VIII. CONCLUSION

Wood waste-based PCM composites represent a sustainable, cost-effective, and efficient solution to enhance solar desalination. These composites capitalize on the dual benefits of thermal energy storage and insulation, extending operational hours and increasing freshwater production relative to conventional solar stills and PCMs. Additionally, they contribute profound environmental advantages by repurposing biomass waste, supporting sustainable material cycles, and reducing reliance on petroleum-derived PCMs. Continued research and development efforts aimed at material optimization, system integration, and scalable manufacturing are essential to elevate wood waste-based PCM solar desalination from experimental validation to practical, widespread implementation, particularly for water-scarce and off-grid communities.

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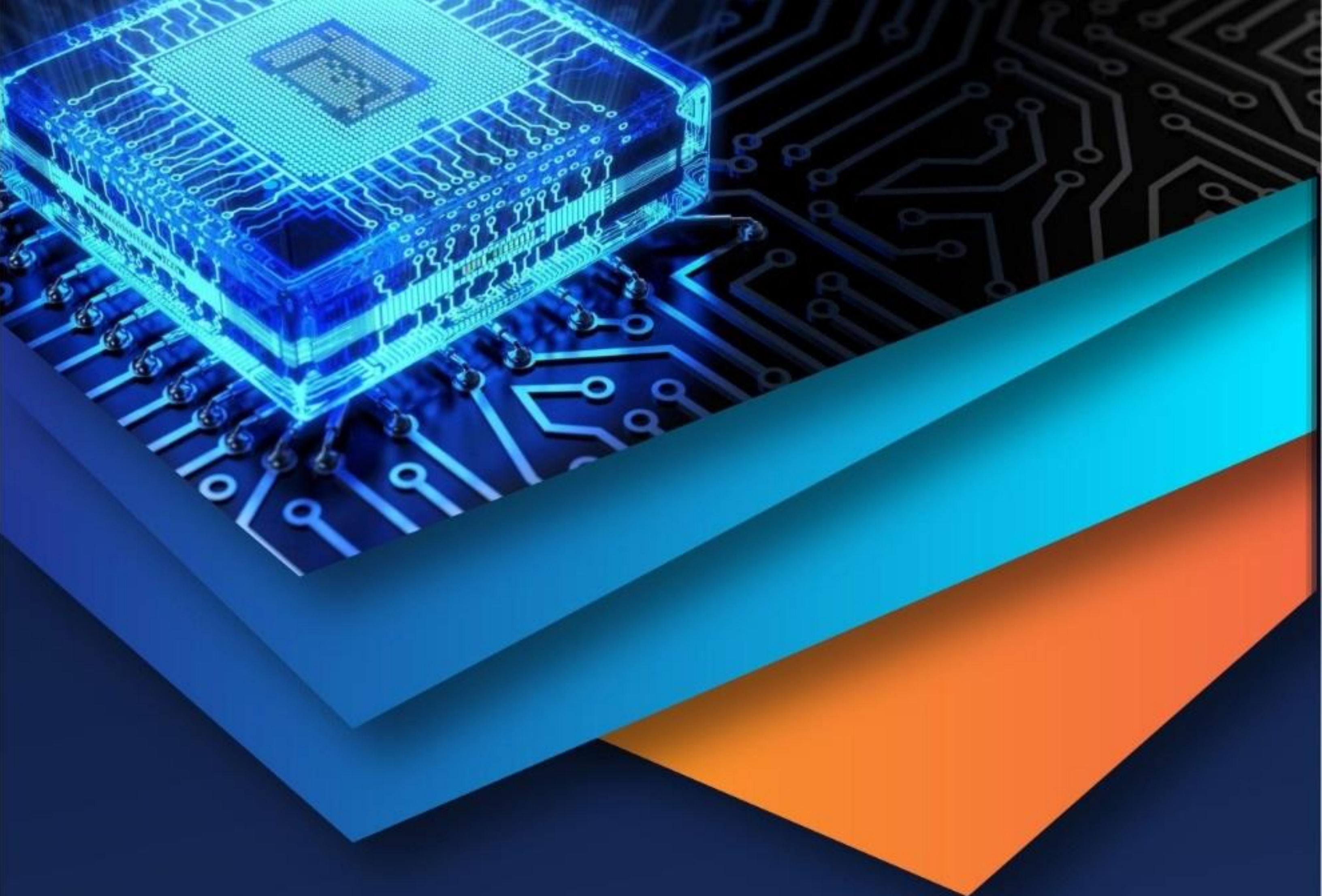

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