Identification of Best Methodologies for Solar Desalination Enhancement: A Systematic Literature-Based Review of Paraffin Wax Phase Change Materials Integrated with Wood Waste Nanomaterials

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Abstract: Solar desalination is a renewable alternative to energy-intensive desalination methods, particularly in the context of water scarcity exacerbated by climate change, industrial expansion, and population growth. However, conventional solar stills suffer from limitations like intermittent solar input and poor heat retention capacity. This paper not only summarizes the earlier findings but also attempts to find out, compare and rank the methodologies which the researchers have used for improving the performance of solar stills by incorporating the phase change material (PCM), especially the paraffin wax and its nano-enhancement using metallic and wood-waste-derived nanomaterials, respectively. A structured criteria-based literature evaluation framework is proposed, which evaluates published methodologies against productivity gain, thermal conductivity improvement, cost, environmental impact and long-term operational stability. The paper identifies experimental and nano-material-selection methodologies that have the best combination of performance and sustainability from this comparative evaluation and proposes a methodological roadmap for future experimental validation of wood-waste-based nano-PCM solar stills. The findings are intended to help researchers choose rigorous, reproducible and sustainable methods for future solar desalination research.

Keywords: Solar desalination; research methodology; phase change materials; paraffin wax; nano-enhanced PCM; wood waste nanomaterials; systematic literature review.

Introduction

Water scarcity is one of the most serious global challenges and it hits arid and semi-arid areas hardest, where traditional water sources are scarce.

The demand for potable water has increased as a result of rapid industrialisation, population growth and the intensifying effects of climate change, making sustainable desalination a research priority [1-2]. Conventional desalination technologies, such as reverse osmosis, multi-effect distillation, and multi-stage flash distillation, are widely deployed at scale, but their high energy demand and operating cost have driven sustained academic interest in renewable-energy based alternatives [3]. The low cost and simplicity to operate make solar desalination and especially the solar still attractive but the basic designs suffer from the inconsistent output due to fluctuating solar radiation and poor thermal storage [4].

Among the several possibilities discussed in the literature are basin insulation, reflectors, wick materials and most importantly thermal energy storage via phase change materials (PCMs) [5-6]. While there is a large body of literature on productivity gains, it is disjointed in terms of experimental methodologies, evaluation metrics and material choices making it difficult for a researcher to ascertain which methodological approach is most defensible and reproducible for future work.

This paper directly addresses that gap. It doesn't just give a narrative summary of previous work, but employs a structured evaluation approach to the existing literature to identify the methodologies that have produced the most consistent, low-cost and environmentally friendly results and then to translate those findings into a recommended method for future experimental research on wood-waste-derived nano-enhanced PCM solar stills.

The specific objectives of this paper are to: (i) systematically organize the existing literature on PCM-based solar desalination by methodological approach; (ii) develop and apply a multi-criteria evaluation framework for comparing these methodologies; (iii) identify the methodology(ies) that provide the best balance of performance, cost and sustainability; and (iv) propose a step-by-step research methodology for validating wood-waste-based nano-PCM solar stills experimentally.

Literature Review

The literature on solar desalination enhancement can be organised into four broad methodological generations, each representing a distinct research approach rather than merely a chronological period.

Passive Design-Based Methodologies

such as insulating basins, using reflective materials, implementing stepped or multi-basin designs, and adopting wick-based absorption surfaces, which were primarily assessed through comparative productivity trials against a standard conventional still [7-8]. These approaches are inexpensive and simple to replicate; however, existing literature consistently indicates that they are unable to maintain output after the cessation of direct solar input, as none of the methods from that time included thermal energy storage.

PCM Integration Methodologies

The second generation of studies used an experimental approach based on installing bulk PCMs, predominantly paraffin wax, below or in the still basin, including El-Sebaii, Arunkumar, and Murugavel, who used controlled day/night productivity comparisons and found output improvements of approximately 25-30% due to latent heat storage and release [9]. These studies are strong methodologically because of their consistent before/after comparison design, but they are weak because low intrinsic thermal conductivity in the paraffin wax limits the rate of heat transfer regardless of the storage capacity [10].

Nano-Enhanced PCM Methodologies

A third methodological approach doped PCMs with high-conductivity nanoparticles such as aluminium oxide (Al_2O_3), copper oxide (CuO), graphene, and carbon nanotubes, then re-ran the same productivity-comparison protocols used in the previous generation [11-12]. This methodology, employed by Sharshir, Kabeel, and others, reported efficiency gains of 45-55%, representing the strongest performance figures in the literature. However, papers adopting this methodology rarely include long-term stability testing or life-cycle/environmental assessment, and several explicitly flag nanoparticle cost, agglomeration, and ecological risk as unresolved methodological gaps [13-14].

Bio-Based Nanomaterial Methodologies

A recent methodological approach substitutes metallic nanoparticles with biodegradable nanomaterials from biomass waste, such as wood-waste-derived nanocellulose and lignin nanoparticles; these studies use a materials-characterisation methodology (surface area, density, thermal conductivity) rather than full system-level productivity testing, so while the sustainability case is strong, comprehensive experimental validation within an operating solar still is lacking [15,16], which represents the principal methodological gap this paper aims to address.

Table 1. Comparative Summary of Methodological Approaches in the Literature

S.No.	Reference (Author, Year)	Key Contributions	Limitations / Research Gap
1	Velmurugan & Srithar (2010)	Energy and exergy analysis of conventional solar stills; identified key efficiency parameters	Low efficiency; no thermal energy storage
2	Sampathkumar et al. (2010)	Reviewed active solar distillation systems; improved productivity via external energy sources	High cost and system complexity
3	El-Sebaii & El-Bialy (2012)	Reviewed advanced solar still designs and performance improvements	Limited focus on sustainable materials
4	Eltawil et al. (2009)	Integrated renewable energy technologies with solar stills	Less focus on passive systems
5	Kabeel & Abdelgaied (2017)	Nanofluid-based productivity improvement over conventional designs	Increased system cost
6	Devkate et al. (2017)	Experimental study on paraffin wax PCM in solar stills	Low thermal conductivity persists
7	El-Sebaii (2015/2018)	PCM (paraffin wax) integration; ~25% productivity improvement	Poor heat transfer due to low conductivity
8	Arunkumar et al. (2018)	Solar still with PCM basin; ~28% yield enhancement	Heat losses and inefficiency
9	Murugavel & Srithar (2019)	Thermal energy storage using PCM; ~30% improvement	Limited heat-transfer capability
10	Panchal (2020/2024)	Reviewed PCM-based and nano-PCM thermal storage systems	Limited nano-material integration in early works

S.No.	Reference (Author, Year)	Key Contributions	Limitations / Research Gap
11	Sharshir et al. (2018/2020)	Nano-PCM with Al_2O_3 nanoparticles; ~45% efficiency gain	High cost and environmental concerns
12	Kabeel et al. (2021)	CuO-based nano-PCM; ~48% performance improvement	Stability and agglomeration issues
13	Manokar et al. (2019/2021)	Paraffin PCM solar still; ~32% improvement	Slow heat charging/discharging
14	Rajaseenivasan (2018/2022)	Graphene-based PCM; ~55% efficiency enhancement	Expensive material; scalability issues
15	Murali et al. (2024)	Nano-PCM composites improving solar still productivity	Focus mainly on synthetic nanoparticles
16	Pushpak & Naveen (2025)	Proposed wood-waste-based PCM for sustainable desalination	Limited experimental validation

Methodology for Identifying the Best Research Approach

To move beyond a narrative literature summary, this paper applies a structured, multi-stage methodology for evaluating and ranking the methodological approaches identified in Section 2.

Literature Identification and Screening

A systematic search was conducted across Scopus, Web of Science, and Google Scholar using combinations of the terms "solar still", "solar desalination", "phase change material", "paraffin wax", "nano-PCM", and "wood waste nanomaterial". Records were screened for relevance, peer-review status, and availability of quantitative performance data, following a PRISMA-style inclusion/exclusion process, before being categorised into the four methodological generations described above.

Multi-Criteria Evaluation Framework

Each methodological approach was then scored against five criteria drawn consistently from the literature:

- Productivity improvement (% gain in distillate yield over a conventional baseline still).
- Thermal conductivity / heat-transfer enhancement achieved by the material or design change.
- Material and implementation cost relative to a conventional solar still.
- Environmental and health impact, including biodegradability and nanoparticle toxicity risk.
- Long-term operational stability, including resistance to agglomeration, degradation, and leakage.

Each methodology was rated on these criteria using a qualitative High/Medium/Low scale derived from the reported findings of the reviewed studies, rather than new experimental data, since the objective at this stage is comparative synthesis rather than primary measurement.

Comparative Ranking Outcome

Application of the framework demonstrated that nano-enhanced PCM methods (Section 2.3) are the most desirable in terms of productivity and heat-transfer improvement criteria and the least attractive in terms of cost and environmental impact. The passive design methods (Section 2.1) proved to be the worst alternative due to the lack of sustainable output. The PCM methods utilizing bulk materials (Section 2.2) appeared to be the most balanced in terms of meeting the five criteria, although their thermal conductivity was the major limitation. The bio-based nanomaterial methods (Section 2.4) are the most cost-effective and environmentally acceptable with a moderate but unproven thermal performance. Overall, the combination of paraffin wax PCM with wood-waste-derived nanomaterials can be recognized as the most desirable method from the perspective of five criteria on condition that its productivity and stability are proved through comprehensive testing at the system level.

Proposed Methodology for Future Experimental Validation

Building on this identification, the following stepwise experimental methodology is proposed for future research:

- Extraction and characterisation of nanocellulose/lignin nanoparticles from wood waste feedstock (particle size, surface area, thermal conductivity).
- Preparation of nano-PCM composites at varying wood-waste nanoparticle concentrations blended with paraffin wax.
- Fabrication of a basin-type solar still with a PCM containment layer, alongside a conventional-still control unit.
- Simultaneous field testing of the nano-PCM still against the control still across representative seasonal solar conditions, recording hourly basin/PCM/ambient temperatures and distillate yield.
- Statistical comparison of productivity, thermal storage duration, and daily/nightly yield distribution between test and control units.
- Life-cycle and cost assessment of the wood-waste nano-PCM composite relative to metallic nano-PCM and bulk-PCM alternatives.
- Long-term cyclic testing (melt/solidify cycles) to evaluate degradation and stability of the composite over repeated operation.

This methodology closes the principal gap identified in Section 2.4 by pairing materials characterisation with full system-level, comparative, and longitudinal testing, and provides a reproducible template for future studies in this field.

Conclusion

From passive modification, the solar desalination technology has evolved through the integration of bulk and nano-enhanced PCMs and is now entering an innovative stage driven by nanomaterials derived from natural organic matter such as wood waste. A systematic multicriteria assessment of the surveyed literature suggests that none of the considered methodologies can be regarded as optimal in terms of performance-cost-environment triad. At the same time, the configuration based on paraffin wax PCMs coupled with the nanomaterial fabricated from wood waste under the framework of the system-level experimental methodology proposed in Section 3.4 was found to be the most promising for further exploration. Its adoption in future studies would allow bridging the identified gap in the solar desalination experimental investigations and would enable the engineering of low-cost and sustainable systems capable of meeting the demands of modern society.

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