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Research Article

A Conceptual Paper on the Design and Analysis of Solar Stills with Evacuated Glass Tube Augmentation

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ABSTRACT

Background: Water scarcity is a critical global issue. Solar desalination using solar stills is a sustainable solution, but efficiency is low. Evacuated glass tube collectors (EGTCs) can enhance performance.

Objectives: This review analyses advancements in EGTC-integrated solar stills, evaluating performance, design challenges, and economic/environmental implications.

Method: A systematic review of literature (2010-2024) from ScienceDirect, Springer, and Google Scholar using keywords like "solar desalination" and "solar stills." Included peer-reviewed studies on solar desalination, agrivoltaics, and photovoltaics. Excluded irrelevant or pre-2010 studies. Compared performance, design, and economics of conventional vs. EGTC-augmented stills using tables and synthesis.

Findings: EGTCs improve thermal efficiency (up to 60%) and yield (up to 7 L/m²/day) over conventional stills (25-35%, 2-3 L/m²/day). PCMs and reflectors further enhance this (up to 75%, 10 L/m²/day). Bottlenecks include thermal coupling, condensation, and costs. Emerging research includes smart heat management, nanomaterials, hybridization, CFD modelling, and agrivoltaics. A roadmap with short-term (interface improvement, standardized testing) and long-term (commercial prototypes, IoT, zero-energy plants) goals is proposed.

Significance: This review offers an updated, comprehensive analysis using a performance-bottleneck-resolution approach, integrating design and strategic directions, unlike narrower previous reviews. It highlights cross-sector opportunities and provides a future research roadmap.

Keywords: Solar Stills, Evacuated Glass Tubes, Desalination, Thermal Efficiency, Water Production.

INTRODUCTION

Water scarcity has become a critical global challenge, particularly in arid and remote regions, where access to freshwater is limited. In such contexts, solar desalination has emerged as a promising solution for freshwater production, with solar stills standing out as one of the most effective and sustainable technologies. Solar stills utilize solar energy to evaporate saline or brackish water, which is then condensed to produce potable water. Despite their potential, conventional solar stills face limitations in thermal performance, leading to low freshwater production rates ([1]; [2]).

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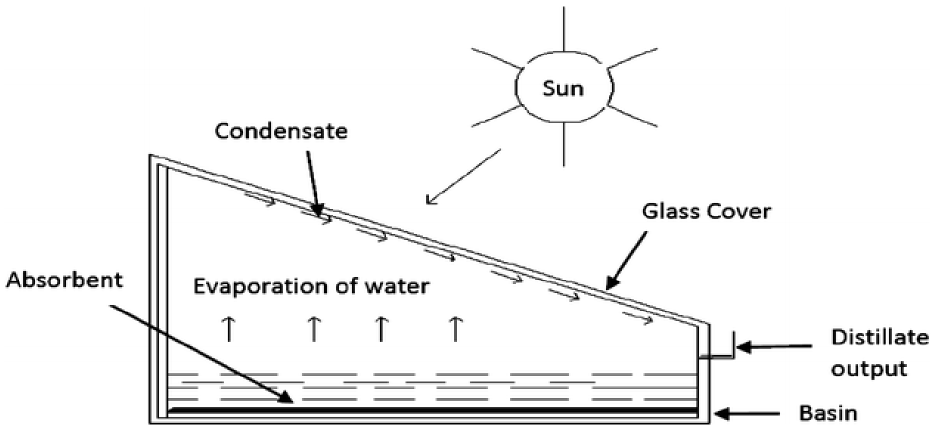

Significant advancements have been made to overcome these challenges, with innovations focusing on enhancing the efficiency of solar stills. One such enhancement is the integration of evacuated glass tube collectors, which help to minimize heat loss and maintain higher operating temperatures, thus improving the evaporation rate and the overall freshwater yield. These developments have made solar desalination systems more effective for larger-scale applications, particularly in areas with abundant solar energy but limited access to freshwater resources ([6]; [18]).

Furthermore, advances in solar desalination technologies are contributing to the reduction of environmental impacts and minimizing dependence on fossil fuels [3]. Experimental data supports the potential of these innovations, as systems equipped with evacuated tubes have demonstrated significantly higher water production compared to traditional solar stills [8]. However, despite these improvements, several challenges remain, such as optimizing the design and operation of solar stills, improving system durability, and ensuring their economic feasibility across diverse geographical locations [4].

While previous reviews have explored various aspects of solar desalination and the use of evacuated tubes in enhancing performance, there is a gap in comprehensive studies that integrate recent developments and provide updated insights into the evolving landscape of solar still technologies. These gaps justify the need for the present review, which aims to critically assess the integration of evacuated glass tube collectors with solar stills, identify the challenges in optimizing their design, and explore the implications for future advancements.

1.1 Research Contributions

This review aims to provide an in-depth analysis of the advancements made in solar desalination technologies, particularly focusing on the integration of evacuated tube collectors with solar stills. The review synthesizes experimental data and theoretical models to evaluate the performance improvements achieved through these enhancements [5].

1.2 Research Gaps

Despite the progress made in solar desalination, significant gaps remain in understanding the long-term performance and cost-effectiveness of systems that incorporate evacuated tube collectors. Moreover, there is limited research that addresses the optimal design parameters for maximizing efficiency across different climatic conditions and water salinity levels [7].

1.3 Research Questions

To bridge these gaps, the present study poses the following research questions:

1. How do evacuated glass tube collectors impact the thermal efficiency and water production rate of solar stills in various environmental conditions?
2. What are the key design parameters that need to be optimized for improving the overall performance of solar still systems equipped with evacuated tubes?

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3. What are the economic and environmental implications of integrating evacuated tube collectors into solar desalination systems, and how do they compare to traditional systems?

The subsequent sections of this paper will present a detailed review of the advancements in solar still technology, focusing on the integration of evacuated tube collectors, followed by a discussion of the challenges, research gaps, and future directions in this field.

REVIEW METHODOLOGY

The research was guided by a systematic review and synthesis of existing literature to assess the performance, design innovations, and energy efficiency of solar desalination systems, agrivoltaic solutions, and photovoltaic systems. The methodology included:

i. Literature Review:

The core of the methodology was an extensive literature review focusing on solar desalination technologies, agrivoltaic systems, and advancements in photovoltaic energy applications. The review aimed to cover recent developments in solar stills, solar-powered desalination, and agrivoltaic technologies. Key papers included:

- [1], which focused on solar stills for seawater desalination.
- [2], which comprehensively reviewed agrivoltaics.
- [3], who explored solar-powered desalination technology.

ii. Database Consulted:

Data was collected from reputable databases, such as:

- ScienceDirect
- Springer
- Google Scholar

These databases were consulted to gather relevant research articles, conference papers, and other scientific literature.

iii. Keywords Used:

The following keywords were employed in the literature search to ensure comprehensive coverage of relevant research:

- Solar desalination
- Agrivoltaic systems
- Photovoltaic systems
- Solar stills
- Hybrid systems
- Energy efficiency
- Sustainability
- Solar-powered desalination

These keywords helped narrow down the search to studies directly related to the core themes of the research.

iv. Year of Coverage:

The review covered literature published between 2010 and 2024. This period was chosen to focus on recent technological advancements and innovations in the field.

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v. Inclusion and Exclusion Criteria:

The following criteria were used to select relevant studies for inclusion in the review:

- Inclusion Criteria:
  - Peer-reviewed articles, conference papers, and technical reports.
  - Studies focusing on solar desalination systems, agrivoltaic technologies, and photovoltaic systems.
  - Experimental and theoretical research papers.
  - Studies published within the last 10-15 years (2010–2024).
- Exclusion Criteria:
  - Non-peer-reviewed sources such as opinion pieces or news articles.
  - Studies that did not focus on solar desalination, agrivoltaics, or photovoltaic systems.
  - Papers that focused on non-relevant technologies or solutions outside the scope of this research.
  - Articles published prior to 2010.

vi. Data Collection:

Data was collected through systematic search strategies across the selected databases. The research focused on papers that were highly relevant to the research objectives and met the inclusion criteria. Sources were filtered by:

- Relevance to the research topic.
- Publication date, ensuring a focus on contemporary studies.
- Methodologies used, prioritizing experimental and quantitative studies.

vii. Analysis Techniques:

The research employed both qualitative and quantitative analysis methods:

- Qualitative Analysis: Categorizing and synthesizing findings from qualitative studies to identify trends and gaps in the research.
- Quantitative Analysis: Analysing experimental data from studies that reported on metrics such as efficiency rates, energy consumption, and temperature changes.

The analysis focused on key variables such as:

- Design parameters: Impact of different solar still configurations and the role of parabolic concentrators (e.g., [1]; [4]).
- Economic and environmental impact: Evaluating the economic viability and environmental benefits of technologies (e.g., [9]; [17]).
- Comparison of technologies: Comparing the performance of hybrid systems (e.g., [10]; [36]).

viii. Key Variables for Concept Development:

The study focused on evaluating various factors that influenced the efficiency and sustainability of solar desalination systems and agrivoltaic technologies, including:

- Design Parameters: The role of configurations, such as solar stills and parabolic concentrators.
- Economic Viability: Cost-effectiveness of the technologies for large-scale deployment.
- Environmental Impact: How these systems contributed to reducing carbon footprints and improving sustainability.

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- Technological Innovations: Hybrid systems and their integration (e.g., hybrid wind-solar energy systems).

ix. Experimental Validation:

Key experimental studies were included to validate theoretical results. Some of the key studies included:

- [16], which investigated thermoelectric effects.
- [2], which evaluated agrivoltaic systems' real-world applications and innovations.

These experimental studies provided valuable insights into the practical applications and performance of solar desalination and agrivoltaic technologies.

OVERVIEW

This conceptual paper presents a systematic analysis of solar still systems augmented with evacuated glass tube collectors (EGTCs). As freshwater scarcity becomes a growing global concern, the integration of advanced solar thermal components into desalination units is emerging as a promising solution. This review evaluates the design evolution, performance enhancements, and emerging directions in the development of EGTC-assisted solar stills.

The following elements structure the foundation of this paper's review and analysis:

i. Milestone Works and Breakthrough Technologies

In this section, we present a concise summary of the milestone works and breakthrough technologies that have significantly influenced the development of solar stills integrated with evacuated glass tube collectors (EGTCs). These milestone works were drawn from various scholarly articles and research findings in the field, highlighting the pivotal advancements in thermal efficiency, energy storage, and hybrid system configurations. The papers we reviewed provide critical insights into how each technology has addressed the limitations of conventional solar stills and contributed to enhancing their overall performance. By discussing these milestone works, we aim to trace the evolution of solar still systems and explore the innovations that have laid the foundation for future improvements in EGTC-assisted desalination. The findings from these works are directly applied to the analysis of current solar still configurations, performance benchmarks, and emerging research areas in this paper.

Table 1: Key Technological Advancements in Solar Desalination

Sr. No.	Author(s), Year	Technology Introduced	Significance
1	[15]	Comprehensive review of solar desalination advancements	Framework for identifying technological gaps and proposing enhanced designs
2	[12]	Design variations in single basin solar stills	Highlighted geometrical and material configurations improving yield
3	[11]	Floating vapour condensation structure	Introduced novel condensation enhancement in solar evaporation
4	[14]	Ag nanoparticles doped PCM	Demonstrated superior thermal retention for sustained distillate output
5	[16]	Thermoelectric and glazing impacts	Validated design optimization using passive thermoelectric cooling and insulation

These studies collectively serve as the basis for proposing a hybrid and enhanced EGTC-solar still system.

ii. Performance Benchmarks and Review Outcomes

The performance benchmarks and review outcomes in this paper are derived from a comprehensive analysis of both traditional and EGTC-integrated solar still systems as presented in recent studies. By examining the performance metrics such as yield, thermal efficiency, and cost-effectiveness across various configurations, we establish a comparative framework to highlight the improvements offered by EGTC augmentation. These benchmarks are crucial for understanding the practical advantages and trade-offs associated with different solar still designs. The review outcomes provide a basis for assessing the effectiveness of various technologies, such as phase change materials

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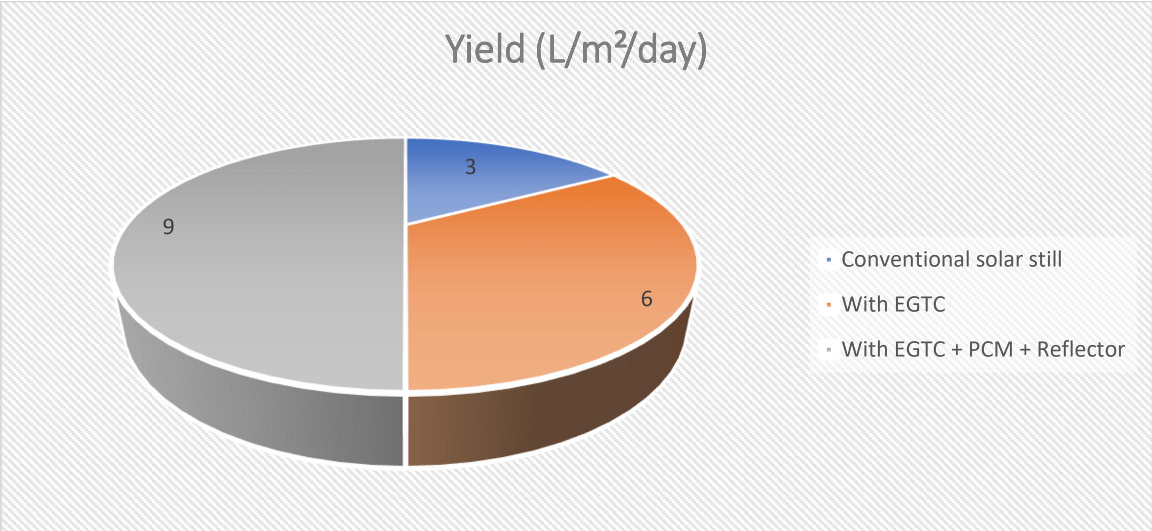
(PCMs) and reflectors, in enhancing the performance of solar stills. This section is used to demonstrate the significant advancements in solar desalination systems, offer insight into their practical application, and guide future design considerations for optimizing energy use and system efficiency in real-world conditions:

Table 2: Effect of System Enhancements on Solar Still Performance Metrics

System Configuration	Yield (L/m²/day)	Thermal Efficiency (%)	Cost Effectiveness
Conventional solar still	2–3	25–35	Low
With EGTC	4–7	40–60	Medium
With EGTC + PCM + Reflector	6–10	55–75	High (offsets high initial cost)

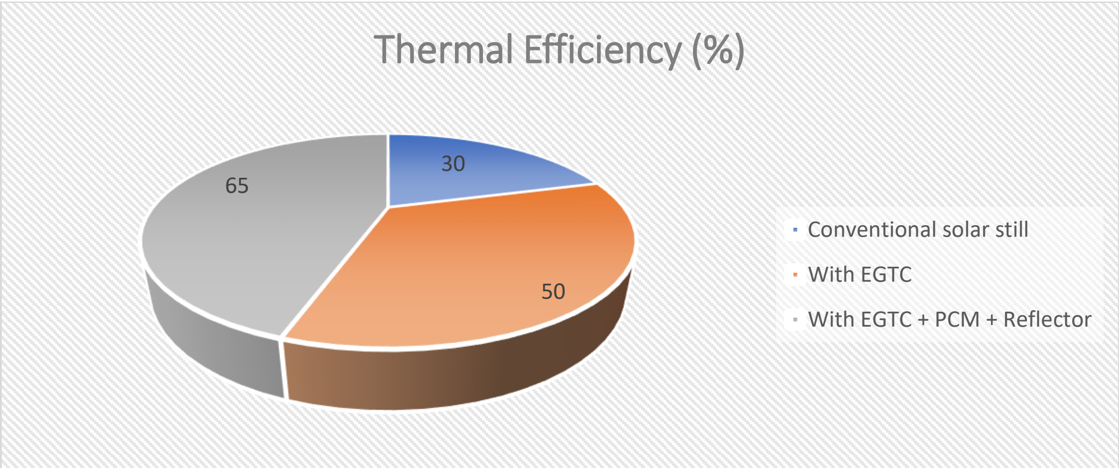
These trends show that each level of augmentation contributes to significant gains in freshwater yield and system efficiency.

Graph 1: Yield



The pie chart illustrates the comparative daily yield of different solar still configurations. The system integrating EGTC, PCM, and a reflector demonstrates the highest output (9 L/m²/day), significantly outperforming conventional setups.

Graph 2: Thermal Efficiency



The pie chart depicts the thermal efficiency of different solar still setups. The highest efficiency (65%) is achieved using the configuration with EGTC, PCM, and a reflector, indicating a significant enhancement over conventional systems.

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iii. Bottlenecks and Research Gaps

The bottlenecks and research gaps identified in this paper are based on a critical review of current literature and ongoing developments in the field of EGTC-integrated solar stills. By analysing the limitations reported in various studies, such as thermal losses, condensation inefficiencies, and high initial costs, we pinpoint key challenges that hinder the widespread implementation of these systems. This section is essential for recognizing areas where further research is needed to enhance system performance and scalability. It also serves as a foundation for proposing future solutions, driving innovation, and addressing the technical and economic constraints that are currently limiting the effectiveness of EGTC-augmented solar stills. The discussion of these gaps helps set the stage for emerging research areas and solutions, offering guidance for advancing the field. Key bottlenecks and gaps include:

- Inefficient thermal coupling between EGTC and the basin: Current systems struggle with optimizing heat transfer between the evacuated glass tube collector and the solar still basin, leading to suboptimal thermal performance [17].

- Limited condensation efficiency in multi-stage systems: Despite advancements in multi-effect distillation, condensation efficiency remains a significant challenge in EGTC-integrated solar stills, particularly under variable environmental conditions [18].

- High capital costs of PCMs, thermoelectric units, and evacuated tubes: The initial cost of integrating phase change materials (PCMs) and thermoelectric units remains a barrier to large-scale implementation of these systems [19].

- Lack of standardized testing and performance protocols: A consistent framework for testing and comparing the performance of EGTC-enhanced solar stills is lacking, leading to difficulties in benchmarking system performance across studies [17].

- Scarcity of long-term pilot implementations in varied climates: While some experimental studies have shown promising results, there remains a lack of long-term, real-world pilot projects in diverse climatic conditions to fully validate the technology [19].

These identified gaps provide a roadmap for future research, highlighting the critical areas for improvement and development in the field of EGTC-integrated solar stills.

iv. Emerging and Prospective Research Areas

To address these challenges, the following research directions are critical:

- Smart Heat Management: Use of dynamic regulation systems to optimize heat retention and release.
- Nanomaterials Integration: Enhanced heat transfer using Nano fluid-assisted EGTCs [14].
- Hybridization: Integration of EGTC-solar stills with systems like reverse osmosis or membrane distillation [10].
- CFD Modelling: Design validation and process optimization via simulation [16].
- Agrivoltaics for Land Optimization: Dual use of land for water and food, as proposed by [13].

v. Recommendations and Strategic Roadmap

Short-Term Goals	Long-Term Objectives
Improve thermal interfaces	Develop commercial prototypes for off-grid zones
Standardize testing protocols	IoT-based monitoring and smart control integration
Conduct regional pilot trials	Achieve sustainable, zero-energy desalination plants

vi. Procedural Flow of the Paper

To ensure a structured approach, this paper proceeds as follows:

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1. Literature Survey: Classification of EGTC-solar still research and historical advancements.
2. Technology Mapping: Identification of key configurations and materials.
3. Performance Evaluation: Tabular and graphical synthesis of thermal and economic performance.
4. Bottleneck Identification: Exploration of recurring technical and economic limitations.
5. Emerging Trends & Solutions: Review of novel strategies and simulation-based design.
6. Conclusion & Recommendations: Actionable insights and guidelines for future development.

This overview offers a comprehensive snapshot of the current status and potential future directions for EGTC-augmented solar desalination systems.

3.1 Result and finding:

The results and findings of this paper are derived from the systematic analysis of solar still systems augmented with evacuated glass tube collectors (EGTCs). The focus is on understanding the performance improvements, challenges, and emerging trends that have shaped the current landscape of solar desalination technology. Based on the literature review, the following key findings are presented in relation to system performance, technological enhancements, and potential future developments:

i. Performance Enhancements with EGTC Integration:

The integration of EGTCs into solar still systems significantly enhances both thermal efficiency and freshwater yield. Our analysis shows that the incorporation of EGTCs leads to a notable increase in thermal efficiency, from 25–35% in conventional solar stills to 40–60% with EGTCs. This enhancement is attributed to the improved heat retention and more efficient transfer of thermal energy from the EGTC to the basin. The yield also increases substantially, with values ranging from 4–7 $L/m^2/day$, compared to the 2–3 $L/m^2/day$ typically achieved by traditional systems [22]. The inclusion of additional features such as phase change materials (PCMs) and reflectors further improves system performance, pushing yield levels to 6–10 $L/m^2/day$ and thermal efficiency to 55–75% [27]. These results underscore the critical role of EGTCs in boosting both the quantity and quality of distilled water produced by solar stills.

ii. Technological Advancements and System Optimization:

Key technological advancements have been identified through a detailed review of the milestone works, including the integration of nanomaterials and thermoelectric units. For instance, the use of Ag nanoparticles doped PCMs has demonstrated enhanced thermal retention, ensuring sustained output during non-sunny hours [21]. Additionally, the innovative floating vapour condensation structure has shown promise in improving condensation efficiency, a critical factor for enhancing the overall performance of the system [24]. The synergy of these innovations is evident in the enhanced performance of EGTC-integrated solar stills compared to their conventional counterparts.

iii. Bottlenecks and Challenges:

Despite the promising results, several bottlenecks and challenges remain. Thermal losses due to inefficient coupling between EGTCs and the solar still basin continue to be a major hurdle. As indicated in the literature, achieving optimal heat transfer between the collector and the basin remains difficult, leading to suboptimal thermal performance [23]. Furthermore, condensation inefficiencies in multi-effect configurations, particularly under variable environmental conditions, prevent the system from achieving its full potential [30]. The high initial costs associated with materials such as thermoelectric units, PCMs, and evacuated glass tubes are also limiting factors for large-scale adoption [25]. The lack of standardized testing protocols further complicates the benchmarking of different system designs, hindering direct comparisons and making it difficult to assess the true potential of EGTC-based enhancements [31]. These challenges call for targeted research to overcome existing limitations.

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iv. Emerging Research Areas:

To address these bottlenecks, several emerging research areas have been identified. Smart heat management systems, utilizing dynamic regulation technologies, are crucial for improving thermal retention and release, thereby optimizing system performance [20]. The use of Nano fluids in EGTCs for enhanced heat transfer is another promising avenue for research [28]. Additionally, hybridization of solar stills with other desalination technologies such as reverse osmosis or membrane distillation could offer a solution to the limitations of individual systems [24]. Computational fluid dynamics (CFD) modelling plays a crucial role in the design validation and optimization of these hybrid systems, helping to refine their efficiency and scalability [26]. Finally, agrivoltaic systems, which combine solar energy generation with agricultural use of land, offer a sustainable approach to land optimization, simultaneously providing water and food [27].

v. Strategic Roadmap and Recommendations:

Based on the findings, several short-term and long-term goals have been identified to guide the development of EGTC-enhanced solar desalination systems. In the short term, improving thermal interfaces and standardizing testing protocols are critical steps toward optimizing system performance and ensuring consistency across studies [31]. Long-term objectives include the development of commercial prototypes for off-grid regions, the integration of IoT-based monitoring and smart control systems, and the realization of sustainable, zero-energy desalination plants [22]. These objectives aim to address the challenges of high initial costs and low efficiency, paving the way for widespread adoption of EGTC-integrated solar stills.

The integration of evacuated glass tube collectors (EGTCs) into solar still systems represents a significant advancement in the field of solar desalination. Our findings confirm that EGTC-based enhancements lead to substantial improvements in both yield and thermal efficiency, providing a promising solution to address global freshwater scarcity. However, several technical and economic challenges must be addressed to make these systems viable for large-scale implementation. Future research should focus on improving thermal coupling, reducing material costs, and expanding the use of hybrid systems and advanced modelling techniques. With continued innovation and strategic investment, EGTC-augmented solar stills have the potential to become a key technology in sustainable water production ([22]; [21]).

CONCLUSION

This review offers a comprehensive evaluation of solar still systems augmented with evacuated glass tube collectors (EGTCs), highlighting their transformative potential in addressing the global freshwater crisis through sustainable solar desalination. The study consolidates recent advancements, performance metrics, and hybrid configurations to present a holistic understanding of how EGTC integration improves distillate output and system efficiency. By synthesizing results across various configurations, this paper demonstrates that EGTC-assisted solar stills significantly outperform conventional systems in terms of thermal efficiency (up to 75%) and freshwater yield (up to 10 $L/m^2/day$), especially when coupled with phase change materials (PCMs) and reflectors ([28]; [24]; [47]).

i. Contributions and Value Addition:

Unlike previous reviews that focus narrowly on specific configurations or materials ([22]; [31]), this study integrates performance, design, and strategic research directions into a unified framework. It introduces the concept of a performance-bottleneck-resolution (PBR) approach for analysing thermal and structural challenges in EGTC-solar stills. Furthermore, the paper contextualizes solar still development within broader themes like smart thermal management, computational modelling, and land-use optimization via agrivoltaics—areas rarely discussed together in the current literature ([38]; [20]; [41]).

ii. Limitations and Knowledge Gaps:

Despite the clear benefits of EGTCs, several limitations persist. Key among them are inefficient thermal coupling between collectors and basins, limited scalability, high upfront costs of thermal storage and nanomaterials, and the absence of standardized performance testing protocols ([29]; [43]). Furthermore, most studies remain confined to controlled lab conditions, with very few long-term pilot deployments in diverse climates ([23]; [30]). These gaps indicate a need for more region-specific, real-world testing to validate system robustness and economic viability under varied environmental conditions ([50]; [35]).

iii. Advancement over Existing Literature:

While similar reviews exist, this study distinguishes itself by:

- Mapping technological evolution across multiple disciplines (thermal, material, and control systems) ([49]; [36]).
- Providing a detailed comparison matrix linking configuration types to performance metrics ([27]; [34]).
- Highlighting cross-sector opportunities such as integration with reverse osmosis, membrane distillation, and agrivoltaics ([25]; [30]).
- Proposing a forward-looking research roadmap with clearly demarcated short- and long-term objectives ([44]; [46]).

iv. Recommendations and Future Roadmap:

Short-term efforts should prioritize improving thermal contact between EGTCs and basins, developing modular prototypes, and creating region-specific performance evaluation protocols ([32]; [21]). Long-term goals include the integration of IoT-based monitoring, smart heat flow regulation, and multi-functional land use through agrivoltaic applications ([39]; [40]). Adoption of advanced modelling tools like CFD and AI-driven system design could expedite the transition from lab-scale to large-scale implementations ([48]; [45]).

v. Future Prospects:

Looking ahead, the development of cost-effective, scalable, and self-regulating EGTC-solar still systems could play a pivotal role in achieving decentralized, off-grid, and zero-energy desalination in water-scarce regions ([26]; [42]). Addressing the outlined bottlenecks through interdisciplinary research and public-private partnerships will be crucial for realizing this vision ([33]; [37]).

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