

Recent Advances in Polymer-Based Thermal Management Technologies for Hybrid PV/T Solar Desalination Systems: A Critical Review

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Abstract

Hybrid photovoltaic-thermal (PV/T) desalination systems are being developed as a new approach that not only generates clean water but also harnesses solar energy. While tremendous progress has been made in terms of design, the thermal management of PV/T desalination systems still poses several problems, such as heat generation, temperature non-uniformity, and inadequate thermal energy storage, all of which adversely affect the efficiency of electricity generation and clean water production. In the past few years, polymers have received increased attention in the thermal management of PV/T systems owing to their low weight, resistance to corrosion, easy processing, and tunability of thermal properties. In this review, recent advances in polymer-based thermal management technologies used in hybrid PV/T solar desalination systems are discussed critically. The review discusses the use of polymers for the encapsulation of PCMs, polymer-based composite heat exchangers, thermally conductive polymer nanocomposites, thermal interface materials (TIMs) based on polymers, membrane-based thermal management approaches, and polymer coating technology for enhanced heat transfer and system performance. The effect of these materials on thermal management, energy storage, heat dissipation, system stability, and overall performance is thoroughly analyzed. Recent advances in computational modeling, thermal optimization using artificial intelligence, and sustainable polymer material design are also highlighted. Moreover, the review highlights some of the present-day limitations concerning thermal conductivity improvement, environmental sustainability, material compatibility, recycling, mass production, and techno-economical viability. Future avenues of research are suggested, such as multifunctional polymer nanocomposites, bio-based and recyclable polymers, smart materials responding to thermal changes, and digital optimization methods for novel generation PV/T solar desalination systems. Summarizing the recent achievements in the field of thermal management based on polymer materials, the review offers an extensive overview of information that can be valuable for scientists and engineers who seek to create efficient and sustainable solar desalination systems.

Keywords: Hybrid PV/T, solar desalination, polymer composites, thermal management, polymer nanocomposites, phase change materials, thermal energy storage, renewable energy

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INTRODUCTION

Scarcity of fresh water has become one of the biggest problems worldwide owing to the rapid increase in the world's population, industrialization, urbanization, and climate change. Even though traditional desalination processes can result in highly pure fresh water, they pose sustainability issues due to high fossil fuel use and consumption of huge amounts of energy. Thus, solar desalination has been widely considered an environmentally-friendly way of producing fresh water due to its ability to make use of renewable sources of energy [1].

There are several ways of performing solar desalination. One of them is the use of hybrid photovoltaic and thermal technology (PV/T). This technique allows not only generating electricity but also recovering heat, which can be used in increasing evaporation rate and, hence, boosting the performance of desalination and making the use of solar energy more effective. Nevertheless, the efficiency of hybrid PV/T systems is rather low due to overheating and poor thermal management [2].

As a solution to overcome such problems, there have been many attempts to investigate polymer-based thermal management technologies. Due to their light weight, corrosion resistance, easy fabrication process, and customizable thermal characteristics, polymers have been successfully used for thermal insulation, heat transfer promotion, PCM encapsulation, polymer coating, membrane, and thermal storage composite. In addition, polymer composites and polymer nanocomposites have provided a lot of potential benefits for enhancing the thermal conductivity, energy storage capacity, and durability of the solar thermal systems.

Numerical modeling and artificial intelligence (AI) have been proven as efficient tools for prediction of thermal behavior and optimization of the systems as well as material selection.

Despite several reviews published on solar desalination technologies, PV/T systems, and thermal energy storage techniques individually, there is no comprehensive review that focuses specifically on polymer-based thermal management techniques for hybrid PV/T solar desalination technologies. In addition, the use of polymer-based materials for thermal management, enhancing heat transfer, thermal energy storage, and sustainable solar desalination has not been explored in any critical review yet [3].

Hence, the purpose of this review is to provide a detailed analysis of the latest research works in the field of polymer-based thermal management techniques for hybrid PV/T solar desalination systems [4]. Different types of polymer-based materials used for thermal management, development in modeling techniques, and the application of AI for optimization are covered in this review. Finally, current research challenges and future research directions are outlined for next-generation solar desalination technologies.

REVIEW METHODOLOGY

A structured literature review has been carried out to identify recent advancements in thermal management techniques based on polymers for hybrid photovoltaic/thermal (PV/T) solar desalination systems. Literature has been acquired from Web of Science, Scopus, ScienceDirect, SpringerLink, IEEE Xplore, and Google Scholar [5]. The review is mainly confined to peer-reviewed journals published between 2020 and 2026 whereas some landmark papers published prior to 2020 have been used only for the sake of background information.

In the literature review, various combinations of keywords – like hybrid PV/T solar desalination, polymer-based thermal management, polymer composites, polymer nanocomposites, thermal energy storage, phase change materials, heat transfer augmentation, and renewable desalination – have been utilized. Duplicate documents, conference proceedings, and unrelated papers have been filtered out.

The selected literature sources have been critically analyzed and categorized into thematic areas such as polymer materials, polymer composites, advanced thermal management approaches, polymer nanocomposites, numerical modeling, artificial intelligence-aided optimization, current problems, and future research directions [6].

The works that were published from 2023 to 2026 were of specific importance because of the fast development of polymer-based nanocomposites, advanced phase change materials, thermally conductive fillers, and AI-based thermal management strategies. The recent studies give information about the improvement of heat transfer, thermal energy storage, membrane characteristics, and system optimization in hybrid PV/T desalination systems.

FUNDAMENTALS OF HYBRID PV/T SOLAR DESALINATION

The PV/T solar desalination technology involves integration of photovoltaic power generation with thermal energy harvesting to optimize the use of the incoming solar energy. In contrast to regular photovoltaic panels that convert a part of the incoming sunlight into electricity while wasting the rest of it in the form of heat, PV/T systems can capture the released heat with the help of a thermal collector.

Usually, a typical PV/T solar desalination system includes such components as photovoltaic panel, thermal collector, heat exchange fluid, thermal energy storage device and a desalination device (solar still, membrane distillation, reverse osmosis, multi-effect distillation).

While solar radiation is being transformed into electrical energy on the photovoltaic cells, the extra heat is being collected in the circulating heat exchange fluid. The captured thermal energy is further fed to the desalination device to raise its temperature and increase the efficiency of evaporation process [7].

There are various benefits of integrating PV/T technology with the desalination process compared to PV or thermal systems that work separately. Electricity production alongside heat generation increases the efficiency of solar energy, minimizes thermal losses, increases the performance of photovoltaic technology by means of cooling and increases the production of fresh water. All these factors make it appropriate for use in remote areas lacking electricity and water sources.

Despite all these benefits, however, the effectiveness of hybrid PV/T solar desalination systems largely depends on efficient thermal management. The higher the operating temperatures are, the lower the efficiency of the photovoltaic cells becomes.

Moreover, poor thermal transfer and low capacity of thermal storage result in insufficient thermal energy available for desalination processes [8]. Thus, the current research concentrates mostly on improved thermal management approaches, especially polymer-based materials and polymer composites, which increase the efficiency of heat transfer, thermal energy storage and system durability in general. The above information gives rise to the discussion of further sections of this review.

Figure 1 shows the scheme of a common hybrid photovoltaic/thermal (PV/T) solar desalination system including the PV/T collector, the thermal storage unit, the heat transfer system and the solar still used to produce electricity and fresh water due to thermal energy utilization. Table 1 presents the comparative review of different hybrid PV/T solar desalination technologies and the use of polymer-based thermal management for increasing their thermal efficiency and freshwater output [9].

ROLE OF POLYMER-BASED THERMAL MANAGEMENT IN HYBRID PV/T SOLAR DESALINATION SYSTEMS

Thermal management plays an important role in boosting the efficiency of hybrid photovoltaic/thermal (PV/T) solar desalination systems. High photovoltaic operation temperatures lower electrical efficiency, while low heat utilization efficiency reduces freshwater generation. Therefore, thermal management using polymer materials is highly valued in view of its heat dissipation capability and high efficiency [10].

Recent developments in polymer composites and polymer nanocomposites have allowed great advances in thermal management due to the introduction of thermally conductive additives such as graphene, carbon nanotubes, and boron nitride. Moreover, polymer PCMs provide the possibility of heat accumulation, which makes it possible to conduct continuous desalination regardless of changing solar radiation.

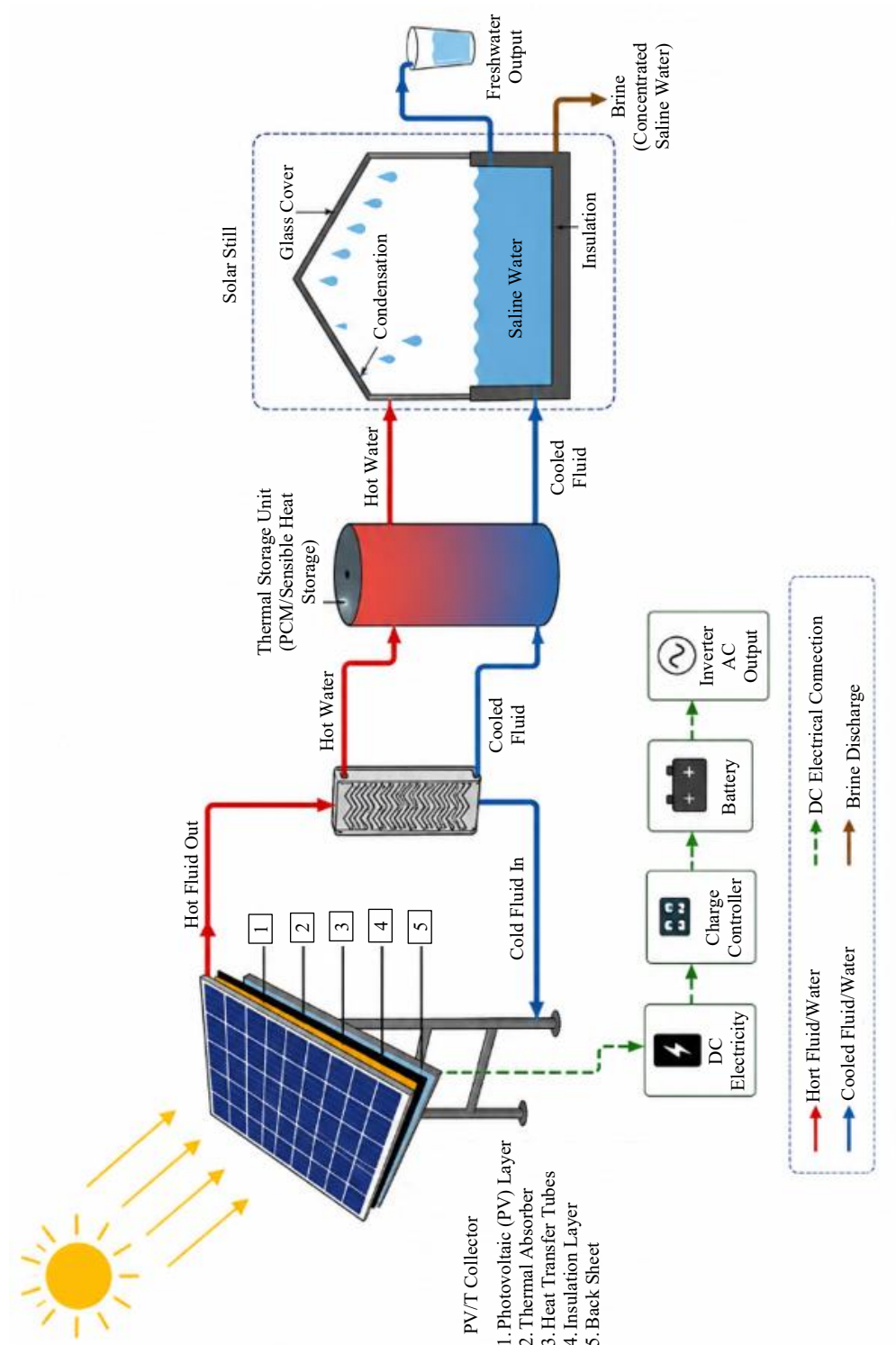


Figure 1. Schematic diagram of a hybrid PV/T solar desalination system.

However, several disadvantages – such as poor intrinsic thermal conductivity, environmental degradation, and high material cost – have constrained the widespread adoption of these materials for practical application in hybrid PV/T solar desalination systems [11]. Therefore, future studies should aim at developing novel multifunctional polymers with increased thermal conductivity, durability, and sustainability to achieve maximum efficiency in next generation hybrid PV/T solar desalination systems.

Table 1. Comparison of common hybrid PV/T desalination technologies (solar still, membrane distillation, reverse osmosis, multi-effect distillation) with their operating principles, advantages, and limitations.

Desalination technology	Operating principle	Advantages	Limitations	Potential role of polymer-based thermal management
Solar Still (SS)	Solar radiation heats saline water, producing water vapor that condenses on a transparent cover to yield fresh water.	Simple design, low installation cost, easy maintenance, suitable for remote areas.	Low freshwater productivity, limited thermal efficiency, high dependence on solar intensity.	Polymer composites, polymer coatings, and polymer-encapsulated PCMs improve heat retention, reduce thermal losses, and enhance evaporation rates.
Membrane Distillation (MD)	A hydrophobic membrane separates hot saline water from the permeate side, allowing only water vapor to pass through the membrane pores.	High salt rejection, operates at relatively low temperatures, suitable for high-salinity feed water.	Membrane fouling, temperature polarization, relatively high membrane cost.	Polymer membranes with improved thermal stability and nanocomposite coatings enhance vapor transport, reduce fouling, and improve thermal efficiency.
Reverse Osmosis (RO)	Hydraulic pressure exceeding the osmotic pressure forces water through a semi-permeable membrane, retaining dissolved salts.	High freshwater recovery, commercial maturity, excellent water quality.	High electricity consumption, membrane scaling, periodic membrane replacement.	Advanced polymer membranes with improved permeability, fouling resistance, and mechanical durability increase process efficiency and membrane lifespan.
Multi-Effect Distillation (MED)	Saline water is evaporated and condensed sequentially through multiple effects, enabling efficient reuse of latent heat.	High thermal efficiency, stable operation, suitable for large-scale desalination.	High capital investment, complex operation, large system footprint.	Polymer-based insulation materials and polymer composite heat exchangers reduce thermal losses and improve heat recovery efficiency.

Figure 2 shows how the thermal management components made up of different polymer materials are used in hybrid PV/T solar desalination systems. Table 2 below highlights the most important polymer-based materials that are utilized in thermal management of hybrid PV/T solar desalination systems. Table 3 is a comparative analysis of the most important polymer-based thermal management technologies in relation to their heat transfer efficiency, cost, durability, and the research stage of development. Figure 3 shows the incorporation of the important polymer materials in hybrid PV/T solar desalination systems along with their functions in heat transfer, membrane separation, insulation, and encapsulation. Table 4 compares the important polymer materials in terms of their properties, uses, advantages and disadvantages in hybrid PV/T solar desalination systems [12].

POLYMER MATERIALS USED IN HYBRID PV/T SOLAR DESALINATION SYSTEMS

Polymer materials have proven to be indispensable for improving the thermal efficiency of hybrid PV/T solar desalination systems thanks to their light weight, anticorrosion properties, stability, and ease of manufacturing. Polymer materials find application in thermal insulation, encapsulation, membrane separations, and thermal energy storage, thereby being an essential component of modern and future desalination technologies [13].

The most common polymers utilized include polyethylene (PE), polypropylene (PP), polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE), and epoxy resins due to their favorable mechanical and thermal properties. Among them, the best salt rejection, vapor permeation properties, and high resistance to chemical degradation are possessed by PVDF and PTFE membranes, while epoxy-based composites are characterized by their good structural and thermal properties within PV/T collectors.

However, a major drawback of these traditional polymers is their poor thermal conductivity. Thus, the attention of researchers has recently been paid to the development of polymer composites and functionalized polymers with increased thermal conductivity, durability, and stability [14].

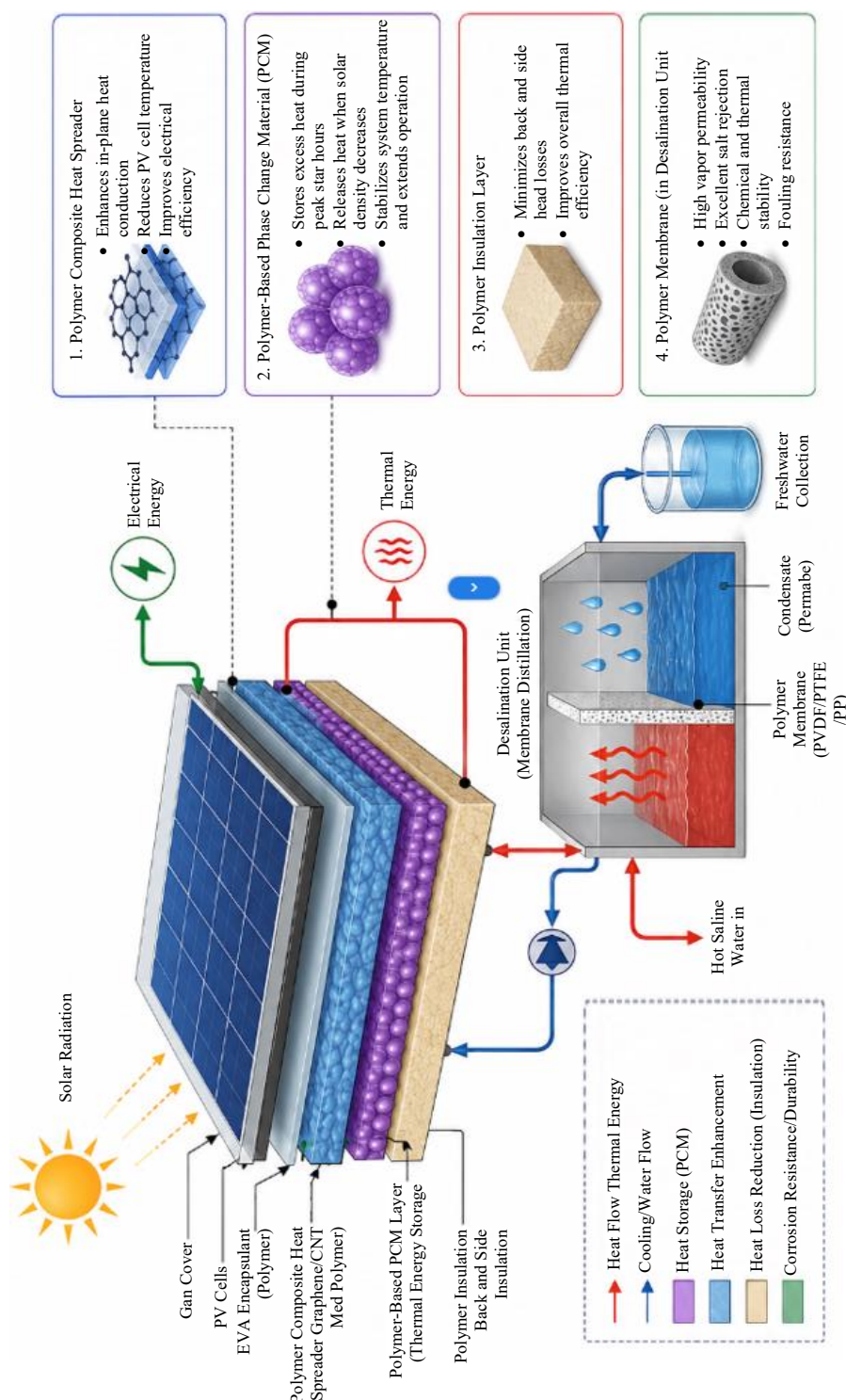


Figure 2. Schematic representation of polymer-based thermal management strategies in a hybrid PV/T solar desalination system.

Polymers differ from other thermal management materials – such as metals and ceramics – in having low thermal conductivity yet high corrosion resistance, light weight, and easy processability. Polymer nanocomposites reinforced with graphene, carbon nanotubes (CNTs), and boron nitride show great enhancement in heat transfer efficiency without compromising their chemical stability even in saline

media. While prolonged UV radiation exposure may lead to thermal aging and degradation of traditional polymers, modern advances in UV resistant polymers and coatings have brought about remarkable enhancement in terms of durability [15].

Table 2. Recent polymer-based thermal management materials employed in hybrid PV/T solar desalination systems.

Polymer material	Application	Major advantage	Current limitation
Polyethylene (PE)	Thermal insulation	Low cost, corrosion resistant	Low thermal conductivity.
Polypropylene (PP)	Collector components	Lightweight, chemically stable	UV degradation.
Epoxy composites	Heat spreaders	Good mechanical strength	Brittle behavior.
Graphene/polymer composites	Heat transfer enhancement	High thermal conductivity	High fabrication cost.
Carbon nanotube/polymer composites	Thermal management	Excellent heat dissipation	Nanoparticle dispersion issues.
Polymer-based PCMs	Thermal energy storage	Maintains stable operating temperature	Leakage and long-term stability.
PVDF membranes	Membrane distillation	High salt rejection	Membrane fouling.

Table 3. Comparison of polymer-based thermal management approaches.

Thermal management strategy	Heat transfer	Cost	Durability	Research status
Polymer insulation	Medium	Low	High	Commercial.
Polymer composites	High	Medium	High	Emerging.
Polymer nanocomposites	Very High	High	Medium	Advanced Research.
Polymer PCMs	High	Medium	Medium	Rapidly Developing.

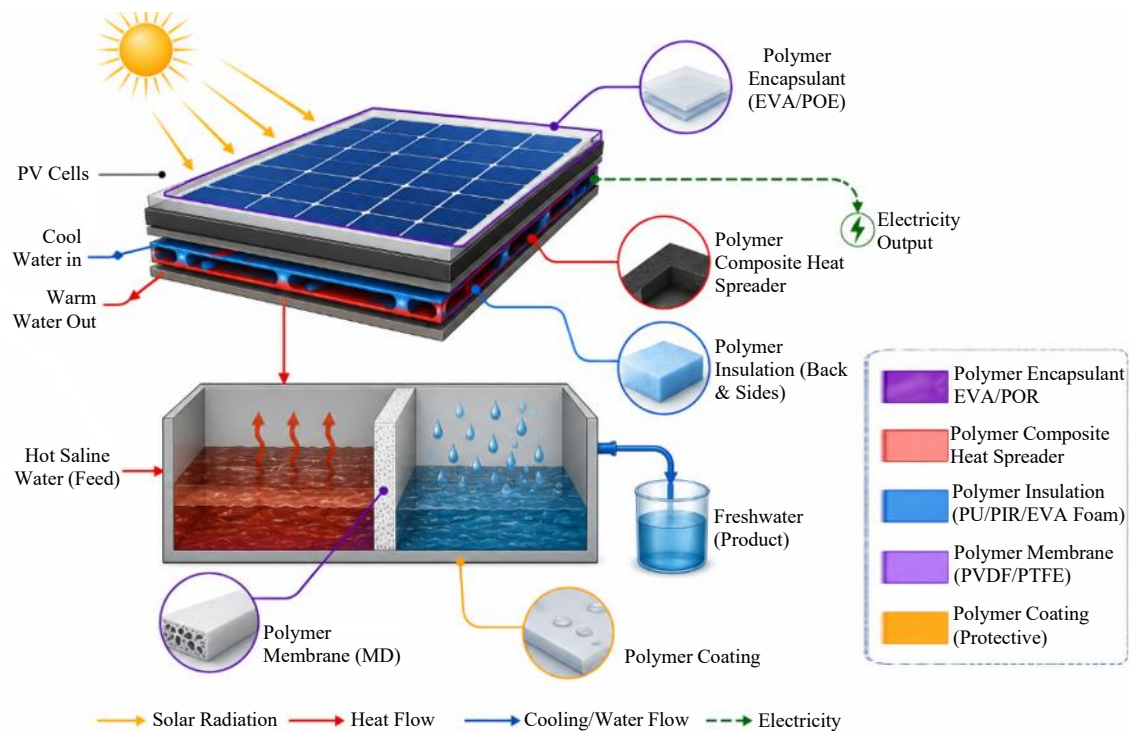


Figure 3. Classification of polymer materials used in hybrid PV/T solar desalination systems (PE, PP, PVDF, PTFE, Epoxy, PCMs, polymer composites, polymer nanocomposites).

Table 4. Comparison of polymer materials used in hybrid PV/T solar desalination systems.

Polymer material	Key properties	Primary application	Advantages	Limitations
Polyethylene (PE)	Lightweight, chemically inert, low thermal conductivity	Thermal insulation, piping	Low cost, corrosion resistance, easy processing	Poor thermal conductivity and UV resistance.
Polypropylene (PP)	High chemical resistance, low density	Collector components, water channels	Good mechanical strength, low moisture absorption	Thermal ageing under prolonged solar exposure.
Polyvinylidene Fluoride (PVDF)	Hydrophobic, chemically stable, high thermal stability	Membrane distillation (MD) membranes	High vapor permeability, excellent salt rejection, fouling resistance	Relatively expensive; membrane wetting under severe conditions.
Polytetrafluoroethylene (PTFE)	Excellent thermal and chemical stability	Hydrophobic desalination membranes	Superior chemical resistance and long service life	High fabrication cost and difficult processing.
Epoxy Resin	High adhesion and mechanical strength	Composite matrices, encapsulation	Strong bonding, structural integrity, corrosion resistance	Brittle behaviour and limited thermal conductivity.
Graphene/Polymer Composites	High thermal conductivity and mechanical strength	Heat spreaders, thermal management layers	Efficient heat dissipation and improved PV cooling	High material cost and complex fabrication.
Carbon Nanotube (CNT)/Polymer Composites	Excellent electrical and thermal conductivity	Thermal interface materials	Enhanced heat transfer and mechanical performance	Nanoparticle dispersion challenges and manufacturing cost.
Polymer-Based Phase Change Materials (PCMs)	High latent heat storage capacity	Thermal energy storage	Temperature regulation and extended desalination operation	Leakage, low intrinsic thermal conductivity, long-term stability issues.

POLYMER NANOCOMPOSITES AND ADVANCED THERMAL MATERIALS

Polymer nanocomposites have gained importance as promising materials for increasing thermal behavior in hybrid PV/T solar water distillation devices. With the incorporation of nanomaterials – like graphene, CNTs, boron nitride, and metal oxide particles in the polymer matrix, the thermal behavior, mechanical stability, and durability of the nanocomposites – have been greatly enhanced than those of conventional polymers.

It has been observed from recent studies that polymer nanocomposites containing graphene and CNT particles are effective in dissipating heat from the photovoltaic cells, which decreases cell temperature and increases the efficiency of the cells. On the other hand, boron nitride polymer nanocomposites have gained a lot of interest due to their high thermal conductivity, electric insulation, and chemical stability [16].

The utilization of advanced thermal materials – such as polymer phase change materials (PCMs) and hybrid nanocomposites – further enhances the performance of the system through efficient thermal energy storage and temperature control under fluctuating conditions of solar radiation. However, there is still ongoing difficulty with issues relating to dispersibility, large scale production, stability, and cost efficiency in practical application. Future studies need to focus more on scalable manufacturing processes, along with the use of multifunctional nanocomposites that possess high thermal efficiency

and durability. Table 5 gives a comparative study of the different polymer nanocomposites used for thermal management in the hybrid PV/T solar desalination system [17].

Polymer-based phase change materials (PCMs) have a very important function to perform in managing the intermittent nature of solar power in hybrid PV/T desalination plants. During times of high solar radiation, PCMs help in absorbing extra thermal energy that is then stored in the form of latent heat. During low solar radiation or at nighttime, this stored thermal energy is slowly released to ensure that the necessary thermal conditions for evaporation of water exist to produce fresh water. In addition to thermal management and reduction in temperature variations, nano-polymer PCMs that contain graphene or carbon nanotube additives have better thermal conductivity and higher rate of charging/discharging.

Table 5. Comparative assessment of polymer nanocomposites used for thermal management in Hybrid PV/T solar desalination systems.

Polymer nanocomposite	Nanofiller	Primary function	Performance benefits	Current challenges
Graphene/Polymer Composite	Graphene nanoplatelets	Heat dissipation	High thermal conductivity, improved PV cooling, enhanced mechanical strength	High cost and filler agglomeration.
CNT/Polymer Composite	Carbon nanotubes (CNTs)	Thermal interface and heat transfer	Excellent thermal and electrical conductivity, improved structural integrity	Non-uniform dispersion and fabrication complexity.
Boron Nitride (BN)/Polymer Composite	Hexagonal boron nitride	Thermal management and electrical insulation	High thermal conductivity with electrical insulation, chemical stability	High production cost and interfacial resistance.
Al ₂ O ₃ /Polymer Composite	Aluminum oxide nanoparticles	Thermal enhancement	Improved thermal conductivity, wear resistance, and durability	Moderate thermal enhancement and nanoparticle agglomeration.
SiO ₂ /Polymer Composite	Silicon dioxide nanoparticles	Surface protection and mechanical reinforcement	Improved stability, hardness, and corrosion resistance	Limited improvement in thermal conductivity.
Polymer-Based Nano-PCM	Graphene/CNT/Metal oxide nanoparticles	Thermal energy storage	Enhanced latent heat storage, faster charging/discharging, improved temperature regulation	Leakage, long-term cycling stability, and manufacturing cost.

CHALLENGES, RESEARCH GAPS, AND FUTURE DIRECTIONS

While polymer nanocomposites have shown great promise in enhancing the efficiency of hybrid PV/T solar desalination systems, several scientific and technical obstacles still need to be addressed. Namely, low thermal conductivity of standard polymers, agglomeration of nanoparticles, poor stability under harsh environmental conditions, fouling of membranes, and expensive manufacturing processes are some of the limitations that prevent wide-spread implementation of these technologies.

The critical evaluation of the current state of the art revealed that most research efforts are dedicated to improving individual materials or components of hybrid systems rather than optimizing the whole structure [18]. In other words, the combination of multifunctional polymer materials, advanced thermal energy storage devices, novel membranes, and smart control methods is not adequately addressed. Moreover, the studies in terms of life-long stability, life cycle assessment, techno-economic assessment, and real-life field trials are rather limited in numbers.

Thus, future studies should be focused on the creation of multifunctional polymer nanocomposites with improved properties and cost-effective manufacturing processes. Besides, the application of advanced artificial intelligence, digital twin techniques, and predictive thermal management strategies in combination with new materials promises a promising future for next generation hybrid PV/T solar desalination systems [19].

CONCLUSION

This review provides a critical analysis of the latest developments in polymer-based heat transfer techniques for hybrid photovoltaic/thermal (PV/T) solar desalination systems. Literature evidence suggests that polymers, which include conventional polymers, polymer composites, nanocomposites, and polymer phase change materials, have an important role in heat transfer improvement, thermal energy storage, membrane performance, and overall system efficiency. Among these, polymer composites reinforced with graphene, carbon nanotubes, and boron nitride have shown great potential in view of their high thermal conductivity, stability, and durability. Yet, there are some challenges related to nanoparticle aggregation, stability of materials, membrane fouling, and the relatively high price of advanced polymer materials that hinder the widespread application of such systems.

Despite significant breakthroughs, the ongoing research mostly concentrates on material-based studies without much attention being paid to system-level optimizations and practical validation. Therefore, future research needs to focus on multifunctional, sustainable, and economically viable polymer materials along with techno-economic, life cycle, and practical system evaluations. Combining advanced polymer technologies with intelligent thermal management and renewable energy utilization is likely to increase commercial viability and sustainability of next generation PV/T solar desalination systems.

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