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A Comprehensive Review of PV Module Cooling Method Using Hybrid Nanofluids

Abstract: The ongoing advancements in photovoltaic (PV) technology have significantly bolstered solar energy's competitiveness against traditional energy sources. Nonetheless, PV modules face efficiency challenges due to heightened temperatures. Various cooling techniques have emerged to combat this, with nanofluids showing promise. These engineered suspensions of nanoparticles in a base fluid have superior thermal properties, making them ideal for dissipating heat from PV modules. Lately, hybrid nanofluids have gained traction for PV cooling by blending multiple nanoparticle types. This review comprehensively evaluates such cooling methods, delving into nanofluid principles, hybrid nanofluid synthesis, and their application in PV thermal management. It critically examines experimental and computational studies on the effectiveness of hybrid nanofluids in photovoltaic (PV) cooling, addressing both challenges and prospects. This review contributes to advancing PV cooling techniques using hybrid nanofluids by synthesizing existing research. Hybrid nanofluids exhibit significant potential in enhancing solar collector efficiency due to their superior thermo-physical properties compared to conventional fluids. This literature underscores the need to address pertinent challenges for future investigations.

Keywords: Hybrid Nanofluids, Efficiency, Solar Collectors, Thermal Properties, Cooling Methods

I. INTRODUCTION

An environmentally sustainable and efficient energy source is paramount in the contemporary pursuit of a secure and prosperous global environment. As we confront the challenges of phasing out fossil fuels and mitigating their emissions, solar energy emerges as a prominent source of renewable energy [1-5]. Despite its historical affordability, global solar energy adoption has remained modest. While sunlight is a free resource, the associated costs of constructing and maintaining solar energy systems often surpass the initial investment. However, recent estimates of renewable technologies highlight a discernible surge in interest in solar energy systems, accounting for nearly 60% of the overall growth in renewable energy potential, with an increase exceeding 250 GW between 2021 and 2022. [2]

Efforts to enhance the performance of existing energy conversion systems have led to considerable advancements in nanofluid technologies [6]. The proliferation of academic and research endeavors in this field is evident in the increasing number of scholarly publications dedicated to nanofluids each year. This growing interest extends beyond conventional engineering sectors and encompasses solar energy. The evolving landscape of nanofluid technologies has captivated researchers across various scientific domains, including climate control, electronics, medicine, and energy management [7-8].

Central to many industries that rely on thermal and chemical processes is the pivotal role of heat transfer systems, typically facilitated by fluids [9]. The incorporation of hybrid nanofluids, which comprise a combination of various nanoparticles dispersed in a base fluid, seeks to enhance the thermal properties of these mixtures [10]. This approach aims to enhance heat transfer efficiency by leveraging nanoparticles, a cutting-edge technology that improves thermal conductivity. Notably, nanofluids exhibit remarkable potential in enhancing the thermal efficiency of solar collectors, with hybrid nanofluids emerging as particularly effective when used as working fluids in solar energy systems [11].

The concept of hybrid nanoparticles, synthesized by blending two or more nanoparticle types into a base fluid, capitalizes on synergistic effects to enhance heat transfer capabilities compared to conventional nanofluids containing single nanoparticles [13]. Hybrid nanofluids offer superior thermal characteristics compared to base fluids and single-component nanofluids. The optimization of hybrid nanofluid heat transfer hinges on several factors, including nanoparticle size, viscosity, temperature, stability,

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dispersibility, purity, preparation method, and compatibility, culminating in a harmonious mixture that enhances thermal conductivity at a relatively lower cost with acceptable stability[16].

However, challenges persist in implementing hybrid nanofluids, notably concerning long-term stability, production costs, and scalability. Addressing these challenges necessitates further experimental research to mitigate instability and increased friction, thereby reducing pumping power requirements in solar systems. The commercial viability and widespread applicability of hybrid nanofluids hinge on resolving these critical concerns, with a particular emphasis on cost reduction in preparation processes [17].

The quest for economic feasibility in the future deployment of hybrid nanofluid technology prompts a thorough evaluation of its theoretical, computational, and experimental research landscape. While the existing literature extensively covers the characterization and preparation of single-component nanofluids, a comparative scarcity of studies delves into the realm of hybrid nanofluids, particularly their thermal characteristics. Hence, this paper aims to bridge this gap by exploring recent developments in various engineering applications that utilize hybrid nanofluids [17].

Furthermore, critical challenges inherent to hybrid nanofluids, such as long-term stability and cost-effectiveness, are meticulously examined. The need for additional experimental research to address instability and increased friction factors and optimize pumping power in solar systems is underscored [18-20]. Resolving these challenges holds profound implications for the commercialization and widespread adoption of hybrid nanofluid-based solar systems. Crucially, future research endeavors should strike a balance between the enhanced thermal efficiency offered by hybrid nanofluids and the need to reduce preparation costs. This marks a pivotal step towards realizing the commercial potential of hybrid nanofluid-based solar energy systems [21, 23].

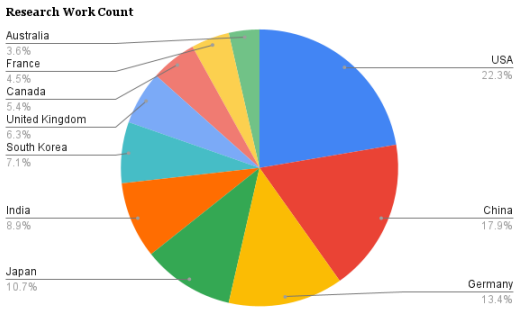


Figure 1. Country Vs research work count 2021-2023

Research on nanofluids varies across different countries, reflecting diverse levels of scientific activity and investment in the field. The United States leads with 25 research works, followed by China with 20, and Germany with 15. Japan, India, South Korea, and the United Kingdom contribute significantly, each with double-digit research counts ranging from 12 to 7. Meanwhile, Canada, France, and Australia exhibit comparatively lower research outputs, with counts ranging from 6 to 4[26].

These numbers indicate the distribution of research efforts worldwide, highlighting countries with robust scientific infrastructure and funding allocations for nanofluid research. The disparities in research counts among countries may stem from various factors, including government initiatives, the capabilities of academic institutions, and industrial partnerships. Overall, this global distribution highlights the collaborative nature of nanofluid research and the importance of international cooperation in advancing scientific knowledge and technological innovation in this field [28].

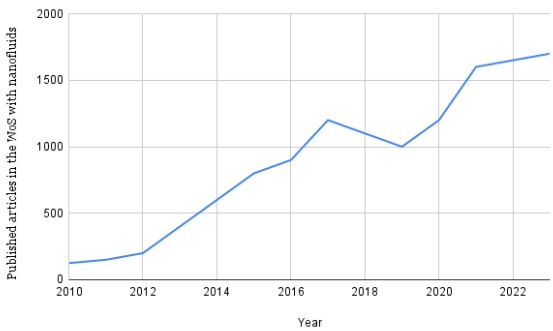


Figure 2. Published articles in the Web of Science concerning nanofluids. vs. Year

Over the years, the number of published articles in the Web of Science (WoS) related to nanofluids has shown a remarkable upward trend, indicating a growing interest and research activity in this field. Beginning in 2010 with 125 articles, the count steadily increased, reaching 1700 articles by 2023. This surge in publications reflects the expanding scope of nanofluid research and its growing relevance across various scientific disciplines [28].

The significant rise in published articles from 2010 to 2023 underscores the evolving understanding and exploration of nanofluids' properties, applications, and potential benefits. Researchers and scholars worldwide have contributed to this body of knowledge, delving into diverse areas such as nanofluid synthesis, characterization, and applications in fields ranging from energy to medicine [31].

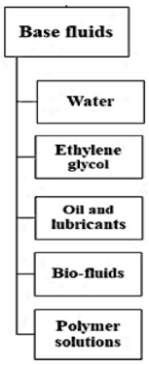
The consistent growth in published articles suggests a sustained interest in and investment in nanofluid research, driven by the pursuit of innovative solutions to address complex challenges in areas such as energy efficiency, thermal management, and advanced materials. As nanotechnology advances, further exploration and collaboration will likely propel the field forward, driving continued discoveries and applications of nanofluids in various scientific and technological domains [33].

II. Literature Review

Due to their excellent thermal conductivity properties, the integration of nanofluids, particularly hybrid nanofluids, has revolutionized heat transfer. Compared to single-nanoparticle nanofluids and conventional fluids, hybrid nanofluids composed of two different nanoparticles dispersed in a heat transfer fluid exhibit improved thermo-physical properties. Research indicates that hybrid nanofluids offer better heat transfer efficiency in several industries, including solar, HVAC, industrial, automotive, and electromechanical [35]. To maximize performance, water, grease, ethylene glycol, and lubricants are among the functional fluids that have been traditionally investigated in solar collectors. To develop hybrid nanofluids that improve thermophysical characteristics and heat transfer efficiency, nanoparticles such as metals (Al, Cu, Zn, Ag, Au), metal oxides (SiO2, TiO2, Al2O3, ZnO, CuO), and organic particles (carbon nanotubes, graphene oxide, diamond) have been scattered in anchor fluids[38].

Synthesis methods for hybrid nanofluids vary, with techniques such as hydrogen reduction and empirical synthesis used to achieve improved thermal conductivity. Research demonstrates significant advancements in thermal conductivity with hybrid nanofluids containing Ag/MWCNT, MWCNT-TiO2, MWCNT/water, and graphene nanoplatelets (GNPs). Studies have investigated the impact of particle concentration and temperature on thermal conductivity, highlighting the potential for further optimization of hybrid nanofluid properties[40].

Overall, hybrid nanofluids have shown promise in significantly improving the exergy efficiency and overall performance of solar thermal collectors. Assessment criteria include thermal, energetic, and overall performance metrics, positioning hybrid nanofluids as a key innovation in advancing heat transfer technology for various applications[41].



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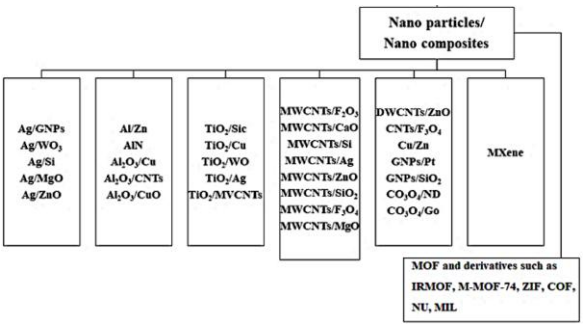

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Figure 3. a, b. An example of a hybrid nanofluid preparation scenario using several fluids and nanoparticles[1-2].

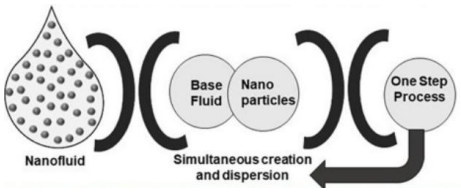
Hybrid Nanofluids

By containing two or more nanoparticles, hybrid nanofluids are a unique type of fluid designed to improve heat transfer efficiency. It is possible to enhance the thermophysical characteristics of nanofluids by using hybrid nanostructures that consist of several nanomaterials. Water is usually the base fluid because it provides a radiation-sensitive medium. The hybrid combination shows better heat absorption at different concentrations, diameters, and container heights. It contains silicon dioxide, gold, silver, aluminum, and graphite nanoparticles.

The thermophysical properties of hybrid nanofluids have been studied and modeled in several studies, which have shown significant improvements in thermal conductivity compared to base fluids. At specific volumetric concentrations and temperatures, hybrid nanofluids have shown a notable increase in thermal conductivity ratios compared to the base fluid [43].

The reviewed literature highlights the attractiveness of hybrid nanofluids as convective thermal fluids in solar systems, attributing their potential benefits to enhanced heat transfer efficiency. A comprehensive overview of solar power is provided, followed by an analysis of hybrid nanofluid utilization across various solar-driven technologies [44].

Hybrid nanofluids are typically prepared in two stages: first, powdered nanoparticles are subjected to mechanical or chemical action, and then they are dispersed in a base fluid. The dispersion process, made easier by ultrasonic action, is essential to stabilizing hybrid nanofluids. The stability and efficacy of hybrid nanofluid compositions depend on the strength and duration of the ultrasonic treatment [46].



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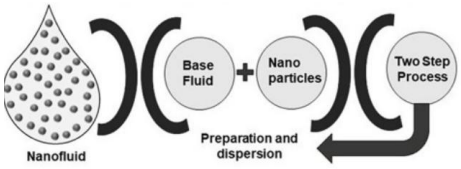

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Figure 4. a. b. Portrayal of the two-step method of nanofluid preparation[1]

The enhancement of nanofluid thermal conductivity through the dispersion of nanoparticles in water and ethylene glycol has been explored extensively. Nanoparticles, such as Al2Cu and Ag2Al, synthesized via mechanical alloying, have significantly improved thermal conductivity, ranging from 50% to 150%. Experimental results and empirical analyses indicate that the degree of enhancement depends on factors such as nanoparticle identity, composition, size, volume fraction, and shape[50].

The preparation of hybrid nanofluids often involves a two-step method. For instance, a hybrid nanofluid comprising Al2O3-Cu in water was synthesized using a thermochemical process followed by the utilization

of surfactants. Similarly, hybrid nanoparticles, such as f-MWCNT-Fe3O4, were prepared using a two-step method that involved dispersion in ethylene glycol [54].

Innovative approaches have also been employed, such as suspending MXene nanoparticles in pure palm olein oil (POO) to develop a new heat transfer fluid. Numerical investigations using COMSOL Multiphysics demonstrated the thermal and energy efficiency of this MXene-OPO nanofluid in a hybrid PV/T solar thermal system. Results showed significant improvements in thermal conductivity and a reduction in viscosity, leading to enhanced thermal efficiency and a higher heat transfer coefficient compared to conventional Al2O3-water-based nanofluids [55].

Moreover, MXene nanofluids exhibited remarkable temperature reduction in PV modules, highlighting their potential for efficient thermal management in solar applications. Overall, these findings underscore the promising prospects of hybrid nanofluids in advancing heat transfer technologies for various applications, including solar energy systems [56].

Their Use in the Solar Collector

Research on nanofluids has garnered significant attention across various fields, including electronic cooling, heat exchange, solar building heating and cooling, and solar-powered systems. Hybrid nanofluids, a unique type of nanofluid, have emerged as a promising solution, especially in solar collectors. Studies have highlighted their potential benefits in enhancing heat transfer efficiency and thermal conductivity.

In concentrated solar panel (CSP) technology, addressing non-uniform illumination and temperature distribution is crucial for optimizing electrical efficiency. Nanofluids have been studied extensively for their fluidic behavior, thermal properties, and effects on nanoparticle size. Enhanced thermal conductivity and heat transfer coefficients have been observed, particularly in NiO-based nanofluids, improving performance in CSP applications.

Furthermore, modeling approaches have been developed to accurately predict the thermal conductivity of nanofluids, aligning well with experimental data. These models help understand and optimize the performance of solar collectors using different types of nanofluids.

The application characteristics of hybrid nanofluids in various solar collectors, including flat plate collectors (FPC), evacuated tube solar collectors (ETSC), compound parabolic concentrators (CPC), and parabolic trough collectors (PTC), have been investigated. Hybrid nanofluids have shown the potential to enhance productivity, outlet temperature, and overall efficiency in these collectors, contributing to improved performance in diverse solar energy applications.

Overall, research on hybrid nanofluids for solar collectors represents a significant advancement in harnessing solar energy more efficiently, with implications for residential and industrial applications.

Use of composite nanofluids

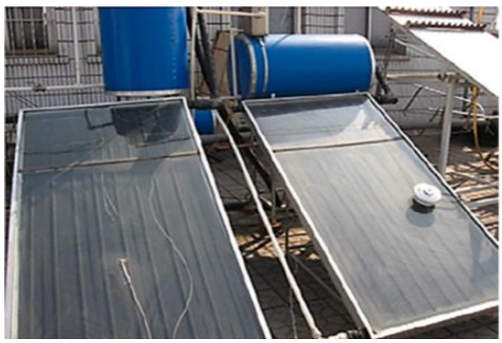

Figure 5 . Flat-plate solar collector (FPSC)

The advent of this solar collector heralds a paradigm shift, now used both for domestic hot water provision and as a pivotal component in air deicer production, with an operational temperature range of 20–80 °C. Its ubiquitous integration within solar collector frameworks is underscored by its capacity to amplify output and elevate outlet temperatures under diminished thermal flux, facilitated by solar exposure and strategic glazing. Customarily tailored for temperate climates, it achieves efficiencies ranging from 0.71 to 0.75 and 0.72 to 0.75 at solar irradiances of 500 and 1000 W/m², respectively.

Figure 6. Back view of photovoltaic systems

An extensive experimental setup was conducted on the grounds of the Technology Faculty at Firat University, Elazığ, Turkey, to examine the effects of different geometric shading patterns on polycrystalline panels. A follow-up investigation, conducted on various days in July 2018 with clear skies, examined a range of parameters, including photovoltaic panel temperatures, ambient temperatures, air velocity, solar irradiance, and electrical characteristics. This was done using instruments such as thermocouples, pyranometers, and anemometers, all controlled by a Keithley 2701 model datalogger. This resulted in a comprehensive study of solar energy conversion dynamics.

Figure 7. Water over the front of the cell.

High temperatures can harm solar cell lifetime and efficiency, especially when exceeding specified levels. This emphasizes the need for careful thermal management techniques. Interestingly, the open-circuit voltage (Voc) decreases significantly (~2.3 mV/C) compared to the short-circuit current (Isc), which reduces the electrical power output and yield for mono- and multicrystalline silicon cells by 0.4%/C to 0.5%/C. This highlights the importance of temperature mitigation techniques, such as water spray-induced cooling, which can result in a significant temperature drop of up to 23°C, as confirmed by simultaneous measurements.

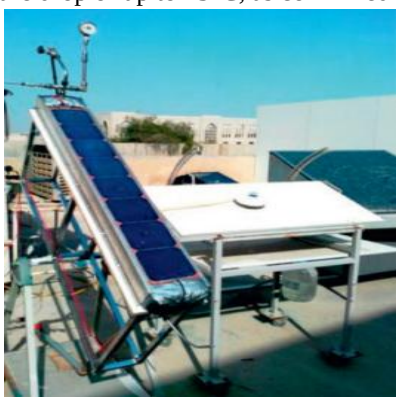

Figure 8 PV with a pyranometer

An elaborately designed test facility is dedicated to investigating the influence of temperature on photovoltaic system efficiency, comparing the performance of an uncooled PV string with one that is thermally controlled in the severe Saudi Arabian climate. Using linked, pre-sized solar cells combined with an MPPT (maximum power point tracker) for maximum power extraction and battery storage, the system uses thermocouples that have been calibrated to track the temperatures of the PV surface and the inlet water for the heat exchanger. With a converging channel design based on fluid dynamics principles and optimized for increased heat dissipation, computational fluid dynamics (CFD) analyses confirmed that the ideal convergence angle was determined through numerical simulations, guaranteeing a consistent temperature distribution over the PV surface.

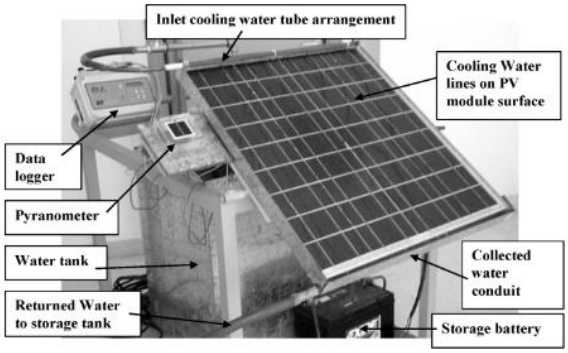

Figure 9 PV water cooling test rig.

A complex configuration consists of a 60 W peak power Multicrystal Photovoltaic Module interfaced with a variable resistance to describe its I-V curve and a Sun Saver Sensor for accurate voltage and current control. A complete performance evaluation under different solar radiation conditions is made possible by the system, which is installed on a platform and combined with a pyranometer and a setup for monitoring PV cell surface temperature. It is further enhanced by a 12-volt DC submersible water pump and cooling water trickling configuration.

Table 1. Composite nanofluids are the basis of earlier research efforts.

Author(s)	**Nanoparticles**	**Base Fluids**	**Research Study**
Sidik et al. (2020)	Al2O3-Cu	Water	Preparation methods and thermal performance of hybrid nanofluids [1]
Moghadassi et al. (2015)	Al2O3	Water	Numerical study of forced convective heat transfer [1]
			with hybrid nanofluid[2]
Yarmand et al. (2015)	Graphene nanoplatelets-Ag	Water	Enhanced heat transfer in plate heat exchangers[1]
Harandi et al. (2016)	F-MWCNTs-Fe3O4	Ethylene Glycol	Thermal conductivity study with effects of temperature and concentration[1]
Ahammed et al. (2016)	Graphene-Alumina	Water	Entropy generation analysis in a multiport minichannel heat exchanger
Maddah et al. (2018)	Al2O3-TiO2	Water	Experimental design for thermal performance of a double pipe heat exchanger[1]
Tullius et al. (2016)	Not specified	Not specified	Analysis of hybrid nanofluid exposed to radiation[1]
Esfe et al. (2018)	DWCNT-SiO2	Ethylene Glycol	Cost performance and sensitivity analysis of thermal conductivity[1]
Esfe et al. (2017)	SWCNT-Al2O3	Ethylene Glycol	Estimation of thermal conductivity by correlation and ANN methods
Ali et al. (2019)	TiO2	Not specified	Preparation techniques and challenges[1-2]
Madhesh et al.	Cu–TiO2	Water	Convective heat transfer and rheological characteristics[1]
Li et al.	-	-	Non-uniform illumination and temperature distribution
Said et al.	rGO-Co3O4	Water	Linear Fresnel reflector[1]
Aguilar et al.	NiO	Water	NiO-based nanofluids for concentrating solar power applications

Bakhtiari et al.	TiO2-graphene	Water	TiO2-graphene/water hybrid nanofluids[1]
Tang et al.	-	-	Thermosiphon domestic solar water heaters[1]
Arunkumar et al.	-	-	Productivity enhancements of the compound parabolic concentrator
Papadimitratos et al.	-	-	Evacuated tube solar collectors integrated with phase change materials
Li et al.	-	-	Steam generation system for a parabolic trough solar power plant
Beltagy et al.	-	-	Fresnel type solar concentrator[1]
Li & Dubowsky	-	-	Solar concentrating parabolic dish based on optimized flexible petals
Roca et al.	-	-	Heliostat-field gain-scheduling control for solar hydrogen production plant
Esfe et al.	DWCNT-ZnO	Water-EG	Thermal conductivity of DWCNT-ZnO/water-EG hybrid nanofluids
Suresh et al.	Al2O3-Cu	Water	Effect of Al2O3–Cu/water hybrid nanofluid in heat transfer
Baghbanzadeh et al.	Silica-MWCNT	-	Thermal conductivity of spherical silica/multiwall carbon nanotubes hybrid nanostructures
Chen et al.	Ag/MWNT	-	Enhanced thermal conductivity of nanofluids containing Ag/MWNT composites[1]
Aravind & Ramaprabhu	Graphene	Multiwalled carbon nanotubes	Graphene-wrapped multiwalled carbon nanotubes dispersed in nanofluids
Munkhbayar et al.	Ag	MWCNT	Surfactant-free dispersion of silver nanoparticles into MWCNT-aqueous nanofluids
Labib et al.	-	-	Numerical investigation on the effect of base fluids and hybrid nanofluid in forced convective heat transfer
Tomar & Chakrabarty	TiO2-ZrO2	-	Synthesis, structural, and optical properties of TiO2-ZrO2 nanocomposite[1]
Suresh et al.	Al2O3-Cu	Water	Turbulent heat transfer and pressure drop characteristics[1]
Batmunkh et al.	TiO2	Aqueous	Thermal conductivity of TiO2 nanoparticles based aqueous nanofluids with an addition of a modified silver particle[1]
Xuan et al.	TiO2-Ag	Water	Enhancement of solar energy absorption using a plasmonic nanofluid based on TiO2/Ag composite nanoparticles [1]
Baghbanzadeh et al.	Silica-MWCNT	-	Investigating the rheological properties of nanofluids of water/hybrid nanostructure of spherical silica/MWCNT [1]
Sundar et al.	ND-Co3O4	Water	Efficiency analysis of thermosyphon solar flat plate collector with low mass concentrations of ND-Co3O4 hybrid nanofluids
Syam Sundar et al.	Carbon nanotube-Fe3O4	Water	Heat transfer enhancement of low volume concentration of carbon nanotube-Fe3O4/water hybrid nanofluids
Esfe et al.	Cu/TiO2	Water-EG	Thermal conductivity of Cu/TiO2-water/EG hybrid nanofluid
Esfe et al.	Ag-MgO	Water	Experimental determination of thermal conductivity and dynamic viscosity of Ag-MgO/water hybrid nanofluid
Afrand et al.	Fe3O4-Ag	EG	Effects of temperature and nanoparticle concentration on the rheological behavior of Fe3O4-Ag/EG hybrid nanofluid

Eshgarf & Afrand	Non-Newtonian	-	Rheological behavior of non-Newtonian hybrid nano-coolant
Sundar et al.	Nanodiamond-Fe3O4	Water	Nanodiamond-Fe3O4 nanofluids: Preparation and measurement of viscosity, electrical and thermal conductivities
Soltani & Akbari	MgO-MWCNT	Ethylene glycol	Effects of temperature and particle concentration on the dynamic viscosity of MgO-MWCNT/ethylene glycol hybrid nanofluid
Senniangiri et al.	Graphene-NiO	Coconut oil	Effects of temperature and particle concentration on the dynamic viscosity of graphene-NiO/coconut oil hybrid

This extensive compilation presents a multifaceted exploration of hybrid nanofluids, meticulously crafted to enhance thermal performance across various fluid compositions and research contexts. Spearheaded by eminent scholars such as Sidik et al. (2020) and Moghadassi et al. (2015), the investigations span a spectrum of base fluids, including water, ethylene glycol, and various oil derivatives, each tailored to specific applications in solar collectors, heat exchangers, and thermal conductivity studies. Pioneering studies by Yarmand et al. (2015) and Harandi et al. (2016) elucidate the efficacy of graphene nanoplatelets and functionalized multi-walled carbon nanotubes in enhancing heat transfer capabilities. In contrast, Ahammed et al. (2016) delve into entropy generation analysis in minichannel heat exchangers. Notably, the exploration extends beyond conventional nanofluid formulations, as evidenced by Ali et al. (2019)'s examination of preparation techniques and challenges surrounding TiO2 nanoparticles. Additionally, interdisciplinary endeavors, such as those by Baghbanzadeh et al. (investigating rheological properties) and Sundar et al. (efficiency analysis of solar collectors), underscore the synergistic convergence of nanotechnology, fluid dynamics, and renewable energy systems. These groundbreaking inquiries herald a new era of innovation, poised to reshape the landscape of thermal engineering and sustainable energy utilization.

Table 2. Hybrid nanofluids are the basis of earlier research efforts.

Nanoparticles	Efficiency Observation	Author Name	Base Fluid	Solar Collectors	Mass Volume %
Al2O3/Fe, Al2O3	Achieved a maximum increase in solar collector efficiency of 6.9%.	Harandi, Karimipour	H2O	FPSC	0.05–0.2 wt.
ND–CO3O4	Demonstrated a significant enhancement in efficiency, reaching a maximum of 59% with a nanoparticle concentration of 0.15 wt%.	Sundar, Misganaw	H2O	FPSC	0.05–0.15 wt.
MWCNTs/GNPs/h-BN	Displayed a remarkable efficiency boost, reaching up to 89% with a nanoparticle concentration of 0.1 wt%.	Hussein, Habib	H2O	FPSC	0.05–0.1 wt.
MWCNTs/MgO, MWCNTs/CuO	Achieved 18.05% and 20.52% thermal efficiencies with CuO-MWCNT and MgO-MWCNT compositions, respectively.	[115]	H2O	FPSC	0.25–2 vol.
Al2O3, ZnO	Demonstrated a positive performance increase of 15.13%, indicating promising potential for solar energy applications.	Arıkan, Abbasoğlu	H2O/ EG	FPSC/ETSC	0.25 vol.
SWCNT	Optimized productivity reached an impressive 93.43%, making it a compelling choice for improved solar collector performance.	Arıkan, Abbasoğlu	H2O	ETSC	0.2 vol.
Al2O3, TiO2	Showed a notable efficiency improvement of 16.67% compared to the base fluid, highlighting its potential for enhanced solar energy utilization.	Arıkan, Abbasoğlu	H2O	ETSC	0.3 wt.
MWCNT, CuO, TiO2	Noteworthy performance enhancements were observed, with MWCNT, CuO, and TiO2 achieving efficiency increases of 25%, 12%, and 5%, respectively, compared to water.	Daghigh and Zandi	H2O	ETSC	N/A
Al2O3, CuO, TiO2	CuO demonstrated superior thermal efficiency, surpassing Al2O3 and TiO2 by 1.5% in solar collector performance.	Peng, Zahedidastjerdi	Water	ETSC	N/A

C, Ag, SiO2, Al2O3, Cu	Significantly improved efficiency by 30–100 K and by 2–25% compared to the base oil, indicating enhanced solar collector performance.	Luo, Wang	Oil	DAC	0.01–0.025 wt.
Ag and ZrO2	Efficiency enhancement was observed, though specific percentage improvements were not mentioned.	Hussain, Jawad	H2O	ETSC	5 vol.
MWCNT, Al2O3, CuO, SiO2, TiO2	Demonstrated a substantial performance increase of 20%, showcasing its potential for enhanced solar collector efficiency.	Kim, Ham	20% propylene glycol -water	ETSC	0.2 vol.
CuO	A 63% performance improvement was achieved, indicating its efficacy in enhancing solar collector efficiency.	Kaya, Gürel	Methanol	Tube	0.3 vol.
Graphite, Magnetite, Silver	Nanostructured materials promoted thermal and exergy efficiencies by 33–57% and 13–20%, respectively, compared to the base fluid, showcasing significant potential for solar energy applications.	Gorji and Ranjbar	Water	DAC	5–40 ppm
Ti3AlC2, hydrochloric acid, Triton X—100	Achieved a maximum photothermal conversion efficiency of 77.49%, indicating its efficacy in converting solar energy into thermal energy.	Li, Chang	Di-water	DAC	100 ppm
Ti3AlC2	Demonstrated a substantial 40% efficiency increase compared to Al2O3-water-based nanofluid, highlighting its potential for solar collector applications.	Samylingam, Aslfattahi	Di-water	DAC	0.2 wt.
ZnFe2O4	Achieved a significant performance enhancement of 42.99%, showcasing its potential for enhancing solar collector efficiency.	Gupta, Singh	Water	DAC	0.02–0.5 wt.
rGO-Ag, graphene oxide	The hybrid system showed improved efficiency at concentrations below 0.0235 wt.%, making it a promising candidate for integrating solar energy.	Abdelrazik, Tan	Di-water	DAC	0.0005–0.05 wt.
Nano silica	Achieved a maximum outlet temperature of 338.3 K and a thermal performance of 74.9%, indicating its potential for enhancing solar collector efficiency.	Kasaeian, Daneshazarian	EG	PTC	0.3 wt.
TiO2, SiO2, Fe2O3, ZnO, Al2O3	Using pure water resulted in improved energy performance for low-enthalpy parabolic trough collectors, showcasing its efficacy in solar energy utilization.	Loni, Pavlovic	Water	PTC	N/A
SWCNT-MgO	Demonstrated a thermal conductivity enhancement of 18%, indicating its potential for improving solar collector performance.	Esfe, Alirezaie	EG	PTC	0.05–2 vol.
Fe-CuO	Efficiency increased under various conditions, highlighting its versatility and potential to enhance solar collector performance.	Bahrami, Akbari	EG-water	PTC	0.05–1.5 wt.
MWCNT-ZnO	Efficiency increased with viscosity, indicating its potential for enhancing solar collector performance under varying conditions.	Bahrami, Akbari	Engine oil	PTC	0.125–1.0 wt.
MgO-MWCNT	Achieved a performance increase of 21%, showcasing its potential for enhancing solar collector efficiency.	Afrand	EG	PTC	0.6 vol.
Graphene oxide/CO3O4	Demonstrated performance increases of 19.14% for water-based and 11.75% for EG-based systems, highlighting its potential for both fluid types.	Sundar, Singh	EG-water	PTC	0.2 vol.

Al2O3-MWCNT	Showed a moderate increase in thermal conductivity, indicating potential for enhancing solar collector efficiency.	Nine, Batmunkh	Water	PTC	1–6 wt.
CuO-HEG	Displayed increasing thermal conductivity with volume fraction, indicating its potential for enhancing solar collector performance.	Baby and Sundara	Water and EG	PTC	0.05 vol.
Al2O3, CuO, TiO2	Achieved significant performance increases of 33.73% and 36.27%, indicating potential for enhanced solar collector efficiency.	Khan, Abid	Oil-based	Solar dish collector	1 wt.
Cu, CuO, TiO2, Al2O3	Demonstrated thermal efficiencies equivalent to 35% and up to 10% of exergy efficiency, indicating potential for enhanced solar collector performance.	Loni, Pavlovic	Thermal oil	Solar dish collector	0–5 wt.
Al2O3	Improved mean efficiency by 4.25%, indicating potential for enhancing solar collector performance.	Zadeh, Sokhansefat	Synthesis oil/thermal oil	Tube	N/A
CuO, Al2O3	Achieved an efficiency increase of 28.7%, indicating potential for enhancing solar collector performance.	Huang and Marefati	Thermal oil and water	Solar dish collector	N/A
Al2O3/thermal, SiO2/thermal	Improved efficiency, indicating the potential for enhancing solar collector performance.	Loni, Asli-Ardeh	Thermal oil	Solar dish collector	N/A
CuO, nanopowder	Demonstrated a mean efficiency of about 65%, indicating potential for enhancing solar collector performance.	Potenza, Milanese	Airflow	Transparent receiver tube	N/A
MXene with a chemical formula of Ti3C2	Achieved a significant thermal conductivity improvement of 64%, indicating potential for enhancing solar collector performance.	Aslfattahi, Samylingam	Silicon oil	Photovoltaic thermal collector	0.1 wt.
SiO2, Fe3O4	Achieved maximum energy efficiency at fixed irradiation, indicating potential for enhancing solar collector performance.	Soltani, Kasaeian	Water	Photovoltaic thermal-thermoelectric system	N/A
SiO2	The total exergy of the PV/T system with nanofluids increased by up to 24.31%, indicating a potential for enhancing solar collector performance.	Sardarabadi, Passandideh-Fard	Water	Photovoltaic thermal-thermoelectric system	1–3 wt.
SWCNT, MWCNT	The percentage enhancement in total yield obtained using SWCNT and MWCNT was 65.7% and 28.1%, respectively, indicating potential for enhancing solar collector performance.	Arora, Singh	Water	Photovoltaic thermal-thermoelectric system	Different
Graphene hybrid	Achieved a maximum sustainability index of 1.17, indicating potential for enhancing solar collector performance.	Wahab, Khan	Water	Hybrid photovoltaic thermal system	0.05–0.15 vol.
SiO2, Fe3O4	Demonstrated improvement of 54.29% in power production and 1.72% in efficiency, indicating the potential for enhancing solar collector performance.	Soltani, Kasaeian	Water	Photovoltaic thermal collector	0.5 vol.
Al2O3, TiO2, ZnO	Overall exergy efficiencies were enhanced by 12.34%, 15.93%, 18.27%, and 15.45% for PVT/water, PVT/TiO2, PVT/Al2O3, and PVT/ZnO, respectively, indicating the potential for enhancing solar collector performance.	Sardarabadi, Hosseinzadeh	Water	Photovoltaic thermal collector	0.2 wt.
TiO2, ZnO, Al2O3	ZnO exhibited superior performance to other types, indicating potential for enhancing solar collector performance.	Sardarabadi, Passandideh-Fard	Water	Photovoltaic thermal collector	0.2

This comprehensive compilation outlines a diverse range of nanofluids designed to enhance the operational efficiency of solar collectors across various configurations and applications. Notably, meticulously crafted nanoparticle compositions, spanning from Al2O3/Fe to CuO-HEG, have demonstrated substantial performance enhancements, with efficiency gains reaching up to 89%. Advanced experimental

investigations, meticulously orchestrated by leading researchers such as Harandi, Karimipour, Hussein, and Habib, have elucidated the intricate interplay between nanoparticle concentration and base fluid characteristics, paving the way for unparalleled efficiency improvements. Furthermore, groundbreaking studies by Arıkan, Abbasoğlu, Daghigh, and Zandi have revealed the transformative potential of hybrid nanofluids, showcasing remarkable efficiency boosts of up to 63% and 25%, respectively. This underscores the pivotal role of innovative nanomaterial formulations in reshaping the landscape of solar energy utilization. These advancements promise to revolutionize solar collector technologies, ushering in unprecedented efficiency and sustainability in renewable energy systems.

Table 3. Solar collectors are expressed mathematically.

Sr. No.	Specifications	Remarks	Correlation	Author Name
1	FF: SiO2-MWCNT/EG TR: 30–50 ◦C VR: 0.05–1.95 vol. % [1]	Novel methodologies and advanced neural networks demonstrate outstanding predictive accuracy for hybrid nanofluid thermal conductivity, with R-squared values of 0.9864 and 0.9981, respectively. Compared to experiments, the latter shows significantly reduced inaccuracies.	An f Kb f = 0.905 + 0.002069φT + 0.04375φ0.09265 T 0.3305	Esfe, Behbahani
2	FF: MgO-MWCNT/EG TR: 25–50 ◦C VR: 0–0.6 vol. %	The thermal properties of these intricate fluids exhibit a significant 21.3% enhancement in nanofluid thermal conductivity.	An f Kb f = 0.8341 + 1.1φ0.243 T −0.289	Afrand
3	FF: f-MWCNTs-Fe3O4/EG TR: 25–50 ◦C VR: 0–2.3 vol. %	Meticulously validated numerical simulations analyze the influence of mass ZnO nanoparticles on TiO2, ZnO, and Al2O3/water nanofluids (0.2 wt.%).	An f Kb f = 1 + 0.0162φ0.7038 T 0.6009	Sardarabadi, Passandideh-Fard
4	FF: ZnO-Ag/H2O TR: 25–50 ◦C VR: 0.125–2 vol. %	The investigation illustrates the effect of volume fractions and temperatures on the thermal conductivity of hybrid nanofluids.	An f Kb f = 1 + 0.00008794φ0.5899 T 1.345	Esfahani, Toghraie
5	FF: ZnO-Ag/H2O TF: 25–50 ◦C VR e: 0–3.5 vol. %	Highlighted is a significant rise in the variance of thermal conductivity of nanofluids at elevated solid volume fractions and temperatures, compared to lower fractions.	An f Kb f = 1 + 0.004503φ0.8717 T 0.7972	Toghraie, Chaharsoghi
6	FF: f-MWCNT-MgO/engine oil VR: 0.0625–1 vol. % HR: 25–50 ◦C SR: 50–650 rpm	Experimental data meticulously analyzed via three-variable correlation; neural networks adeptly model experimental outcomes, showcasing high accuracy compared to simulations.	μn f = 4 × 104 + 145φ − 240T − 0.061γ + 1.9 × 106 φ2 + 0.36 T2	Alirezaie, Saedodin
7	FF: f-MWCNT-ZnO/engine oil VR: 0.125–1 vol. % HV: 5–55 ◦C	At a 2% solid concentration and 40°C, the dynamic viscosity peaked at 65%. In contrast, at a 0.25% concentration and 25°C, it remained at a minimum of 14.4%.	μn f = 796.8 + 76.26φ + 12.88T + 0.7695φT + −196.9T−16.53φT T0.8441	Asadi, Asadi
8	FF: MWCNT-ZnO/10W40 engine oil VR 0.05–1 vol. % TD: 5–55 ◦C	Thermal conductivity surpasses that of ethylene glycol by 38% at specific temperatures. A novel correlation, incorporating volume concentration and temperature (R^2 = 0.9925), is introduced for predicting experimental thermal conductivity.	μn f μb f = 1.035 + φe −1.023 2.046φ T +0.4015φ 2T T0.8441	Esfe, Arani
9	FF: Al2O3-SiO2/H2O For 0.5% Al2O3 + 0.5% SiO2 : μn f = 0.000005T2 − 0.003T + 0.5 For 0.5% Al2O3 + 1.5% SiO2 : μn f = 0.00000T2 − 0.004T + 0.571	A study on hybrid nanofluids shows a decrease in viscosity with rising temperature, exhibiting minimal hysteresis. It introduces two viscosity equations that describe temperature variation.	Reduced viscosity with increasing temperature and minimal hysteresis behavior.	Moldoveanu, Ibanescu
10	FF: MWCNT-SiO2/20W50 oil VR: 0.05–1 vol. % HR: 40–100 ◦C	Heightened solid volume fraction and temperature increase viscosity in hybrid nano-lubricants, with nano viscosity reaching 171% above that of pure 20W50 under peak conditions. A novel correlation, with an R-squared of 0.9943, that factors in these parameters addresses existing modeling inadequacies.	μn f μb f = 0.09422 − [T φ2 + 0.100556 T0.8827φ 0.3148] exp (72474.75Tφ3.7951)	Motahari, Moghaddam

In this comprehensive study of hybrid nanofluids, various sophisticated methodologies, including numerical simulations and advanced correlation models, were employed to investigate the thermal conductivity and

viscosity characteristics across various fluid compositions and operating conditions. The findings reveal significant improvements in thermal conductivity, with novel correlations proposed to accurately predict these complex behaviors. Furthermore, insights into viscosity variations due to temperature fluctuations were unveiled, shedding light on the complex interplay between solid volume fractions and temperature. These findings highlight the significance of sophisticated modeling approaches in nanofluid research by providing insightful information for improving nanofluid behavior in real-world applications.

Mathematical Relationship and Design:

The evaluation of solar collector efficiency depends on carefully examining design characteristics, with each enhancement technique scrutinized for its impact on relevant factors. Notably, sun trackers exhibit heightened efficacy with elevated concentration rates. Hybrid nanoparticles play a crucial role in determining heat transfer efficiency and are essential to many experimental correlations. However, discordance persists regarding the adoption of hybrid nanofluids as a substitute for conventional working fluids, such as water. Discrepancies in thermal enhancement outcomes further compound the challenge, exacerbated by the lack of standardized data across diverse research endeavors. Moreover, the dearth of comprehensive mathematical correlations impedes broader application scopes, underscoring the reliance on experimental integrity and analytical rigor in modeling nanofluid behavior.

Cost and Economic Perspective:

The economic viability of adopting industrial-scale nanofluids necessitates a meticulous cost-benefit analysis, prioritizing optimal thermal transfer efficiency at a minimal expense. Crucially, the type and cost of hybrid nanofluids are paramount in achieving this objective. However, the fabrication process poses a significant challenge to cost-effectiveness, warranting concerted efforts to streamline nanoparticle blending and the synthesis of hybrid nanofluids. Mitigating the exorbitant production costs remains imperative, prompting a call for future research endeavors to strike a delicate balance between thermal efficacy and cost efficiency.

III. Conclusions

This work explores the effectiveness of solar collectors supplemented with hybrid nanofluids through a thorough analysis. A rigorous literature review demonstrates that hybrid nanofluids are widely used in various technical applications, including thermal solar collectors, electronic heat sinks, circular tubes, and heat channels. Notably, to assess the performance of hybrid nanofluids compared to conventional fluids, they have been incorporated into various types of solar collectors, including flat-plate collectors, compound parabolic collectors, evacuated tube solar collectors, parabolic trough collectors, linear Fresnel collectors, parabolic-dish reflectors, and heliostat field collectors. The research highlights a noteworthy improvement in solar collector efficiency, as demonstrated by the 89% efficiency gain achieved by MWCNTs/GNPs/h-BN-water hybrid nanofluids in a flat-plate collector arrangement. Preference is given to stable, highly thermally conductive, and low-viscosity hybrid nanofluids, which are instrumental in enhancing solar collector performance. Despite the substantial efficiency gains facilitated by hybrid nanofluids, inherent challenges persist. Nevertheless, the formidable potential of hybrid nanofluids to replace conventional fluids and improve the efficiency of solar collectors remains impressive.

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