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THERMAL MANAGEMENT OF PHOTOVOLTAIC PANELS USING FRONT-SURFACE THIN FILM NANOFLUIDS: MECHANISMS, PROPERTIES, AND RESEARCH PERSPECTIVES

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Abstract: Photovoltaic (PV) module performance is strongly influenced by operating temperature, with efficiency typically decreasing by 0.4–0.5% per °C rise in temperature. Effective thermal management is therefore essential to sustain electrical output and long-term reliability. This review presents a structured assessment of photovoltaic cooling technologies with particular emphasis on front-surface thin film nanofluid cooling. Cooling strategies are classified into passive and active methods, and recent advances in nanofluid-enhanced systems are critically examined. A bibliometric analysis based on Scopus-indexed publications (2011–2025) reveals a rapid increase in research activity, highlighting growing global interest in nanofluid-assisted and hybrid PV/T cooling systems. Thermophysical properties of TiO_2/water and SiO_2/water nanofluids are analyzed, and widely adopted effective property models are summarized to provide theoretical foundation for thin film cooling applications. Comparative literature findings demonstrate significant reductions in temperature and improvements in efficiency in nanofluid-based rear-surface systems; however, front-surface thin-film configurations remain relatively underexplored. Key research gaps are identified, including the need for optical–thermal coupling analysis, hydrodynamic optimization, and direct comparative evaluation of nanoparticle types. The review concludes that front-surface thin film nanofluid cooling represents a promising pathway for enhancing PV thermal performance and outlines future research directions to support practical implementation.

Index Terms - Photovoltaic cooling; Nano fluid thin film; TiO_2/water Nano fluid; SiO_2/water Nano fluid; Thermal management; PV efficiency; Bibliometric analysis; Renewable energy

1. Introduction

The growing global demand for sustainable and renewable energy has accelerated the deployment of photovoltaic (PV) systems as a key technology for clean electricity generation. Despite Figure 1 illustrates the influence of temperature on the current–voltage (I–V) characteristics of a PV cell. With increasing temperature, the I–V curve shifts downward and to the left, indicating a pronounced reduction in voltage and maximum power point. This behavior confirms that thermal management is essential to maintain stable electrical performance, particularly under high solar irradiance conditions. Experimental studies have reported that crystalline silicon PV modules typically experience an efficiency reduction of approximately 0.4–0.5% per °C increase in temperature [1]

Therefore, effective cooling strategies are required to control temperature rise and mitigate long-term performance degradation. These cooling methods can be broadly classified into passive and active cooling systems based on the cooling mechanism and energy input requirement

Nanofluids—engineered fluids containing suspended nanoparticles—have emerged as a promising enhancement to conventional water cooling systems. Experimental investigations using TiO_2-based nanofluids have shown improved heat removal and electrical performance compared to pure water cooling [2]. Similarly, oxide-based nanofluids in PVT systems have demonstrated improved thermal recovery and overall system efficiency [3]. Passive configurations enhanced with TiO_2 nanofluids have also resulted in measurable power gain [4].

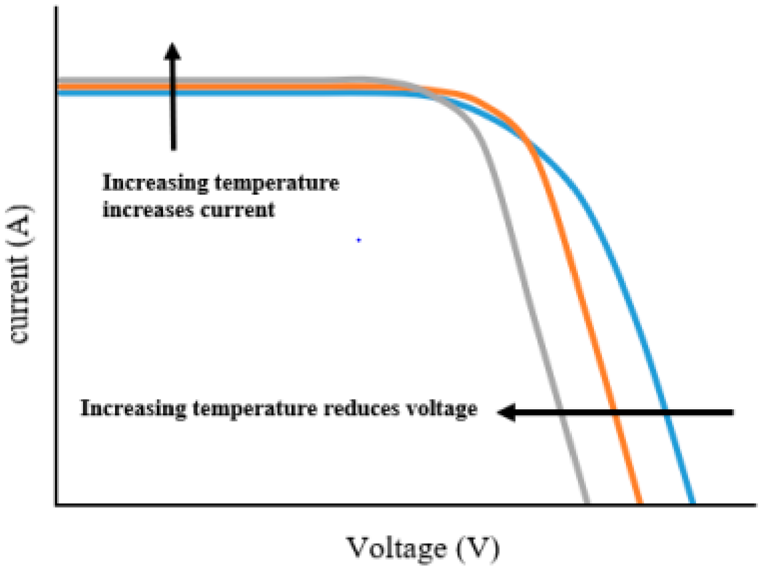

Figure 1 Influence of operating temperature on the I–V characteristics of a photovoltaic cell [1]

Although the majority of previous research has focused on rear-surface cooling configurations, front-surface cooling techniques—particularly thin film cooling—have received comparatively limited attention. In rear-channel systems, heat must conduct through the entire PV structure before reaching the coolant, introducing additional thermal resistance. In contrast, front-surface thin film cooling allows direct convective heat extraction from the glass surface, potentially reducing temperature gradients and improving thermal uniformity.

Among various nanoparticles, titanium dioxide (TiO_2) and silicon dioxide (SiO_2) are attractive candidates for thin film cooling due to their chemical stability and compatibility with water-based systems. TiO_2 offers higher intrinsic thermal conductivity and stronger thermal enhancement, while SiO_2 provides improved dispersion stability and potentially lower optical losses. However, systematic comparative analysis of TiO_2/water and SiO_2/water nanofluids under front-surface thin film conditions remains limited, particularly from a computational fluid dynamics (CFD) perspective.

Therefore, this review presents a structured evaluation of photovoltaic cooling techniques with emphasis on front-surface thin film nanofluid cooling. The study integrates thermophysical property modeling, literature comparison, hydrodynamic analysis, and CFD modeling framework to identify current research gaps and future optimization pathways. By focusing on TiO_2/water and SiO_2/water nanofluids, this work aims to provide a comprehensive foundation for the development of efficient thin film cooling systems for photovoltaic thermal management.

2. Review of Photovoltaic Cooling Techniques

The increasing sensitivity of photovoltaic (PV) efficiency to operating temperature has led to extensive research on thermal management strategies. Cooling techniques developed for PV systems can be broadly classified into passive and active methods based on the mechanism of heat removal and external energy requirement.

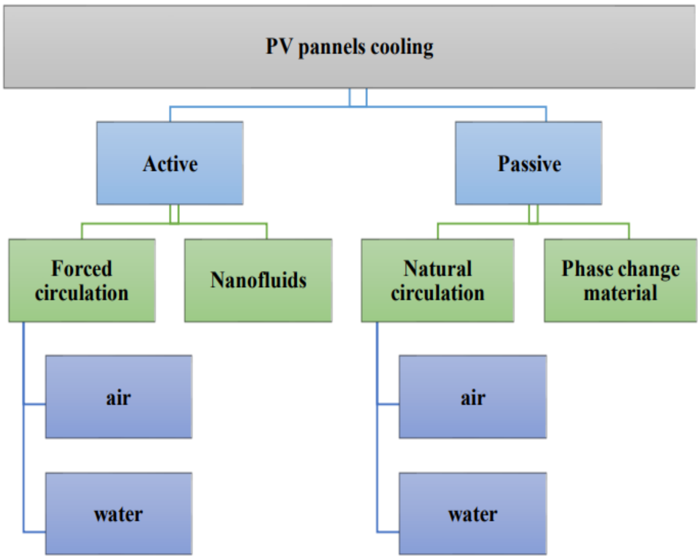

Figure 2 Classification of photovoltaic cooling techniques based on cooling medium and configuration.

The classification of photovoltaic cooling techniques is presented in Figure 2, which organizes existing approaches according to cooling medium and configuration. As shown in Figure 2, passive cooling methods include natural air cooling, extended surface fins, and phase change materials (PCM), while active cooling approaches involve forced air cooling, water cooling, and nanofluid-based cooling systems. Among these, liquid cooling has demonstrated superior heat extraction capability due to higher thermal conductivity and specific heat capacity compared to air. Rear-surface channel cooling and photovoltaic/thermal (PVT) systems have been extensively investigated, with several studies reporting measurable temperature reduction and efficiency enhancement [2][5]

2.1 Passive Cooling Techniques

Passive cooling approaches aim to enhance natural heat dissipation through structural modifications or material integration. These methods include:

- Natural air convection
- Extended surface fins and heat sinks
- Phase change materials (PCM)

Natural air cooling relies on buoyancy-driven convection around the PV surface. While simple and cost-effective, its cooling capability is limited by the low thermal conductivity of air. To improve performance, extended surfaces, such as fins, are attached to the back of PV modules to increase the effective heat transfer area.

Al Aboushi et al. (2022) demonstrated that passive finned cooling enhanced with TiO_2 nanofluid coatings reduced PV surface temperature and increased electrical power output by approximately 5.8% compared to uncooled panels[6]. Although passive methods reduce temperature to some extent, their cooling effectiveness is generally moderate under high irradiance conditions.

Phase change materials (PCM) have also been explored for thermal regulation. PCMs absorb excess heat during phase transition, limiting temperature rise. However, their effectiveness is constrained by limited latent heat storage capacity and thermal cycling issues.

2.2 Active Air Cooling

Active air cooling employs forced convection using fans or blowers to increase heat transfer rates. Compared to passive air cooling, forced air systems provide improved temperature control. However, due to the inherently low thermal conductivity and heat capacity of air, the overall cooling performance remains inferior to liquid-based systems. Additionally, active air cooling increases auxiliary energy consumption, potentially reducing net system efficiency.

2.3 Water-Based Cooling Systems

Liquid cooling using water significantly improves heat extraction capability due to higher thermal conductivity and specific heat capacity. Water cooling is commonly implemented through:

- Rear-surface channel systems
- Sheet-and-tube absorbers
- Photovoltaic/thermal (PVT) collectors

In rear-surface configurations, water circulates through channels attached to the backside of the PV module, extracting heat via conduction from the multilayer structure. Murtadha et al. (2022) investigated two-pass rear water circulation systems and reported notable surface temperature reduction, which was further enhanced when nanofluids were used instead of pure water [2]

Similarly, Satpute et al. (2026) analyzed Al_2O_3-based nanofluids in PVT systems and observed substantial improvement in overall thermal performance due to enhanced heat transfer properties [7]. While water-based systems are effective, they introduce additional structural complexity and thermal resistance between the heat source and cooling medium.

2.4 Nanofluid-Based Cooling Systems

Nanofluids are engineered by dispersing nanoparticles such as TiO_2, Al_2O_3, ZnO, or SiO_2 into a base fluid. The presence of nanoparticles enhances thermal conductivity and convective heat transfer coefficients.

Murtadha et al. (2022) reported that TiO_2/water nanofluid cooling achieved higher electrical efficiency compared to water cooling, with improvements increasing with nanoparticle concentration[8]. CFD-based investigations further emphasize the importance of accurate thermophysical property modeling, as cooling effectiveness strongly depends on Reynolds number, nanoparticle volume fraction, and temperature-dependent conductivity[9].

A comparative summary of representative nanofluid-based PV cooling studies is provided in Table 1, highlighting temperature reduction and efficiency improvement trends

Table 1 Comparative summary of nanofluid-based photovoltaic cooling studies.

No.	Study (Author, Year)	Nanofluid	Cooling Configuration	Temp. Reduction (°C)	Efficiency Gain (%)	Method	Key Finding	Ref
1	Ibrahim (2023)	Al_2O_3/H_2O	Sheet-tube	20.0	15.5	CFD	1.5% vol. fraction found optimal	[10]
2	Sreekumar (2024)	$MXene/H_2O$	Hybrid PV/T	20.0	8.6	CFD	MXene outperformed Al_2O_3	[11]
3	Samylingam (2024)	$MXene/H_2O$	Plate-tube	16.0	16.0	CFD	Thermal gain proportional to flow rate	[12]
4	Nasrin (2018)	$MWCNT/H_2O$	Channel	12.0	4.0	CFD	High pressure drop observed	[13]
5	Salehi (2023)	Al/H_2O	Heat sink	12.5	9.2	CFD	Al nanoparticles offer cost advantage	[14]
6	Sardarabadi (2017)	ZnO/H_2O	Active	11.0	13.0	CFD	ZnO thermally superior to Al_2O_3	[15]
7	Hassani (2016)	Nano-PCM	Cascade	16.0	11.0	CFD	Cascade PCM most efficient	[16]
8	Al-Waeli (2017)	SiC/H_2O	Active	14.5	10.1	CFD	SiC increases effective heat capacity	[17]
9	Ahmed (2019)	TiO_2/H_2O	Active	9.0	6.5	CFD	TiO_2 shows strong stability	[18]

Although nanofluid-based rear cooling systems have demonstrated promising results, most studies focus on channel-based configurations rather than direct surface cooling.

2.5 Limitations of Existing Cooling Approaches

Despite significant progress, current cooling strategies exhibit several limitations:

1. Rear-surface systems require heat conduction through the entire PV structure before extraction.
2. Channel-based cooling increases system weight and complexity.

3. High nanoparticle concentration increases viscosity and hydraulic losses.
4. Limited research exists on front-surface thin film nanofluid cooling.

These limitations motivate the exploration of front-surface thin film cooling, which enables direct convective heat extraction from the glass surface, potentially reducing thermal resistance and improving temperature uniformity.

2.6 Transition toward Front-Surface Thin Film Cooling

Front-surface cooling techniques, particularly thin film nanofluid flow, provide a promising alternative to conventional rear-channel systems. By directly applying a controlled nanofluid film over the PV glass surface, heat can be removed more efficiently with reduced structural complexity. However, such systems require detailed hydrodynamic and thermal analysis to evaluate performance trade-offs.

The following sections therefore focus on the mechanism of front-surface thin film cooling, thermophysical modeling of TiO_2 and SiO_2 nanofluids, and the role of computational fluid dynamics (CFD) in optimizing these systems.

3. Bibliometric Analysis of PV Cooling Research

3.1 Trend Analysis

The annual publication trend of photovoltaic cooling research indexed in the Scopus database is presented in Figure 3. The dataset spans the period from 2011 to 2025 and reflects the growing global research interest in thermal management of photovoltaic systems. A gradual increase in publications is observed between 2011 and 2018, rising from 26 documents in 2011 to 119 documents in 2018. This phase represents the early development period, primarily focused on conventional air and water cooling strategies.

A significant acceleration is evident after 2019, with the number of documents increasing from 161 in 2019 to 311 in 2022, followed by a sharp rise to 565 publications in 2024 and 618 publications in 2025. This rapid growth phase coincides with:

- Increased global emphasis on renewable energy technologies
- Advancements in nanofluid-based cooling systems
- Growing application of computational fluid dynamics (CFD) in thermal optimization
- Expanded research in photovoltaic/thermal (PVT) hybrid systems

The exponential growth trend suggests that photovoltaic cooling has transitioned from a niche research area to a mainstream topic within renewable energy engineering. Notably, the recent surge in publications indicates increasing attention toward advanced cooling techniques, including nanofluid-assisted and front-surface configurations.The bibliometric findings further justify the need for structured analysis and targeted investigation into underexplored areas such as front-surface thin film nanofluid cooling.

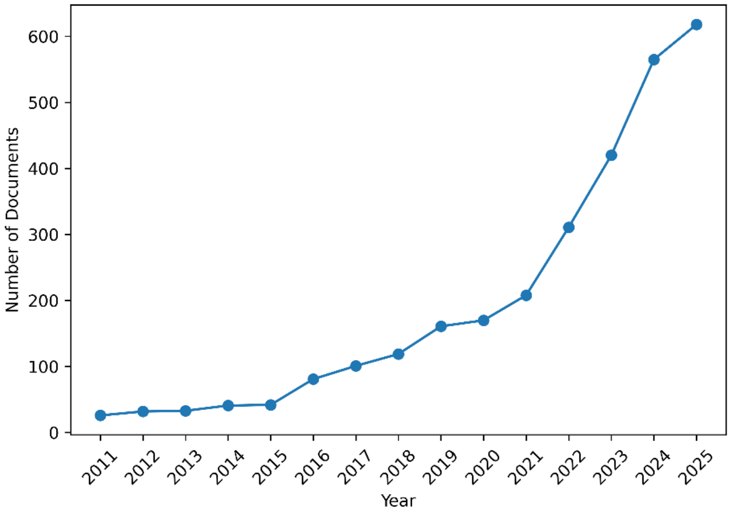

Figure 3 Annual publication trend in photovoltaic cooling research indexed in the Scopus database (2011–2025), indicating rapid growth in research activity over the last decade.

3.2 Country Wise Publications

The country-wise distribution of publications in photovoltaic cooling research indexed in the Scopus database is presented in Figure 4. The analysis indicates that India leads global research output with 383 publications, followed by China (267 documents) and Iran (193 documents).

Developed research economies such as the United States (149 publications) and the United Kingdom (116 publications) also contribute significantly to the field. Additionally, strong research activity is observed in Malaysia, Saudi Arabia, Egypt, Iraq, and Turkey, reflecting increasing global interest in photovoltaic thermal management.

The dominance of emerging and rapidly developing economies suggests that photovoltaic cooling research is closely aligned with regions experiencing high solar irradiance and strong renewable energy deployment initiatives. The geographical distribution further indicates that nanofluid-based and advanced cooling techniques are being actively explored across diverse climatic and research environments.

This global participation supports the expanding publication trend observed in Figure 4 and highlights the international relevance of thermal management solutions for photovoltaic systems.

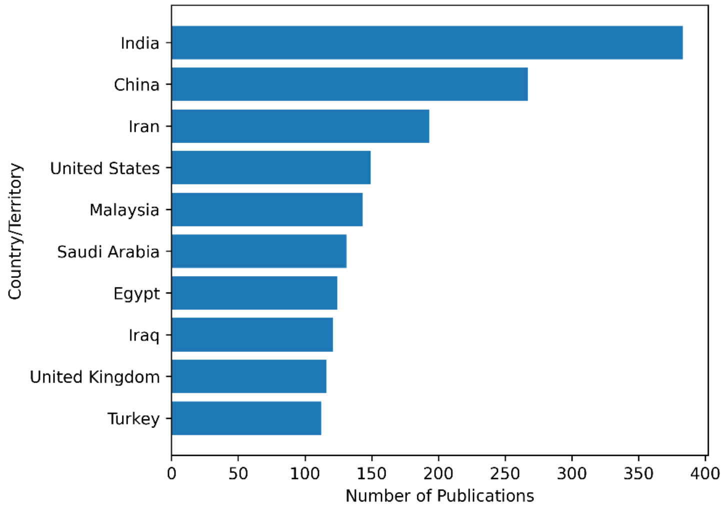

Figure 4 Country-wise distribution of publications in photovoltaic cooling research indexed in the Scopus database, highlighting leading research contributions.

4. Front-Surface Thin Film Cooling Mechanism

Front-surface thin film cooling involves the controlled flow of a liquid layer directly over the glass surface of a photovoltaic (PV) module. Unlike rear-surface cooling systems, where heat must conduct through the multilayer structure before reaching the coolant, thin film cooling enables direct convective heat extraction from the exposed surface, thereby reducing thermal resistance and improving temperature uniformity.

The configuration considered in this review is illustrated in Figure 3, where a nanofluid film of thickness δ flows over the inclined PV surface under the combined influence of inlet momentum and gravitational forces.

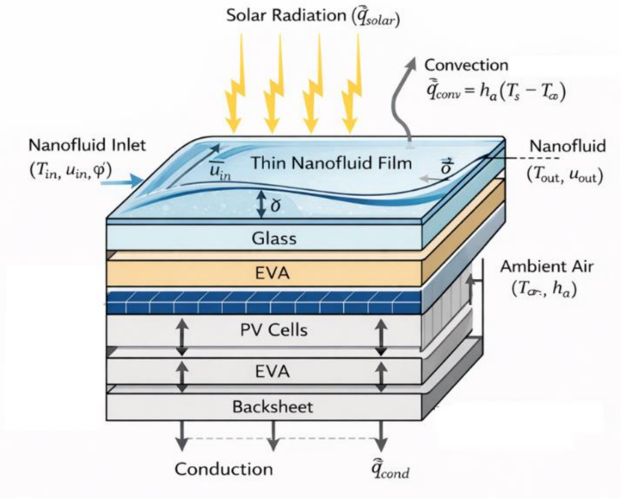

Figure 4 Schematic representation of front-surface thin film nanofluid cooling over the photovoltaic glass surface.

In this arrangement, solar radiation is absorbed at the glass surface, and heat is conducted through the multilayer PV structure (glass–EVA–cell–backsheet). The flowing nanofluid film extracts heat through convection, while ambient air contributes to additional convective losses.

5. Thermophysical Properties of TiO_2/Water and SiO_2/Water Nanofluids

Nanofluids are engineered suspensions formed by dispersing solid nanoparticles into a base fluid to enhance thermal transport properties. In photovoltaic (PV) cooling applications, oxide-based nanoparticles such as titanium dioxide (TiO_2) and silicon dioxide (SiO_2) are widely investigated due to their chemical stability, compatibility with water, and relatively low cost.

The thermophysical properties of the base fluid (water) and nanoparticles considered in many studies are summarized in Table 1.

Table 2 Thermophysical properties of base fluid and TiO_2 and SiO_2 nanoparticles.

Property	**Water (Base Fluid)**	**TiO_2 Nanoparticles**	**SiO_2 Nanoparticles**
Density, ρ (kg/m³)	997	4230	2200
Specific Heat, Cp (J/kg·K)	4182	686	745
Thermal Conductivity, k (W/m·K)	0.6	8.4	1.4
Dynamic Viscosity, μ (Pa·s)	0.001	—	—
Typical Particle Size (nm)	—	20–50	10–30
Shape	—	Spherical	Spherical
Volume Fraction Range (φ)	—	0.1–5%	0.1–5%

TiO_2 nanoparticles possess significantly higher intrinsic thermal conductivity compared to SiO_2, which leads to stronger enhancement in effective nanofluid thermal conductivity. However, TiO_2 also exhibits higher density, influencing flow behavior and potentially increasing hydraulic resistance.

5.1 Effective Thermophysical Property Modeling

For computational fluid dynamics (CFD) simulations, nanofluids are commonly modeled using a single-phase homogeneous approach, where effective properties are calculated through mixture correlations. The governing relations used for density, specific heat, thermal conductivity, and viscosity are summarized in Table 3.

Table 3 Effective thermophysical property models used in nanofluid analysis.[19].

Property	Model	Mathematical Expression
Effective Density	Mixture Model	$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p$
Effective Specific Heat	Weighted Average Model	$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_p$
Effective Thermal Conductivity	Maxwell Model	$k_{nf} = k_f \left[\dfrac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)}\right]$
Effective Viscosity	Brinkman Model	$\mu_{nf} = \dfrac{\mu_f}{(1-\phi)^{2.5}}$

Thermal conductivity increases with nanoparticle volume fraction ϕ, enhancing convective heat transfer capability. As demonstrated experimentally in nanofluid-cooled PV systems, increasing TiO_2 concentration leads to improved heat removal and electrical efficiency enhancement compared to pure water cooling[20].

5.2 Influence of Nanoparticle Volume Fraction

Nanoparticle concentration significantly influences both thermal and hydraulic characteristics of nanofluids. Increasing ϕ:

- Enhances effective thermal conductivity
- Improves convective heat transfer
- Increases dynamic viscosity
- Raises pressure drop

Experimental investigations of TiO_2 nanofluid cooling reported improved PV efficiency with increasing nanoparticle concentration, although excessive concentration affected flow resistance[20]. Numerical studies further emphasize that accurate modeling of temperature-dependent thermophysical properties is essential for reliable simulation results[9].

For front-surface thin film cooling applications, moderate concentration levels (0.5–2% volume fraction) are recommended to balance thermal enhancement and hydraulic stability.

5.3 Comparative Assessment of TiO_2 and SiO_2 Nanofluids

From a thermal perspective, TiO_2 nanofluids provide stronger conductivity enhancement due to higher intrinsic particle conductivity. However, SiO_2 nanofluids offer advantages in terms of lower density and improved dispersion stability, which may reduce hydraulic penalty and optical interference.

Therefore, selecting an optimal nanofluid for front-surface thin film cooling requires evaluating the trade-off between thermal enhancement and viscosity-induced flow resistance. A comparative CFD investigation under identical boundary conditions is necessary to determine the most suitable nanoparticle system for photovoltaic applications.

6. Research Gaps and Future Perspectives

The bibliometric evaluation (Section 3) and comprehensive literature review (Section 2) clearly demonstrate that photovoltaic (PV) cooling research has experienced rapid expansion in recent years. Despite notable progress in passive, active, and nanofluid-based thermal management approaches, several critical gaps remain—particularly in relation to front-surface thin film nanofluid cooling configurations.

6.1 Predominance of Rear-Surface Cooling Investigations

A substantial portion of the existing literature concentrates on rear-surface channel cooling and photovoltaic/thermal (PVT) hybrid systems [2]. These configurations have demonstrated significant temperature reduction and efficiency improvement; however, heat extraction occurs indirectly through conduction across the multilayer PV structure. This inherently introduces additional thermal resistance between the heat generation region and the cooling medium.

In contrast, front-surface thin film cooling provides direct convective heat removal from the glass surface, thereby potentially reducing thermal gradients and enhancing temperature uniformity. Nevertheless, systematic and comparative investigations of this configuration remain limited relative to rear-channel systems.

6.2 Insufficient Comparative Analysis of TiO_2 and SiO_2 Nanofluids

While TiO_2-based nanofluids have been widely studied for photovoltaic cooling applications, relatively fewer studies have conducted direct comparative assessments with SiO_2 nanofluids under identical operating conditions. As discussed in Section 5, TiO_2 nanofluids offer stronger thermal conductivity enhancement, whereas SiO_2 nanofluids may exhibit improved dispersion stability and potentially lower hydraulic resistance.

Future research should emphasize:

- Controlled side-by-side comparisons
- Uniform boundary and operating conditions
- Equivalent nanoparticle volume fractions
- Simultaneous thermal and hydraulic performance assessment
- Electrical efficiency estimation linked to temperature reduction

Such comparative analyses are essential to identify the most suitable nanoparticle system for front-surface thin film cooling applications.

6.3 Limited Consideration of Optical–Thermal Interaction

Unlike rear-surface cooling systems, front-surface thin film configurations introduce a liquid layer directly in the optical path of incoming solar radiation. Although many studies focus on thermal enhancement, the potential impact of nanofluid films on optical transmittance has not been sufficiently addressed.

Nanoparticle concentration may influence solar radiation transmission through scattering and absorption mechanisms, thereby affecting net electrical output. Future investigations should integrate:

- Optical property characterization of nanofluids
- Solar radiation transmission analysis
- Coupled optical–thermal modeling
- Trade-off evaluation between conductivity enhancement and optical loss

Incorporating optical–thermal coupling will enable more realistic and comprehensive performance evaluation.

6.4 Need for Detailed Thin Film Hydrodynamic Optimization

The effectiveness of thin film cooling is highly dependent on hydrodynamic parameters such as film thickness, Reynolds number, and viscosity variation. Although thermophysical property enhancement has been extensively reported, fewer studies systematically analyze:

- Film stability and flow regime behavior
- Pressure drop and pumping power requirements
- Influence of viscosity variation on laminar flow
- Optimization of film thickness for maximum heat extraction

Given that thin film cooling generally operates in the laminar regime, small changes in viscosity can significantly affect flow resistance and energy consumption. Therefore, future work should integrate thermal and hydraulic optimization simultaneously.

6.5 Integration of Performance-Based Evaluation Metrics

A common limitation in the literature is the isolated reporting of temperature reduction without directly linking it to electrical efficiency improvement. As illustrated in Figure 1, PV efficiency decreases linearly with temperature. Therefore, future studies should quantify performance using integrated metrics that combine:

- Surface temperature reduction
- Electrical efficiency enhancement
- Net energy gain
- Auxiliary pumping power consumption

Such comprehensive performance indicators would allow accurate assessment of the overall effectiveness of thin film nanofluid cooling systems.

6.6 Future Research Outlook

Based on the identified gaps, the following research directions are recommended:

1. Development of robust front-surface thin film cooling models.
2. Direct comparative analysis of TiO_2 and SiO_2 nanofluids under standardized conditions.
3. Coupled optical–thermal performance evaluation.
4. Optimization of nanoparticle concentration and film thickness.
5. Experimental validation under real climatic conditions.

Addressing these challenges will advance the understanding and practical implementation of nanofluid-based front-surface cooling systems, contributing to enhanced photovoltaic performance and long-term energy sustainability.

7. Conclusion

The present review has systematically examined photovoltaic (PV) cooling technologies with particular emphasis on front-surface thin film nanofluid cooling using TiO_2/water and SiO_2/water systems. The temperature sensitivity of PV modules, as illustrated in Figure 1, highlights the critical importance of effective thermal management in maintaining electrical efficiency and operational reliability.

The classification of cooling techniques (Figure 2) demonstrates that while passive approaches offer simplicity, active liquid-based systems provide superior heat extraction capability. Among these, nanofluid-enhanced cooling has emerged as a promising strategy due to improved thermophysical properties compared to conventional water cooling. Literature findings summarized in Table 3 confirm measurable temperature reduction and efficiency enhancement in rear-surface and PVT configurations.

However, despite rapid growth in publication activity (Section 3), most existing investigations focus on rear-channel systems. Front-surface thin film cooling remains comparatively underexplored, particularly in relation to hydrodynamic stability, optical–thermal interaction, and direct comparative evaluation of TiO_2 and SiO_2 nanofluids. The thermophysical characteristics summarized in Tables 1 and 2 indicate that TiO_2 nanofluids provide stronger thermal conductivity enhancement, whereas SiO_2 nanofluids may offer improved stability and reduced hydraulic penalty.

Overall, front-surface thin film nanofluid cooling represents a promising and structurally simplified pathway for enhancing PV thermal performance. Future research integrating thermal, hydraulic, and optical considerations is essential to optimize system efficiency and ensure practical feasibility. Continued advancements in nanomaterial engineering and numerical modeling techniques are expected to further accelerate progress in this field.

9. References

[1] S. Salama et al., “Review of Recent Efforts in Cooling Photovoltaic Panels (PVs) for Enhanced Performance and Better Impact on the Environment,” pp. 1–18, 2022.

[2] T. K. Murtadha, A. Ali, A. A. H. Alalwany, S. S. Alrwashdeh, and A. M. Al-falahat, “Case Studies in Thermal Engineering Improving the cooling performance of photovoltaic panels by using two passes

circulation of titanium dioxide nanofluid," Case Stud. Therm. Eng., vol. 36, no. June, p. 102191, 2022, doi: 10.1016/j.csite.2022.102191.

[3] T. K. Murtadha, "Case Studies in Thermal Engineering Effect of using Al 2 O 3 / TiO 2 hybrid nanofluids on improving the photovoltaic performance," Case Stud. Therm. Eng., vol. 47, no. May, p. 103112, 2023, doi: 10.1016/j.csite.2023.103112.

[4] S. Sami, "Analysis of nanofluids behavior in a pv-thermal-driven organic rankine cycle with cooling capability," Appl. Syst. Innov., vol. 3, no. 1, pp. 1–21, 2020, doi: 10.3390/asi3010012.

[5] A. A. Melaibari, N. H. Abu-Hamdeh, A. S. Alorfi, H. A. Z. AL-bonsrulah, and A. M. A. Elsiddieg, "New design for PVT system with elliptic cooling duct involving nanofluid in existence of MHD and utilizing TEG," Case Stud. Therm. Eng., vol. 53, no. October 2023, 2024, doi: 10.1016/j.csite.2023.103815.

[6] A. Al Aboushi, E. Abdelhafez, and M. Hamdan, "Finned PV Natural Cooling Using Water-Based TiO 2 Nanofluid," 2022.

[7] J. Satpute et al., "Experimental evaluation of Al 2 O 3 – water nanofluid for efficiency enhancement in a photovoltaic – thermal system under Western Indian climate," pp. 1–17, 2026.

[8] T. K. Murtadha, A. A. Dil Hussein, A. A. H. Alalwany, S. S. Alrwashdeh, and A. M. Al-Falahat, "Improving the cooling performance of photovoltaic panels by using two passes circulation of titanium dioxide nanofluid," Case Stud. Therm. Eng., vol. 36, no. May, p. 102191, 2022, doi: 10.1016/j.csite.2022.102191.

[9] J. F. Hinojosa and I. Hern, "Heliyon Numerical study of the thermal performance of a single-channel cooling PV system using baffles and different nanofluids," vol. 10, no. July, 2024, doi: 10.1016/j.heliyon.2024.e35413.

[10] A. Ibrahim, M. R. Ramadan, A. E. M. Khallaf, and M. Abdulhamid, "A comprehensive study for Al2O3 nanofluid cooling effect on the electrical and thermal properties of polycrystalline solar panels in outdoor conditions," Environ. Sci. Pollut. Res., vol. 30, no. 49, pp. 106838–106859, 2023, doi: 10.1007/s11356-023-25928-3.

[11] S. Sreekumar, S. Chakrabarti, N. Hewitt, J. D. Mondol, and N. Shah, "Performance Prediction and Optimization of Nanofluid-Based PV/T Using Numerical Simulation and Response Surface Methodology," Nanomaterials, vol. 14, no. 9, 2024, doi: 10.3390/nano14090774.

[12] R. Ratul, M. F. Ahmed, S. Alam, M. R. Karim, and A. A. Bhuiyan, "Numerical study of turbulent flow and heat transfer in a novel design of serpentine channel coupled with D-shaped jaggedness using hybrid nanofluid," Alexandria Eng. J., vol. 68, pp. 647–663, 2023, doi: 10.1016/j.aej.2023.01.061.

[13] R. Nasrin, N. A. Rahim, H. Fayaz, and M. Hasanuzzaman, "Water/MWCNT nanofluid based cooling system of PVT: Experimental and numerical research," Renew. Energy, vol. 121, pp. 286–300, 2018, doi: 10.1016/j.renene.2018.01.014.

[14] R. Salehi, A. Jahanbakhshi, J. B. Ooi, A. Rohani, and M. R. Golzarian, "Study on the performance of solar cells cooled with heatsink and nanofluid added with aluminum nanoparticle," Int. J. Thermofluids, vol. 20, no. August, p. 100445, 2023, doi: 10.1016/j.ijft.2023.100445.

[15] M. Sardarabadi, M. Passandideh-fard, M. Maghrebi, and M. Ghazikhani, "crossmark," Sol. Energy Mater. Sol. Cells, vol. 161, no. November 2016, pp. 62–69, 2017, doi: 10.1016/j.solmat.2016.11.032.

[16] A. Lekbir, S. Hassani, M. R. Ab Ghani, C. K. Gan, S. Mekhilef, and R. Saidur, "Improved energy conversion performance of a novel design of concentrated photovoltaic system combined with thermoelectric generator with advance cooling system," Energy Convers. Manag., vol. 177, no. September, pp. 19–29, 2018, doi: 10.1016/j.enconman.2018.09.053.

[17] A. H. A. Al-waeli, M. T. Chaichan, H. A. Kazem, and K. Sopian, "Comparative study to use nano-(Al 2 O 3 , CuO , and SiC) with water to enhance photovoltaic thermal PV / T collectors," Energy Convers. Manag., vol. 148, pp. 963–973, 2017, doi: 10.1016/j.enconman.2017.06.072.

[18] A. Ahmed, H. Baig, S. Sundaram, and T. K. Mallick, "Use of nanofluids in solar PV/thermal systems," Int. J. Photoenergy, vol. 2019, 2019, doi: 10.1155/2019/8039129.

[19] J. F. Hinojosa and I. Hern, "Heliyon Numerical study of the thermal performance of a single-channel cooling PV system using baffles and different nanofluids," vol. 10, no. June, 2024, doi: 10.1016/j.heliyon.2024.e35413.

[20] T. K. Murtadha, A. Ali, A. A. H. Alalwany, S. S. Alrwashdeh, and A. M. Al-falahat, "Case Studies in Thermal Engineering Improving the cooling performance of photovoltaic panels by using two passes circulation of titanium dioxide nanofluid," Case Stud. Therm. Eng., vol. 36, no. June, p. 102191, 2022, doi: 10.1016/j.csite.2022.102191.