Systematic Review: Enhancing Photovoltaic Performance through Hydrophobic Surface Coatings and Heat Mitigation

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Abstract— Surface coatings are essential for improving the performance of photovoltaic (PV) modules, particularly in challenging environments such as hot and dusty tropical regions or low-radiation subtropical areas. This study reviews recent developments in hydrophobic and heat-mitigating coatings that address two main problems: soiling and overheating. Both issues significantly reduce the efficiency and lifetime of PV systems. By systematically reviewing 32 selected studies, this paper identifies coating materials that combine self-cleaning, thermal regulation, and optical benefits. Among them, three-layer superhydrophobic coatings, silica–silane nanocomposites (e.g., SiO_2–PDMS, HDTMS–SiO_2), and Al_2O_3–H_2O nanofluids showed remarkable improvements in power output, optical transmission, and heat dissipation. For example, a three-layer superhydrophobic coating increased output power by 195.2% under simulated drizzle with heavy soiling, while SiO_2–PDMS nanocomposite films reduced surface temperature by 3.5 °C without reducing efficiency. These findings confirm that coating selection must balance hydrophobicity, heat management, durability, and cost. This review also highlights research gaps, particularly in long-term durability testing and large-scale application. The results provide practical guidelines for selecting appropriate coatings in different climates and suggest directions for developing multifunctional and scalable PV surface technologies.

Keywords— Efficiency; Hydrophobic; Surface Temperature; Self-Cleaning.

I. INTRODUCTION

Energy is a primary need in modern society, and solar power is one of the most promising renewable energy sources to meet increasing global demand while reducing the impact of climate change [1]-[3]. Photovoltaic (PV) technology is expected to play a key role in providing reliable and efficient electricity generation in the future [4]-[7].

The efficiency of PV modules is defined under standard test conditions of 1000 W/m² solar radiation, 25 °C ambient temperature, and a clean module surface [6], [8]. Photovoltaic output is directly proportional to the received radiation and inversely proportional to the operating temperature. One of the challenges in using photovoltaics is maintaining efficiency so that it does not experience a decrease caused by various factors such as temperatures higher than 25°C and the accumulation of dirt on the module surface [8]-[10]. This dirt, besides dust, also includes water scale that forms on the module surface due to the presence of stagnant water that then evaporates and leaves behind difficult-to-remove minerals. Hydrophobic properties allow water to easily roll off the module surface, thus cleaning off dust and other contaminants [2], [11]-[13].

Some methods to improve photovoltaic performance have been developed, such as the use of hydrophobic porous materials for surface coatings and the application of various passive and active cooling systems [7], [11], [13]. Hydrophobic materials on the photovoltaic module surface can prevent the accumulation of dust and dirt, thereby maintaining panel performance, while cooling systems can help lower the module surface temperature to maintain efficiency [6], [7], [14], [15].

Regarding the issue, various techniques have been developed to improve the performance of photovoltaics, including through the surface coating of photovoltaics using materials with certain properties, such as being able to dissipate heat, have anti-reflective properties, and be hydrophobic [7], [11], [15]. Coating materials that can dissipate heat tend not to be anti-reflective, and these coating materials are suitable for use in areas with high solar radiation above 1000 W/m². Coating materials that have anti-reflective properties have a transmittance close to 100%, can transmit almost all the received light, but tend not to be able to dissipate heat, and these materials are suitable for use in areas with solar radiation intensity less than 1000 W/m² [2], [16]. The use of hydrophobic material on the module surface can improve self-cleaning, so that dust and water scale can be minimized. Coating materials that can dissipate heat or have anti-reflective properties can both be hydrophobic.

The use of photovoltaics in tropical regions where solar radiation exceeds 1000 W/m^2 provides an opportunity to obtain greater energy output, but this abundant radiation has the effect of increasing the surface temperature of the panel above 25°C, resulting in a decrease in photovoltaic efficiency [17]. One promising technology to maintain or even improve photovoltaic efficiency is to use a photovoltaic module surface coating with materials that can reduce heat and have hydrophobic properties [15], [18].

In contrast, the use of photovoltaics in subtropical or temperate regions, where solar radiation and temperatures are lower, does not result in a significant temperature increase on the panel surface. However, a photovoltaic module surface coating that is anti-reflective and hydrophobic is still needed to maintain photovoltaic performance [19], [18] .

Increasing the surface temperature of photovoltaic panels can have a negative impact on the efficiency of converting solar energy into electricity, as it can cause a decrease in open-circuit

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voltage and fill factor, which are important parameters in energy conversion [9], [20]. Therefore, efforts to reduce the surface temperature of photovoltaic panels become very important in order to maintain the performance and lifetime of the photovoltaic system [9], [10], [21].

To date, various efforts have been made to improve photovoltaic performance, including the development of coating materials that can dissipate heat or have anti-reflective and hydrophobic properties on the PV surface. Several types of materials have been developed, such as; Silicon dioxide, Tungsten trioxide, Zinc oxide, Copper oxide, Indium tin oxide, Titanium dioxide, Fluoropolymers: Such as PTFE, and others [22], [23].

This systematic literature review is necessary to identify the best current coating materials with heat dissipation and hydrophobic properties, as well as to identify future research directions. Although there is a lot of research on PV coating materials, there is still a gap in the identification of the optimal coating materials to improve PV performance by comprehensively considering both heat dissipation and hydrophobic properties. Most studies only focus on one aspect, either heat dissipation or hydrophobicity, and there is no systematic comparative analysis to identify the most effective materials in both aspects.

The SLR method was chosen because it uses a systematic and transparent method to identify, evaluate, and synthesize relevant literature. This method can provide an overview of the current state of research on this topic and identify research gaps that can be addressed in future studies [24]-[27].

Identify and classify the various types of coating materials that have been developed and tested to improve PV module performance. This classification can be based on the type of material, structure, and application method. Analyze the working mechanism of the coating materials in heat dissipation and providing hydrophobic properties. This analysis includes an explanation of how the coating materials interact with solar radiation, heat, and water to improve the performance of PV modules. evaluate the performance of coating materials in improving the efficiency of PV modules and maintaining a low module surface temperature. This evaluation will be based on quantitative data reported in the reviewed studies, such as increased power conversion efficiency, reduced operating temperature, and increased module lifetime. Compare the performance of various types of PV coating materials to identify the most promising ones. This comparison will be based on relevant performance criteria, such as efficiency, resistance to heat and water, durability, and cost. provide recommendations for the best coating materials to improve the performance of PV modules in various environmental conditions based on a comprehensive analysis of the reviewed literature. These recommendations will consider factors such as effectiveness, cost, and ease of application.

Providing comprehensive and up-to-date information on PV coating materials with heat dissipation and hydrophobic properties. This information will be useful for researchers, engineers, and PV module manufacturers to understand the latest developments in this field. Assisting researchers and practitioners in selecting the right coating materials to improve the performance of PV modules in various environmental conditions. By understanding the characteristics and performance of various coating materials, they can make better decisions in designing and implementing PV systems. Providing direction for future research and development of PV coating materials. By identifying the existing gaps and challenges, this SLR can stimulate innovation in the development of more effective, durable, and cost-effective coating materials. The contribution of this research is expected to help increase the dissemination of PV technology in Indonesia and other developing countries with high solar energy potential.

II. Method

This study applies a systematic literature review (SLR) to identify coating materials with hydrophobic and heat-dissipating properties that can enhance the performance of photovoltaic (PV) modules, especially in tropical regions with high solar radiation. The review process follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a structured and transparent approach for identifying, evaluating, and synthesizing relevant studies.

Several alternative reporting standards were considered, including AMSTAR (Assessment of Multiple Systematic Reviews), OQAQ (Overview Quality Assessment Questionnaire), MARS (Meta-Analysis Reporting Standards), and PRIOR (Preferred Reporting Items for Overviews of Reviews) [28]-[31]. While AMSTAR and OQAQ emphasize the methodological quality of reviews and MARS focuses on meta-analysis, PRISMA is more widely applied for systematic reviews and meta-analyses due to its clarity and comprehensive reporting structure. For this reason, PRISMA was selected as the most suitable guideline for this study [32], [33].

By using the PRISMA approach, this review ensures transparency and reproducibility, while also providing a clear framework to identify research gaps and future directions for the development of PV coating technologies.

To keep the review focused, the research question was formulated using the Population, Intervention, Comparison, Outcome, and Study Design (PICOS) framework, as listed in Table I. In this context, the population refers to various types of coating materials that can be applied to photovoltaic (PV) modules. The intervention is the application of these coatings on module surfaces, while the comparison is made between coated and uncoated modules or those with standard coatings. The expected outcomes include higher energy conversion efficiency, reduced surface temperature, and improved hydrophobic properties. The study design encompasses both experimental and analytical approaches, including laboratory testing, field experiments, and literature-based evaluations. Based on this framework, the central research question of the review is: Which coating materials provide the best combination of heat reduction and hydrophobicity to improve the performance of photovoltaic modules?

The use of the PICOS framework in this study is highly appropriate as it enables a systematic comparison of various coating materials, both against uncoated modules and modules with standard coatings. In this way, the relative effectiveness of each material can be evaluated based on uniform performance criteria, ensuring that the analysis results are more focused and accountable.

The following steps were used to develop a comprehensive search string: Identifying relevant terms from the PICOS framework, particularly in the Population and Intervention aspects; Extracting terms from the formulated research question; Reviewing titles, abstracts, and keywords of relevant literature to identify additional terms; Searching for synonyms, spelling variations, and related terms for all identified concepts; and Constructing a sophisticated search string by combining these terms using Boolean operators AND and OR. The search was conducted on widely used scientific journal databases

TABLE I. SUMMARY OF PICOS

Population	Various types of coating materials that can be applied to photovoltaic modules
Intervention	Application of coating materials on the surface of photovoltaic modules.
Comparison	Comparison of the performance of photovoltaic modules coated with various types of coating materials against uncoated or standard-coated photovoltaic modules
Outcome	Increased efficiency of converting solar energy into electricity. Hydrophobic surface properties of the module. Reduction in module surface temperature.
Study Design	Experimental: Conducting experiments by applying various types of coating materials on PV modules and measuring their performance under controlled conditions. Qualitative: Conducting literature studies and data analysis to compare the performance of various types of coating materials reported in previous research. Quantitative: Performing numerical data analysis from the measurement results of the performance of PV modules coated with various types of coating materials.

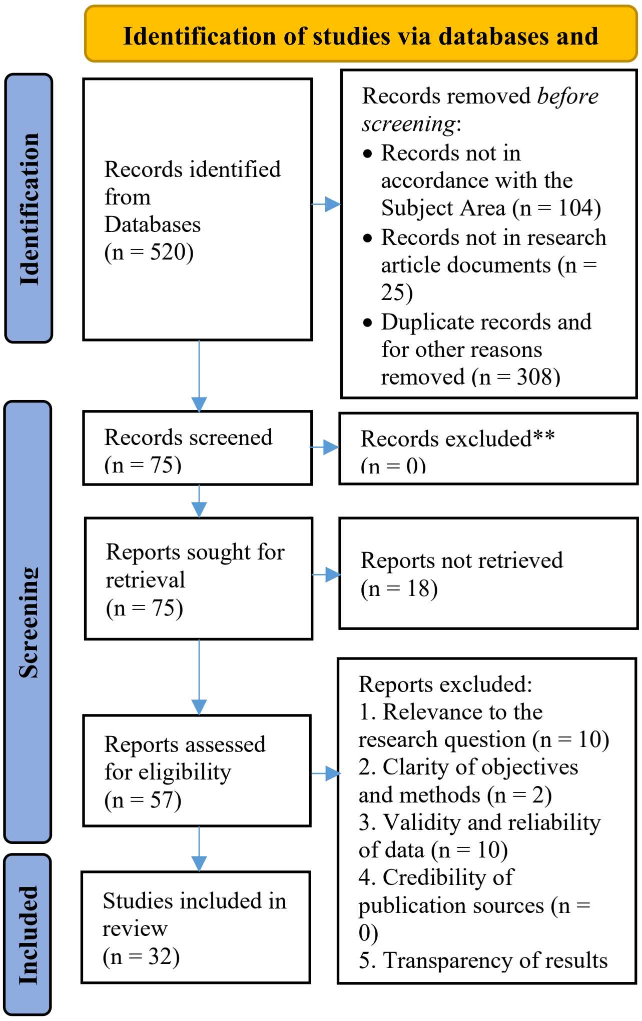

Figure 1. PRISMA 2020 Flowchart

Scopus and WoS, ON OCTOBER 19, 2024 at 10:33 PM using the keywords: ABS (("solar" OR "photovoltaic") AND hobic" OR "water-repellent" OR "water-resistant" OR "moisture-repelling coatings") AND "temperature" OR "thermal" OR "heat" OR "thermodynamic") AND ("efficiency" OR "performance" OR "effectiveness" OR "productivity")).

A summary of search results on October 19, 2024, at 10:33 PM WIB, using the keywords mentioned above, found 520 documents. These documents were then filtered based on inclusion and exclusion criteria according to the PRISMA 2020 flowchart, as shown in Figure 1 [34].

1. Study Selection

From the initial 75 articles identified through database searches, a multi-stage screening process was conducted. First, duplicates and irrelevant titles were removed, leaving 57 studies for further consideration. The abstracts and executive summaries of these papers were then reviewed against the predefined inclusion and exclusion criteria. To ensure reliability, a quality appraisal checklist was applied to each study, assessing relevance to the research question, clarity of objectives and methods, validity and reliability of data, credibility of the publication source, and transparency of results and limitations. Each article received a score of 0 or 1 for these five criteria, and only studies that achieved the maximum score of 5 were included. As a result, 25 studies were excluded due to weak data quality, lack of reliability, or limited relevance. The final selection produced 32 core articles, which served as the primary evidence base for this systematic review.

2. Bias Analysis and Mitigation

Potential sources of bias were carefully examined throughout the review process to ensure valid and reliable findings. Publication bias was minimized by considering not only journal articles but also relevant grey literature and conference proceedings. Selection bias was reduced through a double-screening process, in which two independent reviewers assessed the titles, abstracts, and full texts of candidate studies, resolving any disagreements through consensus. Reporting bias was addressed by checking whether studies reported both positive and negative outcomes, rather than only favorable results. To avoid language and database bias, searches were conducted across multiple databases without language restrictions. Researcher bias was also reduced by using independent reviewers and consensus discussions. These measures collectively helped maintain objectivity and improve the reliability of the synthesis.

3. Handling Heterogeneity

Because the reviewed studies involved different coating materials, experimental designs, and performance indicators, a high level of heterogeneity was expected. To address this, the analysis combined both qualitative and limited quantitative approaches. Qualitative analysis was used to identify differences in study design, material properties, environmental conditions, and measurement techniques. Variations in reported outcomes—such as efficiency improvements, temperature reduction, and water contact angle—were carefully noted. Due to the diversity of methods and results, a full meta-analysis was not feasible. Instead, a narrative synthesis was adopted to present the findings in a structured way, grouping them according to the main function of the coatings, such as heat reduction or hydrophobicity. This approach allowed for a clearer comparison while acknowledging the differences across studies.

4. Data Extraction

After the final selection, 32 articles were examined in detail. Following the research question framework, key information was extracted from each study, including the title, type of coating material, method of application, comparison with control or uncoated modules, performance outcomes, and study design, and the results are presented in Table II. The extracted data were then organized into a structured table to provide an overview of the evidence base. This summary highlights how each material performed in terms of energy conversion efficiency, surface temperature reduction, and hydrophobic characteristics, making it possible to compare their effectiveness across different experimental settings.

III. Results and Discussions

The systematic review shows that a wide variety of coating materials have been investigated to improve the performance of photovoltaic (PV) modules. In general, all coatings provide hydrophobic properties, while some are also capable of reducing surface temperature or enhancing optical transmittance. However, a trade-off is often observed: coatings that reduce temperature tend to lower optical transmittance compared to plain glass, whereas those that improve transmittance may contribute to higher surface temperature. The following section discusses several of the most effective coatings reported in the reviewed studies.

1. Types of Coating Materials

a. Three-layer Superhydrophobic Coating

The interconnected three-layer superhydrophobic coating, inspired by the structure of the human scalp, has demonstrated the highest improvement in PV performance. This coating consists of a bottom layer of long-chain silica synthesized under acidic conditions, a middle layer of silica nanoparticles produced under basic conditions, and a top layer of soot-derived silica nanoparticles that increase roughness and hydrophobicity. The coating achieves a WCA greater than 160° and a water sliding angle below 2°, indicating excellent water repellence. It also increases average optical transmittance by 6.44% compared to plain glass and provides a much wider transmittance bandwidth. Under simulated drizzle with laterite deposition, the coated PV module achieved a maximum output power increase of 195.2%, from 125.43 mW to 370.29 mW, while maintaining performance under harsh conditions such as acid rain and temperature fluctuations [35].

b. Al_2O_3–H_2O Nanofluids

The use of Al_2O_3–H_2O nanofluids improves the heat transfer coefficient by 15.7% compared to water, reducing the negative impact of dust deposition on PV modules. While dust can reduce efficiency by up to 40%, the application of a hydrophobic self-cleaning coating in combination with the nanofluid system reduced this effect and increased efficiency by 26.74%, from 8.6% to 10.9% [21].

c. Silicon Titanium Oxide.

Applying a hydrophobic silicon titanium oxide coating in combination with module inversion has been shown to improvepower generation efficiency by 11%. Coated modules produced a peak power of 2.08 W compared to 2.01 W for uncoated modules. When combined with inversion, the coated panels achieved 25 W peak power, while uncoated and uninverted panels reached only 22.5 W. This demonstrates that coating and orientation strategies can work synergistically [11].

d. SiO_2–PDMS Nanocomposite Films

Roll-to-roll coated SiO_2–PDMS nanocomposite films were effective in reducing the average surface temperature of PV modules by 3.5 °C compared to uncoated modules, without lowering power output. A maximum temperature difference of 5.5 °C was reported with an 8% volume SiO_2 film. These films maintained electrical performance and enhanced hydrophobicity, supporting both cooling and self-cleaning functions [9].

e. Composite Superhydrophobic

A composite of antimony-doped tin oxide nanoparticles, nanosilica, hexadecyltrimethoxysilane, and KH560 produced a transparent superhydrophobic coating with a WCA of 163° and a sliding angle of about 3°. It also demonstrated a 19% reduction in room temperature under simulated sunlight, showing its thermal insulation capability. The coating exhibited strong self-cleaning, anti-icing properties, and resistance to mechanical stress and chemical weathering, with light transmittance of around 70% [36].

f. Methyltrimethoxysilane (MTMS)

Hybrid coatings of methyltrimethoxysilane (MTMS) and colloidal silica nanoparticles, prepared via the sol-gel method, achieved a WCA of 110–120° and surface hardness of 4–5 H. They demonstrated strong dust removal capability, with 75.8% dust removal efficiency after durability testing under Mars-like conditions. The coating remained effective after multiple cycles of thermal and radiation exposure. When combined with trimethylchlorosilane, the WCA increased to 128°, further enhancing hydrophobicity, although these coatings do not significantly reduce surface temperature [7], [37].

2. Qualitative Comparison of Coating Performance

Overall, the reviewed coatings demonstrate strong hydrophobic properties, although their effects on temperature and optical performance vary. Some coatings are effective in lowering the surface temperature of photovoltaic (PV) modules but tend to reduce optical transmittance compared to plain glass. Others enhance optical transmittance and hydrophobicity but may contribute to higher surface temperature. Despite these trade-offs, the coatings consistently improve efficiency by mitigating soiling and temperature-related losses [38]-[41].

Silica (SiO_2) nanoparticles and their derivatives, including silane-based compounds such as methyltrimethoxysilane (MTMS), hexadecyltrimethoxysilane (HDTMS), and tetraethoxysilane (TEOS), are among the most widely applied materials. Their popularity stems from high optical transparency, chemical tunability, and mechanical stability, making them fundamental building blocks for advanced PV coatings.

The most striking result was reported for the interconnected three-layer superhydrophobic coating (ITSC), which increased maximum output power by 195.2% under simulated drizzle with laterite deposition [35]. This result highlights the ability of effective self-cleaning coatings to address not only ordinary dust accumulation but also more persistent soiling, such as sticky mineral deposits. Such coatings provide significant economic value in tropical and subtropical regions where soiling is a major operational challenge.

SiO_2–PDMS nanocomposite films also demonstrated an important advantage: they reduced module temperature by an average of 3.5 °C without affecting electrical output [9]. This type of passive cooling lowers thermal stress on PV cells, which helps preserve efficiency and extend module lifespan, particularly in hot climates where overheating is a common problem.

TABLE II. LIST OF PRIMARY STUDIES IN THE FIELD OF PHOTOVOLTAIC COATINGS

Title	Population	Intervention	Comparison	Outcame	Study Design
Transparent dust removal coatings for solar cell on mars and its Anti-dust mechanism [37]	A transparent hybrid layer made of methyltrimethoxysilane (MTMS) and colloidal silica nanoparticles (SiO2).	Application of a transparent hybrid layer made of methyltrimethoxysilane (MTMS) and colloidal silica nanoparticles (SiO2) on the surface of photovoltaic modules, specifically solar cells intended for Mars.	The performance of the photovoltaic module coated with a hybrid coating (mTMS/SiO2) showed a significant improvement in the dust removal percentage compared to the uncoated glass slide, which showed a negative dust removal percentage in the air due to water adsorption.	Efficiency: fixed Temperature change: Hydrophobic Contact Angle (WCA): 110-120° dust removal percentage 75.8%	This study used MTMS and SiO2 nanoparticle coatings via a sol-gel process. Transparency, water contact angle (WCA), and dust removal performance were tested under extreme, Mars-like conditions. A quantitative analysis was conducted on dust removal before and after durability tests.
Template-free scalable roll-to-roll fabrication of textured transparent film for passive radiation cooling of photovoltaics [9]	Film nanokomposit SiO2 Polydimethylsiloxane (PDMS).	Application of composite film made of SiO2 and PDMS on the surface of photovoltaic modules for passive cooling.	The performance of photovoltaic modules coated with 8 percent volume of SiO2PDMS film showed an average temperature difference of 3.5°C lower than that of control modules (uncoated), demonstrating effective cooling without affecting power generation.	Efficiency: fixed Temperature: drops by an average of 3.5° C Hydrophobic Contact Angle (WCA): increased	This outdoor experimental study evaluated the passive cooling of a new roll-coated SiO2-PDMS film on solar cells. The performance of the new film was compared to a more expensive, traditionally manufactured film by measuring temperature and voltage in various weather conditions.
Superhydrophobic anti-icing coatings with self-deicing property using melanin nanoparticles from cuttlefish juice [42].	Melanin nanoparticles derived from cuttlefish juice, combined with SiO2 nanoparticles	The development of superhydrophobic photothermal coatings uses melanin nanoparticles from cuttlefish juice and hydrophobic SiO2 nanoparticles, which exhibit anti-icing and photothermal properties.	There is no comparison, this study developed a superhydrophobic layer with anti-icing and self-deicing properties, by utilizing melanin nanoparticles from cuttlefish juice and hydrophobic SiO2 nanoparticles. The layer also explores the photothermal effect, which allows for the efficient conversion of solar energy into heat to melt ice.	Efficiency: fixed Temperature: 67.6° C Hydrophobic Contact Angle (WCA): Water droplet icing time up to 144 seconds The ice adhesion strength on the layer is significantly reduced to 25.65 kPa.	The provided context does not contain specific information about the study design, including the experimental, qualitative, or quantitative methodologies for coating materials on PV modules. Therefore, the information cannot be generated.
Sol-gel coating of colloidal particles deposited glass surface pertinent to self-cleaning applications [43]	Silk coid.	The application of sol-gel coatings uses colloidal silica on the surface of photovoltaic modules to improve their self-cleaning properties.	There is no comparator, the focus is on improving the optical transmittance and hydrophobic characteristics of photovoltaic surfaces, which is crucial for its efficiency.	Hydrophobic Contact Angle (WCA): increases Optical transmittance Dust particles adhere to oil-impregnated surfaces	The provided context does not contain specific information about the study design. Therefore, it is not possible to provide an answer based on the given context.
Solar PV Panels-Self-Cleaning Coating Material for Egyptian Climatic Conditions [7].	Dimethyl-siloxane, - Parafin - Gliserol	The application of self-cleaning coating materials on the surface of photovoltaic (PV) modules to improve their electrical efficiency.	Photovoltaic modules coated with monolithic hydrophobic-based coatings using paraffin and dimethyl-siloxane showed significant improvements in electrical efficiency, with improvements ranging from 11.96% to 14.49% compared to uncoated panels.	Efficiency: Increased from 11.96% to 14.49%) Temperature: reduced Hydrophobic Contact Angle (WCA): not measured	This study used an experimental method to measure the performance of PV modules coated with various materials. A qualitative analysis was conducted through a literature review, while a quantitative analysis focused on the electrical efficiency and surface temperature of the PV panels.
Self-cleaning hydrophobic nanocoating on glass: A scalable manufacturing process [44]	Trichloro (1H, 1H, 2H, 2H-perfluorooctyl) silane (TCPFOS).	Application of self-cleaning hydrophobic nano coatings (SCHNs) on the surface of photovoltaic modules, especially glass substrates.	The research paper does not provide a direct comparison of the performance of photovoltaic modules coated with different types of coating materials with those without coating or with standard coatings.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): down from 105 to 64.6Resistant to a variety of environmental factors, including abrasion, acid rain, salt exposure, and extreme temperature cycling maintains optical transmission properties	This study focused on developing a self-cleaning hydrophobic nanocoating (SCHN) through chemical vapor deposition. Its performance was evaluated through durability tests (humidity and UV exposure) and a comparative analysis of optical transmission with pristine glass.
Reduction of Dust and Temperature Effects on PV Performance in Qatar and the Gulf Region [11]	Silicon titanium oxide.	The application of hydrophobic coating materials on the surface of photovoltaic (PV) modules to reduce the effect of dust accumulation.	The study compared the performance of photovoltaic (PV) panels with hydrophobic coatings against uncoated panels. The results show that the paneled	Efficiency: Increased by 11% Temperature: Hydrophobic Contact Angle (WCA):	This study design evaluated the effects of dust and temperature on coated PV modules in Qatar. A quantitative analysis showed an 11%

Title	Population	Intervention	Comparison	Outcame	Study Design
			panel reaches a peak power of 2.08 W, while the uncoated panel reaches 2.01 W, indicating a slight advantage for the panel.	increased	increase in peak power generation for coated panels compared to uncoated ones.
Reducing soiling issues on photovoltaic panels using hydrophobic self-cleaning coating [23].	Vinyltriethoxysilane (VTES), tetraethoxysilane (TEOS), and tetrabutoxytitanate (TTBU), collectively referred to as VTT (VTES-TEOS-TTBU) sols.	Application of hydrophobic self-cleaning coating on photovoltaic (PV) panels to reduce the problem of impurities.	The study focused on the performance of photovoltaic (PV) modules coated with a hydrophobic self-cleaning coating, specifically comparing two methods: post-addition of water to titanium alkoxide (PWTA) and chemically modified titanium alkoxide (CMTA).	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): 110.01° 96% transmission at wavelength 571 nm	This study used a sol-gel and spin-coating method to create a hydrophobic coating. Qualitative and quantitative analyses were performed to examine the effect of material composition (VTES, TEOS, TTBU) on the contact angle, surface roughness, and optical transmittance.
Performance Investigation and Analysis of Anti-Soiling Coatings in Hot Desert Climate [12].	This paper investigates the performance of two types of coatings: hydrophobic coatings and photocatalytic hydrophilic coatings.	The application of hydrophobic coating materials on the surface of photovoltaic (PV) modules to reduce the effect of dust accumulation.	The performance of uncoated photovoltaic modules was found to be higher in terms of external quantum efficiency (EQE) compared to coated modules, with a difference of about 1% across all cell positions.	Efficiency: Increased by 1% Temperature: Hydrophobic Contact Angle (WCA): Uncleaned laminated panels experienced a 12.5% decrease in transmission, compared to 17.6% for unlaminated panels,	This study design tested four coated and four uncoated glass coupons outdoors in Dubai. Performance was analyzed by measuring transmittance, water contact angle (WCA), external quantum efficiency (EQE), and I-V curves before and after exposure.
One-step synthesis of SiO2 nanomesh for antireflection and self-cleaning of solar cell [45].	SiO2 nanomesh.	One-step synthesis of hydrophobic SiO2 nanomesh that can be applied as a coating material on the surface of photovoltaic modules, specifically perovskite solar cells (PSCs).	The performance of perovskite solar cells (PSCs) coated with SiO2 nanomesh showed a significant increase in efficiency compared to uncoated PSCs. The efficiency of PSCs made using high-temperature TiO2 (HT) agents increased from 17.18% to 17.95% due to the anti-reflection effect of SiO2 nanomesh, which contributed an additional 4.48% to efficiency.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA):	The study involved a one-step synthesis of SiO2 nanomesh for anti-reflection and self-cleaning applications. The coating's performance was quantitatively verified on two perovskite solar cells, showing a 4.48% and 4.79% efficiency increase at different reaction temperatures.
Highly Water-Repellent and Anti-Reflective Glass Based on a Hierarchical Nanoporous Layer [13].	Polydimethylsiloxane (pdms).	Application of polydimethylsiloxane (PDMS) coating on hierarchical glass nanoporous layer (HNL) to improve its anti-reflective and water-repellent properties.	The research paper does not provide a direct comparison of the performance of photovoltaic modules coated with different types of coating materials with those without coating or with standard coatings.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): 140 degrees	This study design applied a polydimethylsiloxane (PDMS) coating to hierarchical nanoporous glass to evaluate its anti-reflective and water-repellent properties. A quantitative analysis measured the water contact angle and sliding angle, and SEM was used to correlate surface structure.
Micron-Smooth, Robust Hydrophobic Coating for Photovoltaic Panel Surfaces in Arid and Dusty Areas [2].	SiO2, Hexadecyltrimethoxysilane (HDTMS), Tetraethyl orthosilicate (TEOS), Triethoxymethylsilane (METEOS), dan basis elastomer Sylgard184 dan bahan pengawet.	Application of a transparent hydrophobic layer to the surface of a photovoltaic (PV) module.	The study compares the performance of coated photovoltaic (PV) panels with specially designed hydrophobic coatings against uncoated PV panels.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): 122.78 degrees Transmittance increased by 0.69% good mechanical stability.	This study experimentally applied a hydrophobic self-cleaning film to polycrystalline PV modules outdoors for three weeks. The performance of coated panels was compared to uncoated ones, measuring parameters such as dust accumulation and efficiency.
Improving the light transmission of silica glass using silicone as an anti-reflection layer for solar panel applications [17].	Methylsiloxane, which is a type of silicone.	Application of methylsiloxane coating as an anti-reflection (AR) coating on photovoltaic (PV) glass to improve light transmission and improve the performance of solar panels.	Photovoltaic (PV) modules coated with methyl-silicon show better performance compared to those that only have a standard silica coating. The current density (Jsc) increased from 24,817 mA/cm² to 25,024 mA/cm², and the total efficiency	Efficiency: up from 21,747 to 21,992 percent Temperature: reduced Hydrophobic Contact Angle (WCA): Improves light transmission,	This study design applied a methylsiloxane coating to PV modules to evaluate its performance. A qualitative analysis was done through a literature review, and a quantitative data analysis measured the photovoltaic

Title	Population	Intervention	Comparison	Outcame	Study Design
			increased from 21,747% to 21,992% when using a methyl-silicon coating.		performance, optical transmission, and efficiency after coating.
Improvement in optical and electrical performance of hydrophobic and antireflective silica nanoparticles coating on PMMA for lightweight PV module [46].	Nanoparticles silica (SNP), polymethylmethacrylate (PMMA).	Application of silica nanoparticle (SNP) coatings on polymethylmethacrylate (PMMA) substrates for photovoltaic (PV) modules.	The performance of photovoltaic modules coated with silica nanoparticles (SNP-H PMMA) showed a significant improvement compared to those with bare PMMA. The average short-circuit current density (Jsc) for PMMA SNP-H is 34.37 mA/cm², which is an increase of 3.18 mA/cm² compared to naked PMMA, which has a Jsc of 33.23 mA/cm².	Efficiency: Increased by 3.54% Temperature: Hydrophobic Contact Angle (WCA): 115.96° Maximum transmittance 95.68% at 500-1100 nm waves	This study prepared silica nanoparticles (SNP) for application on a PMMA substrate. Its performance was evaluated by measuring optical transmittance, hydrophobicity, and electrical properties. A quantitative analysis compared the efficiency increase of the treated and untreated PMMA.
Hydrophobic and spectrally broadband antireflective methyl-silylated silica [47].	Tetraethyl orthosilicate (TEOS).	The application of an antireflective (AR) coating on the surface of photovoltaic modules to improve their optical transmission properties.	Photovoltaic modules coated with anti-reflective bi-layer (AR) stacks exhibit superior durability and performance compared to those with mono-layer coatings and uncoated modules. A two-layer stack sintered at 550ºC showed a transmission gain of 8.2 over the blank glass after the aging test, indicating improved optical properties and decreased degradation.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): increased Significant improvement in optical performance.	This study design applied methyl-silylation post-treatment to anti-reflection (AR) layers. The coating's performance was evaluated by measuring optical properties and water contact angle (WCA) before and after exposure to humid heat aging conditions.
Facile one-step spraying preparation of fluorine-free transparent superhydrophobic composite coatings with tunable adhesion for self-cleaning and anti-icing applications [48].	Siloxane acrylate (SAC) copolymer, SiO2 nanoparticles.	Development of a transparent superhydrophobic coating that can be applied to a variety of substrates, including photovoltaic modules, to improve their performance.	There are no comparisons, this study focuses on the development of transparent superhydrophobic coatings that are fluorine-free and can be prepared using a one-step spraying method	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): 162.2 ± 1.8° Transparency ~ 90.83% at 550 nm. The adhesion strength of the coating exceeds 0.8 MPa	The provided context does not contain information related to the study design or experimental, qualitative, or quantitative methodologies. Therefore, an answer cannot be generated from the available context.
Empowering Photovoltaic Panel Anti-Icing: Superhydrophobic Organic Composite Coating with In Situ Photothermal and Transparency [1].	Y6-nanosh, nanosuperhidrofobik (nanosh).	A Y6-NanoSH coating is applied to the surface of photovoltaic modules to improve their performance by preventing ice and ice accumulation.	Y6-NanoSH coated photovoltaic panels exhibit negligible voltage and current fluctuations in freezing conditions, unlike uncoated panels that suffer significant performance degradation.	Efficiency: Temperature: increased Hydrophobic Contact Angle (WCA): 162.5 degrees	This study applied a Y6-NanoSH composite coating to PV modules to assess its anti-icing and anti-frosting abilities. A quantitative analysis measured the voltage and current of the coated module under freezing conditions, showing its effectiveness in maintaining performance.
Effects of self-cleaning technique and nanofluid cooling on performance of photovoltaic solar unit employing sinusoidal surfaces [22].	Nanofluida al2o3-h2o	Examine the impact of self-cleaning coatings on photovoltaic thermal systems, especially in relation to dust deposition on PV panels.	The study shows that photovoltaic modules with a hydrophobic self-cleaning coating significantly reduce dust accumulation compared to those without any coating. The amount of dust deposition on coated glass is reduced to 9 gm², 23.5 gm², 21 gm² and 16 gm² for different types of dust, while uncoated glass has higher settling rates of 25 gm², 44.7 gm², 37.8 gm² and 26.8 gm² respectively.	Efficiency: Increased from 8.6% to 10.9%. Temperature: increases the heat transfer coefficient by 15.7% compared to water. Hydrophobic Contact Angle (WCA): increased	This study used ANSYS FLUENT for numerical analysis of a PV-T unit with sinusoidal walls. It simulated dusty conditions to evaluate the effects of hydrophobic self-cleaning coatings on dust accumulation and electrical efficiency, showing a performance increase.
Effects of nanocoatings on the temperature-dependent cell parameters and power generation of photovoltaic panels [49].	Nnano superhidrofobik.	The application of superhydrophobic nano-coating on the surface of photovoltaic (PV) modules is aimed at reducing dust accumulation, which can affect performance.	Photovoltaic modules coated with superhydrophobic nanocoatings showed an increase of about 6.11% in power generation compared to uncoated panels, regardless of the composition of the layers.	Efficiency: Increased by 6.11% Temperature: Hydrophobic Contact Angle (WCA):	This experimental study investigated superhydrophobic nanocoatings on PV modules, measuring their real-time performance in India. Qualitative and quantitative analyses compared the efficiency,

Title	Population	Intervention	Comparison	Outcame	Study Design
					voltage, and power output of coated versus uncoated modules.
Composite Superhydrophobic Coating with Transparency and Thermal Insulation for Glass Curtain Walls [36].	Antimony-doped tin oxide (ATO) nanoparticles and nanosilica, hexadecyltrimethoxysilane (HDTMS) and KH560.	The application of transparent superhydrophobic composite coating using antimony-doped tin oxide (ATO) and nanosilica, achieves excellent superhydrophobicity (WCA ~163°) and high light transmittance (~ 70%).	No comparisons, The study focused on the effectiveness of self-charging electrostatic dust shields for solar cells in Baghdad, not a comparative analysis of various coating materials.	Efficiency: Temperature: 19% Hydrophobic Contact Angle (WCA): 163° High visible transmittance about 70%,	The provided context does not contain information about the study design or specific methodologies for applying coating materials to PV modules. Therefore, the necessary information is not available.
Base-catalyzed synthesis of superhydrophobic and antireflective films for enhanced photoelectronic applications [50].	Transparent silica sole.	Application of anti-reflective (AR) and superhydrophobic (SH) films on the surface of photovoltaic (PV) modules to improve their performance.	The developed photovoltaic modules coated with antireflective (AR) and superhydrophobic (SH) films show an increase in power conversion efficiency (PCE) due to increased light transmittance compared to uncoated modules.	Efficiency: increased from 11.0% to 11.9% Temperature: Hydrophobic Contact Angle (WCA): 169.7°, SA: 3.0° Average transmittance of 93.1% in the wavelength range of 400-900 nm	This study design used an eco-friendly approach to synthesize transparent silica sol for anti-reflective (AR) and superhydrophobic (SH) films. Film performance was evaluated by measuring average transmittance, static water contact angle, and sliding angle.
Antireflective Superhydrophobic and Robust Coating Based on Chitin Nanofibers and Methylsilanized Silica for Outdoor Applications [51].	Chitin nanofibers (chnfs) and methylated silica (Mosil), phytic acid (PA), polyacrylamide (PAM), and calcium ions (Ca^{2+}).	Application of anti-reflective superhydrophobic coating, specifically binder/CHNFS/Mosil layer, on the surface of photovoltaic modules.	Photovoltaic modules coated with binder/CHNFS/Mosil coatings show a voltage increase per unit area of 0.4 mV/cm² when exposed to sunlight with an intensity of 54.3 × 10^3 lx, showing improved performance compared to uncoated or standard-coated modules.	Efficiency: Temperature: Hydrophobic Contact angle (WCA): 160° and shear angle 8° There is a 5.2% increase in transmission at 550 nm. voltage increase per unit area of solar panel by 0.4 mV/cm²	The provided context does not contain specific information about the study design. Therefore, it is not possible to provide an answer based on the given context.
Fluorine-free approaches to impart photovoltaic systems with self-cleaning and anti-icing features[48].	Nanoparticle Silica, Serate Nano Alumina, Seng Oxide, Zirkonia Hexadecyltrimethoxy Silane (HDMTS)	The application of coating materials on the surface of photovoltaic modules involves the use of a non-fluorination coating strategy to create a hydrophobic surface on a glass substrate.	Photovoltaic modules coated with silica, zirconia, and alumina nanoparticles show better performance in preventing ice formation compared to those coated with zinc oxide, although zinc oxide has higher hydrphobicness.	Efficiency: increased Temperature: increased Hydrophobic Contact Angle (WCA): increased	This study design used an experimental approach to measure the performance of PV modules coated with various materials. Qualitative analysis was conducted through a literature review, and a quantitative analysis involved evaluating numerical performance data.
Performance Enhancement of Self-Cleaning Hydrophobic Nanocoated Photovoltaic Panels in a Dusty Environment [52]..	Nanoparticles of silicon dioxide (SiO2).	The application of coating materials on the surface of photovoltaic modules involves several steps, including the process of optimized coating, measurement of contact angle, and actual coating of PV modules.	The research paper focuses on improving the performance of photovoltaic (PV) panels specifically using a layer of hydrophobic silicon dioxide (SiO2) nanoparticles, comparing them to uncoated PV panels.	Efficiency: higher average electrical efficiency is about 13.79%, compared to 13.29% for uncoated panels. Temperature: Hydrophobic Contact Angle (WCA): increased	This study used an experimental design with two identical PV modules: one coated with hydrophobic SiO2 nanoparticles and one uncoated. Performance was quantitatively measured by comparing their energy output, with a qualitative literature review also included.
A three-layer superhydrophobic coatings inspired by human scalp structure with excellent anti-reflection and durable effects for photovoltaic applications [35]..	Tetraethyl orthosilicate (TEOS), trimethylethoxysilane (TMES), hydrophobic vapor-phase nano-silica, and polyethylene glycol-1000 (PEG-1000).	Development of interconnected three-layer superhydrophobic coatings (ITSC) designed for applications in photovoltaic modules.	Photovoltaic modules coated with interconnected three-layer superhydrophobic layers (ITSC) exhibit a maximum output power that is 2.61 times greater than that of uncoated panels after laterite deposition of saline under simulated drizzle conditions.	Efficiency: increased by 195,2% from 125.43mW to 370.29 mW) under simulated drizzle conditions. Hydrophobic Contact Angle (WCA): 160° (WSA) less than 2°. Transmittance increases by an average of 6.44% in harsh environmental conditions, including acid rain and temperature variations.	This study design applied an interconnected three-layer superhydrophobic (ITSC) coating to a PV panel. A qualitative literature review was used, and a quantitative analysis measured the power output of coated versus uncoated panels under varying dust densities.
Experimental Investigation on Synthesis and Characterization of Self-Cleaning Modified	HDTMS modified nano-sio_2.	The application of super-hydrophobic, optically transparent, and self-cleaning modified nano	- Photovoltaic modules coated with HDTMS-Nano-SiO2 showed a 16% increase in efficiency compared to dusty	Efficiency: 16% compared to uncoated dusty panels and by 6.5% compared to regularly cleaned uncoated panels.	This study designed, synthesized, and applied a modified HDTMS-nano-SiO2 coating to a PV cell. A quantitative analysis showed a 16%

Title	Population	Intervention	Comparison	Outcame	Study Design
Super Hydrophobic Nano-Sio 2 Coating for Solar Photovoltaic Applications: Effects of HDTMS and TEA [53].		coatings on the surface of solar photovoltaic (PV) modules to improve their efficiency.	uncoated solar cells, and a 6.5% improvement compared to uncoated manually cleaned solar cells.	Temperature: Hydrophobic Contact Angle (WCA): 152 degrees Stable at temperatures up to 150° C	efficiency increase. Qualitative analysis was performed with SEM, XRD, and EDX. The coating's stability was evaluated over 40 days.
Evaluating a Self-Charging Electrostatic Dust Shield for Solar Cell applications in Baghdad Outdoor Weather [54].	Tin dioxide (sno2).	Application of self-fillable transparent conductive glass, which is prepared by spraying a thin layer of tin dioxide (SnO2) on the glass sheet, to improve the performance of photovoltaic modules.	There is no comparison, the focus of this study is mainly on the effectiveness of self-charging electrostatic dust shields for solar cells in weather conditions outside Baghdad, rather than a comparative analysis of various coating materials	Efficiency: increased Temperature: Hydrophobic Contact Angle (WCA): conductive glass that uses electrostatic force to remove dust.	This study experimentally tested a self-charging transparent conductive glass to remove dust from solar cells in Baghdad. A quantitative analysis measured the "clearing factor" in relation to ambient temperature and humidity, with a qualitative review of other dust removal methods.
Construction of highly hydrophobic and fast endothermic surfaces using candle soot and nano-TiO2 [55]..	Jelaga lilin, Nano-tio2	Highly hydrophobic and rapid development of endothermic surfaces (HHFEs) using wax soot and nano-TiO2, overcoming water and ice resistance in harsh environments.	No comparison, The study focused on the development of highly hydrophobic and rapid endothermic surfaces (HHFEs) using wax soot and nano-TiO2 to improve water and frost resistance in harsh environments.	Temperature: The temperature of HHFE coated glass rises from 16° C to 38° C in 5 minutes under solar irradiation, Hydrophobic Contact Angle (WCA): 120°	The provided context does not contain information regarding the study design or specific methodologies related to experimental, qualitative, or quantitative approaches. Therefore, an answer cannot be generated from the available context.
Inorganic-Nanoparticle-Based Super-Hydrophobic Colored Coatings for Sustainable Building-Integrated Photovoltaics [56]..	Silika hidrofobik (SiO2), NP emas berlapis silika (auSiO2)	Application of colored coatings on the surface of building integrated photovoltaic modules (BIPV) to improve aesthetics and performance.	The performance of tinted glass modules is compared to blank glass modules in terms of power generation efficiency. The colored glass module achieves a power generation efficiency of 89.5% compared to the blank glass module, which results in a higher cumulative solar PV capacity in spring but lower in winter, maintaining a constant ratio of power generation throughout the year.	Efficiency: produces an average power plant of 205 kWh per month, compared to 230 kWh for empty modules. Temperature: Hydrophobic Contact Angle (WCA): Stable layer	This study used a solution-based process to create self-cleaning colored films for BiPV. The performance of the colored glass modules was compared to bare glass modules over a year. A quantitative analysis of power generation and long-term stability tests were included.
Solar PV Panels-Self-Cleaning Coating Material for Egyptian Climatic Conditions [7],. .	Paraffin and dimethyl-siloxane, glycerol, silicon dioxide (SiO2), titanium dioxide (tio2), and aluminum oxide (Al2O3).	The application of self-cleaning coating materials on the surface of photovoltaic (PV) modules to improve their electrical efficiency.	Photovoltaic modules coated with monolithic hydrophobic coatings using paraffin and dimethyl-siloxane showed a significant improvement in electrical efficiency, with values ranging from 14.3% to 17% compared to uncoated panels, which had lower efficiency.	Efficiency: Increased by by 6,4%. Temperature: lower drop Hydrophobic Contact Angle (WCA):	This study design used an experimental method to measure the performance of PV modules coated with various materials. A qualitative analysis was conducted through a literature review, and a quantitative analysis focused on the electrical efficiency and surface temperature.
Hydrophobic Epoxy Caged Silsesquioxane Film (EP-POSS): Synthesis and Performance Characterization [57]..	Silsesquioxane, hydrophobic epoxy (EP-POSS).	The use of EP-POSS material as a protective layer for solar panels is due to its excellent hydrophobicity and abrasion resistance.	With no comparisons, this paper outlines the synthesis and characterization of silsesquioxane embedded in hydrophobic epoxy through a two-stage organic synthesis process. EP-POSS exhibits strong hydrophobic properties with a contact angle of 125°, associated with micro-nanostructured surfaces.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA): 125° Good thermal stability, with an initial decomposition temperature of 354°C.	The provided context does not contain specific information about the study design. Therefore, it is not possible to provide an answer based on the given context.
Degradation of Hydrophobic, Anti-Soiling Coatings for Solar Module Cover Glass [58].	Hydrophobic fluorine, silica nanoparticles	The application of transparent and anti-fouling hydrophobic coating on the photovoltaic module cover glass is a promising solution to reduce the problem of fouling, which reduces power output and return on investment.	This study mainly studies the degradation mechanism of hydrophobic and anti-fouling coatings and their performance when tested under environmental pressure, without directly comparing them with standard uncoated or modular modules.	Efficiency: Temperature: Hydrophobic Contact Angle (WCA):	This study design used an experimental method to test hydrophobic coatings on PV modules under controlled laboratory conditions, focusing on humid heat and UV exposure. A quantitative analysis measured the water contact angle (WCA) and roll-off angle (RoA) before and after exposure.

Some materials also contribute to temperature reduction through enhanced heat transfer or reduced solar absorption. Monolithic hydrophobic coatings using paraffin and dimethyl-siloxane were noted for reduced temperature alongside significant electrical efficiency increases (11.96% to 14.49% and 14.3% to 17%). Methylsiloxane was also observed to reduce temperature and improve light transmission, thereby enhancing efficiency

Several materials analyzed in this review demonstrate the potential for dual benefits in terms of hydrophobicity and thermal management. SiO_2-Polydimethylsiloxane (PDMS) nanocomposite films can reduce module temperature by 3.5 °C and increase water contact angle (WCA) without decreasing power output, indicating efficient passive cooling alongside water-repellent properties. Paraffin and dimethyl-siloxane also lower temperature and significantly improve electrical efficiency (11.96%–14.49% and 14.3%–17%), while methylsiloxane enhances light transmission, reduces temperature, and increases efficiency, with hydrophobicity suggested by the characteristics of "methyl-silylated silica." Melanin nanoparticles and SiO_2 coatings, although primarily functioning as photothermal anti-icing layers that raise temperatures up to 67.6°C, are also superhydrophobic and relevant for cold, ice-prone environments. Meanwhile, the three-layer superhydrophobic ITSC coating—composed of TEOS, TMES, hydrophobic vapor-phase nano-silica, and PEG-1000—exhibits a WCA of 160°, WSA < 2°, a 6.44% increase in transmittance under extreme conditions, and a 195.2% boost in efficiency during simulated drizzle with laterite deposition, representing an exceptional combination of optical benefits and self-cleaning capability.

While substantial progress has been made in developing coatings for solar panels, significant research gaps remain in achieving and comprehensively validating simultaneous self-cleaning capabilities, temperature reduction, and efficiency enhancement. Fragmented reporting, a lack of long-term durability testing, methodological inconsistencies, and scalability challenges hinder the transition from laboratory discovery to widespread commercial application.

To unlock the full potential of PV technology and ensure its sustained growth, future research must adopt a more integrated and holistic approach. This means prioritizing intrinsic multi-functional design, implementing robust long-term validation under real-world conditions, developing scalable and cost-effective manufacturing techniques, and integrating techno-economic analysis and life cycle assessment from early stages. By strategically addressing these gaps, the research community can accelerate the development of the next generation of PV coatings, which will be crucial for enhancing efficiency, reducing maintenance costs, and extending the lifespan of solar modules across diverse operational environments.

3. Quantitative Comparison of Coating Performance

Several coatings demonstrated measurable improvements, including: (1) Three-layer superhydrophobic coating (ITSC) increased maximum output power by 195.2% (from 125.43 mW to 370.29 mW) under simulated drizzle conditions with laterite deposition, and also produced a 6.44% increase in optical transmittance. (2) Al_2O_3–H_2O nanofluid enhanced the heat transfer coefficient by 15.7% and improved efficiency from 8.6% to 10.9% (+26.74%) through reduced dust accumulation. (3) SiO_2–PDMS nanocomposite film lowered the average surface temperature by 3.5 °C without reducing power output, thereby maintaining stable efficiency. (4) Silicon titanium oxide coating with panel inversion provided an 11% efficiency improvement, reaching 2.08 W compared to 2.01 W in uncoated panels. (5) Paraffin/dimethyl-siloxane coatings improved efficiency by 11.96%–14.49% while simultaneously reducing surface temperature. (6) Methylsiloxane coatings enhanced optical transmission and slightly lowered surface temperature, resulting in improved photovoltaic efficiency.

These findings indicate that although each coating highlights different strengths, multifunctional solutions that balance optical transmittance, hydrophobicity, and thermal management are the most advantageous.

4. Economic Considerations

From an economic standpoint, the selection of coatings should take into account not only efficiency improvements but also durability, application costs, and potential maintenance savings. Silica- and silane-based coatings (e.g., SiO_2, HDTMS, TEOS) are readily available, chemically stable, and relatively low-cost, making them attractive for large-scale applications. Nanocomposite films (SiO_2–PDMS, ITSC) require more complex fabrication processes (e.g., roll-to-roll, sol-gel), but they offer high durability and significant efficiency improvements, which can offset the higher initial costs. Organic-based coatings (melanin nanoparticles, paraffin blends) are cheaper but may face long-term stability issues under UV and high-temperature exposure, leading to more frequent replacements.

Economic benefits also arise from reduced cleaning costs and extended module lifespan. For instance, self-cleaning coatings can reduce manual cleaning frequency by up to 50%, while temperature-reducing coatings lessen thermal stress, prolonging module lifespan by several years. Therefore, cost–benefit analyses should be evaluated based on local climate conditions, dust severity, and the economic scale of PV deployment.

5. Practical Implementation Guidelines

For real-world application, climate, environmental conditions, and economic factors must be considered. Tropical regions with high radiation (>1000 W/m²): Prioritize coatings with thermal dissipation properties (e.g., SiO_2–PDMS, paraffin/siloxane) to maintain efficiency under high surface temperatures. Arid and dusty climates: Superhydrophobic coatings (ITSC, HDTMS–SiO_2, MTMS blends) are recommended to minimize dust accumulation and cleaning costs. Cold/subtropical environments: Apply anti-icing coatings (melanin-based, Y6-NanoSH) that combine hydrophobic and photothermal effects. Large-scale solar farms: Silica-based nanocomposites are recommended due to their availability, scalability (spray or roll-to-roll application), and balance between performance and cost.

Overall, the integration of quantitative evaluation, economic feasibility, and practical implementation guidelines demonstrates that silica–silane-based nanocomposites (HDTMS–SiO_2, SiO_2–PDMS) are the most promising candidates for large-scale PV coating applications. These materials provide the best balance of efficiency improvement, cost-effectiveness, and durability, while specialized coatings (ITSC, melanin-based) can be targeted for specific environments requiring extreme performance.

IV. Conclusion

Based on the analysis, modified silica and silane-based nanocomposites, such as HDTMS-nano-SiO_2 and SiO_2-PDMS polymer composites, are the most effective. They exhibit superior hydrophobicity (WCA>150°), facilitating self-cleaning from dust, and significantly enhancing PV module efficiency. For heat mitigation, SiO_2-PDMS stands out with an average temperature reduction of 3.5°C through efficient passive cooling. Meanwhile, melanin/SiO2 nanoparticles and Y6-NanoSH are effective for anti-icing with photothermal effects. Superior coatings should possess high WCA, tunable thermal properties, high optical transmittance, anti-reflection, robust durability, and scalable, cost-effective synthesis. The silica-silane family is the most versatile, though no 'perfect' material exists for all conditions. The three-layer superhydrophobic (ITSC) coating, composed of TEOS, TMES, hydrophobic vapor-phase nano-silica, and PEG-1000, exhibited exceptional superhydrophobicity (WCA 160°, WSA <2°) and a 6.44% transmittance increase in harsh conditions, including temperature variations. The dramatic efficiency increase (195.2%) under simulated drizzle conditions with laterite deposition indicates an outstanding combination of optical and self-cleaning benefits. Future research should focus on developing multifunctional and intelligent coatings that are adaptive, hydrophobic, and heat-reduction. Standardization of testing and reporting protocols is crucial for robust comparisons. Improved characterization and mechanistic understanding are needed. It is also important to prioritize production scalability, cost-effectiveness, and coating optimization for specific climates and module types to accelerate global industrial adoption.

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