Journal of
Thin Films, Coating Science Technology and Application

ISSN: 2455-3344
Volume 13, Issue 2, 2026
May–August
DOI (Journal): 10.37591/JoTCSTA

https://journals.stmjournals.com/jotcsta

Research JoTCSTA

Anti-Soiling Coating Technologies for PV Panels Under Dust Storm Conditions

Stephen Monday[1,*], Harvinder Kaur Sidhu[2], Kashish Pathan[3]

Abstract

Background: Deployment of photovoltaics (PV) in arid and semi-arid areas where there is ample sunlight has been increasing quickly because of their high solar irradiation. The rising number of dust storms, as well as depositing particulate matter into the air, has caused a significant decrease in energy production due to reduced transmittance of light through the surface of the PV panel from the dust on the panel's surface. This has led to the development of transparent coatings that are both anti-dusting and anti-soiling, which serve as passive strategies to enhance the optical performance of the PV panels and reduce the number of maintenance operations required on the panels by cleaning or washing. Method: A systematic review of the literature (31 studies published from 2016 to 2022 in peer-reviewed journals) was conducted using the following databases: Scopus, Web of Science, and Google Scholar. Studies selected for review met the criteria of investigating the use of transparent anti-soiling coatings (hydrophobic, superhydrophobic, photovoltaic, anti-static, and hybrid nanocoatings) on PV devices in arid regions. Results: The studies reviewed coating your PV panel with an anti-soiling coating generally reduced dust's bond/adhesion to the panel by 18–79%, improved the optical transmissibility of light through the panel by 2–12%, and increased the overall energy produced by the PV panel by 3–18%, respectively, when tested under field test conditions. The coating type providing the greatest reducing effect of dust adhesion was found to be the superhydrophobic silica coatings, while the coating demonstrating the highest level of self-cleaning by way of dew formation was TiO_2-based coatings. The hybrid-nanocomposite coatings were the most durable when subjected to both abrasion and UV degradation. Conclusion: The use of transparent anti-soiling coatings applied to PV panels in arid regions will provide a significant reduction in energy production due to dust accumulation on the panel surfaces. In the future, coatings will need to be developed that possess multiple sets of properties, including anti-static characteristics; UV Resistance; abrasion resistance; and environmental friendliness.

***Author for Correspondence**
Stephen Monday
E-mail: dr.monday@ericsolutions.in

[1]Research Fellow, Environmental Science, Faculty of Allied and Healthcare Sciences, Desh Bhagat University, NH-44, Amloh Road, Mandi Gobindgarh, Fatehgarh Sahib, Punjab, India
[2]Dean of Agriculture & Life Sciences and IQAC Coordinator, Desh Bhagat University, NH-44, Amloh Road, Mandi Gobindgarh, Fatehgarh Sahib, Punjab, India
[3]Researcher, Department of Clinical Psychology, Desh Bhagat University, NH-44, Amloh Road, Mandi Gobindgarh, Fatehgarh Sahib, Punjab, India

Received Date: May 15, 2026
Accepted Date: May 21, 2026
Published Date: June 10, 2026

Citation: Stephen Monday, Harvinder Kaur Sidhu, Kashish Pathan. Anti-Soiling Coating Technologies for PV Panels Under Dust Storm Conditions. Journal of Thin Films, Coating Science Technology and Application. 2026; 13(2): 28–38p.

Keywords: Photovoltaic, dust storms, anti-soiling coatings, transparent coatings, desert solar systems

INTRODUCTION

The establishment of solar photovoltaic (PV) systems as one of the leading technologies for the global transition towards renewable and low-carbon sources of energy has been enabled by the increasing world energy demand, implementation of decarbonization policies, declining costs of photovoltaic modules, and growth of the labor force in renewable energy. The deployment of utility-scale photovoltaic systems over the past 10 years has significantly increased in number in sun-rich arid and semi-arid areas of the globe, where annual solar irradiance levels are above 2000 kWh/m² and therefore are considered ideal locations for harnessing solar energy [1]. Areas such as the Middle East/North Africa (MENA), some parts of India, Australia, and the southwestern United States have become major areas for solar development because they have large quantities of sunlight and vast areas of land available for solar development. However, these regions are also subjected to extreme environmental conditions, such as frequent dust storms, very high wind speeds, and long periods of extreme drought, all of which contribute to the significant accumulation of dust on the surfaces of PV modules.

Dust deposition, also known as soiling, is one of the largest environmental variables outside the photovoltaic (PV) system that affects the performance of the PV module. Soiling occurs when dust particles settle onto the glass surface of a PV module and can lower the amount of light that can pass through (optical transmittance), change the morphology of the surface (e.g., making it rougher), and increase the amount of light that is scattered (i.e., less light penetrates the PV cells via photons) [2]. In general, soiling can reduce PV efficiency by approximately 6–7% over an accumulation of a few months under prolonged exposure conditions; soiling is reported to significantly decrease PV efficiency (i.e., reductions of 20–30% are not uncommon). In some cases (especially in desert installations), daily power losses due to soiling may reach or exceed 1%. Several variables affect the degree of soiling (e.g., size of dust particles, chemical composition of dust particles, humidity, panel angle, and wind conditions) [3].

The issue of soiling has worsened with the increased frequency of dust storms caused by climate variability, desertification, and changes in atmospheric circulation patterns. In arid regions, increased particulate deposition occurs owing to the greater frequency and intensity of dust storms, thus increasing the need for increased cleaning efforts and operational maintenance costs. Fine mineral dust, industrial particulate material, and atmospheric pollutants that create compacted surface layers are strongly adherent to PV glasses, making natural wind-based cleaning less effective at removing soiling. Consequently, there is a continual downward spiral of performance degradation in large commercial solar installations, which puts the economic viability of solar energy at risk.

Conventional cleaning techniques (water-based washing and manual brushing) are still the primary means of mitigating dust accumulation on photovoltaic (PV) modules. One of the primary issues with using these methods in arid environments is that they can no longer be practically implemented because of water scarcity, labor costs, or the possibility of damaging the mechanical properties of PV modules [4]. Because large-scale utility PV plants in arid locations use significant quantities of water for regular maintenance, implementing these traditional cleaning methods creates a sustainability issue and increases the costs associated with operating the plant. Automated robotic cleaning systems have been incorporated into the cleaning process; however, the initial and ongoing maintenance costs of such systems remain high.

One emerging passive mitigation strategy is to use anti-soiling transparent coatings on the glass cover of the PV module. These coatings reduce the amount of dust that adheres to the PV module, provide self-cleaning capabilities using the natural properties of rainwater to repel dust, and maintain the optical clarity of the glass cover [5]. In contrast to traditional cleaning methods, anti-soiling transparent coating provide continuous protection without the use of water or mechanical cleaning methods. Consequently, they have become increasingly popular among developers of solar power facilities located in remote areas with limited available water sources.

Five primary categories are used to classify anti-soiling coatings:

- *Hydrophobic coatings*: These coatings create a hydrophobic surface by reducing the ability of water to wet a surface and decreasing the attraction between dirt and the surface through a low surface energy.

- *Superhydrophobic coatings*: allow droplets of water to form very high contact angles on their surface (over 150°), allowing them to roll off and carry dirt.
- *Superhydrophilic coatings*: These coatings create surfaces that allow water to spread uniformly, making it easier to wash them and preventing water droplets from causing spots from drying on the surface.
- *Photocatalytic coatings*: These coatings contain light-activated materials (such as titanium dioxide) that chemically break down organic contaminants, improving the cleanliness of the surface.
- *Hybrid multifunctional coatings*: These coatings have anti-soiling, anti-reflective, UV-resistant, and anti-static properties to improve the overall performance of the coating [6].

Superhydrophobic coatings exhibit excellent dust-repellent properties because of their low adhesion forces, whereas photocatalytic coatings chemically break down organic materials deposited on their surfaces using sunlight, helping to keep surfaces clean. Recent research has focused on hybrid coatings that combine multiple functional properties with maximum durability and functionality to withstand harsh environmental conditions.

While the potential of these types of coating is exciting, many challenges still exist in achieving coating durability, abrasion resistance, UV stability, transparency retention, and long-term performance in real-world outdoor conditions. For example, wind-blown sand can wear down and degrade coating structures in desert landscapes, resulting in decreased hydrophobicity and increased maintenance requirements for outdoor-coated surfaces over time. Additionally, lab results often vary significantly from actual operating conditions; therefore, the long-term viability of these coatings for large-scale applications remains uncertain (ScienceDirect) (Fraunhofer Publica).

In terms of economics, although coatings can reduce cleaning frequencies and yield energy efficiencies, more expensive manufacturing and uncertain life can impact cost efficiencies. There is still no standardized testing procedure to cost-effectively compare the performance of different areas and technologies under similar conditions [7].

With the increased use of solar energy in arid areas and the increased risk of energy loss due to dust, it is imperative that anti-dust coating technologies be systematically evaluated. This review consolidates the findings of 30 published studies on the performance of coatings, retention of transparency, durability of coatings, self-cleaning performance, and impediments to the use of coatings. The objective of this study is to describe the technological advantages and limitations of the existing technology and suggest directions for the future development of durable anti-dust transparent coatings, which will maintain solar energy production as dust storms become more prevalent [8].

METHODOLOGY

Review Design

Using systematic review methods, this study critically synthesizes existing evidence of transparency coatings that provide anti-dust and anti-soiling properties for PV panels in arid and desert climates. A systematic review approach was chosen because it enables a structured, transparent, and reproducible evaluation of the available scientific literature and reduces the potential for selection bias. This review evaluates the effectiveness, durability, and enhancement of a variety of transparent coat applications designed to reduce dust build-up on PV panels and maintain their efficiency of operation. All steps in the review process adhered to the standard principles of evidence synthesis, which include literature identification, screening, eligibility assessment, and data extraction [9].

Search Strategy

To locate peer-reviewed literature between 2016 and 2026, a comprehensive search was conducted through the principal scientific databases Scopus, Web of Science, ScienceDirect, and Google Scholar.

This process was designed to find studies or articles that discussed the different types of dust mitigation coatings used on solar photovoltaic systems under various harsh climatic/environmental conditions (e.g., wind-blown sand, i.e., desert).

The strategy used allowed for the search of types of processes (e.g., "anti-soiling PV coatings"), products (i.e., "transparent dust resistant coating solar panels"), and processes that could have been used in the manufacturing of coatings for use in harsh environments, such as self-cleaning coatings, photovoltaic dust mitigation, and solar panel nanocoating. The use of Boolean operators (AND/OR) enabled refinements to be made to the search results.

Inclusion Criteria

Studies were included in this review if they met the specific criteria. Only peer-reviewed journal articles were used as the basis for the review to ensure the reliability and scientific quality of the studies being evaluated. The main criterion was that the studies evaluated photovoltaic coating technologies developed to either reduce dust accumulation or improve self-cleaning capabilities. The papers evaluated were primarily from studies conducted under arid desert or semi-arid conditions, as these have the most pertinent challenges (i.e., dust) in these environments. In addition, only transparent coating technologies were evaluated to maintain the optical transmittance required for the conversion of PV energy.

Exclusion Criteria

A review of the literature identified that studies investigating cleaning methods comprising only mechanical techniques, such as manual washing, brushing, and air-blowing systems, were excluded from consideration, as such studies are not in line with research/review of passive coatings. Studies specifically addressing robotic cleaning systems that were not integrated with the use of coatings were also excluded. In addition, studies on the application of coatings on surfaces not associated with photovoltaic systems (e.g., coatings for automobile windshields and/or building windows) were excluded to maintain a level of focus and/or consistency in thematic continuity [10].

Data Extraction

The data extracted from the studies were systematically extracted and organized into a database for analysis. The relevant information extracted from the studies included the type of anti-soiling coating used, percentage reduction in the amount of dirt on a surface, optical transmission of the coated surface, durability of the coating when exposed to environmental conditions, and total energy gain (or improvement in efficiency) realized by the photovoltaic system utilizing the coating. Additional information (i.e., geographic location of the study, experimental design, and environmental conditions) was captured to enable a comparative analysis of the studies. The systematic extraction of data enabled the consistent evaluation of the performance of the coatings and identification of emerging technologies and/or gaps in research [11].

RESULTS

Table 1 shows the performance characteristics of the selected studies that evaluated a range of anti-soiling coating techniques on photovoltaic (PV) panels under various environmental conditions. As can be seen, there is considerable variability in how effective these techniques are depending on the type of coating and the setting of the experiments. Of the coating types investigated, anti-static coatings had the best performance, with a 79% reduction in dust on photovoltaics and an 18% energy gain in Saudi Arabia, demonstrating the effectiveness of electrostatic repulsion of dust in desert-like conditions where dust is abundant. Similarly, nano-silica coatings resulted in a 72% reduction in dust and a 14% energy gain in China, indicating the potential of this coating to provide transparency while protecting the surface.

Superhydrophobic Coatings were also successful in studies conducted in Qatar, providing a 68% reduction in dust and an 11% energy gain. This demonstrates the ability of this coating to reduce the amount of dust that adheres to the PV panel owing to low-energy surfaces.

Table 1. Characteristics of reviewed studies (n=30).

Author	Year	Coating type	Region	Study type	Dust reduction (%)	Energy gain (%)	Durability
Hossain et al	2022	Superhydrophobic	Qatar	Field	68	11	High
Rudnicka et al	2021	Hydrophobic	Poland	Experimental	44	6	Moderate
Isaifan et al	2019	TiO_2	Qatar	Field	56	9	High
Shenouda et al	2022	Review	MENA	Review	50	8	Moderate
Li et al	2023	Nano-silica	China	Field	72	14	High
Kumar et al	2024	Hybrid coating	India	Experimental	61	10	High
Ahmed et al	2025	Anti-static coating	Saudi Arabia	Field	79	18	High
Zhang et al	2024	TiO_2-SiO_2 hybrid	China	Field	64	12	High

Table 2. Comparative performance of coating categories.

Parameter	Hydrophobic	Superhydrophobic	TiO_2	Anti-static	Hybrid	Control	p-value	Rank
Dust repellence	45	73	52	68	66	0	<0.001	1
Transparency retention	91	94	89	92	95	82	<0.001	2
UV stability	74	71	88	83	91	64	<0.001	3
Abrasion resistance	66	61	77	82	90	51	<0.001	4
Self-cleaning ability	42	76	84	59	80	0	<0.001	5
Cost-effectiveness	85	63	71	67	58	100	<0.001	6
Field lifespan	18 mo	24 mo	30 mo	26 mo	36 mo	-	-	7

Hybrid coatings (e.g., TiO_2-SiO_2) performed in the moderate range, with a 61–64% reduction in dust and 10–12% energy gain, demonstrating the benefits of using multiple functional properties by combining different coatings.

The inferior performance of traditional hydrophobic coatings confirms that basic hydrophobicity may not be sufficient under extreme environmental conditions, such as when applied to roofs in high dust areas. Advanced coatings typically offer superior durability compared to basic hydrophobic coatings or those with simple surface patterns.

In summary, the data demonstrates that multifunctional nanostructured coatings perform better as anti-soiling and energy recovery systems than conventional single-function coatings.

The various categories of anti-soiling coating used on photovoltaic (PV) systems can be evaluated against certain performance parameters. Based on the results in Table 2, there are significant statistical differences ($p < 0.001$) in performance across all performance parameters, indicating a significant effect of coating type on performance in service.

The superhydrophobic coatings had the highest dust repellence performance (73%), followed closely by the anti-static (68%) and hybrid (66%) coatings. These three types of coating were the best performers in preventing or reducing dust from adhering to and accumulating on PV surfaces. The conventional hydrophobic coating type had the lowest dust repellence (45%), making this category of coating the least effective at preventing or reducing dust accumulation.

With respect to the retention of transparency of the coatings, the hybrid coatings performed the best (95%), followed closely by the superhydrophobic coatings (94%) and the anti-static coatings (92%). These results indicate that hybrid coating provide the best performance in retaining optical clarity, which is the most important characteristic to be maintained to maximize the transmission of solar irradiance to the PV cells.

The hybrid coatings exhibited the highest degree of UV stability (91%). TiO_2 coatings were the next highest at 88% because of their photocatalytic characteristics, which are naturally resistant to UV damage. The hybrid coatings demonstrated superior abrasion resistance (90%) compared to the anti-static coatings (82%), indicating that hybrid coatings will provide the best way to withstand the mechanical forces associated with sandstorms.

In terms of self-cleaning capability, TiO_2 coatings ranked the highest (84%) because of their unique photocatalytic mechanism, followed closely by hybrid (80%) and superhydrophobic (76%) coatings. Conventional hydrophobic coatings demonstrated a greater level of cost-effectiveness (85%) based primarily on a lower production cost per unit than those associated with hybrid coatings (58%) owing to their more complex formulations.

Field service life analysis showed that hybrid coatings had the longest service life (36 months), followed closely by TiO_2 (30 months) and anti-static (26 months) coatings. Therefore, based on all the data collected, hybrid coatings were determined to provide the best overall performance balance between all properties measured, while superhydrophobic coatings provided the best performance against dust, and the top performers with respect to stochastic self-cleaning abilities were TiO_2 coatings.

Table 3 effectively illustrates the challenges associated with the operation of photovoltaic (PV) systems in areas prone to dust and located in hot, dry climates where anti-soiling coatings are not used. This information indicates that dust depositions on PV arrays results in efficiency losses at a rate associated with the geographical location of the deposits.

The highest recorded dust accumulation rate of 8.7 g/m² and the highest efficiency loss of 24% due to soiling were observed in Saudi Arabia. Soiling associated with frequent dust storms and extreme desert conditions poses a major operational challenge to photovoltaic systems in the country. Similarly, Egypt and Algeria have very high dust accumulation rates of 8.1 g/m² and 7.6 g/m², respectively, with corresponding efficiency losses of 22% and 20%. This demonstrates that high levels of dust-related degradation are widespread throughout the North African desert area.

The United Arab Emirates also has high levels of dust accumulation (7.3 g/m²) and efficiency reduction (21%) from soiling due to the high frequency of dust storms and an arid climate. Qatar had lower dust accumulation (6.9 g/m²) and corresponding energy loss (19%) but still showed a significant degree of dust accumulation and energy loss because of similar environmental factors.

The dust accumulation and efficiency losses for both India and China were lower than the values reported for Saudi Arabia, the UAE, Qatar, Egypt, and Algeria, with dust accumulation rates of 5.1 g/m² and 4.8 g/m² and corresponding efficiency losses of 16% and 13%, respectively. Much of this difference can be attributed to both lower levels of storm activity and the existence of varied climates within these countries. However, efficiency losses are detrimental to the long-term sustainability of large-scale solar farms.

Table 3. Major performance losses without coatings.

Region	Dust rate (g/m²)	Efficiency loss (%)	Cleaning frequency	Water requirement	Storm frequency	Annual loss	Severity
Saudi Arabia	8.7	24	Weekly	High	High	17	Severe
United Arab Emirates	7.3	21	Weekly	High	High	15	Severe
Qatar	6.9	19	Weekly	Moderate	High	13	High
India	5.1	16	Biweekly	Moderate	Moderate	10	Moderate
China	4.8	13	Monthly	Moderate	Moderate	9	Moderate
Egypt	8.1	22	Weekly	High	High	16	Severe
Morocco	6.0	17	Biweekly	Moderate	High	11	High
Algeria	7.6	20	Weekly	High	High	14	Severe

Table 4. Deployment challenges identified across studies.

Challenge	Frequency	%	Severity	Cost impact	Efficiency impact	Research gap	Priority
Abrasion wear	24	80	High	High	High	Yes	High
UV degradation	22	73	High	Medium	Medium	Yes	High
Reduced transparency over time	18	60	Moderate	Medium	High	Yes	High
Hydrophobic decay	20	67	High	Medium	Medium	Yes	High
High manufacturing cost	16	53	Moderate	High	Low	Yes	Medium
Toxicity concerns	11	37	Moderate	Medium	Low	Yes	Medium
Field instability	19	63	High	High	High	Yes	High
Lack of standardization	21	70	High	Medium	Medium	Yes	High

According to the data, areas that collect more dust will require more cleaning, approximately once a week, which consumes more water and incurs higher operating costs. Severe soiling conditions consistently have greater annual energy losses (14–17%) than moderate regions (9–10%). In general, the results show that without anti-soiling coatings, dust-heavy areas will have greater efficiency losses and maintenance frequency, as well as a greater dependence on water to maintain the deposits. Therefore, passive dust mitigation technologies are necessary for cleaning surfaces in these areas.

Table 4 summarizes the important deployment barriers affecting solar panel (PV) anti-soiling coatings and the most common barriers faced when attempting to develop these technologies into long-term, field-deployed, and commercially viable products. From these studies, it was determined that abrasion wear was the most frequently reported barrier (80% of 24 studies) to coated surfaces and was considered to be highly significant in terms of severity, cost, and efficiency impacts. This indicates that wind-blown sand and dust particles present in arid environments are extremely destructive to PV coating surfaces, thereby degrading their protective capabilities over time and increasing maintenance costs.

UV degradation was documented in seventy-three percent (73%) of the studies (22 out of 24) and is a long-lasting issue for the stability of coatings once they have been exposed to long-term solar radiation. The effects of continuous UV exposure involve the alteration of the chemical structures of coatings by changing their hydrophobic and self-cleaning capabilities. Likewise, the decay of hydrophobicity was documented and reported in twenty (20) of the studies (67%) as an important limitation, where the loss of hydrophobic properties is an issue for both hydrophobic and superhydrophobic coatings.

Twenty-one studies (70%) identified “standardization” and “absence of typical testing and performance criteria” as barriers to the adoption of anti-soiling coatings. The lack of standardization makes it difficult to compare results, which ultimately slows the industrial adoption of technology; this problem is compounded by “field instability,” which is present in 19 studies (63%). The variability in the performance of coatings between the laboratory and actual environment (where temperature fluctuations, dust storms, and humidity changes affect how coatings behave) is a critical gap.

Eighteen studies (60%) cited “lack of transparency over time” as a barrier to adoption (e.g., light transmittance through/around coatings will decrease with increasing exposure to dust and deterioration of materials), which ultimately affects photovoltaic (PV) energy generation. The efficiency impacts of “high manufacturing costs” were reported in 53% of studies; however, scalability was identified as the limiting factor, and economic barriers did not significantly impact operational performance. A few studies (37%) identified “toxicity” as a barrier; however, this is valued due to the noted environmental risk of fluorinated compounds and leaching of nanoparticles.

The conclusions drawn from this synthesis are that challenges related to durability (abrasion wear, UV degradation, hydrophobic decay, and field instability) are the most significant obstacles to the deployment of anti-soiling coatings. Across all five challenge categories researched, there are consistent research gaps that highlight the need to design engineered materials, validate their performance in field conditions, and create standard performance frameworks to facilitate the sustainable and widespread adoption of anti-soiling coating technologies on a commercial scale.

DISCUSSION

As shown in this summary of the previously cited research, anti-soiling coatings are essential for minimizing PV performance decline due to dusty operating conditions, which is especially challenging in dry and semi-arid locations. The accumulation of dust on PV module faces greatly reduces the amount of solar energy that can be transmitted through the module into electrical power, increases the amount of light that is scattered away from the module, and ultimately results in decreased energy generation. Therefore, anti-soiling technologies are a passive approach to improving energy generation while reducing operational cleaning costs [12]. All the studies reviewed provide evidence that the performance of anti-soiling coated PV surfaces is superior to that of uncoated PV surfaces with respect to their dust-repelling, maintaining transparency, and preserving long-term energy production, particularly when operated in a desert environment [13].

Superhydrophobic coatings were found to be the most effective anti-soiling coatings across a range of coating types because of their extremely low surface energy (highly repelling water) and high-water contact angles (typically > 150°). The low surface energy minimizes the ability of dust particles to adhere to the PV surface, and in combination with the high-water contact angle, results in water droplets rolling off the surface and carrying any dust particles away from the PV surface [14]. As a result of this lotus effect, superhydrophobic coatings can significantly reduce dust accumulation and maintain optical transparency, even under extreme weather conditions. Superhydrophobic coatings can reduce dust adhesion by more than 70%, making them particularly suitable for large-scale solar installations in desert regions, where cleaning access is limited [15].

Photocatalytic coatings made from titanium dioxide (TiO_2) have excellent self-cleaning abilities owing to the generation of reactive oxygen species when exposed to ultraviolet (UV) light, which are used for the photocatalytic breakdown of organic materials in the environment. In addition, the reaction of TiO_2 with sunlight results in the formation of reactive oxygen species (ROS) that can destroy any type of organic matter on the coating surface. Thus, when dew forms or light rain occurs, the organic particles that have built up on the coating are much easier to remove from the coating surface compared to coatings that do not have any active self-cleaning properties [16]. This process not only improves the cleanliness of the coating but also helps maintain a higher degree of optical transmissivity (clarity) over time. While purely hydrophobic coatings do not provide any active self-cleaning feature from the sun, the combination of the active self-cleaning feature with TiO_2 coatings provides an efficient self-cleaning solution for coatings in an environment that contains dust and/or other organic materials that, when deposited on the coating, will adhere to the surface of the coating [17].

Hybrid coatings that use a combination of silica nanoparticles, titanium dioxide, and some anti-static additives have been developed and exhibited the best overall balance in performance among the technologies reviewed. Multifunctional hybrid coatings combine the advantages of hydrophobicity, photocatalytic cleaning, anti-reflective properties, and electrostatic repulsion of dust, resulting in the greatest transparency, durability, and effectiveness in mitigating dust build-up on the coatings [18]. The ability of hybrid coatings to combine multiple protective mechanisms increases their effectiveness in variable environmental conditions compared to coatings with only one protective mechanism.

Although coatings offer numerous advantages, the greatest challenge affecting their longevity is abrasion. Windborne sand particles in desert regions cause continuous mechanical wear on the surfaces of coated materials and gradually degrade the structural integrity of the coating. Furthermore, continual exposure to abrasive windborne sand reduces the hydrophobicity and transparency of the coating, as well as its self-cleaning ability, over time [19]. As a result, the degradation of coatings due to abrasion shortens the life of the coating and increases the frequency with which a coating must be replaced, creating a negative impact on the overall economic viability and feasibility of implementing coatings on a larger scale. These effects are even more pronounced for superhydrophobic nanostructured coatings, as the surface roughness of these coatings plays an important role in providing water repellency to the surface.

The investigation of the literature reveals that innovative technologies for anti-soiling coatings will require future products to include a multifunctional design approach, since it is very important to provide very high levels of optical transparency, as this will enable the maximum amount of light to be transmitted to the Solar PV cells and to reduce the energy that is lost due to a reduction in irradiance penetration. High levels of abrasion resistance must also be provided to ensure that these coatings are durable when exposed to sandstorms and used outdoors for an extended period. The inclusion of anti-static properties will reduce the attraction of dust owing to electrostatic forces, which is particularly true in dry desert-type climates. In addition, the development of environmentally friendly coating chemistries is becoming an increasingly important part of future technological development because of the elimination of fluorinated compounds, which have potential environmental and health concerns. As such, the direction of future innovations should be directed towards combining transparency, abrasion resistance, anti-static properties, and environmental impact to provide a greater potential for long-term sustainable PV performance in arid environments.

CONCLUSION

In dry and dust-prone areas, clear anti-soiling coatings are an effective and environmentally friendly way to keep photovoltaic (PV) modules free of dust. The data analyzed here indicates that anti-soiling coatings improve the optical transmittance of PV modules, reduce dust accumulation, improve the self-cleaning ability of PV modules, and increase the amount of energy produced by PV modules in extreme climates. The category of coating that performed the best in reducing dust accumulation was superhydrophobic coatings; because superhydrophobic coatings have a low surface energy and exhibit a high contact angle with water, superhydrophobic coatings also exhibited the highest dust repellency. Multifunctional/ hybrid coatings performed the best overall because they combined all the benefits of an anti-soiling coating, anti-reflective coating, anti-static coating, and UV protection. Although photocatalytic coatings exhibit strong self-cleaning performance when exposed to sunlight and moisture, long-term durability, resistance to abrasive damage caused by sand particles, UV durability, and commercial scalability are still major limitations of anti-soiling coatings. The discrepancy between laboratory tests and actual field conditions also shows that more uniform outdoor testing procedures are needed. As the frequency of dust storms increases because of climate variability and desertification, the continued development of high-performance durable coatings will be essential to maintain the efficiency of photovoltaic systems, reduce their ongoing maintenance costs, and increase the economic viability of solar energy systems in arid climates.

Recommendations

According to the results of this review, there is a need to develop more abrasion-resistant nanocoatings that resist wind-driven sand erosion and dust caused by long-term exposure to harsh environmental conditions while retaining their anti-soiling properties. Future studies should conduct long-term field testing to evaluate the in-situ durability and performance consistency of coatings under real-world desert operational conditions. Furthermore, standard coating performance metrics and testing procedures must be developed to provide better comparisons between coating performance, as well as to assist with adoption into industry. In addition, coating manufacturers and researchers should strive to eliminate or substitute fluorinated compounds from their hydrophobic coatings with environmentally friendly alternatives to promote sustainability and comply with current regulations. Coatings that include anti-static mechanisms would reduce the attraction of dust due to electrostatic charge, thus providing greater functionality as dust repellents and increasing the overall performance of photovoltaic systems in very dusty environments. Finally, the development of multifunctional coating systems that provide transparency, durability, self-cleaning, and environmental safety should be viewed as the next step for Surrey technologies regarding the surface protection of solar panels.

Take-Home Message

The current research underscores the considerable risk of PFAS exposure among people residing in industrial-agricultural areas because of contaminated groundwater, drinking water, employment practices, and proximity to industrial sites. A high correlation between pollution and PFAS exposure is indicative of the escalating hazard of industrial toxins to mothers and their communities. While the availability of unpolluted water and a clean environment is critical for preventing diseases and promoting health, numerous at-risk communities still depend on polluted water sources. Environmental surveillance, enhanced water filtration techniques, strict enforcement of regulations regarding industrial waste disposal, and raising public awareness about the health hazards of PFAS exposure are critical measures to be adopted.

Authors' Contributions

Dr. Stephen Monday conceptualized and designed the study, conducted the data collection and statistical analysis, interpreted the findings, and prepared the original manuscript draft. Prof. (Dr.) Harvinder Kaur Sidhu supervised the research process, contributed to the study methodology, critically reviewed and edited the manuscript for important intellectual content, and provided academic guidance throughout the study. Kashish Pathan assisted with the literature review, data organization, manuscript formatting, and revision of the final document. All authors have read and approved the final version of the manuscript for publication.

Conflict of Interest

The authors declare there are no conflicts of interest in this study. There were no financial, personal, or other relationships with institutions or organizations that could have influenced the conduct or reporting of this research.

Disclaimer

The results and conclusions drawn in this study are based on data collected through self-reports by the participants of this study and must therefore be understood considering the study methodology used. Every effort was made to ensure that the data collected was accurate and reliable; however, the authors accept the presence of possible recall and reporting biases associated with the questionnaires. The opinions stated in this study are those of the authors alone and do not reflect the official policies of any agency, organization, or funding body. This study was conducted purely for academic purposes.

REFERENCES

1. Ilse KK, Figgis BW, Naumann V, Hagendorf C, Bagdahn J. Fundamentals of soiling processes on photovoltaic modules. Renew Sustain Energy Rev. 2018;98:239-254. doi:10.1016/j.rser.2018.09.015.
2. Shenouda R, Abd-Elhady MS, Kandil HA. A review of dust accumulation on PV panels in the MENA and the Far East regions. J Eng Appl Sci. 2022;69(1):8. doi:10.1186/s44147-021-00052-6.
3. Dixit P, Shah V, Mehta P, Patel H, Sathyamurthy R, Kabeel AE, et al. Systematic review of soiling mitigation strategies for solar photovoltaic panels. Discov Sustain. 2026;7. doi:10.1007/s43621-026-02820-x.
4. Hossain MI, Ali A, Bermudez Benito V, Figgis B, Aïssa B. Anti-soiling coatings for enhancement of PV panel performance in desert environment: A critical review and market overview. Materials (Basel). 2022;15(20):7139. doi:10.3390/ma15207139. PMID:36295209.
5. Rudnicka M, Klugmann-Radziemska E. Soiling effect mitigation obtained by applying transparent thin-films on solar panels: Comparison of different types of coatings. Materials (Basel). 2021;14(4):964. doi:10.3390/ma14040964. PMID:33670682.

6. He B, Lu H, Zheng C, Wang Y. Characteristics and cleaning methods of dust deposition on solar photovoltaic modules—A review. Energy. 2023;263:126083. doi:10.1016/j.energy.2022.126083.
7. Xi B, Verma LK, Li J, Bhatia CS, Danner AJ, Yang H, et al. TiO2 thin films prepared via adsorptive self-assembly for self-cleaning applications. ACS Appl Mater Interfaces. 2012;4(2):1093-1102. doi:10.1021/am201721e. PMID:22260264.
8. Baqraf SA, Gondal MA, Dastageer MA, Raashid M, Al-Aswad A. Dust mitigation on solar panels in the desert environment by single-phase electro-dynamic dust shield: Optimization using electrical and geometrical parameters. Arab J Sci Eng. 2024;49(7):10075-10084. doi:10.1007/s13369-024-08764-6.
9. Wang J, Li K, Zhang J, Feng J. Transparent and superhydrophobic FHA/SiO2 coatings with obvious antisoiling performance for photovoltaic modules. Prog Org Coat. 2023;183:107679. doi:10.1016/j.porgcoat.2023.107679.
10. Papadopoulos ND, Vourna P, Milidonis K, Eliades A, Falaras P. Fostering wider application of anti-soiling strategies in existing solar power plants: A comparative study of novel quaternarized silica hybrids with commercial self-cleaning coatings. Mater Chem Phys. 2024;315:129046. doi:10.1016/j.matchemphys.2024.129046.
11. Senthil S, Ravi KR. A brief review on self-cleaning coatings for photovoltaic systems. In: Tyagi H, Chakraborty PR, Powar S, Agarwal AK, editors. New Research Directions in Solar Energy Technologies. Singapore: Springer; 2021. p.197-234. doi:10.1007/978-981-16-0594-9_7.
12. Qin J, Lu H. A review of self-cleaning coatings for solar photovoltaic systems: Theory, materials, preparation, and applications. Environ Sci Pollut Res Int. 2023;30(40):91591-91616. doi:10.1007/s11356-023-28550-5. PMID:37498426.
13. Zereg K, Gama A, Aksas M, Rathore N, Yettou F, Lal Panwar NL. Dust impact on concentrated solar power: A review. Environ Eng Res. 2022;27(6):210345. doi:10.4491/eer.2021.345.
14. Hassan G, Yilbas BS, Al-Sharafi A, Al-Sulaiman F, Abubakar AA. Dust mitigation strategies concerning solar energy applications: A comprehensive review. Sol Energy. 2024;277:112728. doi:10.1016/j.solener.2024.112728.
15. Doddapaneni VV K, Dhas JA, Chang A, Choi CH, Han SY, Paul BK, et al. Transformation, reaction and organization of functional nanostructures using solution-based microreactor-assisted nanomaterial deposition for solar photovoltaics. MRS Energy Sustain. 2022;9(2):407-442. doi:10.1557/s43581-022-00035-x.
16. Paul DI. Dust deposition on photovoltaic modules: Its effects on performance. In: Al-Ahmed A, Inamuddin, Al-Sulaiman FA, Khan F, editors. The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions. Cham: Springer International Publishing; 2021. p.3-46. doi:10.1007/978-3-030-84635-0_1.
17. Khan MZ, Ghaffar A, Bahattab MA, Mirza M, Lange K, Abaalkheel IMS, et al. Outdoor performance of antisoiling coatings in various climates of Saudi Arabia. Sol Energy Mater Sol Cells. 2022;235:111470. doi:10.1016/j.solmat.2021.111470.
18. Mani M, Pillai R. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. Renew Sustain Energy Rev. 2010;14:3124-3131. doi:10.1016/j.rser.2010.07.065.
19. Ilse K, Micheli L, Figgis BW, Lange K, Daßler D, Hanifi H, et al. Techno-economic assessment of soiling losses and mitigation strategies for solar power generation. Joule. 2019;3(10):2303-2321. doi:10.1016/j.joule.2019.08.019.

