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

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Abstract

Background Deployment of photovoltaics (PV) in arid and semi-arid areas where there is ample sunlight has been increasing quickly because of their great solar irradiation. The rising number of dust storms, as well as depositing particulate matter to the air, have 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 soiling, which serve as passive strategies to be able to enhance the optical performance of the PV panels and reduce the number of maintenances 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, 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 From 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 were 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 of energy produced by 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 environmentally-friendly.*

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 global transition towards renewable and low carbon sources of energy has been enabled by the increasing world energy demand; the implementation of decarbonization policies; the declining costs of photovoltaic modules; and the growth of the labour force in renewable energy and the deployment of utility scale photovoltaic systems over the past 10 years, which has significantly increased in number in sun-rich arid and semi-arid areas of the globe

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where annual solar irradiance levels are above 2000 kWh/m² and therefore are considered as ideal locations for harnessing solar energy [1]. Areas like 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, which all contribute to significant accumulation of dust on the surfaces of PV modules.

Dust deposition, a.k.a. soiling, is one of the largest environmental variables outside of the PV (photovoltaic) system that impacts how the PV module performs. Soiling occurs when dust particles settle onto the PV module's glass surface and can lower how much light can pass through (optical transmittance), change the morphology of the surface (e.g., making it more rough), and increase how much light 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, but in 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 soiling may reach, or exceed, 1%. There are several variables affecting the degree to which soiling occurs (e.g., size of dust particles, the chemical composition of dust particles, humidity, panel angle, and wind conditions) [3].

With increased frequency of dust storms caused by climate variability, desertification, and changes in atmospheric circulation patterns, the issue of soiling has worsened. In arid regions, increased particulate deposition occurs due to the greater frequency and intensity of dust storms, thus increasing the need for increased cleaning efforts and operational maintenance costs. Fine mineral dusts, 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. As a result, there is a continual downward spiral of performance degradation of large commercial solar installations, which puts the economic viability of solar at risk.

Conventional cleaning techniques (water-based washing and manual brushing) are still the primary means of mitigating dust accumulation on photovoltaics (PV) modules. One of the primary issues of using these methods in arid environments is that these techniques can no longer be practically implemented due to water scarcity, labor costs, or the possibility of damaging the mechanical properties of the 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 cost associated with operating the plant. Automated robotic cleaning systems have been incorporated into the cleaning process; however, the initial and ongoing maintenance costs for such systems are still quite high.

As such, 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 by using the natural properties of rainwater to help repel dust, and maintain the optical clarity of the glass cover [5]. In contrast to traditional cleaning methods, anti-soiling transparent coatings provide continuous protection without the use of water or mechanical cleaning methods and, as a result, have become increasingly popular with 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 low surface energy.

- *Superhydrophobic coatings*: allow for droplets of water to form very high contact angles on their surface (over 150°), allowing them to roll off and carry dirt with them.
- *Superhydrophilic coatings*: These coatings create surfaces that allow water to spread uniformly, making it easier to wash them, causing water droplets to not cause spots from drying on the surface.
- *Photocatalytic coatings*: These coatings contain light-activated materials (like titanium dioxide) that chemically break down organic contaminants, which improves 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, while photocatalytic coatings chemically break down the organic materials deposited on their surfaces by sunlight and help keep surfaces clean. Recent interest has focused on hybrid coatings that combine multiple functional properties with maximum durability and functionality to withstand the effects of harsh environmental conditions.

While the potential for these types of coatings 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 is still uncertain (ScienceDirect) (Fraunhofer Publica).

Also, in relation to 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 performance between 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 technology 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 the impediments to the use of coatings. The objective is to describe the technological advantages and limitations of existing technology and suggest direction 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 synthesises existing evidence of transparency coatings that provide anti-dust & 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 coats applications designed to reduce dust build-up on PV panels and maintain their efficiency of operation. All steps in the review process adhere to standard principles of evidential synthesis, which include literature identification, screening, eligibility assessment, and data extraction [9].

Search Strategy

In order 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., windblown 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, solar panel nanocoatings). 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 qualified under specific criteria. Only peer-reviewed journal articles were used as the basis for the review to ensure reliability and scientific quality of the studies being evaluated. The main criteria were 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 done under arid desert or semi-arid conditions, as these have the most pertinent challenges (i.e.; dust) to these environments. In addition, only transparent coating technologies were evaluated in order 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 comprised of 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 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 included studies were extracted in a systematic manner and organized into a database for analysis. The relevant information extracted from the studies included the type of anti-soiling coating used; the percentage of reduction in the amount of dirt on a surface; the optical transmission of the coated surface; the durability of the coating when exposed to environmental conditions; and the 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 comparative analysis of the studies. The systematic extraction of the data enabled an ability to consistently evaluate the performance of the coatings and to identify emerging technologies and/or gaps in research [11].

Results

Table 1 shows the performance characteristics of selected studies evaluating a range of anti-soiling coating techniques on photovoltaic (PV) panels in 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 for this coating to provide transparency to protect the surface.

Superhydrophobic Coatings were also successful in the 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 due to low energy surfaces.

Hybrid Coatings (e.g., TiO_2-SiO_2) performed in the moderate range, with 61%-64% Reduction in Dust and 10%-12% Energy Gain; demonstrating the benefits of using multiple functional properties by combining different coatings.

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

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

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

The various categories of anti-soiling coatings used on photovoltaic (PV) systems can be evaluated against certain performance parameters, and 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 coatings (68%) and the hybrid coatings (66%). These three types of coatings were the best performers at preventing or reducing dust from adhering to and accumulating on PV surfaces. The conventional hydrophobic coat type had the lowest dust repellence (45%) performance, making this category of coatings 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 coatings provide the best performance at retaining optical clarity – the most important characteristic to be maintained in order to maximise the transmission of solar irradiance to the PV cells.

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

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

In terms of self-cleaning capability, TiO_2 coatings again ranked 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%) due to their more complex formulations.

The field service life analysis showed hybrid coatings have 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 are determined to provide the best overall performance balance between all properties measured; while superhydrophobic coatings will provide the best performance against dust; and the top performers with respect to stochastic self-cleaning abilities will be TiO_2 coatings.

Table 3 is an effective illustration of 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. The information indicates that dust deposition on PV arrays results in efficiency losses that occur at a rate associated with the geographical location where deposits occur.

The highest recorded dust accumulation rate of 8.7 g/m² and the highest efficiency loss of 24% from soiling was observed in Saudi Arabia. Soiling associated with frequent dust storms and extreme desert conditions pose a major operational challenge to photovoltaic systems located in the country. Similarly, both 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 the high levels of dust-related degradation are widespread throughout the North African desert area.

The United Arab Emirates also have high levels of dust accumulation (7.3 g/m²) and efficiency reduction (21%) from soiling due to a 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 are 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 those countries. Regardless, the efficiency losses are still detrimental to the long-term sustainability of large-scale solar farms.

According to the data, areas that collect more dust will need more cleaning, about 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 greater dependence on water to maintain the deposits. As a result, passive dust mitigation technologies are necessary for cleaning surfaces in these areas.

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

Table 4 shows a summary of 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 repeatedly 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 leading to increased costs of maintenance.

UV degradation was documented in seventy-three percent (73%) of the studies (22 out of 24) and is also 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 chemical structures in 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 adoption of anti-soiling coatings. Lack of standardization makes it difficult to compare results, which ultimately slows industrial adoption of technology; this problem is compounded by "field instability," which is present in 19 studies (63%). Variability in the performance of coatings between the lab and the actual environment (where temperature fluctuations, dust storms, and humidity changes will 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 will also ultimately affect 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 operational performance was not significantly impacted by economic barriers. There were few studies (37%) that identified "toxicity" as a barrier, however, this is valued due to the noted environmental risk of fluorinated compounds and leaching of nanoparticles.

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 in order to facilitate the sustainable and widespread adoption of anti-soiling coating technologies on a commercial scale.

DISCUSSION

As you can see from this summary of the previous 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 will result in decreased energy generation. Therefore, anti-soiling technologies are a passive approach to improving energy generation, while also 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 coating across a range of coating types because of their extremely low surface energy (highly repelling to water) and high water contact angles (typically > 150°). The low surface energy minimizes the ability for dust particles to adhere to the PV surface and, in combination with the high water contact angle, results in water droplets rolling off of the surface 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. Superhydrophobic coatings can reduce dust adhesion by more than 70%, making them particularly appropriate 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, due to the generation of reactive oxygen species when exposed to UV (ultra violet) 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; it also helps to maintain a higher degree of optical transmissivity (clarity) over time. While coatings that are purely hydrophobic 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 to the 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. The 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 when compared to coatings with only one protective mechanism.

Though coatings certainly offer numerous advantages, to date, the greatest challenge that affects coating performance longevity is abrasion. Windborne sand particles in desert regions cause continuous mechanical wear to the surfaces of coated materials and gradually degrade the structural integrity of the coating. Furthermore, continual exposure to abrasive wind-borne sand reduces both 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 the 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.

The investigation of the literature reveals that innovative technologies for anti-soiling coatings will require future products to include a multi-functional design approach, since it is very important to provide very high levels of optical transparency as this will enable the most 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 in order to ensure that these coatings will be durable when exposed to sandstorms and when used outdoors for an extended period of time. The inclusion of anti-static properties will reduce the attraction of dust due 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 technology developments due to 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 accumulation. The data analysed here indicate 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 to 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. While photocatalytic coatings exhibited strong self-cleaning performance when exposed to sunlight and the presence of moisture, long-term durability, resistance to abrasive damage caused by sand particles, UV durability and commercial scalability are still the major limitations of anti-soiling coatings. The discrepancy between laboratory tests and actual field conditions also shows that there is a need for more uniform outdoor testing procedures. As the frequency of dust storms rises 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 article review, there is the necessity for developing more abrasion resistant nano-coatings that resist the wind-driven sand erosion of dust caused from long-term exposure to harsh environmental conditions, while retaining their anti-soiling properties. Future studies should conduct long-term field testing to evaluate in-situ durability and performance consistency of coatings under real-world desert operational conditions. Further, standard coating performance metrics and testing procedures must be developed to provide better comparisons between coating performance between studies as well as to assist with adoption into industry. In addition to the above, coating manufacturers and researchers should strive to eliminate or substitute fluorinated compounds from their hydrophobic coatings for 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 repellants 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 that there is a 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 an escalating hazard of industrial toxins to mothers and their communities. While the availability of unpolluted water and the environment is critical for preventing diseases and promoting health, numerous at-risk communities still depend on polluted sources of water. Environmental surveillance, enhanced water filtration techniques, strict enforcement of regulations regarding waste disposal from industries, and raising public awareness about the health hazards of PFAS exposure are critical measures to adopt.

Authors' Contributions

Dr. Stephen Monday conceptualized and designed the study, conducted 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, reviewed and edited the manuscript critically for important intellectual content, and provided academic guidance throughout the study. Kashish Pathan assisted with literature review, data organization, manuscript formatting, and revision of the final document. All authors read and approved the final version of the manuscript for publication.

Conflict of Interest

The authors have declared that there are no conflicts of interest for this article. There was no financial, personal, or other relationship with institutions or organizations that could have influenced the conduct or reporting of this research.

Disclaimer

The results and conclusions drawn in this study have been based on data collected through self-reports by the participants of this study and must therefore be understood in light of 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 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 done purely for academic purposes only

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