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RESEARCH ARTICLE

A Comprehensive Review of the Soiling Effects on PV Module Performance

MUHANNAD J. ALSHAREEF
Department of Electrical Engineering, College of Engineering and Computing in Al-Qunfudhah, Umm Al-Qura University, Mecca 24382, Saudi Arabia
e-mail: mjshareef@uqu.edu.sa

ABSTRACT Photovoltaic (PV) systems are a popular renewable energy source globally, owing to their beneficial environmental and economic properties. However, their efficiency is impacted by various environmental and weather conditions, including dust accumulation, which harms the performance of solar cells, particularly in hot and dry regions. Several researchers have studied how to clean and minimize dust on PV modules. This paper reviews recent studies on the effects of dust on PV systems and effective cleaning methods. Some locations experience power losses of over 1% each day and 80% monthly efficiency reduction due to dust, which is substantial. This paper delivers a thorough review of the issue of dust on PV modules. It analyzes previous research on how photovoltaic (PV) systems function when exposed to a mix of dust accumulation and other environmental factors. It also delves into the development of models to forecast dust accumulation. Furthermore, it examines various aspects of PV module design, including the frequency of cleaning methods, economic factors, and their advantages and disadvantages. Additionally, the study identifies several research gaps that require further exploration. These gaps include developing artificial intelligence-based models for reducing dust accumulation, dynamic optimization models for cleaning schedules, as well as advanced techniques for predicting dust accumulation, taking into account environmental conditions and ageing procedures. This information is essential for engineers, designers, and researchers who work on PV systems.

INDEX TERMS Solar energy, soiling, dust, PV performance, soiling mitigation approach, cleaning period.

I. INTRODUCTION

Growing concerns worldwide regarding the impact of increasing energy consumption on global warming have spurred governments to advocate for the advancement of Renewable Energy Sources (RESs) [1], [2], [3]. Meeting the sustainable development goals set out in the 2030 agenda, which involve increasing the share of RESs in the global energy mix, is now considered indispensable [4], [5]. Out of the various forms of renewable energy, solar energy has garnered considerable interest because of its plentiful availability and economic viability, especially with the utilization of Photovoltaic (PV) panels [6], [7], [8], [9], [10], [11]. These panels have the ability to convert solar irradiation into electricity [4], offering several benefits such as low CO_2 emissions and environmentally sound operation [12]. The PV industry has demonstrated remarkable growth, with total global capacity reaching 942 GW by the end of 2021, including on-grid and off-grid systems [13]. Figure 1 shows the impressive annual growth rate of 162 GW in 2022 [14], demonstrating the significant potential of solar PV systems in the long term due to ongoing quality improvements and cost reductions [15], [16], [17], [18]. There are several uses for solar energy that make use of the thermal energy that radiation carries, including heating the air, heating the water for domestic and commercial use, and solar distillation [19]. Electricity production using solar energy can be achieved through various hybrid systems, such as solar chimneys, concentrated solar power plants, and photovoltaic cells (PV) [20], [21], [22]. The successful application of PV is due to various technological advancements that have increased electrical productivity and reduced its cost [23].

The effectiveness of PV technology is greatly impacted by external environmental factors, including temperature,

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cloud, relative humidity, shade, wind, and absence of solar energy in some regions, thereby serving as its disadvantage [24], [25]. However, several methods and techniques have been devised by researchers to mitigate these negative effects while simultaneously exploiting their positive impacts [26]. For example, high solar radiation increases cell temperature, which reduces their electrical efficiency. To address this issue, researchers designed PV/T systems that generate energy from the heat produced by PV cells while also cooling them using air, water, nanomaterials, and phase-changing substances with nanofluids, enhancing their productivity [27], [28]. Dust accumulation and pollutants on the cell surface is another weather factor that affects the performance of PV cells by acting as a barrier between the cells and irradiation, leading to decreased efficiency [29].

Dust refers to any substance or particles in the atmosphere less than 500 μm in diameter, it includes solid inorganic and organic particles such as soil, smoke, volcanic vapor, bacteria, pollen, fungi, microfibers, and eroded limestones [30].

Except for fracture, MSHA defines dust as solid particles that persist in the atmosphere without changing their physical or chemical characteristics. Dust comes in various sizes, shapes, volumes, and chemical concentrations, which depend on geographical location and local activities. Soiling refers to the accumulation of dirt, dust, and contamination on solar PV module surfaces, causing adverse optical effects that hinder solar irradiance transmittance and overall performance. Following solar irradiation and temperature, dust accumulation is the third largest factor impacting the performance of solar PV modules. However, soiling loss levels are difficult to generalize, given that the severity of soiling is affected by geographical location and seasonal climatic conditions. This issue requires rigorous research [31], [32].

Dust formation on solar panel surfaces is influenced by weather conditions, topography, and metropolitan regions. Variables such as shape, circulation, weight, width, structure, charge, and chemistry are significant factors in studying dust particle generation [33], [34], [35]. Dust formation on PV systems is also influenced by humidity, wind speed, PV panel tilt angle, and time [36], [37], [38]. Soiling on PV modules due to dust, dirt, and grime causes power loss during various weather elements such as wind, pressure, and temperature [39]. Figure 2 demonstrates the various causes of dust formation on solar panels and the correlation between selected variables. The impact of dust on the performance of solar PV panels is a well-researched topic, and various studies have been published on the subject. Factors such as the type of PV panel, tilt angle, temperature, solar radiation, wind speed, dust, and relative humidity all affect the performance of PV systems [40], [41]. The combination of these factors impacts the PV system's operating properties, including the current and voltage, which are essential power-generating elements.

Several research works have addressed the impact of dust accumulation and proposed different cleaning methods. For example, studies have shown that substantial losses of power reaching up to 80% occur in desert areas due to dust accumulation [42]. In addition, literature reviews have investigated the effects of dust on PV module performance in specific climatic conditions and potential mitigation measures [43]. There has also been much research on how air pollution and soiling affect PV module performance, as well as its techno-economic implications [44].

Despite several decades of research on the influence of dust accumulation on PV systems, the problem of energy loss remains a significant challenge that requires permanent solutions for sustained efficiency of PV modules [45]. Several academic papers have discussed different techniques for managing the influence of dust on PV modules and reducing its negative effects [46]. Reviews have documented strategies for preventing and addressing dust accumulation on PV modules. In 2016, there was a considerable rise in research and development publications focusing on mitigating the effects of dust on PV module efficiency, with an increase of approximately 80% from 2015 [47].

Reference [42] seeks to examine, categorize, and discuss the most notable advancements within the field of PV cleaning research. The primary focus of this study is to assess how cleaning methods impact the efficiency of PV systems. It is worth noting that this research article provides a comprehensive review of cleaning techniques employed to counteract the influence of dust on modules, but the timeframe of analysis only spans from 1940 to 2020.

In contrast, [34] conducts a thorough review of the diverse environmental, operational, and maintenance factors that affect the performance of solar PV modules. However, it lacks in its evaluation of different cleaning approaches.

Meanwhile, [43] offers a review of the consequences of dust accumulation on PV module performance and provides measures to mitigate these effects. Nevertheless, this paper does not address soiling modeling and forecasting, nor does it make comparisons between various cleaning methods.

In [41], the influence of crucial elements in dust accumulation on the surface of PV modules is outlined, including factors like relative humidity, rainfall, and gravity. The study examines and addresses the decline in power production capacity observed in PV modules situated in diverse global locations due to the deposition of dust on their surfaces. It can be inferred that most reviews in this area often neglect crucial elements. These include the comparison of cleaning methods, integration of soiling modeling and forecasting, examination of the economic aspects of cleaning methods, present a future perspective on PV, and conducting an assessment that identifies potential challenges and opportunities for further research.

Therefore, this paper seeks to address the gap in the aforementioned review papers. It starts by exploring different aspects of photovoltaic module design and also investigate existing studies on the operation of photovoltaic (PV) systems when subjected to a combination of dust accumulation and other environmental conditions. Additionally, it delves into the prediction of models for dust accumulation.

Moreover, this study examines various cleaning methods that can be used during the operation of PV systems to optimize their cleaning frequency and scheduling.

The review also contains a section on the frequency of cleaning techniques, economic aspects, and their benefits and drawbacks.

The assessment highlights potential difficulties and possibilities for additional research.

The findings of this investigation may be used as a foundation for further research projects, analyze the gaps and weaknesses in the previously examined research.

This review is organized methodically and can be divided into several sections, each of which provides a comprehensive summary of the topic. The first section explains the background and establishes the need for this particular review.

Section II examines various aspects of photovoltaic module design that are relevant to the topic, including tilting angle, orientation, glazing surface characteristics, and solar panel height.

Section III is focused on discussing dust particle properties in depth. There will be a discussion about dust, including its properties, origins, and demonstrates the numerous soiling processes.

Section IV introduces how solar panels become soil over time, the effects that soiling has on the efficiency of the PV panels, and methods for reducing the negative impact of soiling.

Section V discusses soiling prediction and modeling, which is divided into two sections: Environment and Soiling and Soil Simulation and Estimation. It also discusses the environmental factors that affect dust accumulation on PV panels, and the corrective actions needed to address concerns with losses of power and reduced performance brought on by dust accumulation.

Section VI discusses the process for eliminating dust on a surface, as well as several mitigation methods for soiling each with its own advantages and disadvantages.

Furthermore, an analysis of the cleaning frequency of PV panels is conducted, taking into account the PV system's location. Additionally, this section evaluates the economic aspects of cleaning PV modules.

Section VII discusses the future prospects for PV technology and cleaning techniques.

Section VIII summarizes the research gaps that were found in the literature review and proposes ideas for future research and discussion.

Finally, Section IX gives a conclusion to the review.

II. PV MODULE AND SYSTEM CHARACTERSTICS

Solar energy systems are designed for efficient energy generation from abundant sunlight. However, the properties of PV systems are usually unchanging, and if proper cleaning schedules are not maintained, these properties can lead to a loss of efficiency due to soiling.

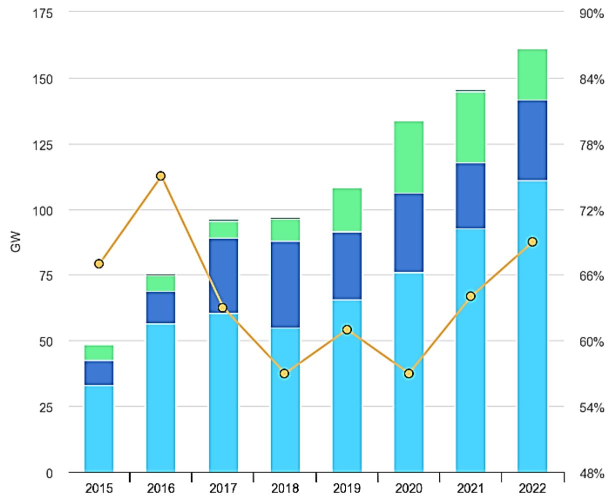

FIGURE 1. The source from IEA shows the amount of solar PV capacity added on a yearly basis divided by application segment. The data is for the years 2015 to 2022 and the source is from IEA located in Paris [2].

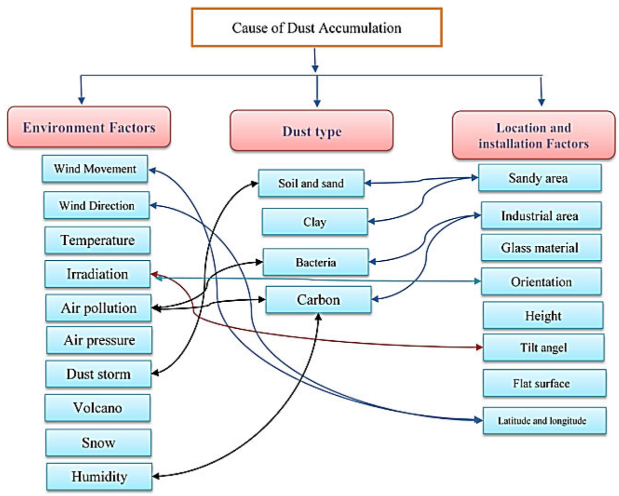

FIGURE 2. Causes for dust accumulation on PV panels [48].

A. PV PANEL TILT ANGLE AND ORIENTATION

The tilt angle and orientation of PV panels have a significant impact on their performance. In a study by Salim et al. [49] in Saudi Arabia, the effects of dust accumulation on power generation were analyzed over a period of eight months. The monthly output power reduction was found to be 32% when compared to clean ranges with a tilt angle of 24.6°. However, information on the physical parameters of the PV system at the test location was not included in this inquiry. Accumulated dust and dirt block solar radiation causing a decline in energy efficiency over time. Hassan et al.'s experiment [50] showed a decrease in power output within the first 30 days of dust exposure. Without proper cleaning routines, the entire production capacity fell by 33.5% within one month and by 65.8% within six months. Sayigh et al. [51] further found that the transmission of dust-covered glass panels decreased

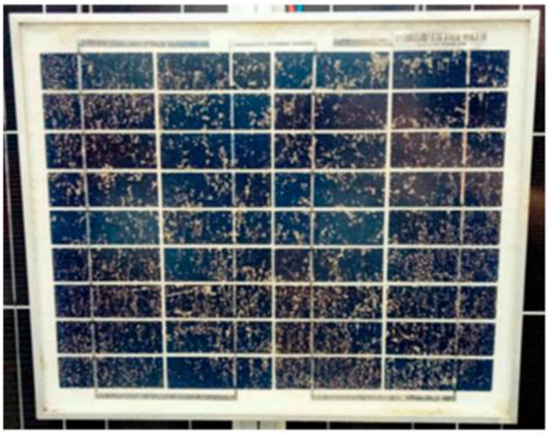

FIGURE 3. Shows the dust accumulation density for a PV panel of 13.2 g/m^2 [52].

FIGURE 4. Shows a testing facility for outdoor PV panels with clean and dirty panels [52].

after 38 days of exposure to different tilt angles of 0°, 15°, 30°, and 45°. Transmission reduced by 64%, 48%, 30%, and 17%, respectively. Dust accumulated on solar PV panels can be observed in Figure 3 [52]. El-Shobokshy and Hussein [53] conducted research analyzing the effect of different types of dirt on the efficiency of PV cells. They found that low air velocities cause contamination on all PV surfaces. Similarly, Hottel and Woertz [54] conducted a three-month performance examination of solar collectors exposed to dust from railway tracks near an industrial area, which led to a significant reduction (4.7%) in net capacity compared to the expected values. This reduced performance was ascribed to the soiling of dust by rain and snow in USA, and recommended usage of solar collectors that can clean themselves. Dust accumulation also raises maintenance costs and cleaning expenses for solar PV panels [55]. Michalsky et al. emphasized the importance of sufficient data to develop efficient solar PV systems that consider measures for collecting and removing dust [56].

For optimal power generation in the northern hemisphere, PV modules should be positioned facing south, while in the southern hemisphere, PV modules should be oriented north of the equator to ensure they are exposed to prolonged and direct sunlight for maximum energy collection. In a study by Elminir et al. [57], it was observed that glass samples placed in the northeast experienced higher dust accumulation compared to other directions due to nearby manufacturing emissions carried by the wind.

The efficiency of PV glass was significantly affected by both dust density and surface orientation, leading to reduced power generation efficiency. The analysis revealed that density of dust ranges from 15.84 to 4.48 g/m^2 caused a drop in solar PV transmittance by 52.54 to 12.38 %. A reduction in inclination angle and an increase in dust deposition on the glass plates resulted in a substantial reduction in solar PV transmittance, notably at a 150° inclination angle and a 450° north orientation. Small particles from various places were transported by wind from the northeast, including cement manufacturing industries, which accumulated on the glass plates.

B. GLASSING SURFACE FEATURES

The external surfaces of solar system modules are affected by airborne dust, resulting to considerably lower PV module output efficiency and fell solar cell glazing transmittance. Mustafa et al. [58] conducted experimental tests on a number of solar modules with affected component surfaces due to air pollution-related dust deposition and observed up to a 26% decrease in PV productivity as dust density increased from 0 to 22 g/m^2. Similarly, Semaoui et al. [59] observed a 32% decrease in PV output due to dust deposition in the desert areas of Algeria over eight months. Dust accumulation on panels can block solar radiation by 60-70% if solar PV modules are not cleaned regularly for a year [60]. In central Egypt, Hegazy [61] carried out an experiment for a year at a desert temperature. The most significant factor affecting dust deposition conditions was found to be the solar panel tilt angle. A 45° tilted glass plate exposed to dust and pollutants resulted in an 8% reduction in solar transmittance within ten days of exposure, as observed by researchers in Roorkee [62]. Elminir et al. [57] also conducted a study on solar panel tilt angles and solar coverage rates, where various concentrations of dust deposition on PV panels and inclination angles of 0° to 60° were used. There was a decrease in equivalent transfer power from 52.54% to 12.38%.

Figure 4 shows the research infrastructure for investigating outdoor dust accumulation, while the output power on the P-V curve of solar PV surfaces before and after dust accumulation is depicted in Figure 5 [52]. Researchers conducted a study on the Dust's effect on the transmission of polished materials in the dry environment of India's Thar desert [63]. They found that the glass transmission decrease ranged from 5.67% to 19.17% across tilt angles of 0°, 45°, and 90°. The decrease rates of acrylic light transfer were 8.29%, 13.98%, and 23% for the same tilt angles. Mastekbayeva [64] reported that the solar system's performance relies on the ability of a

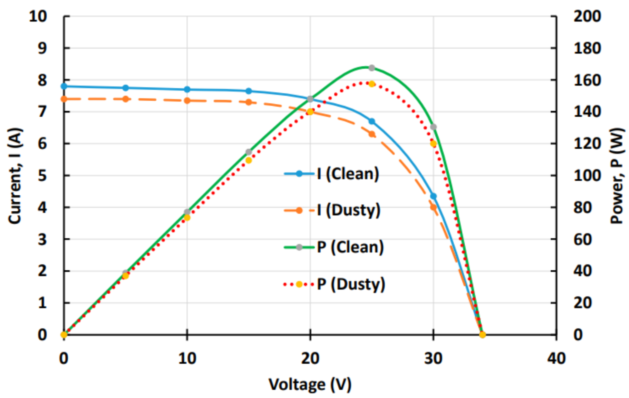

FIGURE 5. Shows the difference in PV output power between clean and dirty solar panels [52].

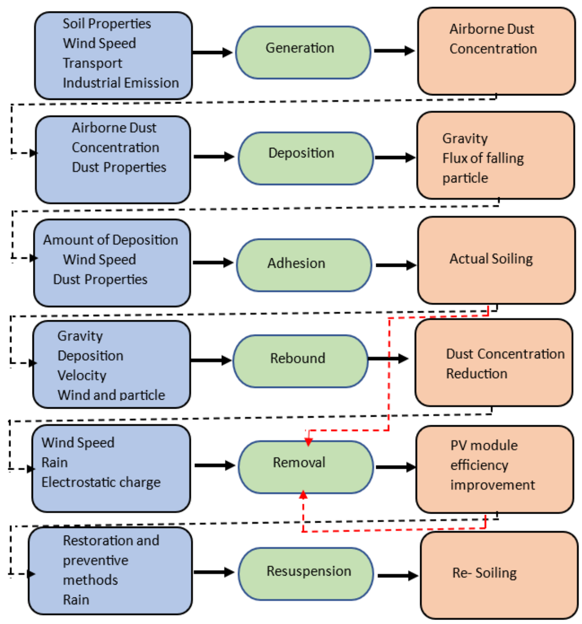

FIGURE 6. The life cycle of accumulation of dust and the elements that influence it.

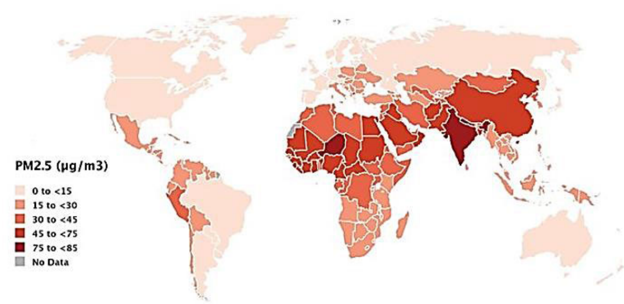

FIGURE 7. Shows the PM 2.5 concentrations for the year 2019 that are weighted by population were distributed across the world [70].

glazing to transmit sun radiation. Another study analyzed dust accumulation's impact on how well solar radiation is transmitted through 0.2 mm low-density polyethylene glazing.

C. SOLAR PANEL HEIGHT

The amount of soiling on the surface of a solar power plant depends on its installation height. It is possible for dust deposition to decrease as the panel is installed higher up. In a study by Quang et al. [65], it was discovered that the concentration of dust particles near metro lines was lower for panels placed 5 meters above the ground due to automobile exhaust pollution. In another study conducted by McGowan and Clark [66], the concentration of ambient particulate matter (PM10) dust and dust deposition was reported. For panels less than 5 meters in height, PM10 concentrations peaked at approximately 125 $\mu g/m^3$; but for those at 100 meters, it decreased to 95 $\mu g/m^3$. Dust deposition on PV panels is reduced due to the wind velocity as air moves over deployed modules, according to observations made by researchers [32]. Indoor tests on PV modules were conducted under controlled conditions by Beattie et al. [67]. Due to nonlinearity, the panel arrangement's height had to be changed. It was observed that as the height of the solar panels increased, the accumulation of dirt on the panel surfaces decreased.

III. PV SOILING MACHANISIM

Soiling on PV modules occurs through a process where dust particles are generated from various sources, transported globally through entrainment, and eventually deposited on the PV module surfaces. Figure 6 shows the complete soiling cycle, the generation process comes first, then entrainment, transportation, and deposition on surfaces, removal or resuspension comes last.

A. DUST GENERATION

The generation of dust particles occurs from diverse sources, including desert storms, vehicle emissions, plant material, construction debris, microscopic organisms etc. [46]. A small quantity of dust or particles is quickly accumulated in the atmosphere, whilst others are initially deposited on the ground before evaporating into the atmosphere as a result of natural or human activities like wind and storms. The concentration of dust in the atmosphere is influenced by factors like local topography, climate, industry, and agriculture.

Figure 7 shows the atmospheric dust concentration in different locations worldwide, with the MENA region recorded as having the highest concentration. The main areas contributing to the generation of dust that makes up global dust due to desert dust are Northern and Southern America, Central Asia, the Arabian Peninsula, Western and Eastern China, Australia, and South Africa. However, these regions do not have the same level of dust activity [68], [69].

Tanaka and Chiba [68] have reported that Saharan dust is responsible for 58% of the total global dust emission and provides 62% of the tropospheric dust.

Although there is no consensus on the size loss contribution, the majority of particulate matter falls between 0.1 μm and 1000 μm in size, with $< 20\mu$m diameter particles further classified into deposited particle matter, total suspended particles (TSP), particulate matter (PM) 10, and PM 2.5, which refer to particles with diameters of 50 μm or less, 10 μm or less, and 2.5 μm or less, respectively [71], [72], [73].

The shape, size, surface properties, and weight of the particles have an impact on the transportation of dust in the atmosphere [74], with finer particles with diameter of 5 μm resulting in a larger reduction in solar radiation transmittance. Figure 7 shows the different locations worldwide with high concentrations of fine dust. These properties vary depending on diverse factors such as climatic conditions, topography, agricultural and industrial activities, construction, and human activity, thereby making it a location-based issue to determine the actual dust composition. The generation phase of dust involves the entrainment and transportation stages, with velocities of friction at the threshold and vertical flux being the primary factors that influence dust generation [47].

The process of generating dust involves two main phases: entrainment phase and transport phase. During the entrainment phase, particles are created from different sources, such as erosion and industrial/agricultural activities, and are carried into the atmosphere by wind. Dust particles can become suspended through various mechanisms, including aerodynamic lift, saltation, and disintegration [47].

The amount of entrainment activity depends on different factors such as location, climate, and human activities [70]. Once suspended in the atmosphere, dust can travel long distances through the wind. For instance, Sub-Saharan Africa and Europe have both received thousands of kilometers of Sahara Desert dust, while the Gobi Desert's dust can reach cities like Seoul, Tokyo, and Beijing. This transboundary movement of dust poses a major challenge [70].

Desert dust is the primary source of global dust MENA region, as indicated in Figure 7. This presents a significant threat to the survival of the PV industry in the area. Furthermore, there are other areas across the world where high concentrations of dust particles are present in the atmosphere and transported across long distances.

B. DUST DEPOSITION ON PV

The settling of dust particles on a surface is known as deposition, which is affected by the speed of wind and properties of the particles [75]. Dust particles settle more rapidly closer to their source and less rapidly at greater distances [70]. There are three categories for dust deposition on PV panels based on their means of transport, namely dry deposition, wet deposition, and shadow deposition mechanisms [76]. In dry deposition or dry weather conditions, dust particles stick to the surface of the solar panel due to adhesive forces [76], [77]. Wet deposition occurs when atmospheric dust is mixed with precipitation such as rain, snow or fog and is then deposited onto the PV panels [76]. Shadow deposition can be described as an intermediate stage between wet and dry deposition and occurs when water droplets contained in dusty air mix with clouds or fog before being deposited on the PV panels [76]. Dust accumulation, commonly referred to as soiling, is a significant factor impacting the effectiveness of PV modules and is regarded as the second largest influence following the effects of temperature and solar irradiation. Figure 8 illustrates several factors affecting dust accumulation on solar PV modules which are elaborated on in the final part of this paper.

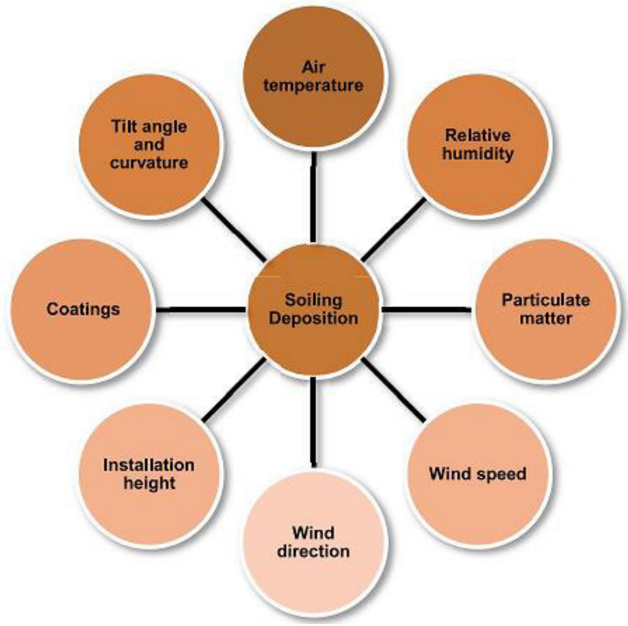

FIGURE 8. Shows the factors that influence the accumulation of dust on a PV [77].

1) DUST PROPERTIES AND MORPHOLOGY

The rate at which soiling occurs on PV panels is influenced by the properties of the dust particles. When compared to larger, coarser dust particles, smaller dust particles with a diameter of less than 1 μm accumulate more quickly. [74]. This is because larger particles are affected more by inertial and gravitational forces, while Inter-particle forces that affect smaller particles include electrostatic forces, cohesive forces, and Van der Waals forces.

Dust particles with charged electrostatic properties land and accumulate faster than those with neutral ones as a result of coalescence [71]. Different dust morphology also affects PV performance. Large-sized dust samples with porous structures allow lighter particles to pass, Dust particles with an angular or diagonal form have superior optical characteristics than those with an oval or spheroid shape [78]. The morphological properties tend to balance out and contribute to the transmittance value. Bird droppings also impact PV performance, with the optimal tilt angle being at 40° having the lowest deposition, while 0° has the highest deposition, according to research by Sisodia and Mathur [79]. The influence of dust sample morphology on PV performance was explored by Hachicha et al [30]. Their findings indicated that

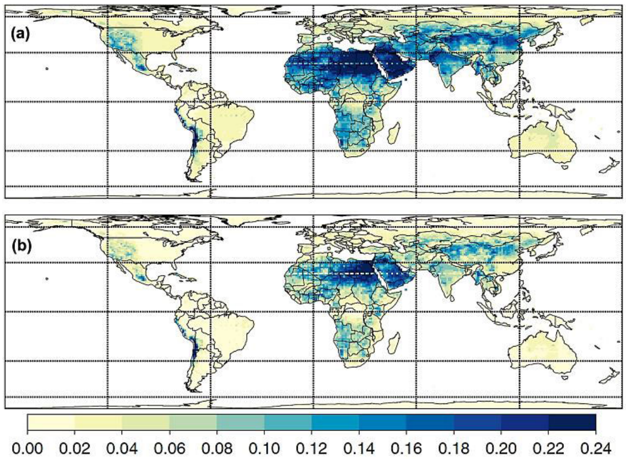

FIGURE 9. Annual average decline in PV CFs from 2003 to 2014 owing to (a) atmospheric aerosols and soiling, and (b) PV module soiling [83].

there is a direct correlation between normalized PV power and dust density, with a decrease of 1.7% per g/m^2 increase in density. Furthermore, dust accumulation was observed to decrease as the tilt angle of the PV module increased, with decreases of 37.63%, 14.11%, and 10.95% being noted at tilt angles of 0°, 25°, and 45°, respectively.

2) SURFACE PROPERTY

The surface properties of a PV module were also discovered to significantly impact dust accumulation rate, with varying effects depending on the type of surface fabrication. Surfaces with a coating layer had less effect on dust settlement than those without [74]. When compared to glass surfaces, PV modules with surfaces made from tedlar, plastics, and epoxy are more likely to accumulate dust [80].

IV. SOILING'S EFFECT ON SOLAR PV FOR GENERATION

The accumulation of grime and airborne dust is a significant environmental issue globally, and it causes a considerable decline in solar irradiation reaching PV module surfaces, resulting in significant financial losses for the industry. Typically, soiling results in a daily loss of over 1% in PV power output, as well as a monthly loss of up to 80% in PV efficiency [81], [82]. As shown in Figure 9, Soiling is responsible for almost 80% of the entire losses in PV capacity factors worldwide. However, in regions with heavy air pollution such as Indo-Gangetic plains and North China, PV module soiling accounts for less than 50% of the overall loss [83]. It is important to note that regions with high solar radiation that are arid and semiarid, especially subtropical desert regions like those in North Africa and Middle East, experience a more significant reduction in PV capacity factors due to soiling.

A. SOILING'S EFFECT ON SOLAR PV POWER GENERATION IN FIELD AND OUTDOOR EXPERIMENTS

In recent years, there has been an increase in studies examining the natural soiling's effects on solar PV power generation due to the global rise in solar PV installations. One study by Neher et al. [96] analyzed the top 20 PV markets, representing roughly 90% of global PV capacity in 2018, and estimated that soiling caused a reduction in solar PV power generation by at least 3-4%, which equates to a revenue loss of over €3-5 billion. Soiling-related decreases in solar PV power generation were expected to reach 4-7% worldwide by 2023. In areas with soiling exposure and high solar irradiation such as Nigeria, Oman Morocco, United States, India, and Pakistan, several research has examined the impact of soiling on the performance of solar PV [97], [98]. For instance, in Oman, researchers found that the reduction in PV output efficiency ranged from 5.5% to 18% across six cities over one year [99]. In Lahore, Pakistan, study revealed a 30° tilted panel soils at a rate of around 0.8% every day, which is among the greatest soiling rates recorded in different urban settings across South Asia and the Gulf area [100]. A variety of other studies provide detailed descriptions and elaborations on the evolution of soiling research in the solar energy field.

A recent study in Nigeria examined the impact of dust on four types of PV technologies: Monocrystalline Silicon, Polycrystalline Silicon, Cadmium Telluride, and amorphous Silicon [101]. The results showed significant yield and efficiency losses: amorphous Si, for instance, experienced a 78.3% yield loss and an efficiency decline of 78%, while cadmium telluride experienced a yield loss and efficiency decline of 77%. Similarly, polycrystalline and monocrystalline Si both suffered yield losses of 70% and 68.6%, respectively, and efficiency declines of 71%. Another study conducted outdoor research and found that leaving monocrystalline PV modules uncleaned for 100 days resulted in a 10% decrease in output [102]. The researchers recommended PV modules should be cleaned at least once a month. Finally, a study on solar photovoltaic systems in California found that the average daily soiling loss was 0.051%, with 26% of locations suffering losses of more than 0.1% per day [103]. Soiling losses were more severe at locations with small tilt angles of less than 5°.

A number of studies have been conducted to investigate the effect of dust on PV module performance. Salim et al. conducted an eight-month study near Riyadh, Saudi Arabia, which revealed a 32% reduction in PV output due to dust accumulation [104]. Tanesab et al. also carried out a study in Perth, Australia, leaving a PV module exposed to dust for 18 years without cleaning, which resulted in an 8-12% degradation in performance [105]. Sanusi investigated an amorphous silicon PV module in southern Nigeria during the Harmattan season and found a 20% degradation in output over three months without cleaning [106]. Klugmann-radziemska tested deterioration of PV power performance in Poland in a unique way, examining the physical and chemical characteristics of dust on 37° tilted panels, which resulted in a maximum daily loss of 0.8% [107]. The average annual degradation of PV module performance was recorded at 25.5%, and 3% power loss. Picotti et al. [72] conducted a

TABLE 1. Summarizes the recorded influence of soiling on solar PV power generation.

Location	Climate	Type and front surface of PV	Tile angel (°)	Duration of study	Dust deposition density (g/m^2)	PV modules parameters	Reduction (%)	Ref.
Dhahran, KSA	Desert	Poly and mono c-Si, glass	26	6 months	6.184	Power output	Greater than 50	[85]
Sharjah, UAE	Desert	Poly c-Si, glass	45	2 weeks	N/A	PV efficiency	19.95	[30]
Aswan, Egypt	Desert	Poly c-Si, glass	45	10 months	N/A	Power output	25.5	[86]
Islamabad, Pakistan	Subtropical	Poly c-Si, glass	60	30 days	3.179	Power output	7.95	[87]
Lalitpur, Nepal	Temperate	Poly c-Si, glass	27	5 months	9.6711	PV efficiency	29.76	[88]
Hong Kong, China	Subtropical	CIS thin-film, glass	0	3 months	N/A	PV efficiency	16.11	[89]
Phitsanulok, Thailand	Tropical	a-Si, glass	N/A	30 days	0.268	Electricity generation	3.5	[90]
Ouargla, Algeria	Desert	Monoc-Si, glass	30	8 weeks	4.3619	Max. power output Open circuit voltage Short circuit current	8.41 0.51 6.1	[91]
Athens, Greece	Temperate	Poly c-Si, glass	30	2 weeks	0.1	Power output	2	[92]
Evora, ´ Portugal	Temperate	Mono c-Si, glass	15	Dust event	1.067	Max. power output	8	[93]
Santa Clara, US	Temperate	N/A	greater than 20	108 days	N/A	PV efficiency	22	[94]
Santiago, Chile	Semi-arid	Poly c-Si, glass Mono c-Si, glass Thin-film, glass	32	30 months	N/A	Electricity generation (daily)	0.19-0.83 0.19-0.79 0.23-0.62	[95]
Perth, Australia	Temperate	a-Si, N/A Poly c-Si, N/A Mono c-Si, N/A	32	1 year	N/A	Max. power output	9.12-9.99 8.42-8.89 8.48-12.18	[96]

thorough analysis of how accumulation of dust affects PV modules, while Inês et al. [108] and Yu et al. papers with detailed descriptions and references to research on dust accumulation on solar energy systems. Darwish's review is critical of the research questions used to investigate dust accumulation on solar PV performance [46]. The impact of dust accumulation on power loss for various solar PV technologies was studied by the authors in [110] near Riyadh in Rumah. The PV panels were installed at a 15° tilt angle relative to the zenith and mounted at 16° due south. The rates of soiling loss for all PV technologies examined over a period of 30 days ranged from 2% to 18%. Figure 10 shows the soiling losses for different PV technologies. In terms of the rate of dust accumulation, there was a definite seasonal pattern, with losses of approximately 16% in April (the dustiest month) compared to only around 2% in July (the least dusty month). The weight of soil on glass samples was measured each month in two positions, i.e., tilted to 15° and horizontal orientations. Figure 11 presents the soil weight for each month under both orientations as a function of weeks of exposure. In summary, the weight of accumulated soil exhibited a strong correlation with dust accumulation loss, which was modeled using a simple exponential equation.

The 'a' coefficient is determined based on the best fit between measured data and the model, achieved by minimizing the gaps between the observed and modeled values squared for a given month and PV technology type. The model includes the following properties:

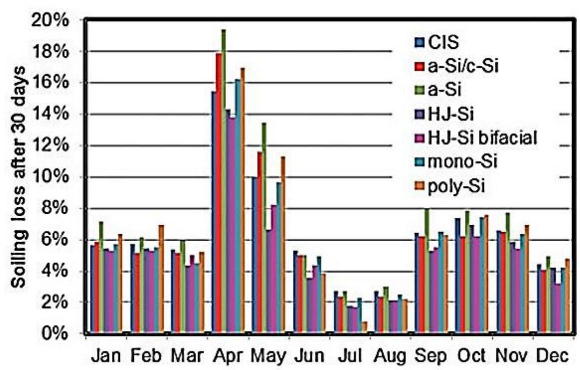

FIGURE 10. **Shows the decline in efficiency caused by dirt accumulation in several types of PV systems after 30 days of exposure [110].**

$$L_s(0) = 0 \text{ and } L_s \rightarrow 1 \text{ as } t \rightarrow \infty$$

Table 1 summarizes field and outdoor experiments that looked at how soiling affected the generation of PV power. The study shows that soiling reduces the output and efficiency of PV modules over time, and depends on factors such as

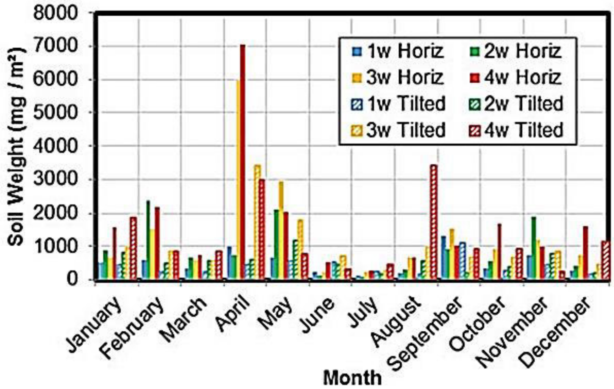

FIGURE 11. Displays the total weight of dust that has gathered on both the horizontal and tilted glass (tile angle of 15°) samples every month [110].

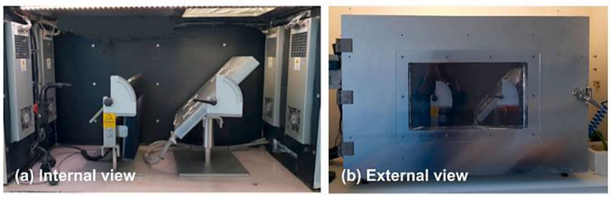

FIGURE 12. Shows an indoor soiling chamber [84].

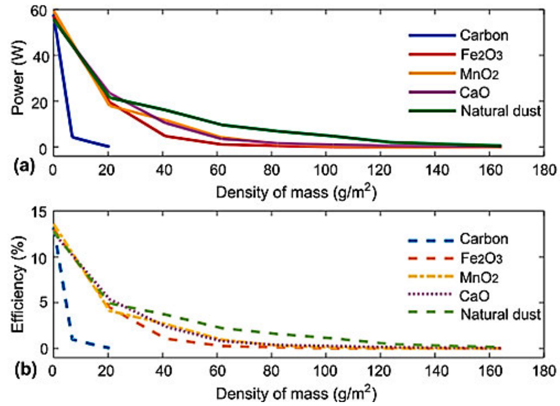

FIGURE 13. Shows how the type of dust particle species and its deposition density might impact [114].

TABLE 2. Compares the effect of dust samples on a PV module in a laboratory environment.

	Voltage (V)		Ampere (A)		Power (W)	
Dust weight	100 g	200 g	100 g	200 g	100 g	200 g
No dust	20	20	5.3	5.3	106	106
Barke	17.3	16.8	4.3	4.1	74.39	71.4
Buraimi	18	17.65	4.9	4.7	88.2	77.66
Liwa	17.5	16.9	4.45	4.25	77.875	71.83
Masqat	17.45	16.85	4.35	4.2	75.9	70.77
Saham	16	16.03	4.42	4.02	70.72	64.44
Sohar	15.9	15.1	4.35	4.15	69.165	62.66

environmental conditions, installation parameters, and PV module design.

In general, the Middle East experiences more significant losses in PV power generation due to soiling, leading to a maximum reduction in power output of over 50% and a decline in PV efficiency of about 40%. Conversely, Soiling reduces power generation by 1% to 8% in Europe. While studies have concentrated primarily on the effects of soiling on crystalline silicon PV modules, research that explores the impacts on other PV module types is necessary.

B. SOILING'S EFFECT ON SOLAR PV POWER GENERATION IN INDOOR EXPERIMENTS

Experimental investigations were carried out indoors to evaluate the effect of soiling on solar PV power generating efficiency. Using a test chamber and solar simulator, Jiang et al. [111] found that the PV output efficiency decreased as the dust accumulation density increased from 0 g/m^2 to 22 g/m^2, with a range of 0% to 26%. The findings further pointed out that the efficiency of PV output degraded more at varying solar irradiation intensities. Similarly, Munoz-García et al. [84] conducted several experiments using a climatic chamber (refer to Figure 12) to imitate soiling processes in a desert climate. The findings revealed that dust accumulation densities ranging between 1.30-1.63g/m^2 could decrease generation of power by 4.73% to 6.90%. Rao et al. [112] conducted an experiment that showed a reduction of 45% to 55% in the PV power output due to dust density of 7.155 g/m^2. Kazem and Chaichan [113] performed a laboratory test using samples of dust were gathered from six cities in Oman to determine how PV modules are affected by soiling. The results, as seen on Table 2, showed that distributed dusts of 100 g and 200 g reduced the output power of a PV module by 35% to 40%. Darwish et al. [114] carried out simulations to examine the decrease in PV output power and efficiency at a constant irradiation of 600 W/m^2 due to dust particles, such as CaO, MnO2, Fe2O3, carbon, and natural dust. Carbon particles were found to have the most important factor affecting the performance of the PV, with the efficiency falling from 13.2% to 0.03% and output power falling from 57.82 W to 0.135 W as the carbon dust density increased from 0 to 20.27 g/m^2 (refer to Figure 13).

Several controlled indoor experiments have investigated the effects of dust accumulation on the performance of PV panels, without taking into account other weather conditions [111], [115]. For instance, PV panels were subjected to industrial dust and continuous light by Sulaiman et al, which resulted in an indicated 50% drop in efficiency [116]. Other research utilizing natural dust found a 35% monthly efficiency loss [117], while those using artificial dust, such as mud and talcum, showed a significant decrease in efficiency [118]. In the UAE, Hachicha et al. performed indoor and outdoor investigations with dust collected from a building's roof. The findings show a linear relationship between normalized power and dust density, with a slope of -1.7% per g/m^2 [30]. Muñoz-García et al. carried out an experiment in an indoor setting to explore the effects of dust accumulation on desert weather conditions, such as optical transmittance losses. According to the study, the density of the dust (g/m^2) had an impact on power losses that varied from 4.73% to 6.90% and the circumstances in which it accumulated [84]. In addition to performance losses, PV panels can suffer other kinds of harm from the accumulation of dust, including sand erosion and reduced permeability-related surface damage, both of which contribute to further degradation in solar cell performance [119]. The impact of dust on the efficiency of PV modules was examined by Mani and Pillai, who specialized in dust particle physical characteristics. Their research demonstrated that finer dust particles weighing approximately 2 mg/cm^2 resulted in a 30% decrease in PV output compared to coarser particles weighing around 8 mg/cm^2, which led to a 10% drop in output [120]. Kazmerski et al. [32] studied the bonding mechanisms and morphology of dust accumulation on PV module surfaces to investigate the interaction between dust particle adhesion and the module's chemical properties. Their research revealed that adhesive force is profoundly influenced by the chemical bonding of dust particles.

C. MODELING RESEARCH ON THE EFFECT OF SOILING ON SOLAR PV POWER GENERATION

Various modeling studies have been conducted to investigate how soiling affects PV modules. For instance, three models, including, response surface methods, multiple linear regression and artificial neural network models, were created by Zitouni et al. [121], to determine the losses in the production of electricity resulting from soiling. Their findings revealed that on dry and rainy days, soiling decreased daily electricity generation by 0.61 kWh and 0.03 kWh, respectively, in Morocco. The total losses amounted to 82.5 kWh, corresponding to 28% of the total test period's maximum generating capacity. Similarly, Pulipaka et al. [122] used regression to quantify the effect of dust particle size on solar PV power generation losses and the energy production of soiled PV modules was predicted using neural networks. You et al. [123] estimated the losses in PV module efficiency resulting from soiling in Tokyo, Sanlucar la Mayor, Taichung, Doha, Walkaway, Malibu, and Hami. Their study showed that the efficiency loss in Tokyo was the lowest at about 4%. while Doha experiences over 80% reduction in PV efficiency.

V. MODELING AND PREDICTING SOIL CONDITIONS

This field is closely related to the generation of power and the creation of maintenance schedules [75], [124]. When the level of soiling is anticipated in advance for the next day or week, effective operations can be instituted to enhance electricity production and minimize O&M expenses. To achieve this optimization, plans must be created for PV battery charge or discharge as well as thermal energy storage in CSP plants. Advanced methods like ANNs [125] are often used to solve complicated problems that have no analytical or empirical solutions.

TABLE 3. Important points in the section on soil modeling and forecasting.

Key Items	Summary
Environment and Soiling	• Indicates the environmental elements that influence soiling deposition. • Thi`process is significantly influenced by factors like rainfall and particulate matter. • Discusses the application of numerical tools like ANN and CFD to predict soiling.
Soiling Simulation and Estimation	• Assessing the rate of soiling is still a widely used measure for local assessment. • There is few research on the effect of soiling spatial distribution on solar power plants, as well as intra-surface assessment.
Cleaning Modeling and Scheduling	• The current research focuses on presenting various techniques to optimize cleaning schedules, taking into account different cleaning frequencies, costs, and energy sell prices. • The current research focuses on presenting various techniques to optimize cleaning schedules, taking into account different cleaning frequencies, costs, and energy sell prices. • There is not enough research on adjusting cleaning frequency based on the seasonality of soiling. • Even with the best cleaning schedules, soiling can still lead to significant financial losses.

The prediction and modeling of soiling can be classified into three sections, namely Environment and Soiling, Soiling Simulation and Estimation, and Cleaning Modeling and Scheduling. The key details of these subdivisions are summarized in Table 3.

A. SOILING AND THE ENVIRONMENT

Figure 8 displays the primary environmental parameters that impact soiling deposition, along with geometric and surface physico-chemical characteristics [126]. Regarding these environmental and geometric factors, each is described below:

1) CONCENTRATION AND CHARACTERISTICS OF AIRBORNE DUST

Airborne dust concentration and properties: Dust is made up of tiny solid particles that are smaller than 500 μm in diameter, including things like sandy soil particles that have been transported by wind, pollen from plants, dander from animals, and particles known as PMs generated by the burning of fossil fuels, the release of pollutants from vehicles and the waste generated from construction activities among other sources. The concentration of airborne dust is the main contributor to soiling and varies based on the location of the PV modules [81], [120], [127]. Micheli and Muller [128] performed a study on 20 solar PV soiling stations in the US and observed that the average daily levels of PM2.5 and PM10 had a strong correlation with the rate of soiling. They found that the coefficient of determination was 0.82. It means that a large amount of PM pollution can cause a significant amount of soiling. Additionally, dust may have varying physical and chemical attributes depending on where it originates from, resulting in different levels of dirt accumulation on PV surfaces in different areas. Broadly speaking, dust deposition is influenced by several forces, including electrostatic forces, capillary forces, gravitational forces, and macroscopic intermolecular forces [127], [129]. Ilse et al. [130] suggest that capillary forces play the most significant role in the adhesion of dust particles to PV surfaces across all particle sizes. Following capillary forces are Van der Waals forces, whereas gravitational forces and electrostatic forces have negligible effects. Isaifan et al. [131] discovered that capillary forces are the primary factor that controls the adhesion of dust particles to PV surfaces, with 98% of total forces being due to capillary forces under high relative humidity, whereas Van der Waals forces are the primary factor in dry environmental conditions. Conversely, according to the study conducted by Chanchangi et al. [127], the primary factors responsible for adhesion of bigger dust particles are inertial and gravitational forces, while Van der Waals forces have the greatest influence on smaller particles. Sarver et al. [132] discovered that intermolecular attractions for dust particles below 10 μm have an inverse relationship with their size. For instance, fine dust particles smaller than 1 μm tend to adhere uniformly to the PV surface more than coarse dust particles larger than 5 μm. This, in turn, causes optical losses such as increased sunlight scattering or absorption and decreased transmittance [74], [105].

2) WIND DIRECTION AND SPEED

During a specific testing period, it was observed that wind speed had minimal impact on the temperature of the PV system, according to a study [133]. However, an increase in air temperature was found to significantly reduce solar panel voltage while causing only a minor boost in the output current. In another investigation, Rounis et al. [134] utilized a numerical model to compare single and multiple inlets in building-integrated transparent PV systems for new constructions. The scientists evaluated how well these systems function in hot areas with varying wind patterns during the summer season, taking into account both their thermal and electrical capabilities. when compared, the electrical performance of several building-integrated transparent PV systems was found to be 1% higher than that of a single integrated system, contributing up to 7% power to a 120-kW solar system's total output, while improving thermal performance by up to 24%. The efficiency of a PV system was evaluated at 57% by testing a proposed system and analyzing how factors such as sun radiation, temperature, air velocity, and the condensed condensation chamber affect its performance [135]. The accumulation of dust on a solar module surface is highly dependent on the surrounding air, as dust is transported by air currents and can build up gradually or be dispersed rapidly. The amount of dust that collects on the surface of PV modules can differ depending on the wind speed and the motion of airborne dust particles. In simulated studies, Goossens and Offer [136] as well as Goossens et al. [137] assessed the deposition of dust particles on PV collectors and discovered that the wind's direction had a much greater influence on its accumulation than air velocity. At a minimum wind speed of 6.5 m/s, there was a significant increase in dust accumulation in Libya, which was mainly driven by average monthly wind speed [138]. The amount of dust created is influenced by the direction of the wind and the orientation of PV surfaces [57]. Kohli [139] conducted research indicating that the accumulation of tiny dust particles on the PV panel surfaces deteriorated performance more than the accumulation of larger dirt particles. They discovered that as the dust particle size dropped below 50 μm, the wind's ability to remove the particles diminished significantly. At wind speeds lower than 25 m/s, particulates smaller than 10 μm were not removed. The study's main discovery was that the smaller the size of the dust particles, the greater the attraction force between them and the air. Therefore, in areas with strong winds, it is crucial to design, construct, and install weather-tolerant PV systems to resist high wind speeds and prevent any potential damages.

3) RAINFALL

Rainfall plays a significant role in soiling PV modules, as abundant rainfall can help clean the soiled surfaces, and light rain can worsen the problem. The soiling rate has a clear statistical correlation with rainfall, according to Micheli et al. [126]. Similarly, Caron and Littmann [140] found that rainfall significantly affects soiling trends in California. In particular, the Central Valley experienced a decrease in the soiling rate from 10.5% per month to below 1% due to frequent rainfall between mid-October and November 2010. However, short and soft rainfall can lead to wet deposition of dust particles from the air, which can intensify the soiling process of PV modules. Valerino et al. [141] observed that light rain events with a rate of less than 5 mm/h did not remove the soiling on PV panels but rather increased dust deposition, causing a higher soiling rate. Therefore, it is crucial to have the appropriate frequency and intensity of rainfall to maintain and improve PV performance while minimizing the negative effects of soiling.

4) PARTICULATE MATTER (PM) AND PRECIPITATION

Soiling is significantly impacted by particulate matter, which is related to atmospheric particle concentration. Regions with high PM levels experience more particle deposition and, as a result, reduced performance. For this reason, desert or near-desert areas tend to have soiling-related losses that are as much as five times greater than semi-arid regions [142]. Numerous studies have identified PM as the most influential factor in explaining soiling ratio [143], [144].

Rainfall serves as the primary natural cleaning agent, and its effectiveness depends on factors such as rainfall intensity, surface tilt angle, and particle adhesion [145]. As the tilt angle of a surface becomes steeper, the effective surface area decreases and raindrops are more apt to slip, reducing particle deposition. However, precipitation can in some cases exacerbate soiling when there's high atmospheric particle concentration and light rainfall, as seen with the long-range transport of Saharan desert dust to the Iberian Peninsula in Figure. 14 [93]. Morocco experiences a distinctive event referred to as ''red rain'' that can negatively impact the efficiency of PV power plants. As a result, a large amount of pressurized water is needed to effectively clean the PV power plants.

5) TEMPERATURE AND RELATIVE HUMIDITY

The amount of humidity and temperature in the environment is a significant factor in how well dust particles stick to PV modules. According to Chanchangi et al. [127] and Jamil et al. [74], in dry or semi-dry climates with high temperatures and low relative humidity, dust particles can be easily carried by the wind. Furthermore, an increase in relative humidity can lead to a higher rate of soiling on PV modules due to the heightened adhesion forces. According to the research conducted by Said and Walwil [146], it has been found that the adhesion force experiences an increase of approximately 80% when the relative humidity increases from 40% to 80%, as depicted in Figure 15. According to Figgis et al. [147], adhesion force also increases as relative humidity reaches 30-50%, and it becomes even stronger when relative humidity goes beyond 60-70%. Another crucial factor in soiling rates is the water vapor condensation that occurs on PV module surfaces. During the night and dawn, the PV surface becomes cooler than the surrounding temperature due to radiative cooling, while the ambient temperature decreases, the concentration of water vapor saturation decreases, and this results in an increase in relative humidity.

When the temperature of the surface of PV modules drops below the dew point temperature, water vapor condensation occurs on the surface, leading to a significant increase in the adhesion of dust particles due to capillary forces greater cementation and particle caking, as depicted in Figure 17 [148], [149]. In Qatar, Ilse et al. [150] observed frequent dew formation that caused nanoscopic needles of the clay mineral palygorskite to become cemented together, which greatly increased the adhesion of dust particles. Dew formation on PV modules in various desert regions has also been noted [132]. Additionally, dust particle morphology plays a crucial role in the optical losses incurred by dust deposited on PV surfaces.

6) DEW

Dew is not a parameter of the atmosphere but a process that plays a crucial role in natural surface cleaning and presents a duality. In literature, it has been identified as a cleaning agent for surfaces as well as a factor that can intensify soiling effects [75], [151], [152]. The evaporation of dew can improve cementation processes, resulting in a stronger bond between particles and surfaces [151]. Conversely, heavy dew formation, especially on surfaces with high slopes, can naturally clean them [132].

B. ESTIMATION AND SIMULATION OF SOILING

The objective of soiling modeling is to comprehend how various environmental factors such as air temperature, relative humidity, wind speed, direction, rainfall, and atmospheric particle concentration impact the deposition of particles [153], [154]. To achieve this, it is recommended that soiling models be developed based on measurements of soiling effects in a specific region for a minimum of one year. This method enables the recognition of seasonal characteristics and the computation of dirt accumulation rates during intervals of rainfall, as illustrated in Figure 17. Gathering extra information over a prolonged duration can aid in generating a more dependable statistical assessment to ascertain whether dirt accumulation rates persist consistent over various years or fluctuate according to corresponding atmospheric circumstances. Unfortunately, the literature contains no information on the repeatability of seasonality, highlighting the need for further investigations in this area. With this information at hand, it is feasible to construct a representation of the level of soiling that occurs between instances of rainfall. The effectiveness of cleaning surfaces during rain can be influenced by different factors including the amount of rain, the angle of the surface, the number of particles, and the force of adhesion between particles and surfaces. Therefore, in order to create a reliable model, it is important to evaluate the recoveries of the effect of soiling on surfaces caused by both rainfall and dew, while taking into account different levels of soiling. To achieve a precise representation of the build-up of soiling and its effects, it is necessary to create a model that takes into account atmospheric factors and the concentration of particles in the air. In the past few years, there has been an increase in the use of Artificial Neural Network (ANN) techniques because of their capability to recognize intricate non-linear connections between predictors and predictands. This method has been effectively utilized in various areas related to solar energy, for instance forecasting of irradiance [155], forecasting of power output in PV plants [156], and evaluating the impact of soiling [143], [157], [158]. The ANN-based algorithm requires vast datasets for input and output to train it and enable it to characterize data across various scenarios [159].

In a study by [157], ANNs were utilized to model the soiling effect between two consecutive days, ΔCI.

Several statistical correlations were discovered between ΔCI and wind speed when considering different relative humidity levels. Likewise, ΔCI was also observed to be linearly related to particulate matter PM10 when analyzing different wind speed levels. However, the results showed poor agreement with low regression coefficient r_2 [158].

FIGURE 14. Shows the Very-High Concentration Solar Tower at IMDEA Energy in Spain, where the heliostat is affected by a light rain(Left); and the Fresnel mirrors at the Green Energy Park in Morocco, which have experienced a red rain event (Right) [77].

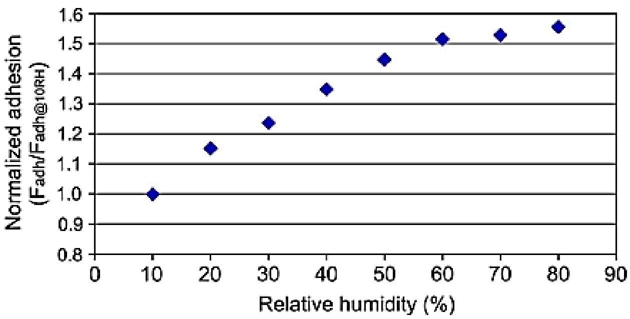

FIGURE 15. Demonstrates how the adhesion forces of 48 μm silica bead dust particles to a PV surface are affected by the relative humidity [146].

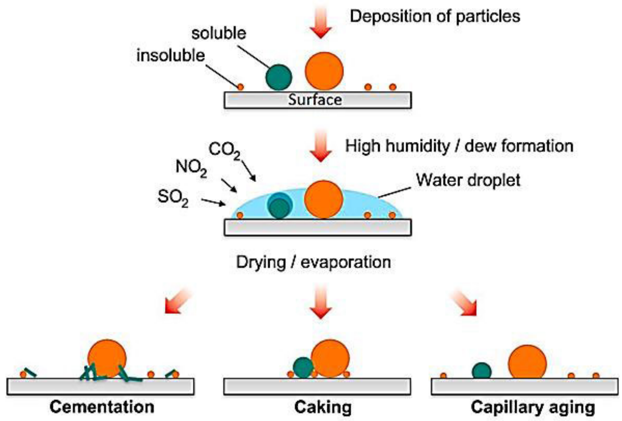

FIGURE 16. Shows the various mechanisms in which the adhesion of dust particles to surfaces can increase, including cementation, particle caking, and capillary forces [130].

Despite this, such an approach can help assess if one of the predictands has a more significant impact on the predictor than others. Figure 18 displays an Artificial Neural Network (ANN) which was trained to enhance the power generation of a soiled PV module by using factors such as time, irradiance, and temperature. This led to an r_2 value of more than 0.98.This approach proves to be very promising for studies related to soiling. Another approach to simulate dust deposition is Computational Fluid Dynamics (CFD). This method focusses on factors like tilt angle, obstacles present on the installation site and schedule for cleaning. One example is when the study conducted by [161] aimed to imitate the behavior of rooftop PV and its relation to particle deposition based on different azimuth and tilt angles, as well as particle size. Based on the simulation outcomes, it was discovered that the azimuth and tilt angles had a greater impact on dust accumulation compared to the size of the dust particles.

Particles that have a size of approximately 100 μm are more likely to be deposited when they experience lower impact velocities compared to particles of different sizes. Similarly, solar panels with lower tilt angles ($\leq 5°$) experience more soiling. In Figure 19, the quantity of particles deposited is shown based on the orientation and tilt angle. It is recommended to perform experimental validation along with any CFD analyses. Ideally, it is recommended that these simulations include coefficients acquired from outdoor measurements, as they are essential when it comes to setting up solar power plants, studying wind stream fields, and evaluating the impact of dust accumulation concerning the differences between roof-mounted and ground-mounted PV systems, as well as their tilt and azimuth angle dependencies [161]. Other studies, such as [162], wind fields are simulated to precisely predict the buildup and dispersion patterns of dust on PV panels. This is accomplished using specialized equations for dust deposition. Having access to a comprehensive, long-term database on soiling, as well as data on particulate matter specific to a particular area, can enhance the accuracy of these models. This, in turn, aids in pinpointing the best locations for the installation of solar power plants. Furthermore, conducting Computational Fluid Dynamics (CFD) simulations under various dynamic conditions is essential for capturing the daily and seasonal variations in behavior.

Reference [163] introduces a real-time assessment technique capable of promptly gauging the level of dust accumulation. This is achieved by comparing the measured irradiance with the computed irradiance. Simultaneously, the paper puts forth an irradiance calculation approach, along with three simplified methods, to compute the real-time effective irradiance. These methods emphasize solving equations once certain circuit parameters have been measured.

VI. MITIGATION STRATEGIES FOR PV DUST REMOVAL

The accumulation of dust on solar PV modules can result in reduced energy generation and a shortened lifespan, as the chemical properties of these particles may cause discoloration, corrosion, and delamination. Therefore, it is crucial to effectively clean soiled PV surfaces to minimize the impact of soiling. Various strategies to address this issue fall into two categories: restorative and preventive approaches. These approaches, illustrated in Figure 20, encompass natural cleaning, manual cleaning, mechanical cleaning, anti-soiling coatings, and electrodynamic dust shields.

A. RESTORATIVE SOILING MITIGATION APPROACHES

1) NATURAL CLEANING

Normally, rainfall, wind, and gravity serve as a natural means to clean soiled PV modules [127]. While rainfall can

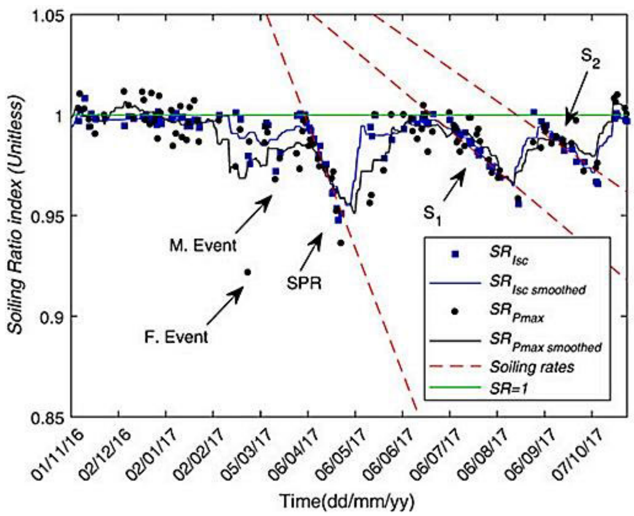

FIGURE 17. **Shows the ratio of soiling for short-circuit current and maximum power output, which was obtained from reference [160].**

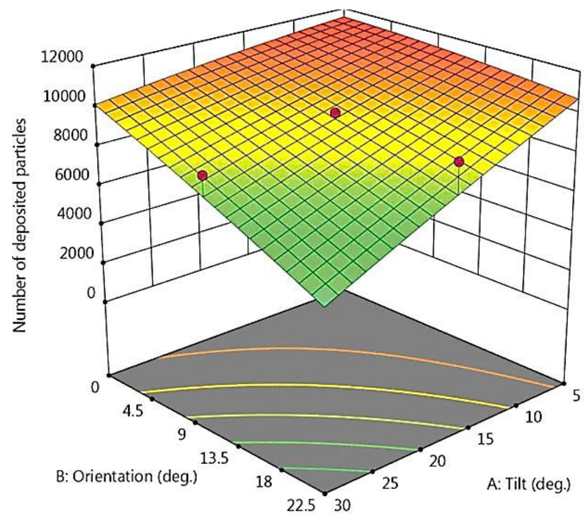

FIGURE 19. **Displays a response surface that describes how particles accumulate based on tilt, azimuth, and dust particle size [161].**

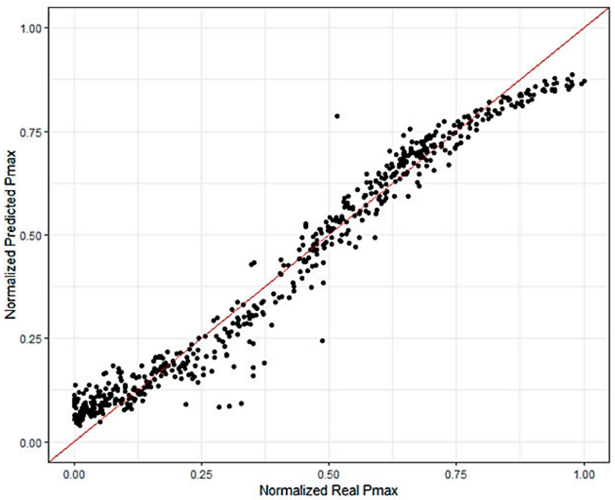

FIGURE 18. **Refers to the utilization of ANN for the purpose of predicting the maximum power output of a soiled PV module [159].**

effectively clean soiled surfaces, it also leads to decreased energy generation during rainy days. Rainfall proves more effective in areas with light soiling rates, such as Europe, as it has a greater chance of removing deposited dust particles from PV surfaces. For example, in southern Europe, rainfall measuring 2.2mm has a 50% chance of completely cleaning soiled PV modules. Although the western coast of South America and the western United States experience minimal dust deposition, the scarcity of rainfall in these regions poses a difficulty in restoring PV surfaces to their initial state. This, in turn, exacerbates the effects of soiling to some extent [83]. The tilt angle of PV modules plays a significant role in natural cleaning, as horizontal positions are less helpful to rainfall cleaning in comparison with inclined positions increasing the tilt angle of PV modules from 0° to 90° helps the removal of dust particles from the surface through the utilization of gravity [164]. Large-sized dust particles from the surface can also be removed by wind, particularly for PV modules located in high installations [47]. As per Jiang et al.'s findings [165], wind can efficiently remove large dust particles that are over 1 μm in diameter. However, small-sized dust particles cannot be cleaned by wind as high wind velocities are required for particle resuspension.

Reference [166] discovered that even if the rainfall was less than 1mm, it successfully cleaned the PV that was covered in dust and enabled it to function normally. Rain can reduce daily losses to the minimum limit of 4.4%. However, during dry seasons when rainfall is rare, the accumulation of dust can cause daily losses in PV performance to increase by over 20%. Another research study conducted by [167] examined the decrease in PV efficiency in Perth, located in Western Australia, known for its moderate weather conditions. They found that the PV productivity, which relied on natural cleaning methods through wind and rain, fluctuated during different seasons throughout the year.

The decrease in cell productivity was found to be greatest at the end of summer and spring while the productivity increased as winter approached, reaching a maximum level by the end of winter, according to the research. The researchers recommended using rain as a cost-effective and efficient cleaning technique that reduces dust accumulation on PV modules. Reference [88] conducted a study in Kathmandu, which has heavy rainfall in winter and large quantities of dust accumulation in summer. Practical measurements revealed that dusty and naturally polluted PV cells experienced a decrease in efficiency of up to 29.76% over five months due to dust accumulation density. By the end of the study period, the largest density of accumulated dust was found at the bottom of the PV cells at a rate of 6711 g/m^2.

2) MANUAL CLEANING

This approach involves using soft-bristled brushes, similar to those used for cleaning windows in buildings, to remove

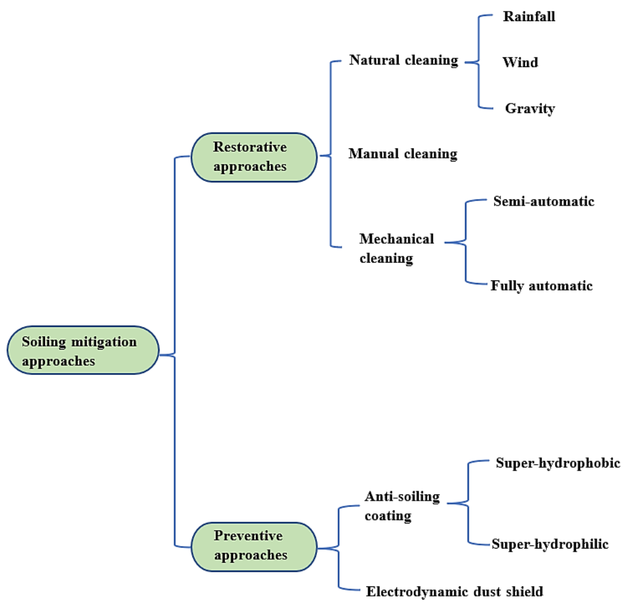

FIGURE 20. Shows a summary of the different approaches used to prevent soiling, organized into different categories.

accumulated dust and dirt from the PV cells as shown in Figure 21. These brushes can supply washing water directly and continuously, making them a more effective method than cleaning with rainwater or compressed water. However, direct contact with the PV cell surface may cause slurry due to variations in brush pressure across the surface. This method is costly since it requires trained personnel. An experiment was carried out in [115] to ascertain the effectiveness of foam brushes made of nylon, cloth, and silicone rubber (as illustrated in Figure 22) in enhancing the PV efficiency. According to the study results, some of the materials utilized during the experiment had a positive effect on the PV efficiency, with no noticeable persistent negative effects. According to the authors, using high-quality brushes is critical for achieving effective cleaning without damaging the PV surface. The research group in [168] found that using a high-quality brush is crucial for achieving efficient cleaning of the PV surface without causing any adverse effects.

3) MECHANICAL CLEANING

A Various mechanical and automated methods are employed for cleaning PV module surfaces, such as wiping, vibrating, blowing, brushing by drones or robots. These procedures need less manual labour and make use of automation systems. Powerful and independent robotic cleaners, as seen in Figure 23 [169], can clean solar panels autonomously in large solar plants. A water-saving and efficient alternative for cleaning PV modules in solar power plants is a hydraulic arm mounted on a tractor shown in Figure 24. This solution is easy to operate, compact, portable, suitable for small places and requires only one person to handle it [170].

Drones are a novel technology in the PV field that are easy to control, efficient in data logging, reliable in inspection and monitoring, and are preferred over fixed robotic or manual cleaning methods. Recent reports [171], [172] indicate the growing use of drones in monitoring, examination, and maintenance of solar PV panels. Some studies even analyse possibilities of implementing PV cleaning techniques that can be adapted to drones [172]. The researchers determined that brush and microfiber-based cloth wipers are the most suitable options for cleaning solar PV panels using drones, largely due to their small size, low weight, and ease of operation. Various commercial drones are currently available for cleaning large-scale PV farms, such as the Cleardron, which uses computer vision, artificial intelligence, and sensor technology to detect and clean panels using a glass cleaning device and a detachable container of cleaning fluid [173].

Another option is the Hercules 10 Spray drone [174], developed by Drone Volt, which has a powerful pump and spray system capable of spraying up to 3 liters of fluid per minute, as depicted in Figure 25. Aerial Power is a fast and water-free cleaning method that takes advantage of a drone's downward airflow to clean the PV panel [175].However, drones have certain limitations, such as a limited flight time and recharge duration, which can be mitigated by optimizing the cleaning cycles and customizing the power source. Using drones for PV cleaning comes with distinct advantages, such as mobility, autonomy, and the ability to clean panels on an as-needed basis, thus avoiding the high costs associated with fixed robotic approaches. Additionally, depending on the cleaning approach taken, drones can be used for waterless cleaning [172]. At present, the use of drones for cleaning solar panels is still in the developmental stages. The piezoelectric technique employs vibration technology to clean the module surface, and it is capable of achieving a power efficiency restoration of approximately 95% for PV modules [176]. The wipers and brushes used for cleaning are regulated by a programmable logic controller (PLC) and microcontroller. Similarly, robotic cleaning techniques involve automated module cleaning. However, there are some shortcomings associated with these methods, including high energy consumption requirements and high initial expenses associated with implementing automated cleaning systems. Additionally, the mechanized systems require regular maintenance, and the effectiveness of these techniques against severe soiling is not well established [177].

B. PREVENTIVE SOILING MITIGATION APPROACHES

The application of an anti-soiling coating is a technique used to minimize the accumulation of dust on the front surface of solar panels, and thereby reduce the need for frequent cleaning. The coating should possess specific qualities, such as high transparency, resistance to reflection and UV light, as well as durability, low-cost and easy to produce [132]. Some innovative materials, such as superhydrophobic and

FIGURE 21. Shows a manual cleaning [151].

FIGURE 22. Shows the process of cleaning through the utilization of a vacuum section [168].

FIGURE 23. Shows Solar-powered cleaning robot [178].

super-hydrophilic have gained increasing popularity in recent years for reducing dust accumulation on PV modules [180].

1) SUPER HYDROPHOBIC PLANE (SHOP)

The application of a porous external layer is utilized for cleaning solar panels. The approach involves adding a hydrophobic coating and a thin barrier to the PV surface, which prevents water droplets from collecting. To clean the panel, the surface is tilted at an angle as shown in Figure 26 to allow rainwater or cleaning water to settle in lower areas, quickly evaporating and leaving dissolved waste. However, the technique's suitability in dry weather remains to be verified for economic feasibility under different environmental conditions [181]. The low screen efficiency due to ultraviolet irradiation

FIGURE 24. Shows a hydraulic arm attached to a tractor [179].

presents a limitation, but waterproof glass or paint can reduce this effect. Although this method effectively prevents dust accumulation during rainfall, it requires water or precipitation to be effective. Precise structure or nanostructures can enhance the method's effectiveness in reducing dust accumulation on PV surfaces, according to research studies [182].

2) SUPER HYDROPHILIC PLANE (SHIP)

This method is a preventive measure that employs a self-cleaning technique. The process is hydrophilic, which means it attracts water to the surface, the opposite of hydrophobicity that repels it. The approach involves the use of nano-pattern fabrication and TiO2 (Titanium dioxide), which is a cost-effective material that is non-toxic, has high light transmittance, chemical stability, and durability. Nevertheless, the surface coating's degradation from prolonged exposure to ultraviolet rays causes more dust accumulation, requiring washing and drying after rainfall [74], [184].

This method combines all the benefits of the SHOP technique and has an extra advantage of chemically interacting with organic dirt via ultraviolet light, which results in breaking it down and dissolving it in water [185]. This method's effectiveness beats that of SHOP technique since it acts as a suspension material between dust and the PV surface, and it has a more extended viability [186].However, dust accumulation occurs as the efficiency of the layer declines with ultraviolet irradiation. Although this cleaning method works moderately well with rain, regular washing is necessary in dry climates according to [187]. Reference [188] use TiO2 film and optical stimulation to create a chemically stable, sturdy, transparent, non-toxic, and economically viable film for visible light [189]. Studies suggest that this method reduces dust accumulation but does not entirely restore PV efficiency.

3) ELECTRODYNAMIC DUST SHIELD

The technique called electrodynamic dust shield (EDS), or electrodynamic screen can effectively prevent accumulation

FIGURE 25. Shows the use of a spray drone to clean solar panels [174].

FIGURE 26. Shows the Super hydrophobic coating Kleen-Boost [181].

of dust on the surfaces of PV panels by generating an electric field that repels or moves dust particles [190], [191]. To create this field, high voltages are applied alternately to parallel electrodes on a substrate, producing electrodynamic traveling waves. These waves attract the charged dust particles and carry them away from the PV panels surface through the Coulomb force, toward the EDS edge [190], [191]. This is shown in Figure 27.

EDS is considered a promising method for mitigating soiling on PV surfaces. The method was able to remove 90% of accumulated dust within a span of two minutes, and it has been implemented in dry, arid, and desert areas according to the findings of the study [132]. A common EDS structure has been displayed in Figure 27. The approach is quite fast in comparison to other techniques, and it uses minimal energy. It does not require a complex control system as a small controller linked to sensors can be utilized instead. There is a possible drawback to using this system since the screen could deteriorate as a result of ultraviolet irradiation. Moreover, creating the electrical field requires a high amount of voltage, which could result in a decrease in PV generation efficiency of up to 15%.The method has been found ineffective in removing wet or cement dust particles, and its efficiency is constrained to the elimination of micro and small particles, as per research findings. This technique is useful in dry climates and can prolong the longevity of PV. Replacing screens with polymer or weather-resistant glass can decrease the harm caused by ultraviolet irradiation. Researchers in [192] have employed an electric dynamic screen as a protection measure against dust accumulation on PV. The study reveals that increased voltage leads to more dust being eliminated during the process.

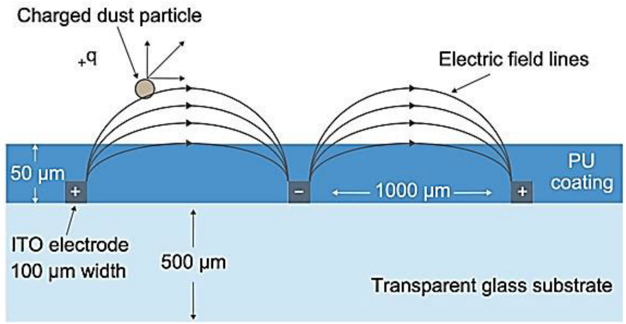

FIGURE 27. Shows a cross-section of an electrodynamic screen [191].

The research conducted by [193] investigated the effectiveness of using an electric dynamic system to remove dust from PV panels. The research evaluated how the mass of dust accumulated on a PV surface affects it and discovered that gradually turning on the electrodes of the system causes static charging of the dust particles, which facilitates their removal by using an alternating electric field.

This method successfully removed more than 90% of the dust accumulation in just two minutes. Studies in [194] and [195] identified voltage as the primary variable in this cleaning process. Even with low voltage levels, the screen used in the study was able to remove a significant portion of the accumulated dust. The researchers concluded that there was a direct correlation between voltage and dust removal - the higher the voltage, the more dust was cleared from the surface of the board studied. On the other hand, the utilization of a dynamic electric screen for cleaning PV carries significant expenses when it comes to its implementation and ongoing use. Also, this method does not involve any cleaning fluids, which ultimately restricts its functioning to certain types of dust. Furthermore, it cannot eliminate wet mud particles from the PV surface.

C. COMPARATIVE ANALYSIS OF SOILING MITIGATION TECHNIQUES

In Table 4, the benefits and drawbacks of the restorative and preventive approaches for mitigating soiling are presented. The study concludes that there is no universal method to address soiling problems at a specific site, since the effectiveness of soiling removal, technical reliability, labor costs, and other factors must be taken into account. Although anti-soiling techniques have been successful in reducing soiling on PV modules, they do not eliminate the need for cleaning. Therefore, manual and mechanical cleaning techniques continue to be the most suitable ways to address soiling.

D. CLEANING PERIOD

As previously stated, the presence of dust has adverse effects on PV panel efficiency, making their cleaning economically and in terms of performance important [196]. Finding the best cleaning schedules is crucial for maximizing economic advantages. However, there is no set cleaning interval for PV panels because the cleaning frequency is usually determined by the region's soiling rate [197].The environmental conditions of the installation location, such as particle type, source of particles, wind speed, precipitation and humidity, and soiling rate, mostly determine the optimal cleaning frequency [198], [199]. According to [61], it is recommended to clean PV panels on a weekly basis in areas with moderate dust. Additionally, all equipment should be cleaned after a dust storm to ensure it operates efficiently.

The study conducted in [200] aimed to determine the rate of soiling for PV systems installed in Mesa, which is situated near Phoenix, AZ, USA. The PV systems had a slope of 20°, and the daily soiling rate (average loss of full power energy due to soiling every day) was found to be -0.061% during the highest soiling period.

In [201], a new model was used to determine that PV panels in desert regions need cleaning every 20 days, considering a 5% decrease in output power and particle concentration of 100 $\mu g/m^3$. The authors in [116] proposed a technique for determining the optimal cleaning frequency of grid-tied PV systems by utilizing a cleaning tolerance coefficient. Cleaning intervals for manual techniques in central Saudi Arabia were determined in [110] to be around 20 days for handwashing and 9 days for washing tractors. [203] compared soiling rates in bifacial PV systems and mono facial minimodules in Santiago and found the latter to be 0.301% per day and the former to be 0.236% per day, with a rear-side soiling rate of 0.0394% per day for bifacial PV panels.

Several studies have investigated the ideal cleaning schedule for PV modules based on their location by considering practical and financial constraints. They measured power drop or efficiency loss and found that regions closer to sources of dust had to be cleaned more frequently.

The use of rain as a method for cleaning PV surfaces has been studied and has varying efficacy depending on the climate. For example, according to a study conducted by [204], rain was found to be effective in removing larger particles such as pollen in urban areas in Belgium; however, it was not capable of removing fine particles. In Navarra, Spain, research [205] showed that a daily rainfall of 4 to 5 mm or more was sufficient to clean a surface and restore PV performance. Rain's ability to clean inclined surfaces was observed to be different from horizontal ones. While some studies indicated that light rain was insufficient and even made surfaces dirtier [31], [206], other studies conducted in Malaga, Spain [207], and Mesa, Arizona, USA [32] demonstrate that even rainfall as low as 1 mm can help to recover PV performance. Nevertheless, light, and scattered rain may not be effective in cleaning surfaces in areas with high dust levels [85].

Although regions with high levels of suspended dust in the air may experience increased accumulation due to rain, this phenomenon can occur worldwide. The efficiency of rain washing varies across different areas of a tilted PV module's surface, with more efficient rinsing achieved at the bottom due to runoff created by raindrops hitting the upper part of the surface. As a result, the top zone receives less impact from rain washing. On the other hand, if rainwater is not drained, it can cause more accumulation and dissolution of particles at the lower edge [32], [204]. The evaporation of

TABLE 4. The assessment of several PV module soiling mitigation approaches.

Soiling mitigation approaches	Benefits	Drawbacks
Natural cleaning	• There is no fee	• Unsuitable for tiny dust particles • The dependence on surrounding geography and weather conditions.
Manual cleaning	• An efficiency of about 100% for soil removal. • Low start-up costs	• Labor expenses are high. • It is not ideal for areas with limited water supply. • The surface can be easily scratched or otherwise damaged.
Mechanical cleaning	• This approach boasts a 95% efficiency in removing dust without requiring any manual intervention. • It has an electromechanical controller that activates the cleaning process automatically. • Additionally, it requires little to no labor cost, making it cost-effective. • Finally, it also helps in reducing the surface temperature.	• The cost of getting started is high. • The expenses associated with maintenance and operation are high too. • The surface can be susceptible to abrasion and damage.
Anti-soiling coating	• An approach for mitigating passive soiling that doesn't require external labor and other resources . • To enlarge the periods between cleanings.	• Reducing PV efficiency. • The requirement for cleaning is not eliminated. • Relying on rainfall or dew.
Super-hydrophobic plan	• Prolonged lifespan. • Improved anti-soiling performance using nanostructure.	• Uncertainty regarding durability due to exposure to ultraviolet irradiation.
Super-hydrophilic plan	• Incredibly durable . •Greater efficiency compared to super-hydrophobic coating.	•Contributing to increased soiling accumulation when the coating deteriorates.
Electro dynamic shield	• It has a 90% efficiency rate in removing dust in dry environments. • It has a speedy cleaning action.	• It may not work as well with wet or cemented dust particles. • It may also be less effective in areas with high humidity. • To operate, it requires a high-voltage electricity supply. • It has a high initial cost.

water droplets may also have a negative impact on PV performance by causing cementation [32], [107]. Reliance on wind to eliminate particles from PV module surfaces is equally unpredictable as relying on rainfall. Fine particles smaller than 10 μm cannot be efficiently removed through wind, and only particles with a larger size can be blown away from a dry surface. Particles can only become airborne from a surface when the wind speed exceeds 3 to 4 m/s. Moreover, adhesion forces like capillary force are usually too strong for wind action to separate particles of varying sizes from a surface [130]. Thus, keeping a regular check on the performance of PV modules and establishing a cleaning schedule for these modules is a reliable and cost-effective approach to retain their efficiency.

Research studies have examined the impact of dust accumulation on PV panels in the MENA region, and one report suggests that the cleaning frequency can range from every 12 to 15 days [196]. Different research was conducted that used an internal approach to identify the rate of dust accumulation in three large-scale PV systems situated in the Middle East. The research estimated that the rate of dust accumulation was roughly 0.1% per day [208]. In [172], it was recommended that PV panels in a hot desert climate should be cleaned on a weekly basis, particularly during the summer months. An evaluation of dust deposition on the PV system at the Hashemite University in Jordan concluded that the cleaning frequency should be every two weeks based on the environmental conditions [209]. In general, the research findings indicate that the frequency of cleaning PV panels is affected by environmental factors such as how fast dirt accumulates on them, and the amount of soil removed during cleaning can also affect how often they need to be cleaned. Table 5 provides a summary of the research studies reviewed.

TABLE 5. Shows a categorized summary of the research studies reviewed on cleaning frequency.

Reference	Location	Cleaning Frequency
[61]	Minia region, central Egypt	It is recommended to clean on a weekly basis.
[201]	Desert areas	The cleaning interval is set at 20 days.
[110]	Central Saudi Arabia	Handwashing had an ideal cleaning period of 20 days, whereas tractor washing had an optimal cleaning interval of 9 days.
[203]	Santiago, Chile	The daily soiling rate for the mono facial minimodule is 0.301 %, while for the bifacial module, it is 0.236 %.
[196]	MENA region	The cleaning period is estimated to be between 12 and 15 days.
[208]	Middle East	The average soiling rate is shown to be 0.1% /day.
[172]	Desert areas	Weekly cleanings of the panels are recommended, especially during the summer.
[209]	Jordan	It is preferable to clean every 14 days.

E. ECONOMIC EVALUATION

The cost of cleaning is a critical factor that influences the efficient operation and maintenance of PV systems [210]. Soiling is a primary parameter that significantly impacts operation and maintenance costs, particularly in desert regions, and should be carefully considered [211]. The expense of cleaning PV systems is mainly decided by how often they are cleaned within a certain timeframe, like monthly or yearly. A research study conducted in 2006 discovered that cleaning a 100 kWp PV system twice during the dry summer season in Los Angeles (CA, USA) could result in a total revenue increase of \$1500 with the California Solar Initiative incentive program and \$3000 with the European feed-in tariffs program [184]. Different research conducted on two 1 MWp PV plants in the rural areas of southern Italy compared their washing expenses and income. The results showed that the combined washing cost for both systems was \$4.58. A separate study examined the financial implications of cleaning soiling and snow from PV systems in three European areas [212]. This study found that cleaning PV panels in Helsinki (Finland) does not have any economic advantage, while locations such as Murcia (Spain) and Munich (Germany) show economic benefits. A similar evaluation of Stockholm (Sweden) found that cleaning soiling and snow from PV panels in the region is not financially viable [213]. In the central region of Saudi Arabia, they have tested different cleaning methods which included manual cleaning and cleaning with the help of washing tractors. The average cost for manual cleaning is \$3.68 per kW per year, while the cost for manual cleaning with the assistance of a washing tractor is \$1.5 per kW per year [110]. Researchers studied the use of a proposed nanocoating on solar panels in MENA areas with high temperatures and discovered that it has the potential to produce an economic advantage of \$20.94 per MW per year [210], [214]. In the end, it has been demonstrated by two sites located in the Algerian Sahara that it could be profitable to clean PV panels twice per year, at a cost of \$15843 per MW, if the level of soiling exceeds 7% [211], [215]. An assessment conducted in Jordan revealed that the average per-day cost of cleaning PV panels is approximately \$0.212 per kWp [196], [216]. According to research conducted by [172], different methods and tools for cleaning without water were tested in desert climates. The study revealed that the most cost-efficient method cost a total of \$21.07 per m^2 per year. A summary of the research papers reviewed, and their outcomes can be found in Table 6.

VII. FUTURE PRESPECTS FOR PV TECHNOLOGY AND CLEANING TECHNIQUES

According to the literature, there are three different scenarios for the future growth of PV technology: a pessimistic, an optimistic/realistic approach, and a very

TABLE 6. Shows a categorized summary of research papers reviewed on economic evaluation.

Reference	Location	Conclusions
[196]	Jordan	PV panel cleaning costs roughly $0.212/kWp on average per day.
[110]	Central Saudi Arabia	Manual cleaning costs approximately $3.68/kW/ year, while using a washing tractor to clean costs about $1.5 /kW/ year.
[210]	The MENA countries	The use of the proposed nanocoating results in an economic benefit of approximately $20.94 /MW/ year.
[211]	The Sahara Desert of Algeria	If the PV modules are cleaned completely twice a year and the level of soiling is greater than 7, cleaning would result in a profit of around $15,843/MW
[184]	Los Angeles, CA, USA	The California Solar Initiative incentive program would lead to a rise in the total revenue of $1500.
[130]	The rural areas of southern Italy	Each PV plant incurred a washing expense of $4.58 in total.
[212]	Munich , Murcia ,Helsinki	In Murcia and Munich, it is cost-effective to clean PV plants, whereas in Helsinki, it is not financially viable.
[213]	Stockholm	It is not cost-effective to remove soiling and snow from PV panels.
[172]	Desert areas	The most economical cleaning method costs $21.07/m²/year.

optimistic/technologically advanced strategy [217], [218]. These scenarios consider the impact of cost and environmental performance and are depicted in Figure 28. There are based on reducing the cost of both the module and the Balance of System, shortening the energy pay-back time, using mature industrial technology, improving efficiency, integrating with buildings, and incorporating energy storage technologies. According to a very optimistic scenario, it is predicted that the global PV power will reach 9 TW by 2050 with the help of various energy storage systems, and new technologies and materials will make up 50% of the PV market by 2050. According to the optimistic scenario, annually installed capacity for PV systems could reach 1.7 TW and 2.4 TW by 2040 and 2050, respectively. This would be achieved through the expansion of crystalline Si, thin films, and novel devices in their most suitable market sector. However, the pessimistic scenario predicts that the production of electrical energy from PV systems could reach 0.39 TW and 0.53 TW by 2040 and 2050, respectively.

The PV module or cell is critical for all the aforementioned scenarios. PV technology can be divided into three

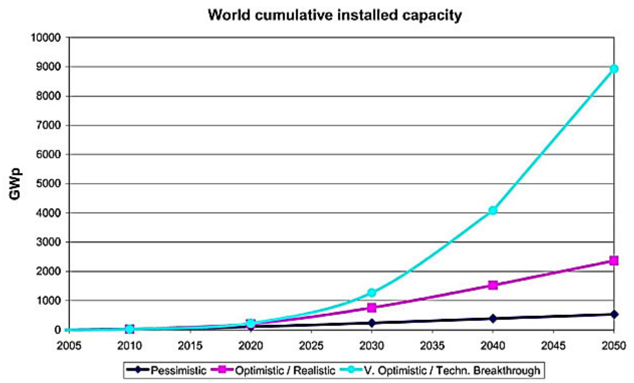

FIGURE 28. Shows three potential scenarios for worldwide PV installation capacity by 2050 [216].

groups known as generations. The first generation comprises of crystalline silicon cells, the second generation includes thin film cells, and the third generation is made up of emerging solar cells. Each generation has its own advantages and disadvantages, and the efficiencies of each type of solar cell technology are summarized in Table 7. Despite the growth of the PV market, there are still challenges to its implementation, including technical challenges such as future raw materials and high temperatures, and non-technical challenges such as raw material availability and high prices [217], [219]. Studies conducted by [73], [219], [220], and [221] have demonstrated that the performance of PV cells (current-voltage and power-voltage curves) can be greatly affected by various environmental factors. These factors include temperature gradient, surface soiling effects, dust deposition and exposure to sunlight.

Choosing the appropriate cleaning method for PV technologies is crucial. The selection process is influenced by various factors, including the type of PV module (generation), the properties of the dust that has accumulated on the module, the PV array's capacity, the installation and weather conditions. These aspects are linked and must be addressed while deciding on the optimum cleaning approach for a PV module. In order to select the best method, it is necessary to consider the benefits and drawbacks of both restorative and passive/preventive cleaning methods as outlined in Table 4, and compare them to the relevant selection criteria For instance, a site with high levels of dust, low rainfall, and low wind speed, and a small tilt angle requires more effective cleaning techniques, such as mechanical or electrodynamics screen cleaning methods, for high-capacity PV arrays of all generations. On the other hand, low-capacity PV arrays of various generations can make use of manual and passive techniques at identical specific sites. In the end, self-cleaning methods such as: hydrophilic and superhydrophobic are more appropriate for locations with minimal dust, moderate rainfall, and wind speeds, and small or high tilt angles.

Additionally, the natural cleaning technique is well-suited for areas with large dust particles and small or high tilt

TABLE 7. Provides an overview of the efficiency, technology, and generation of every type of solar cell.

Generation	First		Second			Third	
Technology cell type	Crystalline Silicon		Thin film				
	Mono	Poly	a-Si	Cu (In,Ga)Se2	(CdTe)	Emerging Dye sensitized	Perovskite
Efficiency of laboratory cells (%)	26.3 [222]	22.3 [224]	12.3–14 [225]	19.9–22.9 [227]	16.5 [228]	7–11.9 [229]-[230]	14.1 [231]
Efficiency of commercial modules (%)	16–18 [223]	15–17 [223]	4–6 [226]	8–11 [226]	5–9 (227]	---	---

angles. Furthermore, cost considerations are another crucial factor when selecting a cleaning method for a particular type of PV technology, as this can have a significant impact on the levelized cost of energy (LCOE) per kilowatt-hour, enabling it to compete with other energy systems. Research indicates that the development of raw materials is critical to the effectiveness of self-cleaning methods, heavily dependent on the type and application of coating materials. To extend the longevity of a coating layer, it is important to select coating materials that have suitable surface characteristics for a particular location. In desert areas, combining cleaning methods like hydrophilic, superhydrophobic film, and natural and active techniques (such as wind, rain, and mechanical vibration) can create a powerful cleaning approach. Lastly, drone technology can be employed to assist the self-cleaning method for large PV arrays installed in desert regions.

VIII. RESEARCH GAPS AND CHALENGES

After conducting a review of related research papers, several research gaps have appeared. Firstly, with regards to measuring the impact of soiling on PV panels, there exists a considerable difference in the reported losses in efficiency during the same period of study. This difference could be due to other factors that influence dust accumulation on PV panels or insufficient control measures in cleaning cycles. Consequently, future quantification efforts of soiling losses should account for all relevant factors, such as location, weather conditions, design parameters, and cleaning. Secondly, it was observed that comparing the soiling losses of various PV technologies, like crystalline (mono or poly) and thin film, in different locations or periods of study, yields different results. In order to help PV contractors and designers choose the appropriate PV panels for specific locations, it would be extremely valuable to conduct structured comparative research that takes into account all the factors that impact soiling and monitors them across various technologies under similar conditions. While the review found many research studies that examined the impact of solar irradiance and dust accumulation on PV panels, several confirmed that other factors also significantly contribute to dust accumulation, which negatively affects panel performance. Not many research studies have examined all of these factors at the same time and for a long enough period. These factors involve factors such as design parameters, installation settings, the weather, and place characteristics.

Most research on PV systems has focused on economics by increasing panel efficiency and reducing costs, but there has been insufficient attention paid to the impact of environmental factors on system performance. Additional investigation is required to create innovative approaches for decreasing the negative impact of soiling on the performance of PV system while taking into account economic constraints and comparing them with traditional PV systems. This research aims to propose an innovative solution to address the problem of soiling and enhance overall performance.

Only a small number of research studies have comprehensively examined the impact of various climatic conditions on the deposition of natural and artificial dust particles on PV modules in different locations worldwide. Further research is necessary to gain a clear understanding of how geographical climates affect dust production. Regions such as North China, Middle East and North Africa. East are considered dust sources that transport dust particles to other regions globally. Consequently, areas that do not usually generate as much dust can still be exposed to the dust coming from these sources.

Our research has identified areas that have been ignored in previous studies and should receive greater attention in future research. It is recommended that future studies specifically focus on identifying methods to reduce the amount of dust accumulation around PV power plants and carry out comprehensive investigations that consider all major factors that influence the performance of dusty PV panels in different weather conditions, such as temperate and rainy tropical climates.

However, comparing the results of various studies on the effects of soiling can be challenging due to differences in measurement methods and metrics used. To address this issue, there are now innovative instruments available, such as DustIQ from Kipp and Zonen, or Mars from Atonometrics, that can provide consistent measurements of the impact of dust on PV systems. These small sensors can be installed throughout PV power plants to measure the amount of dust accumulation and can be linked to software that sends an alert when the threshold for acceptable soiling has been surpassed. It should be noted that research should also be carried out on how these sensors correlate with different PV technologies.

It is recommended to perform studies on the impact of soiling using the sun's spectrum and carrying them out outdoors whenever possible. Laboratory studies can differ from real-world conditions as the atmosphere is a complex system that includes the deposition of soiling. Therefore, artificial tests should only be conducted when evaluating different sensors. In addition, it is necessary to collect data for several years to determine the actual degree of soiling for a particular location and establish statistical significance. However, it is not practical to rely on manual measurements alone. Therefore, new instruments and techniques are currently being developed to rapidly evaluate and observe the impact of soiling on solar fields, mainly for photovoltaics, using camera-based approaches.

Additionally, employing techniques such as artificial intelligence to predict dust storms is a useful strategy that can aid plant operators in selecting the optimal cleaning procedures for PV modules.

Despite significant research into cleaning methods and materials for PV panels, pre-scheduled cleaning cycles continue to be dominant for medium to large PV panels. A more accurate cleaning schedule driven by robust predictive models that consider all relevant factors for at least a year is urgently required to enhance economic and performance outcomes for such systems. Current predictive models for PV panel performance focus mainly on a limited range of indicators such as output power or efficiency, which can vary significantly depending on the PV system's panel type or supporting equipment such as inverters. A preferable approach would be to adopt the performance ratio as a performance indicator, which accounts for the impact of meteorological factors and location characteristics and is commonly used by PV consultants for evaluating performance. To improve the accuracy of predictive models, all relevant factors must be considered, including real-time images and videos of dust accumulation, cloud movement, fog, etc. This may require several models to process various types of data effectively.

Further research is needed to develop drone image-based techniques that can effectively reduce dust accumulation on PV panels. By utilizing an artificial intelligence system, a cleaning method that requires minimal auxiliary energy consumption can be identified. To optimize the performance of solar-wind hybrid energy systems, technical improvements that consider dust in the atmosphere and deposition on their components can be made using computational technologies. To achieve these goals, additional studies are required to create artificial intelligence-based models for reducing dust accumulation, which will assist in determining appropriate cleaning strategies based on model patterns. Additionally, investigating hybrid cleaning methods to identify the most economical and suitable materials and combinations would be beneficial.

Humidity and dew, combined with dust, can cause a soiling situation that results in cementation and increased difficulty in cleaning PV panels. Using water or solution for cleaning can increase costs, making this a significant challenge for researchers to address. Another challenge is accurately measuring soiling and dust thickness, as well as their adhesive properties. To overcome these challenges, use R&D nanotechnology and meteorology and development can be utilized to identify new cleaning materials and coatings that can prevent different types of dust accumulation in dry or humid environments. On the other hand, it is important to ensure that any new materials satisfy multiple requirements, such as being non-toxic, adaptable to various PV technologies, having excellent transparency to solar irradiation, and being reasonably priced.

In order to conserve water and reduce costs, researchers should utilize more efficient water usage methods and prioritize water recycling and filtering. To minimize energy consumption, it is also important to minimize power usage for water pumping. Although implementing a controlling system to measure and detect the decrease in PV efficiency and utilizing an automated cleaning robot may pose a difficulty, it has the potential to enhance cleaning accuracy compared to periodic methods. However, researchers must further investigate and develop an innovative and effective solution to this challenge.

In order to optimize cleaning methods, it is crucial to have a comprehensive understanding of the dust characteristics and properties in a given location. This includes factors such as composition, accumulation rate, size, shape, optical behavior, and electrostatic deposition behavior. It is also important to take into account environmental factors like wind speed and direction, humidity levels, precipitation, storms, and pollution levels when determining suitable cleaning methods. Additionally, determining whether a chemical solution is necessary for dust particle removal is necessary.

Exploring the possibility of near-zero water consumption techniques could be a promising avenue. However, achieving the same level of cleanliness without utilizing a liquid agent may prove to be challenging. It might be more practical to develop cleaning methods that enhance cleaning effectiveness and decrease water usage. The Water Resource Group has projected that water demand will exceed water supply in multiple countries by 2040 [232]. As a result, it is crucial to adopt proactive mindsets and policies to address this concerning issue.

IX. CONCLUSION

The performance of PV technology is vulnerable to the accumulation of dust, posing significant challenges, including financial losses in regions with abundant solar resources, which has stimulated interest in research worldwide. In reviewing the impact of dust on PV systems, dust particles and their sources were described, alongside the mechanics of dust formation and factors influencing it. The effects of dust on the PV modules were discussed, and various relevant publications were presented. The soiling of PV modules is a complex procedure influenced by various factors such as the environment conditions and the way the modules are set up. The problem of soiling has yet to be fully resolved, as soiling losses range from 1% to more than 50% and vary across regions.

The analysis evaluated multiple cleaning methods based on technical and financial factors. The review concluded that manual and mechanical cleaning are the most trustworthy approaches to cleansing PV modules, however, they can be costly. Even though preventative methods such as anti-soiling coatings may reduce cleaning frequency, ongoing maintenance with a mitigation technique is still essential to boost PV module efficiency. The successful utilization of a cleaning technique depends on the climate of the location.

The important findings are summarized as follows:

- The accumulation of dust particles on PV modules surfaces impacts their efficiency by reducing the amount of sunlight reaching the cells and decreasing their average lifespan.
- Different factors, such as the type, size, and shape of dust particles, and weather conditions like humidity, wind, and temperature, also impact the efficiency of the PV modules.
- Cleaning methods for PV systems have undergone thorough examination, comparison, and analysis, taking into account technical and economic considerations. The most effective cleaning approach is determined by factors like system size, design, location, water availability, and the characteristics of the dust. While cleaning frequency suggestions range from weekly to monthly, there is no universally applicable standard, as it is tailored to the specific system and local weather conditions.
- Drones offer promise for cleaning but have limitations like flight time and charging constraints. Robotic cleaning has high energy consumption and initial costs, requiring further research and development (R&D).
- Future research should focus on AI models for understanding dust accumulation and optimizing cleaning techniques. Further R&D is needed for efficient cleaning strategies and exploring hybrid cleaning methods.

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MUHANNAD J. ALSHAREEF was born in Riyadh, Saudi Arabia, in 1988. He received the B.Sc. degree in electrical engineering from Umm-Al-Qura University, Saudi Arabia, in 2011, the M.Sc. degree in electronics and electrical engineering from Coventry University, U.K., in 2016, and the Ph.D. degree in electrical engineering from Aston University, U.K., in 2019. He is currently an Assistant Professor with the Department of Electrical Engineering, Umm-Al-Qura University. His research interests include photovoltaic modeling and control, intelligent control, nonlinear systems control, and optimization techniques, such as genetic algorithm, particle swarm optimization, and control and protection of dc microgrids.