Review

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Review

Impact of Dust Deposition on Solar Photovoltaic Systems: A Comprehensive Review of Performance Degradation, Regional Variations, and Mitigation Strategies

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Abstract

Solar energy is emerging as a cornerstone of the global renewable energy transition, with projections indicating that photovoltaics (PV) could contribute up to 90% of electricity generation by 2050. However, environmental factors, particularly dust deposition, pose a significant challenge to the long-term performance and efficiency of PV systems. Dust accumulation varies widely across different geographic regions, influenced by climate, land use, humidity, and pollution. Arid and semi-arid areas experience the highest deposition rates, while tropical and temperate regions are affected by seasonal rainfall and urban pollutants. This review comprehensively examines the impact off dust on PV performance, highlighting factors such as surface roughness of PV module, panel tilt angle, seasonal variations, wind dynamics, and dust composition. Furthermore, the review assesses various dust mitigation strategies, including manual and water-based cleaning, robotic systems, hydrophobic coatings, and electrostatic methods. By synthesizing global studies and presenting a holistic view of dust effects, this paper provides critical insights for optimizing PV design, maintenance, and operational strategies to ensure sustained energy yield and reliability in solar energy systems worldwide.

Keywords: solar energy; photovoltaic efficiency; regional diversity; dust accumulation; soiling effect; environmental impact; mitigation strategies; sustainable energy

1. Introduction

1.1. Background & Importance of Solar PV Systems

The global energy landscape is undergoing a transformative shift towards renewable energy, with solar energy at the forefront. Projections indicate that by 2050, solar photovoltaics (PV) could account for up to 90% of global electricity generation[1], driven by technological advancements and supportive policies. Solar energy is among the most promising renewable energy sources for mitigating global warming and the energy crisis [2], offering a practical means of generating power from sustainable sources rather than relying on fossil fuels. Due to the rapid and sustained growth from 2010 to 2050 of global electricity generation from solar photovoltaic (PV) systems, in 2010, solar PV contributed only 30 TWh, reflecting its early-stage deployment[3]. Figure 1 illustrates a sharp increase to 250 TWh by 2015, followed by accelerated growth to 850 TWh in 2020, due to declining module costs, supportive policies, and large-scale installations. The estimated value for 2025 shows a significant jump to 2,260 TWh, indicating solar PV's transition into a mainstream energy source [4]. Future forecasts project an exponential rise, with generation expected to reach 6,000 TWh by 2030 and 10,500 TWh by 2035. By 2040 and 2045, solar PV output is projected to grow to 15,000 TWh and 20,000 TWh, respectively. By 2050, global solar PV generation is projected to reach approximately 25,000 TWh, underscoring its critical role in meeting future global energy demand and decarbonization targets. However, the performance and efficiency of PV systems are significantly influenced by environmental factors, particularly dust accumulation [5]. Dust deposition on solar panels can lead to substantial losses in energy yield, particularly in arid regions or areas with high industrial activity. The impact of dust is not uniform; it varies across different geographical locations due to variations in climate, land use, and atmospheric pollution[6].

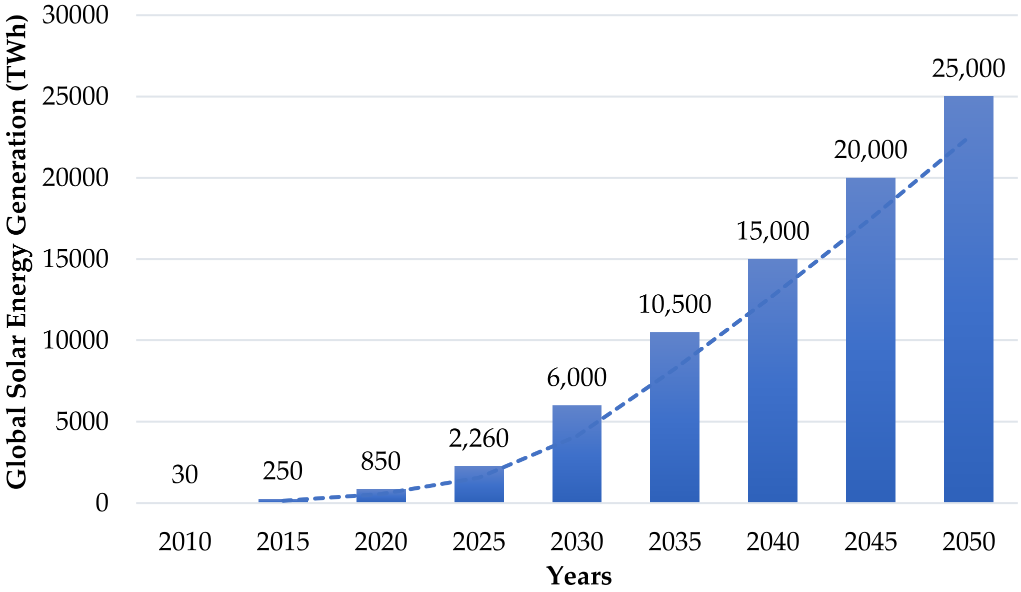

Figure 1. Global solar photovoltaic energy generation forecast by 2050.

At the same time, urban air pollution increases the deposition of carbon-based particles, contributing to efficiency losses. In contrast, the arid climates of the Middle East and North Africa experience frequent dust storms, leading to heavy dust deposition, and the coarse nature of desert dust often causes rapid degradation of PV modules [7]. Similarly, regions near the Sahel in Africa experience severe dust accumulation due to dry, windy conditions, with limited rainfall exacerbating dust-related performance losses [8]. In Europe, while dust accumulation is generally lower in temperate regions, industrial pollution and agricultural activities contribute to the deposition of fine particulates. For instance, a single dust storm can lower power production by 20% [9], while dust can lower PV performance by 25% to 35% in a month [10]. To visualize the global distribution of dust concentrations, the following map in Figure 2 illustrates areas with varying levels of dust deposition [11].

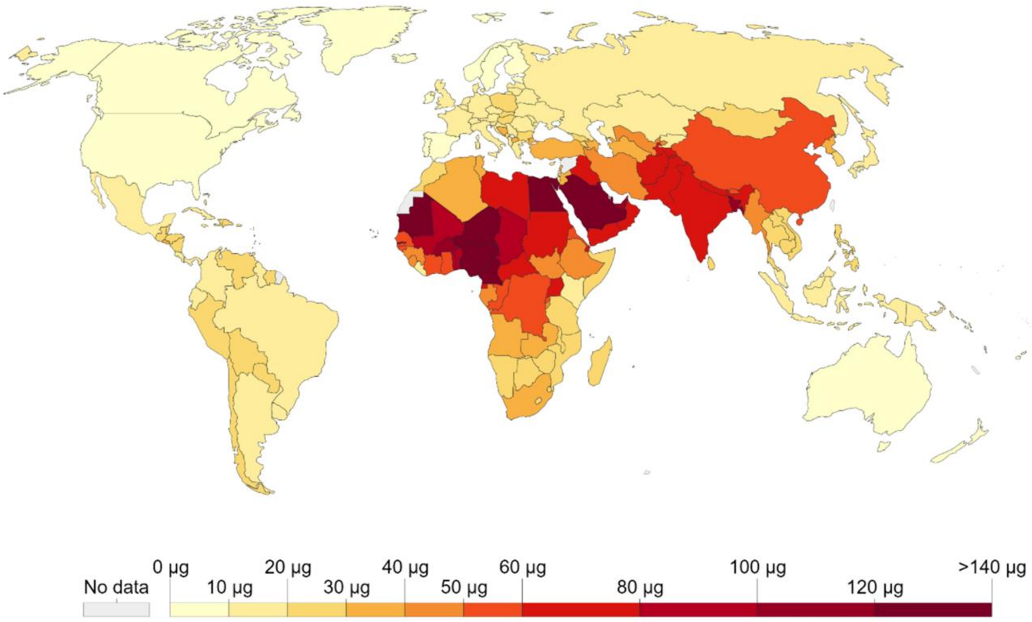

Figure 2. The geographic distribution of dust density worldwide, measured in micrograms per cubic meter (µg/m3) [12].

According to research, the tilt angle of the panels, the local environment, and the actual composition of dust are the primary determinants of dust accumulation on PV surfaces [13]. These are the main factors influencing dust aggregation [14]. Several important factors, such as dust particle size, shape, and composition, significantly affect the amount of light reaching solar panels [15,16]. The accumulation of dust on the grid solar panel modules is seen in Figure 3. The map highlights the impact of dust, showing that dust accumulation poses significant challenges to PV performance across different regions, emphasizing the need for tailored dust mitigation strategies. Understanding the spatial variability of dust deposition is essential for optimizing the design, maintenance, and operation of solar energy systems worldwide.

Figure 3. Scenario of natural dust accumulation on solar photovoltaic panels in different locations.

Recent initiatives to reduce dust accumulation and enhance PV cleaning have focused on both passive and active strategies [10]. These procedures encompass design, installation, and operation.

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Furthermore, numerous techniques and experimental tools have been developed for power plant dust monitoring, revealing difficulties in measurement outcomes. Innovation and the development of novel methods to address dust-related issues and improve PV system efficiency under challenging conditions have been highlighted in recent PV cleaning research [17]. In the subsequent sections, this review paper examines the various factors that influence dust accumulation on PV panels, the methodologies used to assess its impact, and the strategies implemented to mitigate its effects, thereby ensuring the sustained efficiency and reliability of solar energy systems worldwide.

1.2. Objectives of the Review Work

This review aims to provide a comprehensive analysis of the impact of dust deposition on rooftop solar PV systems by synthesizing findings from existing research across different geographic regions and climatic conditions. The specific objectives of this review are as follows:

- To summarize global research on dust-induced PV degradation: By reviewing previous studies, this paper will analyze the extent of performance losses due to dust accumulation and highlight the key findings from different regions.
- To identify variations in dust accumulation across different climates: The review will compare studies conducted in diverse environmental settings to understand how dust accumulation patterns vary and influence PV performance.
- To discuss dust characterization, mitigation strategies of dust accumulation, and future research directions to enhance PV system efficiency in dusty environments.

2. Methodology

A systematic framework for the review paper on rooftop solar PV performance deterioration caused by dust accumulation is shown in Figure 4. The review begins with defining the scope and objectives, establishing the relevance of rooftop PV systems in modern energy systems, and setting the context for the study. It then introduces the background and importance of PV systems, highlighting their role in sustainable energy generation and urban deployment. Subsequently, the framework classifies dust and soiling materials, categorizing the different types of dust affecting rooftop PV modules by origin and composition. This is followed by an analysis of the factors affecting dust deposition, encompassing environmental, dust-related, system-level, and regional influences.

The next stage examines the impact of dust on PV performance, focusing on power loss mechanisms, efficiency reduction, and reliability concerns. The framework further emphasizes geographic and climatic variations in dust accumulation, recognizing that soiling behavior and degradation rates vary significantly across regions due to differences in climate, land use, and pollution levels. Finally, the framework culminates in the evaluation of dust mitigation strategies for rooftop PV systems, covering both preventive and corrective measures. The review concludes with results and recommendations, synthesizing findings from the literature to provide practical insights and to identify future research directions and challenges that will guide further advances in improving the long-term performance and sustainability of rooftop solar PV installations.

Figure 4. Step-by-step process of the proposed work.

2.1. Classification of Accumulated Dust Material on PV

Accumulated dust on photovoltaic (PV) modules can be broadly classified based on its origin, composition, and physical characteristics, as reported in previous studies. The most common category is mineral dust, originating from soil, sand, and desert environments, and mainly composed of silica, quartz, and aluminosilicates [18]. This type of dust is dominant in arid and semi-arid regions and causes significant optical losses due to light scattering and absorption [19,20]. Anthropogenic or urban dust consists mainly of fine particles generated from vehicle emissions, industrial activities, and combustion processes [21]. These particles are rich in carbonaceous matter and metal oxides, exhibiting high absorptivity and strong adhesion to PV glass surfaces. Several studies report that, despite lower mass deposition, anthropogenic dust can cause disproportionate power losses due to its optical and thermal properties. Organic and biological dust includes pollen, plant debris, microorganisms, and biofilm-forming materials commonly observed in agricultural, tropical, and vegetated regions. Although often less dense than mineral dust, this category forms sticky layers that enhance further dust accumulation and complicate cleaning processes, thereby indirectly accelerating performance degradation[22]. In coastal and humid environments, marine or saline dust becomes significant. This dust type is primarily composed of sodium and magnesium salts transported by sea spray and aerosols [19]. Saline particles promote wet adhesion, crystallization, and surface abrasion, leading to persistent soiling and potential material degradation of PV modules [21].

Additionally, several studies highlight the presence of mixed or composite dust, especially in urban–agricultural transition zones, where mineral, organic, and anthropogenic particles coexist[23]. The performance impact of such dust is highly variable and strongly dependent on local climate, particle size distribution, and humidity [24]. Table 1 presents a comprehensive classification of dust and soiling materials commonly affecting the performance of solar photovoltaic (PV) modules, highlighting their sources, composition, and performance impacts as reported in reputable journal literature.

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Table 1. Accumulated Dust Material Classification for Solar Photovoltaic Panels

Category	Types	Typical Composition / Origin	Impact on PV Performance	Ref.
Mineral Dust	Desert dust, soil, sand, and clay particles	Quartz, feldspar, clay minerals (silica, aluminosilicates)	Significant optical attenuation due to scattering and absorption is typical in arid regions	[25,26]
Anthropogenic/Industrial Particulates	Engine exhaust, urban soot, industrial emissions	Carbonaceous particles, metal oxides	Fine absorptive particles that increase light loss; higher adhesion in polluted areas	[25,26]
Organic/Biological Particles	Pollen, biofilms, plant debris, microorganisms	Organic matter, cellulose, biological residues	Creates sticky layers, potential biofilm formation; can trap more dust	[27]
Bird & Animal Droppings	Bird excreta, insect deposits	Mixed organic/inorganic components	Causes localized shading and hot spots; strong adhesion, high optical blockage.	[25]
Agricultural Emissions / Mixed Soil	Crop dust, fertilizer dust	Mineral + organic components	Variable effects depending on composition and weather	[27]
Coastal/Saline Particles	Sea salt, saline dust	$NaCl$, $MgCl_2$ from coastal environments	Salt crystals promote micro-scratching and wet adhesion, relevant for coastal PV installations.	[28]

The category of different types of dust, such as mineral Dust, organic/biological particles, bird & animal droppings, agricultural emissions / mixed Soil, coastal/saline particles, anthropogenic/industrial particulates made of different raw materials of dust components. Figure 5 shows the raw materials of different categories of dust components. Sand is made up of particles that are either sandy, metallic, or have a diameter between 0.02 and 2 mm (0.0008 and 0.08 in). They originate from dust in desert regions and occur in large quantities in rocks. The authors [29] are also highly difficult, have almost no cleavage, are nearly insoluble in water, and do not break down.

Cement is a mineral powder that has been finely ground and is typically gray in color [30]. The three most crucial raw materials used to make cement are marl, clay, and limestone. Cement, when combined with water, acts as an adhesive to hold hard rock, gravel, and sand together as concrete [31]. Both underwater and in the air, the cement solidifies, and once it reaches this stage, it stays that way. Typically, cement is offered as a uniform bulk dry product. To guarantee the necessary stability, dependability, and processability in the application, its features are standardized[32]. Limestone is a sedimentary rock composed of calcium carbonate that is utilized in the cement and building materials industries. It can be white or gray in color [33,34]. Silica Gel ($\mathrm{SiO2}$) is an amorphous type of silica that comes in tiny packets[29]. It has the capacity to both evaporate and absorb vast volumes of water. Small silica gel packets are present in anything that is eventually affected by excessive moisture or accumulation. They are thus mostly used as dehumidifiers and drying specialists [35]. The eighth group of the periodic table contains the chemical element iron. It's a delicate solid. High temperatures and damp air cause pure iron metal to rust quickly. Tiny iron metal particles that are generated as trash in industrial regions spread throughout the atmosphere and build up on PV [36].


Sand
Cement
Limestone
Silica Gel ($\mathrm{SiO2}$)
Iron Metal
Sulphur
Brown Soil
Calcium Carbonate ($\mathrm{CaCO3}$)
Fly ash
Sawdust
Black Silicon Carbide

Figure 5. Raw Materials of different categories of dust components [37].

Sulphur precipitated is used in products like topical creams that treat psoriasis, eczema, and acne in the personal care and pharmaceutical sectors. Based on several tests, sulfur was selected as an antibacterial and keratolytic ingredient in both products [38]. Brown soil dust is the second greatest major particle source after sea salt, and it has a significant impact on air quality. The dust in the atmosphere is made up of dust microparticles, which originate from a variety of sources, including soil dust that has been raised by wind, volcanic eruptions, and air pollution[29]. Dust in homes, workplaces, and other human environments contains trace amounts of plant pollen, as well as skin, animal fur, textile fibers, and paper fibers. Along with several other materials that could be present in the surrounding environment, they also include burning meteorite fragments[39]. Many shells, including chalk, plant ash, limestone, marble, and bones, contain calcium carbonate ($\mathrm{CaCO3}$), a white precipitate that is produced by transferring carbon dioxide to a $\mathrm{Ca\,(OH)2}$ suspension in water. It is also utilized in medicinal formulations. Common sand, calcium carbonate, was primarily formed by different living forms, including coral and shellfish, over the last half-billion years. Numerous investigations have looked into calcium carbonate[40]. Among the most durable and efficient materials in the synthetic mineral spectrum, black silicon carbide finds use in a wide range of applications, such as non-aero parts surface finishing and general blasting, anti-slip flooring, vibratory finishing devices, secure processing, coated and bonded abrasives, and polishing compounds [41]. Sawdust, also known as wood shavings, is a waste product or by-product of woodworking processes like sawing. It is made up of tiny wood particles. These tasks can be completed using hand tools, portable power tools, or woodworking equipment. Additionally, several forest-dwelling animals, birds, and insects produce wood dust as a byproduct [32]. The particulate particles released from exhausts and chimneys during the burning of fossil fuels is referred to as fly ash. Significant amounts of particulate matter are produced when fossil fuels are burnt, and these concentrations vary depending on the fuel type, combustion quality, and other factors. Depending on the geography, local weather, combustion system conditions, and other factors, incinerator stacks release particulate matter in a variety of sizes and forms [42]. These released particles vary in size from one to several tens of microns [43]. Other names for fly ash include coal and soot, all of which refer to particulate particles. The circumstances of combustion and the particles generated affect these particles' physical and chemical characteristics, including how well they absorb light [44]. Overall, this classification demonstrates that dust composition is as critical as dust quantity in determining PV performance degradation. Understanding these categories provides a foundation for region-specific mitigation strategies and optimized maintenance planning for rooftop PV systems.

2.1.1. Factors Affecting Dust Deposition

Several factors contribute to the retention of dust on PV panels, influencing their long-term performance[45]. The site's characteristics and the extent of local human and natural activities, such as traffic, industry, and sandstorms, all of which are thought to be sources of dust generation, shape the rate at which dust accumulates [46]. The farther away from the source of the dust creation, the lower the deposition rate[47]. Figure 6 illustrates the key factors influencing dust accumulation on photovoltaic (PV) modules, grouped into four major categories: environmental factors, dust-related factors, PV module factors, and regional factors. It is important not to underestimate how much rainfall affects dust deposition [48]. According to research by the researcher[49] on the natural settling process of PV panels in Krakow under varied weather conditions, the intensity of rainfall has a significant impact on the dust-settling process. Another study [50] claims that dust particles may be removed from the panels by rainfall with an intensity of at least 38 mm/h. It should be mentioned, too, that when the dust density hits 40 mg/m^3, the purifying effects of heavy rain become saturated[51]. Furthermore, raindrops have a propensity to collect airborne particles and promote dust formation on PV modules when there is light rainfall. Shorter periods of light rain actually encourage the accumulation of dust on the PV panel surface, turning the dust into a muddy material[52]. Wind may have a big impact on PV modules that are exposed to the outside. Dust deposition on PV panels is caused by an increase in wind velocity at low wind speeds, which encourages the transmission and dispersion of particles in the atmosphere [53].

The typical wind speeds at the location are insufficient to fully resuspend fine particle dust sticking to the surface of PV modules when wind speeds are low [54]. Rather, the deposition of tiny particle dust is encouraged by these modest wind speeds [55]. The deposition of particulate matter is also influenced by wind direction, which is even more significant than wind speed[56]. In another study [48], a test rig was constructed with four standard orientations and seven inclinations to examine the effect of wind direction on dust deposition on PV panel surfaces. When the inclination angle was less than 45 degrees, it was discovered that at the same inclination angle, the density of dust deposition was greater on the PV panels' south-facing surface. An important factor in the buildup of dust on PV modules is relative humidity. Water capillary bridges develop between the particles and the panel surface in conditions with high humidity and dew. This promotes the dust particles' condensation and coalescence, which results in the creation of gel-like materials [57]. Additionally, the cemented dust particles' adherence to the PV module is strengthened by the presence of relative humidity [49,58,59]. Relative humidity between 40% and 80% can boost particle adhesion by up to 80%, which encourages deposition on the component's surface, claim Said et al. In order to promote deposition on the component's surface, a relative humidity between 40% and 80% can boost particle adhesion by up to 80% [56].

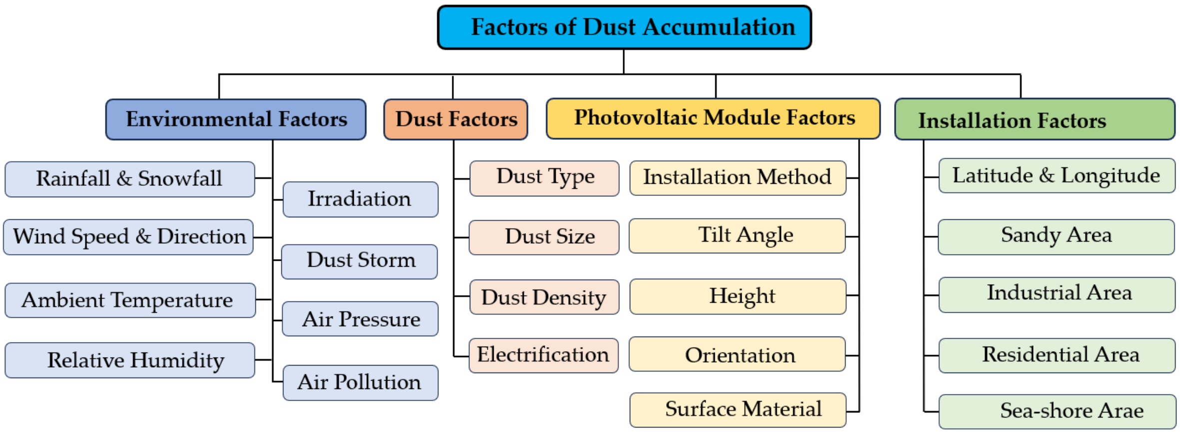

Figure 6. Different types of factors of dust accumulation on the PV module.

According to studies done in southern Spain by [60], dust deposition during the rainy season causes a daily decrease in solar radiation of less than 4% when PV modules are washed by rainwater. On the other hand, dust accumulation during the summer might result in daily irradiation losses of more than 20%. The significance of taking into account the seasonal impacts of dust deposition on PV performance is shown by this. However, dust particles can also escape from PV modules due to the thermophoretic effect. The impact of the temperature differential between the PV module and the surrounding air on dust collection was examined [61]. The size of the particles affects the rate of dust deposition. CFD was used [62]to simulate the deposition of 11 distinct dust particle sizes close to PV panels at varied wind speeds. Interestingly, at a wind speed of 1.3 m/s, dust particles of a moderate size (100µm) have the highest tendency for deposition. On the other hand, the deposition trajectory is similar to lower wind speeds at 2.6 m/s, with a maximum deposition rate of 150µm diameter dust particles. The greatest deposition rate is 0.28 percent at a dust diameter of 10µm, while the minimum deposition rate is 0.13 percent for particles with a diameter of 50µm [63], [64–67]. Soluble salts, carbon quasi-molecules, and other substances make up natural dust[66].

The rate of dust deposition on PV modules is affected differently by different kinds of dust particles. Atomic force microscopy was used by Kazmerski et al.[53] to evaluate dust adherence on PV panels. Their experiment's findings showed that dust particles with organic and dissolved mineral components tended to stick together more firmly than those without. The amount of dust that deposits on the surface of PV modules is significantly influenced by the quantity of dust in the air. More dust is deposited on the PV modules when there is a higher concentration of dust in the air [68]. An electrostatic field is created while PV modules are operating, polarizing and charging the dust particles. Dust deposition is significantly influenced by this process, which is called the electrostatic effect[69,70]. PV modules can be installed in a number of ways, including building photovoltaic integration, pole mounting, roof mounting, ground mounting, and solar awning mounting[71]. Every mounting technique has a unique effect. PV arrays are the usual configuration for both ground-mounted and roof-mounted PV modules, although other approaches mostly include isolated installations [72]. The orientation and tilt angle of PV module installations are important variables that affect the pace at which particles settle on the panel surface. There is often less dust collection on the PV panels at greater tilt degrees because dust particles are more likely to slide off the surface owing to gravity[73]. In order to study dust deposition on slanted PV panels under various circumstances, Heydarabadi et al.[74] performed numerical simulations. They decided to use 0°, 15°, 30°, 45°, 60°, 75°90°, tilt angles. The results show that the maximum amount of dust deposition for particles larger than 10 um happens at a tilt angle of 45 °. When the particle size is smaller, the highest value happens at a 90-degree tilt angle. The surface characteristics of PV panels, which may vary with the material used, significantly affect the rate of dust deposition[75]. When compared to uncoated surfaces, coated surfaces typically have less of an effect on dust deposition [76]. Jiang et al.

investigated the accumulation of dust on the surfaces of epoxy resin, polycrystalline silicon, amorphous silicon glass, and monocrystalline silicon glass. The findings showed that, in contrast to the other two kinds of surfaces with clear glass coverings, epoxy-covered polysilicon surfaces were more likely to accumulate dust[77]. Overall, the dust-accumulation factor emphasizes that dust-induced PV performance loss is a complex, multi-parameter phenomenon. The interaction of environmental conditions, dust properties, module design, and regional characteristics determines the extent of optical losses, power degradation, and maintenance requirements. Understanding these factors is essential for developing region-specific mitigation strategies, optimizing PV system design, and ensuring long-term energy yield and reliability.

3. Analysis of PV Performance Degradation

3.1. Impact of Dust Accumulation on Solar Photovoltaic Performance

A significant factor in the performance deterioration of solar photovoltaic (PV) modules is dust deposition, which primarily reduces the amount of incident solar irradiance reaching the active cell surface. Through light scattering and absorption, deposited dust layers reduce optical transmittance, thereby lowering short-circuit current and total power output. In this section, the study analyzed the impact of dust on solar PV systems during the period, PV system type, climate conditions, and seasonal variations.

3.1.1. Impact of Dust on PV Performance Considering Deposition Duration

PV panels may experience a decrease in optical characteristics like transmittance and reflectance as a result of dust and other air pollutants depositing on them. The impact of dust on PV panel performance at the UAE's power plants was investigated by Dhaouadi et al. [78] The transmittance of PV panels at a tilt angle of 25° After 15 weeks of dust collection, it dropped by 30%. This suggests that improper cleaning practices may reduce the transmittance of nearby PV modules by up to 33%, resulting in a substantial loss of PV power output. According to Gholami et al. [9] the relative transmittance of PV modules rapidly decreased in Isfahan, Iran, due to the presence of natural dust deposition. The relative transmittance dropped by 20% after just eight days, and then by 25% after seventy days. Crucially, dust collection raises panel temperatures, which in turn affects PV panels' output power, in addition to reducing the transmittance of PV glass panels. Lakshmi et al.'s study [79] in tropical India assessed how four distinct dust kinds affected photovoltaic modules. From 61.42% to 73.51%, the data showed that coal, sand, brick dust, and chalk dust all contributed to large power losses. Dust degrades the PV module's electrical, optical, and thermal properties, reducing its performance. The power and efficiency reductions due to dust accumulation over the PV module's lifetime are shown in Table 2.

Table 2. Power loss of the PV module due to dust for multiple durations.

Ref.	Location	Duration	Soiling Loss of PV System
[80] 2023	Slangor, Malaysia	5 weeks	The Solar photovoltaic module experienced a 20% efficiency loss due to overheating and dust accumulation.
[81] 2022	Dhahran, Saudi Arabia	6 months	The power of the PV module dropped more than 50%
[82] 2022	Shiraz, Iran	6 months	approximately 9% soiling power loss of PV modules with increasing dust density
[83] 2022	Melaka, Malaysia	1 month	The PV module's power output performance declined by 7.29%, although the dust effect was mitigated.
[44] 2021	Niˇs, Serbia	168 days	Maximum fly ash-induced power decrease of the solar modules, up to 87.2%
[84]	Baghdad, Iraq	2 months	The PV system's production drops by 35–40%.

2020			
[85] 2020	Dakar, Senegal	30 days	Reduce the total power of the transmittance by more than 50% at a dust density of 3.3 g/m2.
[86] 2018	Tehran, Iran	70 days	PV power production was reduced by 21.47% due to dust accumulation on the surface (6.0986g/m2).
[87] 2017	Shaanxi, China	8 days	According to relative transmittance, the PV module's power production decreased by 20%.
[51] 2016	Norway and South Africa	7 days	For every 10 mg/m2 of dust, there is a 2.8% reduction in PV transmission power.
[88] 2016	Aswan, Egypt	21 days	At a 15° tilt angle, accumulated soiling causes a 5% drop in output power.
[89] 2015	Perth, Australia	18 years	Dust deposition causes a 16–29% loss in PV output, whereas delamination causes a 71–84% decrease.
[90] 2015	Dhahran, Saudi Arabia	6 weeks	Significant reduction in PV power generation of up to 10%–17% of global efficiency
[91] 2014	Thailand	60 Days	7.28% maximum power reduction due to the soiling of the PV module
[92] 2013	Dhahran, Saudi Arabia	8 months	PV module 49% maximum power reduction due to dust effect
[93] 2013	Limassol, Cyprus	10 weeks	For 10 weeks 8% maximum power reduction by dust effect
[94] 2012	Taiyuan. China	2 weeks	32.6% maximum power reduction
[95] 2011	Puglia, Italy	8 weeks	6.9% maximum power reduction
[96] 2001	Tehran, Iran	8 days	Short time duration, 43 % maximum power reduction of the PV module
[97] 1997	Cologne, Germany	5 years	24 % maximum power reduction
[98] 1988	Sokoto, Nigeria	4 months	60% maximum power reduction
[99] 1987	Kuwait	14 months	55% maximum power reduction

3.1.2. Dust Impact on PV Performance for Various Climates and System Types

Dust accumulation varies considerably across geographical regions, with arid and semi-arid climates experiencing the highest deposition. The experiment was conducted by [100] to investigate the impact of the physical properties of the dust particles deposited on the PV module's surface. They employed three different types of limestone elements—limestone, carbon, and cement with an average diameter of 10, 5, 50, 60, and 80 µm. The differences between dust deposition densities and the four parameters of short circuit current, output power, solar radiation, and fill factor. The findings indicate that the short circuit current is more reduced for carbon particle deposition at 28 g/m2 than for cement at 73 g/m2 for 10 micro and limestone at 125 g/m2 for 50 µm, 168 g/m2 for 60 µm, and 250 g/m2 for 80 µm. They discovered that, in contrast to cement and limestone particles, carbon particles absorb more solar light. Asl-Soleimani et al.[96] conducted the study in Tahan, Iraq, and [101]in Egypt. They found that a PV module's output power may decrease by more than 60% in six months and by more than 66% in a year. Another investigation [102] tested a PV module up to 4g with randomly dispersed ground clay (bentonite) to ascertain the impact of dust deposition. They found that the PV module's conversion efficiency decreased by 10%, 16%, and 20% for 0.1g, 0.2g, and 0.3g, respectively. Another study[103] using talcum powder and mud revealed that the power losses of

PV modules can reach 18.2% and 16.2%, respectively. They also discovered that dirt deposition on the PV module's front sheet can reduce its efficiency by 50%. The experiment examined how dust settling affected the PV module. Three forms of dust, often found in urban and other environments, were employed in this investigation: ash particles (less than 10 μm in diameter), limestone particles (less than 60 μm), and red soil particles (less than 150 μm). For a dust deposition of 10g/m2, Jiang et al. (2011) found that the short circuit current decreased by 10% for monocrystalline silicon, 14% for polycrystalline, and 16% for amorphous PV modules with white glass and epoxy front sheets [104].

According to [118], the average daily energy decrease caused by dust settling on PV modules over the course of a year is around 4.4%; if there is no rainfall for an extended period of time, this reduction might reach 20%. According to [92], there was a 50% decrease in output power following six months of exposure in Dhahran, KSA. The effects of dust in Mexico City were examined by [119]. On level surfaces, he noticed that the dust settling rate varied between 24 and 102 gm−2d−1. After 60 days, the dust settles When there is no precipitation on the PV modules, the performance ratio drops by around 15%. However, there is little annual generation reduction as a result of dust deposition. The influence of dust settlement was assessed by[120] using both indoor and outdoor trials. The power loss resulting from the 1.4g/m2 dust thickness in the outside test was 5–6% of the maximum influence yield; whereas, the power loss resulting from the indoor recreation setup, where the dust thickness was 7.155g/m2, was 45–55% of the highest possible influence yield. During a 108-day waterless period in the late spring, [121]found that the effects of dust caused changes in the efficiency of a large PV commercial site (86.4 kWdc) from 7.2% to 5.6%. The significant impact of dust deposition on PV performance under different climate variations is highlighted in Table 3. The decrease in yield energy for the amorphous silicon PV module was 3.50% with 260 mg of dust and 7.28% with 425 mg of dust accumulation, according to [91]. Energy losses for monocrystalline silicon were 2.96% with 260 mg of dust and 5.79% with 425 mg of dust, while energy losses for multicrystalline silicon were 2.83% with 260 mg of dust and 6.03% with 427 mg of dust. Additionally, they provided the mathematical relationship between the PV module's output power and dust deposition.

Table 3. Dust impact on PV performance under climatic variations.

Ref.	Location	Climate	System Type	Dust Deposition (g/m²)	Efficiency Reduction (%)	Key Findings
[19]	India	Tropical	Rooftop	4.4	16–50	Found significant seasonal variations, with the monsoon reducing dust accumulation.
[105]	UAE	Arid	Ground-Mounted	5.44	12.7	Reported that wind-blown sand in desert environments severely affects PV performance.
[106]	Egypt	Arid	Rooftop	5.0	30	Highlighted that high dust deposition rates in urban areas result in rapid degradation.
[107]	Iraq	Arid	Ground-Mounted	1.75	5–13	Observed that humidity enhances dust adhesion, worsening performance losses.

[108]	Saudi Arabia	Arid	Ground-Mounted	8.0	30	Found that frequent dust storms lead to high PV degradation in desert regions.
[109]	Malaysia	Tropical	Rooftop	3.2	10–18	Concluded that rainfall partially cleans PV panels, but dust buildup still affects efficiency.
[45]	Global	Mix	----	0.35–0.63	0.1–1.4	Showed that industrial pollutants mixed with dust increase deposition rates.
[110]	Morocco	Semi-Arid	Ground-Mounted	6.5	5-10	Reported that PV efficiency drops rapidly in the absence of regular cleaning.
[111]	Egypt	Arid	Rooftop	7.5	20	Stated that the tilt angle influences dust accumulation, with flat panels experiencing higher losses.
[112]	USA	Temperate	Rooftop	2.5	5–12	Demonstrated that dust particle size impacts efficiency loss, with finer particles being more problematic.
[113]	Pakistan	Arid	Ground-Mounted	5.8	28	Observed that solar irradiance loss due to dust leads to underestimated energy yield predictions.
[114]	Oman	Arid	Rooftop	6.0	32	Found that high humidity in coastal areas leads to sticky dust, making removal harder.
[115]	Saudi Arabia	Arid	Rooftop	----	2-21	Stressed the importance of frequent cleaning schedules in desert conditions.
[116]	Iraq	Arid	Rooftop	----	23.1–31.4	Showed that biological dust (pollen, algae growth) is a major factor in PV efficiency losses.

[117]	Global	Mix	----	6.086–21.47	2.8–50	Found that rural and urban dust sources influence deposition rates differently.

3.1.3. Impact Analysis Based on Seasonal and Climatic Conditions

Photovoltaic solar energy technologies and their uses have received international academic attention and are currently grabbing the attention of investors [122]. A number of environmental factors, such as wind speed, rainfall, air temperature, and dust accumulation on the surfaces that shield the systems, affect the power output of solar energy systems[123,124]. Therefore, it is vital to address the kind of dust deposition and how it impacts PV module performance. Dust accumulation on protective surfaces has a significant impact on energy output, according to a review of the literature [56,75,125]. Without natural removal or cleaning, the seasonal distribution of solar energy losses from dust accumulations on panels indicates notable effects of more than 0.5% near South and Central Australia, peaking around 3% around the Lake Eyre Basin in all seasons[126]. In tropical regions, dust accumulation on photovoltaic (PV) panels tends to peak during dry seasons when rainfall is minimal. NASA data has been used in a multi-criteria decision-making framework to evaluate the operating capabilities of solar systems in Iran [127]. This framework examines cleaning techniques utilizing multi-criteria decision-making and discusses the dust deposition process, its seasonal influence on radiation, and its effects on solar systems. Dust deposition-induced energy loss in solar panels has also been predicted using the Markov model [128]. Three distinct power rates have been used to examine three cleaning scenarios: weekly, monthly, and seasonal.

The performance of PV modules may be significantly impacted by the effect of ambient temperature on dust deposition[60]. Seasonal differences in temperature have been linked to variations in dust formation, which in turn can affect solar radiation, according to studies. When PV modules are cleaned by rainwater during the rainy season, dust deposition causes a daily decrease in solar radiation of less than 4%, according to studies done in southern Spain by Zorrilla-Casanova et al[60].[135]Nonetheless, the accumulation of dust throughout the summer might result in irradiation losses of more than 20% every day. This emphasizes how crucial it is to take into account how dust deposition affects PV performance throughout the year. In outdoor studies carried out in Brighton, UK, Ghazi and Ip [135] examined the effect of dust on PV modules. They discovered that, in comparison to dust deposition alone, weather had a greater detrimental effect on PV module performance. This implies that while evaluating the performance of PV modules, the combined impact of temperature variations and meteorological conditions should be taken into account. In Ulaanbaatar, Mongolia, Eredavaa et al. [136] investigated how dust deposition affected the transmittance of solar collector glass tubes. Their results showed that the glass tubes had significant dust contamination throughout the cold season, especially in modules slanted at a 60 degree angle. The relative transmittance of these modules dropped by as much as 50% during the course of 20 weeks. Another study investigated the impact of dust buildup on PV in Kathmandu, which is known for its summertime dust deposition and wintertime heavy rains. The practical measurements revealed that, in comparison to cells cleaned every day, the density of dust deposition over a 5-month period reduced the efficiency of dusty and naturally contaminated PV by up to 29.76%. Over the course of the investigation, the highest dust density—6711 g/m2—accumulated near the bottom of the PV[137]. Overall, incorporating seasonal data into dust mitigation planning—through automated cleaning systems and self-cleaning technologies—can enhance the long-term efficiency and reliability of PV systems. Table 4 summarizes the findings on the seasonal Impact of dust on solar PV performance, considering dust deposition, efficiency, and effects.

Table 4. Seasonal Impact of Dust on PV Performance.

Study	Location	Season	Average Dust Deposition (g/m²)	Efficiency Drop (%)	Observed Seasonal Effects
[19]	India	Dry	5.2	20–50	Higher dust accumulation in summer due to lack of rainfall; efficiency drops significantly.
[100]	Egypt	Dry	7.5	30	Dust adhesion increases with high temperatures, requiring frequent cleaning.
[109]	Malaysia	Wet	2.8	5–12	Frequent rainfall reduces dust accumulation, maintaining PV efficiency.
[129]	China	Desert	1.5	63	Desert environments significantly increase dust deposition, resulting in severe performance losses.
[106]	Egypt	Wet	3.1	15	Humidity increases dust adhesion, affecting PV efficiency even in wet seasons.
[18]	Saudi Arabia	Dry	10.5	35	Wind-driven sandstorms lead to higher dust accumulation in the summer.
[127]	Iran	Hot season	0.8	30	Dust intensity is notably higher in the southwest, center, and southeast of Iran during spring and summer.
[130]	China	Dry	0.524	38.25	seasonal effects on dust deposition or efficiency drop
[131]	Oman	Dry	**	5	Dust accumulation is lower during the non-summer period compared to the summer period.
[114]	Oman	Wet	3.8	12	Coastal humidity increases sticky dust accumulation, requiring additional cleaning.
[132]	Turkey	**	**	**	observed seasonal effects on dust deposition or efficiency loss
[133]	Asia	Dry	**	7.84	weekly decrease in PV efficiency due to dust
[132]	Middle East	Dry	0.045 to 100	4–35	Summer/dry season: High deposition and efficiency loss
[134]	Spain	Dry	**	80	Dust storms in dry seasons cause rapid degradation of PV efficiency.

Study	Location	Season	Average Dust Deposition (g/m²)	Efficiency Drop (%)	Observed Seasonal Effects
[134]	Portugal	Wet	**	3-7	Tropical rainfall helps remove natural dust, thereby maintaining PV performance.

4. Mitigation Strategies

4.1. Dust Mitigation Strategies for Solar PV Systems

Dust accumulation on solar PV panels significantly reduces their efficiency, making effective dust mitigation strategies crucial for maintaining optimal power output. These strategies can be categorized into traditional cleaning methods and advanced dust prevention techniques. This section provides a comprehensive analysis of different approaches, highlighting their benefits, limitations, and suitability for rooftop solar PV installations, which has been summarized in Table 5. Moreover, the various dust mitigation strategies for solar power systems are illustrated in Figure 7.

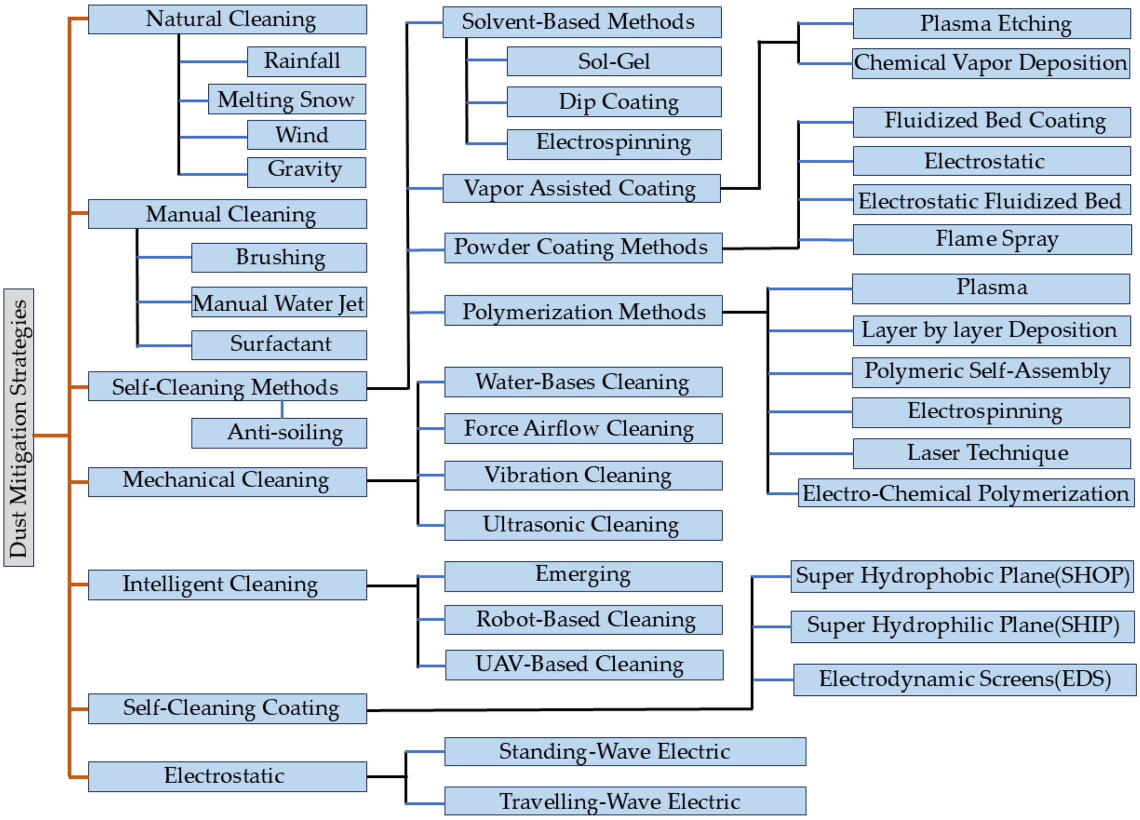

Figure 7. Various dust mitigation strategies for solar power systems.

Table 5. Different research papers address PV cleaning techniques in different locations.

Locations	Year	PV Cleaning technique	Key findings	Ref.
Qatar	2019	Clothwipers, vacuum cleaners, brushes, and some combinations	For weekly cleaning frequency, the microfiber-based cloth wiper improved its performance by an average of 3.1% and 7.7% in the summer and winter	[138]

India	2022	Self-cleaning coatings	Analyzed the performance evaluation, cost-effective deposition techniques, and the lifetime of self-cleaning coatings	[139]
Turkey	2022	Natural cleaning technique	0.94% of the dust removal effect was obtained due to rainfall	[140]
India	2018	The automated water-free cleaning device	A 9.05% improvement was obtained in energy output in one month	[141]
India	2017	Automated cleaning system	15 to 20% improvement in conversion efficiency	[142]
India	2010	Automated cleaning system	Compared to the solar PV module, the tracking-cum-cleaning device improved the output energy by 30% in terms of Daily energy generation	[143]
Morocco	2021	Manual cleaning technique	Cleaning with a robot once a week is more profitable than doing it manually twice a week (gain of $15 per month); in the case of CSP, the cost can be further decreased by 13%	[110]
India	2022	Automatic cleaning by the wiper	The solar system efficiency was improved by15–20%	[144]
China	2022	Water-free cleaning robot	The efficiency improvement ranged from 11.06% to 49.53%, with an average dust cleaning rate of 92.46%.	[145]
USA	2016	Natural cleaning technique	Natural rainfall is enough to clean the surface of solar PV modules	[146]
Saudi Arabia	2018	Automated, robotic dry cleaning technique	Robots that use silicone rubber foam brushes can effectively clean the dust from the PV surface at a low Cost and without damaging the surface of the PV	[147]
Pakistan	2020	Manual and washing tractor cleaning techniques	Manual cleaning and washing, tractor-assisted cleaning techniques were compared to techno economically	[148]
Egypt	2020	Mechanical vibrator cleaning technique	Vibration system applications improve performance more than self-cleaning coatings	[149]
Pakistan	2021	Automatic self-cleaning mechanism	35% improvement was obtained in the efficiency of the PV module	[150]
Bahrain	2018	Manual and natural cleaning techniques	7% loss in the energy output of the PV cleaned once a year, compared to 17% loss cleaned naturally	[151]
Spain	2020	Natural cleaning techniques	Probability of a 50% reduction in a soiling ratio by 2.2 mm rainfall	[52]
Iraq	2020	Water-based cleaning technique	Tide Surfactant No.(3) with water improves the generating power by upto 7.4%, and surfactant No.(4) improves energy produced by about 5.9%	[152]
Jordan	2015	Portable robot system	The portable robot system device was developed and could clean 80% surface of the solar PV module	[153]

Qatar	2019	Electrodynamic dust shield cleaning technique	Electro dynamic screen could reduce soiling loss by 16–33%	[154]
China	2018	Wind cleaning technique	The wind successfully removed particles with a diameter bigger than 1µm	[140]
Egypt	2013	Water mixed with surfactants	The efficiency remained constant with the cleaning of the surface with a mixture of cationic and anionic surfactants mixed with water, and the efficiency was decreased by 50% after 45 days by cleaning with only water	[155]
USA	2017	Electrodynamic dust shield cleaning technique	95% power output of CSP can be restored by electrodynamic screen-film laminated cleaning technique	[156]
Qatar	2017	Electrodynamic dust shield cleaning technique	The parameters of the electrodynamic screen for the optimal cleaning efficiency of the PV module were analyzed	[157]
USA	2008	Electrodynamic dust shield cleaning technique	The electrodynamic dust screen cleaning model was made for the solar PV module, effectively removing the dust from the surface	[158]

Dust buildup on PV module surfaces not only lowers the module's performance but also shortens its lifespan. PV module cleaning has become crucial. Based on three climatic zones—low latitude, mid-latitude, and high latitude—Mani and Pillai [19]suggested mitigation and cleaning techniques. Depending on the dust deposition densities, there are several cleaning techniques to lessen the effect of dust settlement on the PV module's surface.

4.1.1. Natural Cleaning of Solar Photovoltaic Panels

Natural cleaning eliminates dust without the need for human involvement by using environmental elements including wind, rain, and gravity. Since it doesn't require any energy or equipment, this method is the most economical. Its effectiveness, however, is very erratic and differs depending on the region and the time of year. In arid or high-dust settings, it is frequently insufficient to maintain optimal efficiency, even if it can greatly reduce soiling in some areas. The most popular substance for washing PV panels is pure water. Because water is not very conductive, there is little chance of corrosion during the cleaning process, making water cleaning quite safe. However, because of the naturally moist atmosphere (high rate of dew formation and rainfall), dust deposition is a minor problem [159]. Rainfall and dew increase the power output of dusty solar panels, but they are insufficient and infrequent in arid areas, thus they cannot be relied upon to remove dust. Furthermore, no correlation has been found between variations in efficiency and rainfall[160]. A number of strategies have been put out to stop the creation of dew, such as cleaning the PV surfaces every night, flipping the PV modules over to face the ground, or covering the top surface with plastic sheets until the early hours of the morning [107]. In many places, such as Spain, rainfall serves as the main natural cleaning agent during wet seasons [161]. However, inverted modules are used to improve the cleaning process; field tests showed that this technique reduced the soiling rate by 50%[162]. Furthermore, the ratio of effective irradiance for both cleansed and soiled surfaces is known as the Soiling Ratio (SR)[52]. Through a "sliding" action, where the snow layer collects dust and transports it away as it melts and slides off the surface, melting snow cleans PV panels. Because of the heavy weight and friction of the sliding snow, this procedure can be very successful. But snow accumulation itself can be a significant barrier, occasionally cutting power production completely until it goes away. Research on special coatings to make snow slide off more quickly and effectively is ongoing[163,164]. Additionally, wind is essential for the natural removal of dust from the surface. Smaller particles (less than 50 μm) cannot be adequately removed because of the adhesive force between the dust particles and the PV module surface, whereas larger particles can be removed with ease[165]. Because the wind speed rises with elevation, it is important to put the system at a higher height rather than a lower one in order to effectively remove dust by the wind. Another crucial factor that balances dust particle deposition and removal is wind speed[166]. Two methods of natural dust cleaning are shown in Figure 8.

Figure 8. Natural dust cleaning methods of PV module.

The idea of resuspension was used to analyze the wind cleaning process on solar PV surfaces using a model that included the various impacts of torque, adhesion force, and hydrodynamic force. The purpose of the study was to ascertain the effects of particle size and the necessary velocity for dust removal. The findings demonstrated that the surface was covered in dust particles ranging in diameter from 0.1 to 100 μm. The dust particles were removed using wind and shear velocities ranging from 0.8 m/s to 220 m/s and 0.2 m/s to 57.5 m/s, respectively. The findings showed that while dust particles with a diameter of less than 1 μm were difficult to remove because higher shear velocities were required, larger particle sizes with a diameter of more than 1 μm could be readily removed from the PV surface by wind [167].

Dust accumulation on the PV module's cover is influenced by the inclination angle. Although it can reduce the quantity of solar energy captured, tilting the module's surface toward the ground can decrease dust collection caused by gravity[168,169]. Compared to a stationary solar system, the solar tracker has been shown to reduce dust accumulation on PV panels by 50%, potentially improving PV performance[81]. Thus, it is crucial to determine the ideal tilt angle that maximizes the collection of solar radiation while minimizing the formation of dust. Furthermore, the impact of inclination is contingent upon the current meteorological circumstances. In Singapore, for example, there was no appreciable change in dust deposition when solar modules' inclination angle was changed[170].

However, because of the fluctuation in the amount of solar radiation received at the module surface, the tilt angle of the module has an impact on PV efficiency. Determining the ideal tilt angle is therefore crucial to maximizing the performance of the PV modules. The type of application and the environmental conditions of the year will largely determine this angle [96,171]. Dust deposition on the PV module glass cover was prevented by a high temperature differential between the PV module's surface and the surrounding air, despite the fact that high module temperatures reduce energy conversion [172]. Furthermore, an inclined dust screen is positioned over the PV panel in place of tilting the PV surface, which reduces the rate of dust deposition by over 40% [173].

4.1.2. Manual Cleaning of Solar Photovoltaic Panels

In manual cleaning, dust is physically removed off PV surfaces by human operators using brushes, towels, or sponges[174]. Although it is an inexpensive and straightforward method, it is time-consuming, labor-intensive, and subject to surface scratches and module breakage concerns [175]. Despite these limitations, proper manual cleaning can increase efficiency by more than 90% [176]. It is still frequently used for small-scale projects or in areas with cheap labor costs [164,177].

Brushing: To remove accumulated dust and debris from PV panels, the manual cleaning method uses cleaning instruments such nylon, cloth, and silicone rubber foam brushes [24]. This method usually uses a straight brushing technique, which successfully gets rid of adhesives and tough dirt[81]. To avoid any possible harm to the solar modules, it is recommended to use high-quality brushes[75,178]. A revolutionary silicone rubber foam automated brush that efficiently boosts output power by clearing the collected dust. Because of its low cost and ability to effectively clean solar panels without causing harm to their surface at high frequencies, this new brushing technique is seen as promising for dust reduction in solar energy applications[147].

Manual Water Jet: High-pressure water streams are used in the manual water jet approach to remove impurities [10,175]. Bird droppings and extensive soiling that dry treatments miss can be effectively removed with it[10,177]. Results show that although water jets are quite effective at cleaning, they use a lot of water, which makes them less sustainable in arid areas[163,175]. Furthermore, applying cold water to hot panels during periods of high sunshine can result in thermal shock[117,174].

Surfactant: To reduce surface tension and enhance the removal of greasy or sticky residues, chemical solutions and surfactants are added to water[179]. Certain surfactants can boost cleaning effectiveness by up to 20% when compared to pure water, according to research[10,179]. Additionally, certain specialized solutions produce a short-term protective layer that postpones further dust accumulation[179]. To avoid contaminating soil and groundwater, the environmental effects of chemical runoff must be carefully controlled [174,180]. The most popular manual cleaning systems are illustrated in Figure 9.

Figure 9. Manual cleaning methods

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4.1.3. Self-Cleaning Methods of Solar Photovoltaic Panels

Self-cleaning surfaces reduce particle adhesion by using the "Lotus effect" with super-hydrophobic or super-hydrophilic coatings. Whereas hydrophilic surfaces produce a thin water coating that removes particles, hydrophobic surfaces encourage water to bead and roll off, taking dust away. These coatings can minimize dust collection by as much as 50%, according to studies. Their effectiveness is mostly reliant on the humidity of the surrounding air and the occurrence of precipitation to initiate the cleaning process.

Anti-soiling: By reducing the frequency of cleaning, anti-soiling coatings provide an additional layer of protection that may extend the life of panels. However, certain coatings require reapplication every three to five years because they deteriorate after prolonged exposure to UV light[180,181]. Hybrid systems that combine automatic cleaning with anti-soiling coatings are more beneficial in areas with moderate amounts of factory dust and pollution. Robotic brush systems with nanostructured coatings are used in rooftop PV installations in Germany to reliably restore efficiency (95–98%) in a variety of weather conditions[72]. Water use is only one aspect of environmental concerns. Volatile organic compounds and other hazardous chemicals may be released during the production and application of anti-soiling coatings [182].

Solvent-based Method: This active cleaning method dissolves tough dirt and bird droppings by using robotic equipment or sprayers to apply chemical solutions or surfactants[179]. When it comes to eliminating "cementation" layers that water cannot remove, the solvent technique works very well[159,179]. In comparison to conventional dry brushing, experimental studies employing 3D-printed robots and chemical solutions prepared in the lab showed notable efficiency recovery in panels with heavy, sticky buildup [10,179].

Sol-Gel: It is a wet chemical process used to create nanostructures, particularly metal oxide nanoparticles. This technique involves dissolving a metal alkoxide in either water or alcohol, followed by heating and stirring to produce a gel by hydrolysis or alcohololysis. Using a straightforward sol–gel method, Deepanjana et al. [183] produced a transparent self-cleaning film. Sol-coated surfaces exhibit 2◦ hysteresis and 150◦ static contact angles. The coating decreased reflection from 8.7% to 3.2% and enhanced transmission from 91.8% to 95.5% [12]. Using the dip coating process, functionalized nano-sized silica particles are applied to glass surfaces to provide a hydrophobic surface. The liquid droplet infusion (cloaking) on the dust particle surfaces is tracked and monitored using high-speed recording equipment [184]. Using the electrospinning technique, hydrophilic, optically transparent, hydrophilic Silica (SiO2) modified Titania (TiO2) nanofibrous thin films have been created on glass substrates for use in solar cells that require self-cleaning. After soiling, the coating's optical transmittance was more than 16% higher than that of the glass substrate. In comparison to the uncoated substrate, which displayed 9.08% and 22.2%, the soiling density dropped by up to 38.9% and 64.9%, respectively, and the photovoltaic (PV) efficiency increased by 0.8% and 1% for tilt angles of 33.4° and 60°, respectively[185].

Ultra-thin, consistent protective layers are applied on PV glass using vapor-assisted techniques, such as Chemical Vapour Deposition (CVD)[174]. In order to preserve the coating's anti-reflective qualities and offer anti-soiling advantages, this method guarantees excellent durability and exact control over the coating's nanostructure [12,176]. Although vacuum-based equipment is very successful in protecting surfaces at the molecular level, its use is often restricted to large-scale industrial manufacture due to its high cost[174,177]. A dry etching method that uses plasma instead of strong acids as an etchant. Thin films of the necessary chemicals are deposited on the substrate[175].

A thin layer of film is deposited through a gaseous medium encircled by a substrate through chemical reactions carried out at a high temperature. Compressed air from electrostatically charged dry powders is applied to the earthed coated film using a spray cannon. This technique resulted in a 30% increase in visible light transmission[186]. Applying dry fluoropolymer or silicone-based powders that are thermally bonded to the substrate is commonly referred to as powder coating in solar applications[12]. Compared to liquid-based sprays, this technique produces a strong, weatherresistant barrier that is thicker and more resilient[174,176]. Although they must be applied carefully to prevent substantial shadowing or reduction in light transmittance, findings indicate that powder-coated surfaces display greater mechanical stability and resistance to sand abrasion in harsh Saharan settings[12,187]. The thermodynamic performance of a particle-driven Brayton cycle for CO2 recompression, simulating a fluidised bed heat exchanger (FBHX) and a solar particle receiver. They reported that the power cycle and the FBHX's thermal efficiency were 50.5% and 99.1%, respectively[188].

The electrostatic fluidized bed powder coating technique uses a remote charging medium to ionize dry air that has previously been delivered via a fluidization column and driven to flow from a plenum chamber through a porous plate into a powder reservoir. A cloud of ionized powder is created as the charged powder particles oppose one another and rise from the fluidizing bed chamber's base. Before the curing procedure, the charged particles are drawn to the substrate and briefly stick to it when a grounded workpiece is dipped in the cloud[189]. The idea is based on the burning of atomized and gaseous raw materials in an atmospheric oxy-fuel flame. The mass feed rate is the primary determinant of the nanoparticles' ultimate size. This method's drawback is that it requires a specialized burner to create micron-sized liquid droplets[175,186].

To produce a low-energy, non-stick finish, polymerization entails directly applying thin-film polymers, like PTFE or PMMA, to the panel surface[174,190]. The utilization of reusable biomass digestate polymers as a sustainable coating option is highlighted by recent study[190]. A compromise between protection and light absorption can be achieved by engineering these polymeric layers to be both super-hydrophobic and anti-reflective [176]. By avoiding the "baked-on" dust effect, efficiency studies show that these films can preserve 95–98% of the initial power output[163,164]. For these coatings, TiO2 sol contains a block copolymer that serves as a structure-directing agent. This structure encourages the creation of regular pores in the TiO2 thin film, which significantly lowers the coatings' refractive index values (~ 1.31) and increases their transparency (4% antireflection gain) [191].

The electrostatic charge interactions between the heterogeneous layer, such as those between polyanion and poly-cation, are the basis for this approach. creating a film on the substrates layer by layer. Large-area AR coating deposition on non-flat surfaces is made possible by this technique, which also makes it simple to manage the film thickness and offers a wide variety of materials for AR coating fabrication [192,193]. The potential for developing low-cost, lightweight, and flexible systems has made the use of polymeric and other organic materials as active components in electroactive devices more and more appealing. Only a small number of layers can alter the interface between the donor and acceptor blocks in this approach, which, when properly tailored, increases device efficiency thrice[194]. By decreasing reflectivity and keeping solar panels cleaner, laser-treated glass shows promise for improving solar panel efficiency. With anti-reflective coatings, power production might rise by as much as 8%. However, major obstacles to its broader acceptance include expensive production costs, environmental concerns, and some loss of transparency. Approximately 16% of the identified issues impact transparency, which subsequently affects performance. To enhance the practicality of this technology, there is a critical need to focus on improving durability, cost-effectiveness, and sustainability[195]. This chapter describes the synthesis of conducting polymer films, which are utilized as transducers in sensors and electrocatalysis, by chemically and electrochemically polymerizing monomers on solid electronic conductor materials with high work function. The drawback of chemical polymerization is that additional purification and characterization are needed for confirmation. Low yield and poor product solubility are drawbacks of electrochemical polymerization; the former makes the process unsuitable for large-scale polymer manufacturing. Nonetheless, doping, redox scan mode, polymerization cycle, and electrode material type can all influence the type of product that is produced in electrochemical polymerization[196].

4.1.4. Mechanical Cleaning of Solar Photovoltaic Panels

The main method of mechanical cleaning is to physically remove dust from PV surfaces using brushes, scrapers, or robotic devices. Soft materials like nylon can be used for brushes to prevent scratches on glass. Because they can manage large-scale installations and function independently, robotic mechanical systems are becoming more and more common. Even while it works well, too much brush pressure can result in micro-scratches that lower transmittance over time. Robotic brushing systems frequently remove dust with efficiencies of over 90%. Water bases Cleaning: One popular mechanical cleaning method is water-based cleaning[197–199]. It entails utilising a pump and tubing to link a reservoir to a nozzle that is placed on the PV panels. To properly remove dust, a large amount of high-pressure water is subsequently sprayed onto the panel surface through the nozzle[10]. To increase the effectiveness of dust removal, high-pressure water is occasionally combined with specific cleaning agents[10,155,200,201]. Water also aids in cooling the photovoltaic panels [10,202]. Nevertheless, this approach is unsuitable for dry and semi-arid areas with acute water scarcity[75]. A portion of the PV power generated is also consumed by the use of high-pressure water pumps, and the wet panel surface may draw more dust particles, which would reduce panel efficiency. Additionally, using low-temperature water to clean panels with high surface temperatures can cause thermal shock, which could harm the panels[10,81].

One popular mechanical cleaning technique is forced airflow cleaning [203]. This technique uses compressed air equipment that consists of a compressor, a nozzle, an air storage tank, and an airflow management valve. The PV panels power the compressor, and the airflow management valve directs compressed air from the storage tank to the PV panels. Dust accumulation on the PV modules' surfaces is successfully removed by this procedure[204–206]. The mechanical cleaning systens are shown in Figure 10.

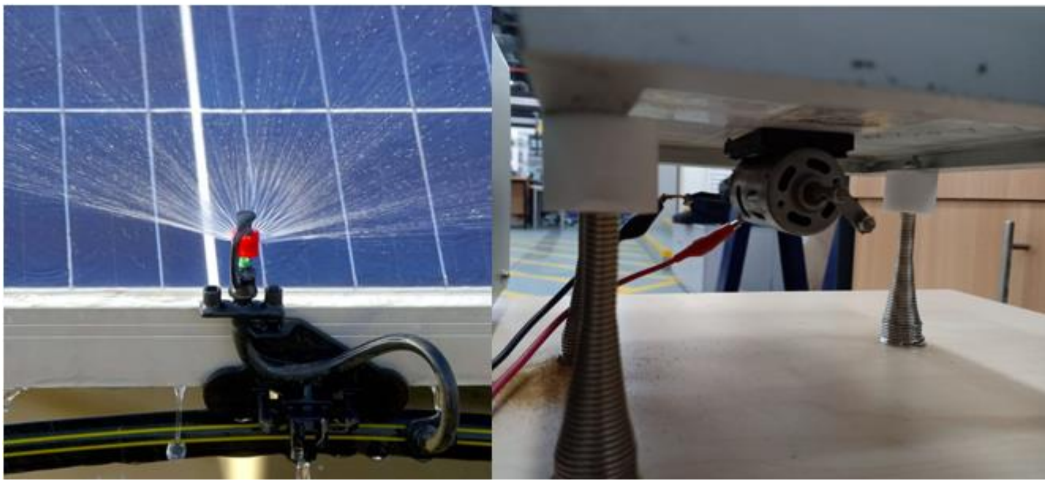

Figure 10. Conventional Mechanical Cleaning Methods

The forced airflow cleaning method has the advantage of not relying on water resources, making it particularly suitable for arid and semi-arid regions with high ambient temperatures and limited water supply. Additionally, through better cooling, the compressed air helps to improve the PV modules' performance as it cools down[207]. It is crucial to remember that the compressor requires some of the electricity produced by the PV panels in order to function, which could reduce the PV modules' efficiency.

Piezoelectric technology is used in vibratory cleaning techniques to produce vibrations that efficiently clean solar module surfaces [89,208,209]. In order to reduce dust particle adhesion to the panel surface, these techniques use mechanical vibrators that are affixed to the panel and generate harmonic excitation forces[204]. The vibrator, which is usually located on the panel's back, makes sure that only the dust is removed without harming the glass's surface. [199]and others presented a vibrational self-cleaning process in which the fundamental frequency of the solar panel is stimulated by an external vibration source. The PV module's power-generating efficiency may be restored to roughly 95% with this vibrating cleaning method, which also removes the requirement for water and manual labor [112]. In order to remove impurities like dirt and grease that are immersed in aqueous

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media, ultrasonic cleaning technology uses the phenomena of ultrasonic cavitation in liquids[210]. This method is frequently used to clean a variety of materials, such as ceramics, metal, glass, and even PV panel surfaces[206]. Even the smallest dust particles can be efficiently removed by ultrasonic cleaning technology, which can penetrate deep crevices. Its cleaning effectiveness is demonstrated by the frequency range of 20 to 80 kHz that is commonly employed for dust cleaning [211]. It is important to note, though, that this approach typically calls for a specific power source[10].

4.1.5. Intelligent Cleaning of Solar Photovoltaic Panels

AI and sensors are combined in intelligent cleaning to optimize schedules based on soiling levels in real time. IoT and machine learning algorithms are basic methods for forecasting efficiency declines. According to unique research, these solutions can cut down on wasteful water and cleaning expenses. Making sure panels are only cleaned when the cost of power outages outweighs cleaning costs maximizes efficiency. New approaches concentrate on passive, water-free technologies such as self-cleaning nano-coatings and Electrostatic Dynamic Shields (EDS)[12,176]. EDS repels dust particles without making mechanical contact by using high-voltage travelling waves[212,213]. The "lotus effect" is used by super-hydrophobic and photocatalytic coatings to let wind or rain naturally remove debris[163,174]. With the capacity to maintain up to 90% panel cleanliness, these techniques are very effective in arid regions where water is limited [176,212]. Four different Intelligent cleaning systems are shown in Figure 11.

Figure 11. Intelligent Cleaning Methods

The application of robotic cleaning methods demonstrates how intelligent technology may be incorporated into mechanical cleaning procedures. In order to efficiently clean PV panels, this technique usually uses robotic arms, locomotive carriages, and robotic devices [178,179] that follow a preset course on their surface. These robotic systems can carry out genuinely intelligent cleaning chores because they are outfitted with cutting-edge characteristics like wireless charging, night operation, and panel spanning[72].

As a state-of-the-art automated cleaning method, robotic cleaning greatly increases overall cleaning efficiency by simulating human actions and cleaning PV panels quickly and continuously. However, it is crucial to recognize that the deployment of automated cleaning systems requires complex mechanical and control designs due to the relatively high initial and ongoing expenditures[214]. With its convenient control, effective data logging, and remote monitoring capabilities, drone cleaning has become a key intelligent cleaning technology. PV panels are currently being monitored, inspected, and cleaned using it [215,216]. Excellent autonomy and mobility are provided by drone cleaning, enabling the creation of personalized cleaning schedules according to particular needs. It uses cutting-edge technologies like real-time analysis, data mining, machine learning, and image synthesis, and it can function in any weather. These developments greatly improve PV panels' cleaning and operating efficiency. It's crucial to be aware of drone cleaning's limitations, though. Stains on PV panels may be difficult to remove since cleaning solutions have a limited carrying capacity. Additionally, due to the rapid depletion of their batteries, drones have limited endurance and short flight times. As a result, research and development is still ongoing for the use of UAVs to clean PV panels[81].

4.1.6. Self-Cleaning Coating of Solar Photovoltaic Panels

Nanomaterials are used in self-cleaning coatings to form a protective layer that reduces dust adhesion and makes removal from the environment easier. To lower the surface energy of PV glass, these coatings mostly use passive or photocatalytic (titanium dioxide) processes. In arid areas, they can greatly increase energy yield by increasing light transmission by up to 6%. However, environmental deterioration and expensive initial application costs frequently pose a threat to their long-term efficacy. A solar energy system's cleaning capabilities can be improved by altering its surface to have a superhydrophobic quality. A SiO2-based porous surface with poor wettability and high water droplet mobility is called a superhydrophobic surface[186,189]. The idea behind this technique is to put a small layer of hydrophobic coating to the PV's surface, which serves as a barrier to keep water and dust from sticking to it[217,218]. Rainwater or water cleaning methods make it simple to eliminate dust buildup from extremely hydrophobic surfaces. Although this method is effective in areas with a lot of rainfall, it might not be appropriate in arid climates. Water or precipitation is needed to remove the dust particles since this layer stops them from sticking to the PV surface[219].

Strong water attraction and a contact angle that is almost zero (contact angle ≈ 0°) are characteristics of super-hydrophilic surfaces[220]. On certain surfaces, water droplets can dislodge dirt particles from the surface by spreading out rapidly [221]. This can be accomplished by applying a thin layer of titanium dioxide (TiO2) nanofilm on the nanostructured glass's surface [222]. Super-hydrophilic surfaces are inappropriate for solar PV modules in arid regions with minimal rainfall, even if they are reasonably effective in wet conditions and can have cleaning effects with rainwater [223]. However, because they don't need polymer-based coatings, they are more durable and resilient than hydrophobic surfaces[224]. Other benefits of TiO2 coating over hydrophobic coatings are stability, non-toxicity, cost-effectiveness, and transparency to visible light[225]. Nevertheless, the solar energy system's performance cannot be fully restored.

In recent years, numerous researchers have looked into the usage of electrodynamic screens (EDS), which are mostly employed to accomplish automatic dust removal by electrostatic force[226,227]. It is made up of a row of transparent parallel electrodes implanted in a transparent dielectric film and positioned on a glass substrate. The dust falling on the surface of the EDS films will experience electrostatic charge exchange between the surface atoms that are in contact with the upper surface of the dielectric layer when the EDS is activated with a phased voltage pulse. This will result in the donor atoms being positively charged and the recipient atoms being negatively charged. The moving electric field will then sweep the charged particles away, creating a cleaning effect[228]. This technique is now commonly utilized in dry, arid, and desert regions[210,212] because it can remove 90% of the dust that has accumulated on PV panels in less than two minutes without the need for water or labor[76,229,230]. Improvements have been suggested[212,231], although this approach is less successful at removing moist or small dust particles [210,214]. Furthermore, the electric field produced by EDS requires a high-voltage power supply, which reduces power generation efficiency by 15% [76,141,214].

4.1.7. Electrostatic Cleaning of Solar Photovoltaic Panels

By coupling a high voltage to gravity, this waterless technique uses electrostatic forces to keep dust away from solar panels. Particles fall away with negligible power usage when they move reciprocally between parallel screen or wire electrodes. Steeper panel tilt and low-frequency high voltage enhance efficiency. However, heavy humidity or extremely fine particles may reduce its efficiency. A schematic diagram of the electrosurgical cleaning method is illustrated in Figure 12.

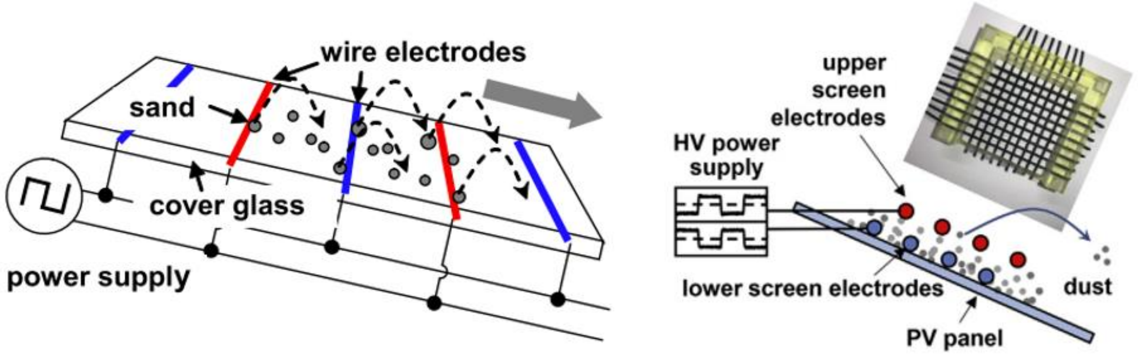

Figure 12. Electrostatic Cleaning Methods

The standing-wave method generates a pulsing electric field by applying a single-phase alternating voltage to parallel electrodes[12,163]. Dust particles vibrate in this field and rise to the surface before being carried away by wind or gravity[12,176]. In desert settings, it works especially well to remove coarse particles like sand [163,177]. In comparison to multi-phase traveling-wave systems, it usually exhibits inferior transport efficiency, despite providing a low-energy option for large-scale plants [12,117].

This sophisticated technique creates a moving electric field across the panel surface using multi-phase (often three-phase) AC power [12,117,176]. Dust particles are actively carried in a particular direction toward the panel edges by this "traveling wave"[12,163]. According to research, it achieves clearance rates close to 90%, making it noticeably more effective than standing-wave systems, particularly for fine lunar or desert dust[163,212]. It is a reliable option for automated, waterless maintenance since it successfully stops dust re-deposition[117,176].

4.1.8. Advantages and limitations of the common PV cleaning methods

The various dust cleaning and mitigation strategies for PV systems, highlighting their advantages and limitations, are shown in Table 6. Manual cleaning is low-cost and simple but labor-intensive and may damage PV surfaces. Water-based methods effectively remove dust but are less sustainable in water-scarce regions. Robotic systems reduce labor and ensure consistent cleaning, though they require high initial investment and maintenance. Hydrophobic coatings and self-cleaning glass lower maintenance needs but may lose effectiveness over time. Electrostatic and air blower systems are eco-friendly and water-free, yet they often consume significant energy. The choice of method depends on environmental conditions, resource availability, and cost.

4.2. Performance Evaluation of the Dust Cleaning Method

4.2.1. Advantages and Limitations of the Common PV Cleaning Methods

The efficiency of different PV cleaning methods varies depending on environmental conditions, dust characteristics, resource availability, and system design, with each approach offering distinct trade-offs between effectiveness, cost, sustainability, and maintenance requirements, as illustrated in Figure 13.

Table 6. Comparison of Dust Cleaning and Prevention Techniques.

Technique	Description	Advantages	Limitations	Ref.
Manual Cleaning	Hand-held tools or mechanical brushes are used to remove dust from PV surfaces.	Simple, low-cost, effective in localized areas, and easy to implement.	Labor-intensive, it can be abrasive, and risks damage to the PV surface if not done correctly.	[146,232]
Water-Based Cleaning	Using water jets or hoses to wash away dust from PV panels.	Effective in removing large quantities of dust quickly and thoroughly.	Water usage may be excessive, especially in arid regions, which can lead to concerns about water runoff.	[138,233]
Robotic Cleaning Systems	Automated robotic devices that move along PV modules and clean using brushes or sponges.	Reduces human labor, provides precise cleaning, and minimizes surface abrasion.	High initial cost, requires maintenance, and may struggle with complex panel layouts.	[234]
Hydrophobic Anti-Dust Coatings	Coatings applied to PV surfaces that repel dust particles due to their water-resistant properties.	Long-term protection reduces the need for frequent cleaning and improves cleaning efficiency.	Coating degradation over time can be expensive and may not be effective in high-density dust environments.	[235,236]
Electrostatic Cleaning	Uses electrostatic fields to attract and remove dust particles from PV panels.	Requires minimal water usage, is effective for small particles, and is environmentally friendly.	Environmental conditions can influence the high installation cost and effectiveness.	[213,237]
Self-Cleaning Glass	Glass coatings with self-cleaning properties often use a combination of hydrophobic and photocatalytic effects to break down dust particles.	Minimal maintenance required, self-cleaning under sunlight, and efficient in moderate dust conditions.	Expensive, may not be fully effective in high-dust accumulation areas, and it can degrade over time.	[176,238]

Technique	Description	Advantages	Limitations	Ref.
Brush-Based Mechanical Systems	Automated mechanical brushes that sweep over the surface to remove dust.	Energy-efficient, low water consumption, and adaptable for large installations.	Risk of abrasion on PV surfaces, potential for damage to delicate components, and high operational costs in remote areas.	[178,239]
Air Blowers and Compressed Air	Utilizes compressed air to dislodge dust particles from PV panels.	Quick, water-free solution that is effective in dry regions with moderate dust accumulation.	High energy consumption is inadequate for heavily adhered dust, which can lead to dust redeposition.	[203,205]

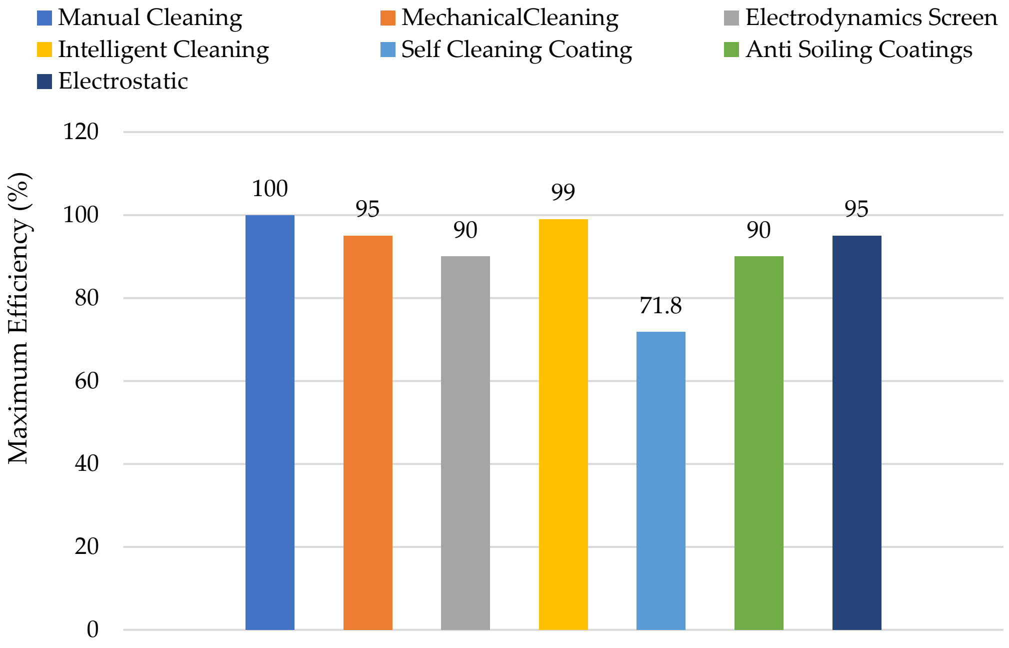

Figure 13. The maximum efficiency of the various solar photovoltaic panel cleaning methods[143,228,240–243].

4.2.2. Operational and Labor Costs and Human Safety Levels of Different Cleaning Methods

The comparison of common mitigation strategies of PV modules based on operating cost, labor expenses, water waste, and human safety in this section. A basic impression of the many characteristics of PV cleaning techniques, technologies, and approaches is given in Figure 14. However, further research is needed to identify metrics that truly characterize these technologies and to evaluate them economically. In this section, M1, M2, M3, M4, and M5 represent washing and brushing (Manual), Water Spray Machine, Self-coating method, Static Robotic Cleaning, and Portable Robotic Cleaning, respectively. The numerical value represents the intensity of cost and human safety.

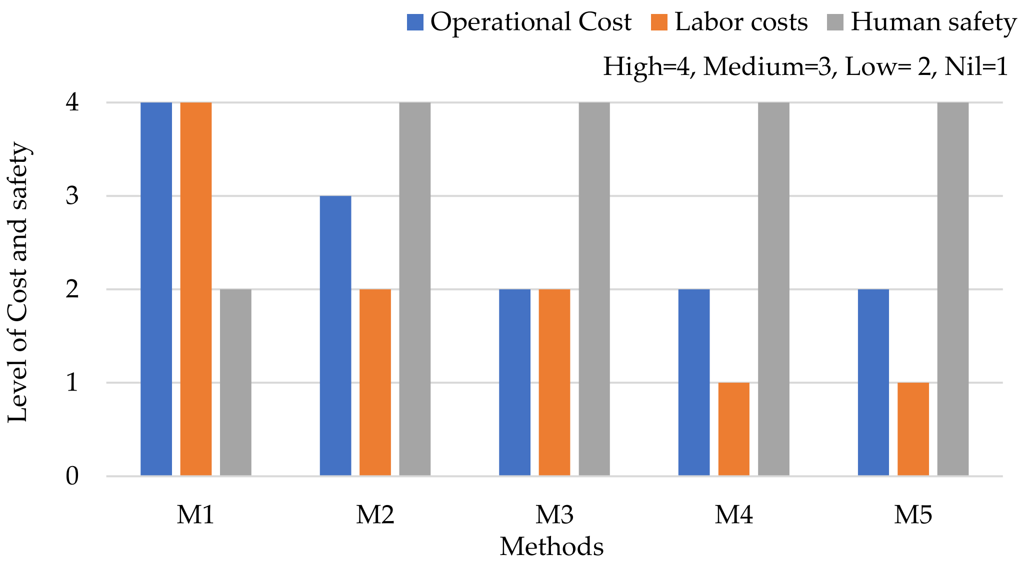

Figure 14. Comparison of operational cost, labor cost, and human safety between various cleaning methods[153], [244–247].

5. Discussion

The findings of this review indicate that dust accumulation is a dominant and region-dependent factor driving performance degradation in photovoltaic (PV) systems. Consistent with earlier studies, the literature confirms that dust-induced optical losses are the primary mechanism responsible for power reduction, mainly through decreased transmittance, increased light scattering, and absorption. However, this review extends previous work by emphasizing that PV systems experience more complex and soiling behavior compared to ground-mounted systems due to their proximity to localized pollution sources and urban activities. When interpreted in the context of prior studies, the results demonstrate strong agreement regarding the influence of dust type and environmental conditions on degradation severity. Studies conducted in arid and semi-arid regions consistently report mineral dust as the primary soiling agent. These findings validate earlier hypotheses that dust composition—not merely dust quantity—plays a critical role in determining PV performance loss.

The reviewed mitigation strategies also align with existing literature, which identifies cleaning as the most effective short-term solution for restoring PV performance. Manual and robotic cleaning methods consistently achieve high recovery efficiencies, confirming conclusions drawn by previous experimental and field-based studies. However, this review places these findings in a broader operational and sustainability context, showing that water consumption, labor intensity, and safety risks limit the long-term viability of frequent cleaning. Preventive approaches such as anti-soiling coatings and design optimization are shown to reduce cleaning frequency but exhibit variable long-term effectiveness, reinforcing conclusions from earlier studies regarding coating durability and environmental sensitivity. In a broader context, the findings underscore that PV performance degradation cannot be addressed through isolated mitigation techniques. Instead, the reviewed evidence supports a systems-level interpretation, where degradation mechanisms, regional climate, system design, and maintenance practices interact dynamically. This perspective advances prior research by highlighting the need for integrated mitigation frameworks that combine preventive measures, intelligent monitoring, and adaptive cleaning strategies.

Several future research directions emerge from this review. Standardized methodologies for quantifying soiling rates and performance losses are needed to enable meaningful cross-study comparisons. Additionally, further research should integrate techno-economic analysis with performance data to identify cost-optimal mitigation strategies for different regions. Finally, the growing potential of AI-based monitoring and condition-based maintenance warrants deeper investigation to improve operational efficiency and reduce lifecycle costs. Overall, by synthesizing results from previous studies and interpreting them within a unified framework, this review provides a broader understanding of dust-induced degradation in rooftop PV systems and establishes a foundation for future research aimed at enhancing the reliability and sustainability of distributed solar energy systems.

6. Conclusions

This review comprehensively examined dust-induced performance degradation in rooftop photovoltaic (PV) systems, emphasizing degradation mechanisms, regional variability, and mitigation strategies. The findings confirm that dust accumulation is a dominant environmental factor limiting the long-term energy yield and reliability of PV installations. Even moderate soiling levels can significantly reduce optical transmittance, leading to measurable power losses, mismatch effects, and, in severe cases, hotspot formation that may compromise module lifespan. The review highlights that dust characteristics and environmental conditions vary substantially across regions, resulting in highly location-dependent soiling behavior. Arid and semi-arid regions are primarily affected by mineral dust, urban and industrial areas by fine anthropogenic particulates, and coastal regions by saline aerosols that promote strong adhesion and surface degradation. These regional differences underscore the inadequacy of uniform mitigation solutions and the necessity for climate- and site-specific performance assessment and maintenance strategies. Mitigation approaches were critically analyzed, revealing that cleaning-based methods remain the most effective for immediate performance recovery, while preventive measures such as anti-soiling coatings and optimized system design can reduce dust accumulation rates and maintenance frequency. However, each technique presents trade-offs in terms of cost, durability, and long-term effectiveness. Emerging technologies, including automated robotic cleaning, electrostatic dust removal, and intelligent monitoring using imaging and data-driven techniques, show strong potential for improving operational efficiency, particularly in water-scarce and highly polluted environments. Despite advances in understanding and mitigation, the review identifies key research gaps, including the lack of long-term rooftop-specific datasets, limited standardization in soiling measurement, and insufficient integration of techno-economic analysis with performance degradation studies. Addressing these gaps is essential for developing optimized, scalable, and cost-effective solutions for PV systems. In conclusion, ensuring the sustainable and reliable operation of rooftop PV installations requires a holistic, region-specific approach that integrates dust characterization, system design optimization, smart monitoring, and adaptive mitigation strategies. The insights presented in this review provide valuable guidance for researchers, system designers, and policymakers seeking to maximize the long-term performance and contribution of rooftop solar PV systems to global energy sustainability.

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