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Review

A Review of Dust Deposition Mechanism and Self-Cleaning Methods for Solar Photovoltaic Modules

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Abstract: Large-scale solar photovoltaic (PV) power plants tend to be set in desert areas, which enjoy high irradiation and large spaces. However, due to frequent sandstorms, large amounts of contaminants and dirt are suspended in the air and deposited on photovoltaic modules, which greatly decreases the power efficiency and service life. To clean PV to improve efficiency, many methods were proposed. It was found that the application of the self-cleaning coating on PV modules can effectively reduce dust deposition and improve the efficiency of PV. This paper reviews the dust deposition mechanism on photovoltaic modules, classifies the very recent dust removal methods with a critical review, especially focusing on the mechanisms of super-hydrophobic and super-hydrophilic coatings, to serve as a reference for researchers and PV designers, and presents the current state of knowledge of the aspects mentioned above to promote sustainable improvement in PV efficiency. It was found that the behaviors of dust on photovoltaic modules are mainly deposition, rebound, and resuspension. Particles with a diameter of 1–100 μm are most easily deposited on photovoltaic modules. The use of self-cleaning coatings, especially super-hydrophobic coatings, is beneficial to the rebound and resuspension of particles. The research gaps and development prospects of self-cleaning coatings are also discussed in this paper.

Keywords: photovoltaic; cleaning methods; dust deposition; efficiency; self-cleaning coatings

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1. Introduction

Many countries have now joined the carbon-neutral initiative [1]. Fossil fuels such as oil, coal, and natural gas produce large amounts of greenhouse gases that place an irreversible burden on the environment [2]. Solar photovoltaic (PV) technology is considered to be one of the most important resources for the future [3,4]. However, with PV panels being installed outdoors in desert areas, dust particles in the air can be deposited on the PV modules, significantly reducing the light transmission of the PV panels and affecting the PV efficiency [5,6]. The photovoltaic panel is composed of covering glass, EVA, battery, EVA, and back sheet from top to bottom. Finally, all parts are fixed together by an aluminum metal frame [7] (Figure 1). There are two main factors affecting the efficiency of photovoltaic panels: reflection and scattering caused by dust [8]. The thin glass will reduce the absorption loss of light, so the transmissivity is high. The influence of environmental factors on thick glass is relatively small. When the sun shines on the PV panels, on the one hand, the panels reflect 8–10% of the light; on the other hand, the accumulated dust absorbs or scatters some of the light [9]. It was found that among all the factors affecting the efficiency of PV module products, such as dust, blowing wind, humidity, temperature, and installation elements, such as altitude and light intensity, play a crucial role [10–12]. Kaldellis et al. tested the power generation efficiency of PV modules in polluted areas at the same light intensity and operating hours, while solar PV efficiency was reduced by 30% [13]. Moreover, higher dust density leads to lower PV efficiency [14]. Gholami et al. developed a 70-day experiment to recognize the impact of dust deposition on PV performance in Tehran, Iran. It was concluded that the parameters will change after 70 consecutive days without rain. Surface dust deposition was 6.0986 (g/m^2), resulting in a 21.47 (%) decrease in power output [15]. Therefore, keeping the surface of photovoltaic modules clean is essential to improve their performance in electricity generation.

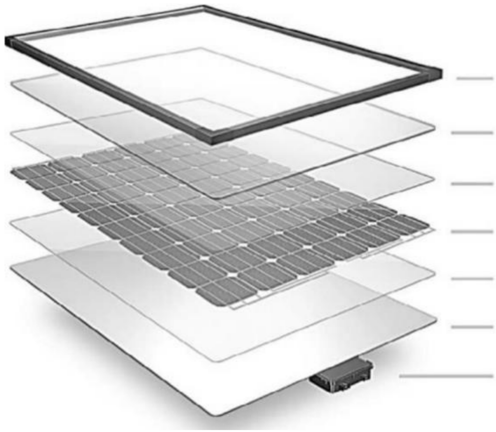


Figure 1. The components of a solar panel [16].

At present, the PV cleaning methods are mainly natural cleaning, manual cleaning, mechanical cleaning, and self-cleaning. The improper cleaning methods will not only lead to incomplete cleaning but also destroy photovoltaic panels. In desert areas, mechanical cleaning is chosen by most of the PV plants due to the lack of water resources. Even in areas where water is not scarce, the washing method is regarded as an uneconomical way due to low efficiency and heavy labor requirement [17,18]. Self-cleaning is a unique capability of many superhydrophobic surfaces. It is manifested by rinsing pollution particles with water droplets running on the surface (either driven by sliding or rolling motion [19]). Traditional surfaces have stronger adhesion to contaminants [20]. Additionally, the self-cleaning mechanism is explained by the ability to expel dust particles by the action of spherical water droplets [21–24]. By using self-cleaning coatings on PV modules, the removal efficiency of dust can be improved, and dust deposition can be partially prevented. However, current studies and reviews mainly focus on the effects and efficiency of self-cleaning coatings, while few studies emphasize the behavior and mechanism of dust deposition on them. Therefore, this paper summarizes the dust deposition behavior and mechanism of self-cleaning coatings on photovoltaic modules and summarizes the latest research on self-cleaning coatings. It is found that the solution to improve the photoelectric conversion efficiency of PV modules is to inhibit dust deposition, promote dust rebound and resuspension, keep the surface dry and inhibit dust cementation. It is found that superhydrophobic is more suitable for photovoltaic modules. The development of superhydrophobic coatings is largely limited by expensive superhydrophobic materials, the durability of nanoparticles, stability of coatings, precipitation/curing problems, impact problems, and wetting problems of emulsifiers. To solve these problems, some scholars proposed a theoretical wetting model to simulate natural superhydrophobic coatings. For the practical application of superhydrophobic coatings, all these models need to be further improved. In future research, advanced theoretical models can be further studied to understand the mechanism of superhydrophobic coatings in detail. Nanoparticles were introduced into the preparation of superhydrophobic coatings to improve the performance of the coatings.

When solid particles such as dust, pollen, and bird droppings accumulate on PV panels, they produce shadows and hot marks that can completely block the light and raise the surface temperature of PV. Photovoltaic modules whose surfaces are partially hard shielded will form hot spots as the temperature increases, as shown in Figure 2. The performance of those photovoltaic modules will be greatly reduced or even damaged [25]. When small dust is deposited on PV modules, it weakens the light intensity and forms amorphous fuzzy shadows, known as soft shielding. Soft shielding can greatly inhibit the light transmission intensity of PV glass and suppress power generation [26].

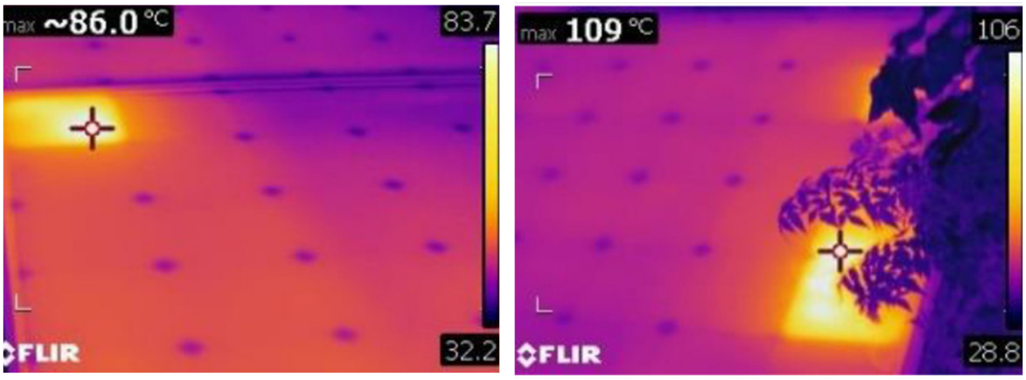


Figure 2. Diagnostic analysis of modules misclassified as hot spots in field tests and precision tests [25].

Dust deposition includes three processes: deposition, rebound, and resuspension according to Figure 3 [27–29]. The deposition and removal of particles was previously studied using microscopic photography and videography. The characteristics of dust deposition are influenced by wind flow, air humidity, the installation method of PV modules, the particle diameter and composition, and other environmental factors [30]. The increase in dust deposition velocity will promote the deposition rate of dust particles. However, dust particles that contact photovoltaic modules are easy to bounce off the surface under high wind velocity. In addition, higher wind velocities can affect deposition, causing an increase in the resuspension rate and the fraction of recombination [31]. Additionally, resuspension will occur when the lift force is greater than the forces that hold the particles to the surface (interception, gravity, and mass inertia [32]).

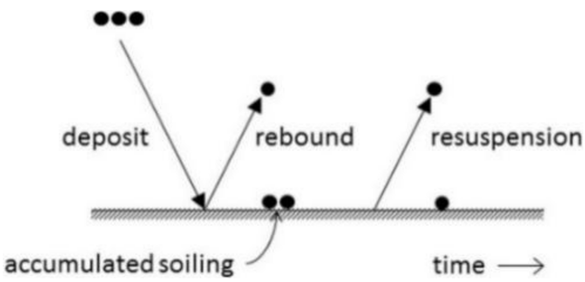


Figure 3. The behaviors of dust particles on PV modules [28].

According to the photovoltaic effect, the intensity of solar illumination and the temperature of the PV module itself are two decisive factors affecting PV performance [5]. When particulate matter blocks the light radiated by the PV module, the dust deposited on the PV module rises in temperature and thus forms hot spots. When the temperature increases, the open-circuit voltage of the PV module decreases rapidly and the short-circuit current slowly increases [31]. Therefore, the deposition of dust seriously affects the characteristics of PV modules [32].

2. Mechanisms of Dust Deposition

Dust is defined as tiny particles suspended in the air with a particle size of 0.1 μm to 1 μm. [33]. Dust deposition can affect the performance of photovoltaic modules [34]. It is necessary to further study the mechanism of dust deposition and investigate the intrinsic effects of dust on PV modules.

Figure 4 illustrates the forces on the particles during the collision. The dust deposition process is closely linked to the action of these forces. The origin is set as the contact point between the particle and the PV plate. The space rectangular coordinate system with the z-axis as the normal direction of the contact surface is established [35]. The forces (liquid pressure, gravity, etc.) that can cause particles to be deposited on the inner inclined panel are referred to as deposition forces. The separation force refers to the resistance and contact force that can cause the particles to leave the panel. A deposition force greater than the separation force will result in the particles being deposited on the panel. Analysis of these forces will help to provide insight into the deposition behavior of the dust and how the dust is re-removed. As particle size decreases, liquid evaporation will greatly accelerate the agglomeration and fouling process of particles [36].

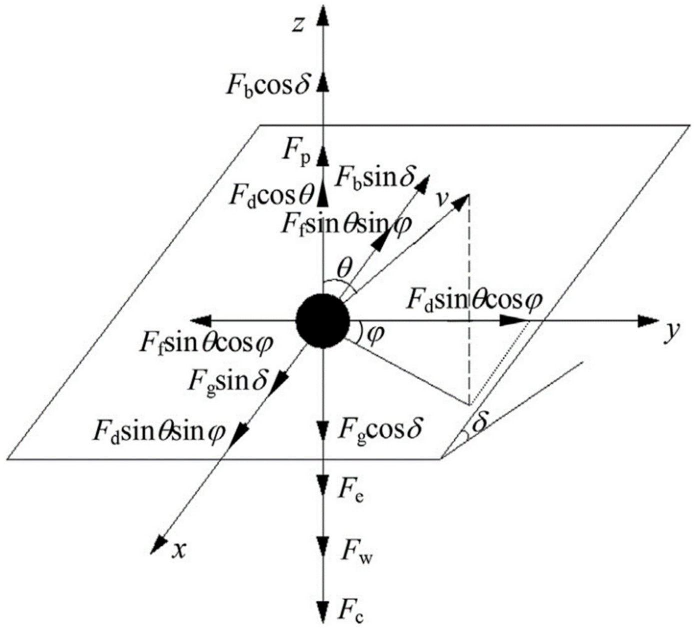


Figure 4. Schematic diagram of particle forces acting on an inclined plate [32].

2.1. Particle Deposition

Depending on the ratio of viscous forces to gravity, the dust deposition behavior can be classified into three mechanisms: gravitational deposition, inertial deposition, and Brownian–Anne motion. In general, when dust particles are larger than 100 μm in diameter, the gravitational force is much stronger than the viscous force, leading to gravitational deposition. When the particle is smaller than 1 μm, the viscous force is much stronger than gravity, and it does Brownian motion. When the particle is between 1 and 100 μm, the gravity and viscous force are similar. Gravity deposition and inertia deposition are the main mechanisms of dust deposition on PV modules. The deposition trend of particles from the atmosphere is described by its deposition velocity V_{Stokes} [28,37,38]:

$$V_{\text{Stokes}} = \frac{\rho d^2 g}{18\mu} \tag{1}$$

According to Equation (1), when the density is high and the diameter is large, the deposition rate is fast, and it is easier to deposit on PV modules. Kenneth et al. obtained an empirical formula for kinematic viscosity v_{inertial} by simulating the deposition and rebound process of particles on a grease collector plate [39]:

$$v_{inertial} = 1.12\ u \times e^{-\frac{30.36}{d}} \tag{2}$$

It can be seen from Equation (2) that increasing the relative velocity of friction between dust particles and airflow will reduce the ratio of particles to airflow (u) and the kinematic viscosity. When v_{inertial} is substituted into Equation (1), it is found that the deposition rate increased, and dust particles are easier to deposit.

2.2. Particle Rebound

When the particle has enough incident velocity to escape the adhesion between the surface and the particle, it will rebound and return to the airflow rapidly. The energy required for the particle to overcome the adhesion forces from the surface is the work of adhesion. When the kinetic energy of the particle is greater than the adhesion work, the dust particle will rebound [39]. Zhao et al. found that the normal component of particle rebound velocity was negatively correlated with humidity, but positively correlated with particle size, inclination angle, and wind speed [40]. The kinetic energy of a dust particle is related to its size and incident velocity. Reducing the adhesion of particles to the surface can promote the rebound of particles. Experimental data from Bateman et al. show that particles that are smaller than 1 μm have a low deposition velocity, thus they are difficult to collide with the surface. Large particles that are larger than 100 μm have high kinetic energy and it allows them to rebound off the surface rapidly. Therefore, the medium-sized particle is more likely to deposit on PV modules [41].

2.3. Particle Resuspension

Resuspension refers to the process by which particles escape from the surface and return to the airflow when the aerodynamic force acting on the particle is stronger than the adhesion force. The process requires the particles in a turbulent environment, and they will be separated from the surface by rolling or sliding. According to the airflow resistance to particle calculation in Equation (3) [42]:

$$F_{drag} = \frac{3}{2} ßfæ_{air} d^2 u^2 \tag{3}$$

According to Equation (3), the re-levitation force is positively correlated with the square of particle size. The adhesion between dust particles and surfaces is proportional to the contact area between them. Particles whose size is greater than 100 μm have a higher resuspension rate. From the mechanism of deposition, it is found that the parameters affecting the deposition process include particle size, surface adhesion, particle incidence rate and environmental factors.

Overall, the impacts on dust accumulation of photovoltaic modules include:

1. Particles with a diameter of 1–100 μm are most likely to be deposited on PV modules.
2. It will promote the process of rebound and resuspension by increasing the incidence velocity.
3. While suppressing the process of deposition, it promotes the course of rebound and the process of resuspension, which is conducive to the self-cleaning of photovoltaic modules.
4. It will promote the process of rebound process and resuspension by increasing the incidence velocity.

3. Influencing Factors of Dust Deposition

The deposition of dust particles prevents the sunlight from reaching the PV and reduces power generation [26]. A variety of factors such as wind speed and direction, surrounding environment, and installation design can affect dust deposition on PV surfaces [15]. Particle size, particle velocity, and particle adhesion to the surface are three important parameters that affect dust deposition. The macroscopic factors associated with these three parameters are classified according to the physicochemical properties of the particles and environmental factors. The influence of dust physicochemical properties and environmental factors on dust deposition is discussed in the following sections.

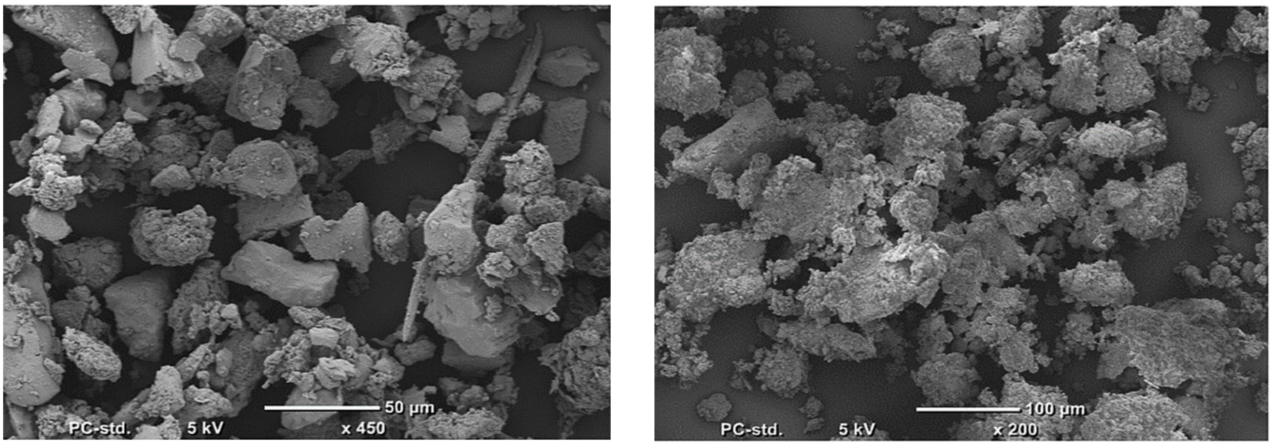
3.1. Physicochemical Properties of Particles

Experiments on dust deposition include the characterization of the properties of the dust itself. [43–45]. Lu et al. used CFD simulation software for dust accumulation on windward roof solar PV systems. The simulation results show that, together, the wind blowing direction, the dust's gravity, and inertia affect the accumulation behavior. The accumulation rate increases to a value at first and then decreases as the dust accumulation diameter becomes larger, influenced by the size of the particle diameter. The maximum accumulation rate reaches 0.28%, when the size of the dust is around 10 μm. When the diameter is 50 μm it corresponds to a minimum accumulation rate of about 0.13%. However, when the dust diameter is >5 μm, the simulation results show that gravity has a greater influence on the dust accumulation rate at this point. The accumulation rate influenced by gravity can be reduced by up to 75% for dust particles of 50 μm. For particles with diameters <5 μm, the effect of gravity is less than 5%. Therefore, according to CFD simulation results, the dust accumulation rate increases and then decreases for progressively larger particle sizes. The deposition rate of larger dust particles (50 μm diameter) is lower than that of smaller dust particles (10 μm diameter) [45]. It usually occurs in dust storms [46–48].

Dust suspended in the air can cause severe corrosion on PV panels [49]. Hacke et al. demonstrated the effect of different soils, under different humidity conditions, on the corrosion of PV panels. It was found that the erosion of PV surfaces by sea salt increased with increasing relative humidity. Katarzyna et al. [50] studied the effect of solid particles on PV modules. The correlation of particle deposition over time with particulate pollution in the air was obtained. The amount and intensity of precipitation and humidity were obtained to have a significant effect on the deposited dust.

Said et al. conducted dust deposition experiments using particles with uniform particle size distribution. It is found that a more compact accumulation distribution was obtained. The distribution reduces the gap between particles, allowing light to pass through them. Therefore, the available PV cell area for light capture was reduced, leading to a more severe degradation of photovoltaic performance [51]. Tanesab et al. studied ROTA dust and PNK dust, and their SEM images are shown in Figure 5. Three panels were randomly selected for placement in the Renewable Energy Outdoor Test Area (ROTA) at Murdoch University, all at an inclination of 32° and facing north. Two pc-Si and two mc-Si panels at Politeknik Negeri Kupang (PNK), both with an inclination of 15° and pointing north, were randomly selected in 1997 to represent NTT (Nusa Tenggara, Indonesia, a tropical climate region, Indonesia). When ROTA dust has a higher content of clay and fines than PNK dust, it causes a more uniform distribution of light over the PV module. As a result, the gaps through which light can pass are smaller, resulting in a greater loss of solar radiation [52]. Dust particles can absorb lower wavelengths of light and reflect longer wavelengths of light [53]. Medium and small-sized particles are the main contributors to the large scattering of incident light. Small-size dust particles scatter more than large-size dust particles because of the large contact area of the small size [54,55].

The deposition of dust is unfavorable for the photovoltaic module to receive light. The dust density is positively related to the performance loss of the photovoltaic module. Julius et al. adjusted the dust concentration on photovoltaic modules from 0 to 0.04 mg/cm^2 in the experiment, and the light transmittance of glass-covered panels was reduced by 18.34%. Although the open-circuit voltage of PV modules has little effect, the short-circuit current decreases seriously, and the output power decreases from 5% to 12%. The average daily and annual peak sunshine hours are 5.3 h, and the daily energy loss reaches 60 W/h [56]. Kaldellis et al. studied the performance of PV panels. The results show that when the dust density is the highest, the photovoltaic module receives the minimum light intensity, and the power generation is reduced by 6.5% [55].



(**a**) (**b**)

Figure 5. SEM images of dust [49]. (**a**) ROTA dust; (**b**) PNK dust.

The reduction of normal spectral transmittance of PV glass cover is related to dust density and inclination angle of photovoltaic modules [31,50–59]. It can be seen from Figure 6 that the higher the dust deposition density, the more serious the reduction of transmissivity. There is a linear correlation between the deposition density and power loss in the process of dust deposition [54]. However, when dust deposition is heavy enough, the linear correlation no longer exists [28]. Elminir et al. [60] studied the effect of dust deposition density in eight directions and six tilt angles, as shown in Figure 7. It is found that an increase in tilt angle decreases the dust particle deposition density on the PV modules and that dust is more easily deposited on horizontal surfaces than on tilted surfaces [61]. After one month of horizontal and vertical exposure, the transmittance of the two glass covers decreased to 30% and 88%, respectively [62]. Lu et al. predicted the dust accumulation on PV panels by numerical simulation and obtained similar conclusions [63]. Yao et al. [64] obtained that dust affects the dust particle density on the PV panels in various ways by testing the dust density under natural conditions. The functional relationship between the tilt angle of the glass cover and dust density is concluded.

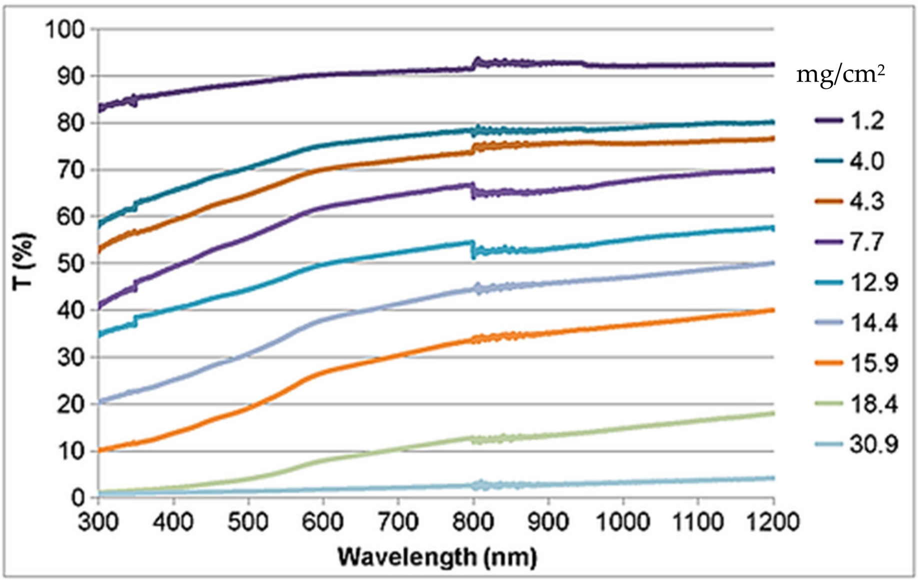


Figure 6. Influence of deposition density on transmittance [54].

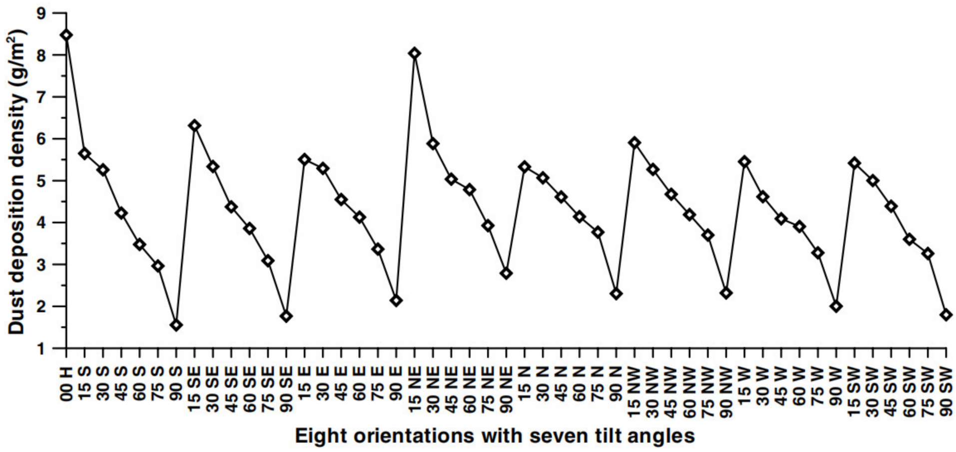


Figure 7. Exposure of glass samples to seven tilted angles and eight different orientations of the experimental setup [10].

When the photovoltaic module is working, an electrostatic field will be formed and dust particles will be polarized and charged, which is called the electrostatic effect. Charged dust particles on photovoltaic modules will absorb dust particles in the air, resulting in more serious dust deposition [5,20,62]. Liu et al. studied the mechanism and properties of dust deposition on solar photovoltaic modules under electrostatic action. Figure 8 illustrates the principle and mechanism. It was found that frequent collision can transfer physical charges, which can charge both objects, affecting the behavior of dust deposition [63]. The initial temperature of the electron-neutral sand is the same, $T_a = T_b = T_0$. T_a refers to the temperature of particle a, T_b refers to the temperature of the particle b, and T_0 refers to the initial temperature of particles a and b. The internal energy conversion caused by the collision will cause the temperature rise of the particles. The ion concentration in the adsorbed water film was increased. Ions will migrate from hot to cold particles through the contact interface. The hot particles have a negative charge, and the low temperature has a positive charge.

3.2. Environmental Factors

By investigating the location distribution of the photovoltaic industry, it was found that photovoltaic modules were usually installed in highly polluted areas [65]. Environmental factors will affect the incident velocity of particles and the adhesion force of photovoltaic modules. In this part, the two parameters are mainly analyzed. Dust deposition has a critical impact on photovoltaics. In the test of photovoltaic module engineering application in an area with serious air pollution, the output power has been greatly reduced, and the capacity has been reduced by about 30% [5]. Dust deposition is easily influenced by dust concentration, with more severe dust accumulation indicating higher particle concentration. However, the effect of dust concentration in the air on the morphology and performance degradation of PV modules is irregular. The light transmission function of the panel degrades the most when the PV module is facing the wind direction [10,46,47,61]. Natural dust consists of soluble salts, carbon quasimolecules, and other components [66]. Kazmerski et al. used atomic force microscopy to measure the adhesion of dust to photovoltaic panels. The experimental results showed that particles containing soluble minerals and organic components had higher adhesion forces than dust particles without these components [67].

The resuspension rate of dust particles has a threshold value of minimum wind speed. When the wind speed exceeds a value, the resuspension rate will increase significantly [29]. Under the same dust density, wind velocity is positively associated with light transmittance [68]. However, the negative effects of increased wind velocity are more severe than the positive effects [47]. Oh et al. suggested that the thermophoretic effect could reduce dust deposition, especially submicron particles could be significantly reduced [69].

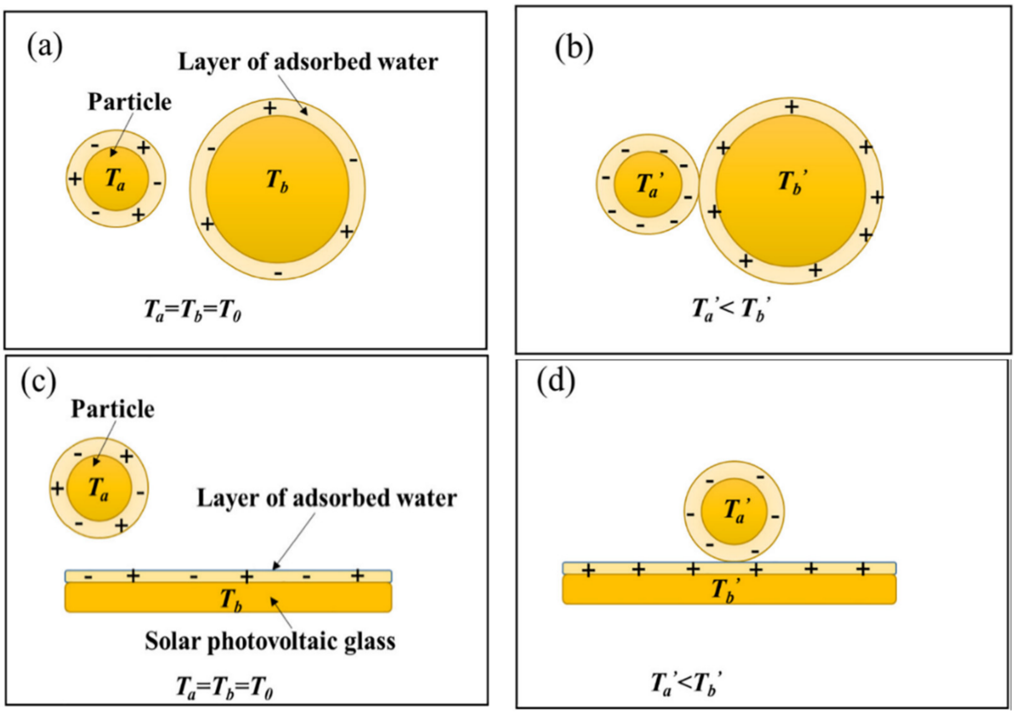


Figure 8. Schematic diagram of solar panels and charged particles [65]. (**a**,**b**) The temperature change process of particle to particle collision; (**c**,**d**) The temperature change process after a particle collides with a rough glass panel.

The adhesion between dust and surface mainly affects the process of particle rebound and resuspension. The resilience of tiny particles decreases with increasing relative humidity [41]. There is a limit value of relative humidity for each particle. When the ambient relative humidity is below the minimum limit, the resuspension rate is constant [70]. High humidity causes water vapor in the air to condense on the PV panels [51,71]. The soluble salt in dust particles will cause serious corrosion to photovoltaic modules, and the service life will be shortened after being dissolved by water [5,45,56,72]. Water gives dust a hygroscopic or soluble component. Dewdrop promotes the agglomeration of dust particles through capillary force. The large particles serve as the skeleton and the small particles fill the gap between the large particles, which is called the cementation phenomenon. These structures will further promote the formation of cement [73]. Under the influence of water, the cemented dust particles will form stronger adhesion to photovoltaic modules [28,29,48,61]. Restoring the performance of photovoltaic modules through dust cementation requires heavy labor costs to completely remove the dust masses [28,58]. If the dust masses are not cleaned up in time, it will lead to the accumulation of multilayer granular cement, which increases the difficulty of cleaning. It can even lead to permanent performance degradation of photovoltaic modules [74,75].

3.3. PV Properties Affecting Dust Deposition

The surface property of a PV module has a great influence on the dust accumulation rate, which varies according to the surface structure [18]. The effect of coated surface on precipitation is less than that of an uncoated surface [61]. Compared with the surface made of glass, the dust accumulation rate on the surface of photovoltaic modules made of Tedlar (an insulating material used for thermal insulation of spacecraft), plastic, and epoxy resin (a super glue) are higher [26,76]. Moreover, PV installation design, such as the tilt and azimuth angle of the PV module, also has a significant influence on dust accumulation rate.

By adjusting the surface characteristics of photovoltaic modules, the adhesion between dust and surface can be effectively reduced. Kim et al. measured the resuspension rate of particles. It shows that a surface with low surface energy can effectively reduce the adhesion between dust and surface to improve the rebound rate and resuspension rate of dust particles. It is worth knowing that the resuspension rate is the same under low humidity. However, the resuspension rate of hydrophilic particles decreases with the gradual increase of humidity, while that of hydrophobic particles has little change [72]. The hydrophobic coating can quickly remove condensation and inhibit the negative effects of photovoltaic modules operating in wet environments. It can effectively maintain performance and prolong the service life of photovoltaic modules [77].

Different types of dust would cause different results of dust deposition rate, but the rules observed by different photovoltaic modules at the same experimental operation are similar [47]. Particle size, incidence velocity, and dust composition are the most undisturbed factors in dust deposition. The adhesion force can be adjusted to promote the rebound and resuspension process of dust particles to prevent dust deposition, and to improve the efficiency of dust removal. The effective methods to promote the rebound and resuspension process include:

1. Keep the surface of photovoltaic modules dry, which can reduce the adhesion of dust particles and inhibit dust cementation.
2. The large tilt angle is conducive to the separation of dust on photovoltaic modules. The inclination angle is related to the latitude of the photovoltaic module installation, improper setting of the inclination angle will also affect the performance of the photovoltaic module.
3. Consider the choice of surface coatings for photovoltaic modules. Self-cleaning coatings are adopted to reduce surface adhesion, which will promote particle rebound and resuspension and improve the cleaning efficiency of photovoltaic modules.

4. Self-Cleaning Coatings

In the third part of the article, the influence on dust deposition is analyzed in terms of the physicochemical properties of the particles and environmental factors. Using self-cleaning is the most desirable way to remove dirt from the surface. The film applied to the surface by self-cleaning is usually superhydrophobic or super-hydrophilic. In the following, the super-hydrophilic and superhydrophobic materials are described separately.

Current dust removal methods include natural dust removal, mechanical dust removal, vibration dust removal, electrostatic dust removal, and physical and chemical dust removal [45,78]. Natural dusting through weather, such as rain, is ineffective. Even in sandstorm weather, if the photovoltaic modules are not cleaned in time, dust particles will adhere more firmly [76]. The main method of dust removal is manual or machine cleaning with water, but these methods have high costs and low cleaning efficiency [1,21,31]. It is worth noting that an improper cleaning process can cause mechanical and corrosive damage to photovoltaic modules. In areas where water is scarce, only mechanical methods can be used [79,80]. The method of vibration dust removal and electrostatic dust removal is to separate the dust particles from the photovoltaic modules by inertia force and electric force. However, these two methods are only applicable to dry dust particles and have poor removal ability for cementation [45,81].

Through the study of the mechanism of dust deposition, there are three directions to solve the dust deposition problem. They are preventing dust deposition, preventing dust particles from interacting with each other, and promoting dust particle rebound and resuspension, respectively. The application of super-hydrophilic and super-hydrophobic self-cleaning coatings on PV modules can effectively prevent and reduce the problem of dust deposition [82–84]. Researchers compared and evaluated the impact of self-cleaning coatings on photovoltaic panel power generation. They found that PV modules coated with self-cleaning coatings lost 2.5% of their power output per day, while modules that were uncoated lost 3.3% per day [10,85,86].

4.1. Super-Hydrophilic Coating

Surface self-cleaning is achieved through droplet repulsion (hydrophobic) or droplet dispersion (hydrophilic) properties [87]. Water contact angle (WAC) is a very important parameter to test surface hydrophobicity and hydrophilicity. When WAC < 90°, the surface is hydrophilic, and when WAC < 10°, the surface is super-hydrophilic. The dust adhering to the super hydrophilic surface will diffuse in the water drop when it contacts the water drop, and then leave the photovoltaic panel surface with the washing of rain.

Super-hydrophilic coatings have been applied in antifogging and self-cleaning due to their photocatalytic and reflection-enhancing properties [84]. Figure 9 shows the SEM images of super-hydrophilic coating. It was found that a uniform layer can be observed on the substrate surface, which is composed of small particle-size TiO_2 [85]. The super-hydrophilic titanium dioxide coating was applied to PV modules and shows excellent photocatalytic performance and high hydrophilicity under ultraviolet light. The coating can degrade organic dust into carbon dioxide, water, and inorganic substances, etc. [9,88]. The super-hydrophilicity of the coating allows the water that falls on PV modules to spread, penetrate the dust layer, and form a water film beneath the dust layer. The coating makes it easier to clean dust deposition on PV modules [61,89]. However, the photocatalysis of the coating has a minimum light intensity requirement, and the performance of the coating will be degraded in the case of insufficient light [90].

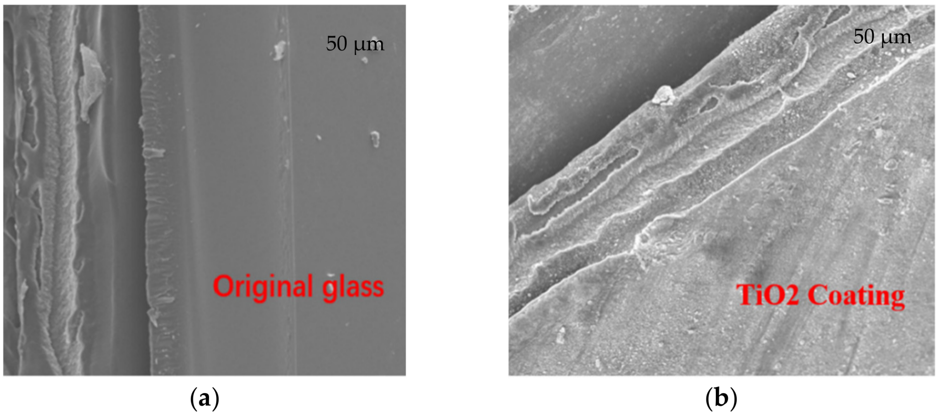


Figure 9. SEM images of super-hydrophilic TiO_2 coating [81]. (**a**) Original solar glass; (**b**) Solar glass with TiO_2 coating.

The antireflective and super-hydrophilic nanoporous SiO_2 coating prepared by aerosol impact spraying technology has a nanoporous structure. The high surface roughness and porosity resulting from this structure make the coating super-hydrophilic and anti-reflective. This anti-reflective property allows for the covered panels to have higher light transmittance than bare panels, which allows the photovoltaic cells to capture more light.

The formation of a water film somewhat hinders the accumulation of dust on the PV panels. However, it is difficult to form it in dry areas, so the cleaning effect is not ideal [61]. If a small amount of water that failed to form a water film is not removed in time, it will promote dust cementation and increase the difficulty of dust removal [91]. At the same time, the high surface energy and surface roughness brought by super-hydrophilicity will increase the adhesion between dust and surface, inhibit the rebound and resuspension of dust particles and promote dust deposition. Additionally, the coating has insufficient mechanical strength and is liable to break when exposed to the natural environment [87,92].

4.2. Super-Hydrophobic Coating

Super-hydrophobic coatings have been regarded as a promising solution to prevent dust deposition on PV modules [15,93–95]. Dust accumulation on PV modules is reduced by promoting the rebound and re-suspension of dust particles [96]. The contact angle between super-hydrophobic coating and droplet is greater than 150° [97]. Water droplets that fall on PV modules roll quickly along the surface of the module to remove dust from the module. The residual probability of droplets on photovoltaic modules is reduced, and dust cementation, reaction, and corrosion of photovoltaic modules are reduced. Superhydrophobicity is a low-cost and high-yield self-cleaning solution for photovoltaic modules. Roslizar et al. prepared a superhydrophobic fluorinated ethylene propylene cap that could be affixed to the panel. At similar dust accumulation levels, the performance recovery of PV modules coated with superhydrophobic coating was 65.8% compared to clean glass, which was only 12.3% [98]. The dust removal effect of panels at different tilt angles was studied by Zhang et al. It indicates that the panels with superhydrophobic coating had significantly higher spectral transmittance and photovoltaic efficiency. Figure 10a,b shows the SEM images of clean glass before dust deposition and glass with super-hydrophobicity, respectively. Look to see the distinct micro-nano structures that can be found on the glass with superhydrophobic coating, which can significantly reduce the adhesion energy on the glass surface. Figure 10c,d shows the SEM images of the clean and coated panels after dust deposition. It can be found that the dust particles on the panel with superhydrophobic coating are less and the diameter of the deposited dust particles does not exceed 20 μm, which is also much smaller than the diameter of the clean glass. The results show that it is difficult for large particles to be deposited on the superhydrophobic surface due to the low adsorption energy [8,99,100]. Pan et al. [101] proposed the introduction of a rough surface discretization model to solve the particle-rough surface adhesive contact force problem. The deposition properties of particles on surfaces with superhydrophobicity were investigated. The results show that small particles are less likely to be deposited on superhydrophobic surfaces, especially those with larger velocities.

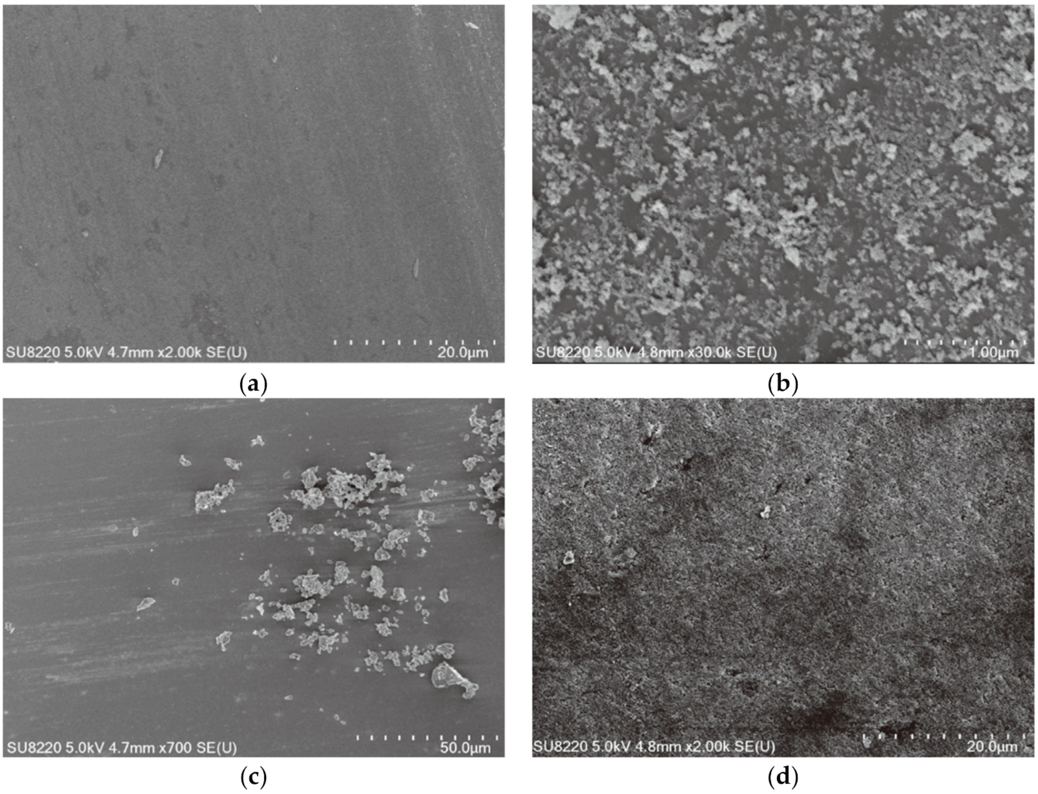


Figure 10. SEM images of the glass surfaces without/with super-hydrophobic coating before/after dust deposition [100]. (**a**) Glass without super-hydrophobic coating before dust deposition; (**b**) Glass with super-hydrophobic coating before dust deposition; (**c**) Glass without super-hydrophobic coating after dust deposition; (**d**) Glass with super-hydrophobic coating after dust deposition.

Since the cleaning ability and efficiency of traditional dust removal methods are limited in arid areas, it is of great significance to prepare suitable self-cleaning coatings [102]. There are many technologies for preparing superhydrophobic coatings, as shown in Figure 11 [103]. Kiluev et al. [104] used two machining methods, wire electrical discharge machining (WEDM) and die sinking EDM, to prepare superhydrophobic and super-hydrophilic surfaces. Performance depends on the medium used in the EDM process. The results show that the structure of the material in deionized water leads to the super-hydrophilic effect on the surface and the hydrophobic effect is introduced in the hydrocarbon oil. Lu et al. [105] developed a hydrophilic coating with anti-oil and photocatalytic activity. The technology used is the spray casting process. To solve the problem of oil scale in hydrophilic materials, a new and effective way was proposed in this study. Liu et al. prepared an effective self-cleaning super-hydrophobic coating with fluoroalkyl silane [106]. Pan et al. found that the super-hydrophobic film composed of nanostructure and silica soil can reduce the peak spectral transmittance and the minimum PV power efficiency [107]. Lu et al. tested the light transmittance of glass coated with super-hydrophobic coatings and found that the super-hydrophobic coatings were effective in inhibiting the reduced light transmittance caused by dust deposition [108].

Figure 11. The schematic diagram of multiple superhydrophobic coating manufacturing methods [103].

Due to the harsh working conditions of photovoltaic power generation, super-hydrophobic self-cleaning coatings have higher requirements for mechanical strength [109]. Binrui et al. prepared multilayer multifunctional nanocomposites by a molding process, which remained in a super-hydrophobic state after 30 sandpaper abrasions, 40 tape peelings, 24 h of strong alkali, or 60 min of acid etching [106]. Harprabhjot et al. prepared super-hydrophobic coatings by combining cerium dioxide with polytetrafluoroethylene (PTFE). The composite material reduces the friction coefficient of the coating. By applying severe mechanical wear (testing with high adhesive tape peeling, cyclic sandpaper wear and file wear) and severe chemical corrosion (testing with sulfuric acid, hydrochloric acid, and sodium hydroxide solution) to these multilayer multi-functional nanocomposites (MMNC), it was found that MMNC showed strong water repellency. In addition, it was found that MMNC has a strong ability to resist water impact. Therefore, the experimental data result shows that the composite material has little effect on the hydrophobicity of the coating, but the wear rate is greatly reduced [107].

1. Both super-hydrophilic and super-hydrophobic coatings are effective in dust prevention utilization. However, the super-hydrophilic coating needs to achieve a self-cleaning effect through rainfall, which is limited by regional weather conditions [59,90]. Therefore, the super-hydrophobic coating is more suitable for the prevention of photovoltaic components. However, there are still many drawbacks to the dustproof aspect of using self-cleaning coating on photovoltaic modules, including:
2. Although there are studies on improving the mechanical strength of coatings, the mechanical strength of coatings is still not enough to cope with the harsh natural environments, such as sandstorms and hail, in the engineering application of photovoltaic modules [109].
3. The super-hydrophobic coating with poor condensation resistance will have structural failure in the exposed environment, and the coarse surface structure will be permeated and filled by condensed water, failing super-hydrophobic performance. However, most super-hydrophobic coatings are poorly explored. Therefore, it is significant to discuss how to prevent the structural failure of super-hydrophobic coatings [21,108,109].
4. Coatings applied on PV modules are always exposed to high levels of solar radiation, which suffer serious natural degradation, so it is necessary to study the degradation rate of the coatings in the natural environment [20,84].

5. Discussion

The behavior and mechanisms of dust accumulation on panels were reviewed. It is considered that environmental conditions, relative humidity, wind speed, temperature, dust particle size, and concentration all have important effects on dust accumulation. In addition, the PV modules themselves and the installation were also studied. Among them, the dust deposition characteristics of PV modules with a northward tilt angle of 32 degrees were studied. To improve the efficiency of PV panels, the focus should be on dust deposition on the PV module surface; therefore, the article classifies and critically reviews the dust removal methods in recent years. The article highlights the mechanisms of superhydrophobic and super-hydrophilic coatings for researchers and PV panel designers. The analysis concludes that the use of self-cleaning coatings, especially super-hydrophobic coatings, is more conducive to particle rebound and resuspension. Moreover, as super-hydrophilic coatings are susceptible to regional weather conditions, super-hydrophobic coatings are more suitable for preventing dust accumulation on PV modules. Therefore, it is necessary to study the theoretical wetting model of super-hydrophobic coatings in the future to promote the application of super-hydrophobic coatings. Meanwhile, the mutual verification of numerical simulation results and experiments is also essential.

6. Conclusions

The efficiency of PV modules can be effectively improved by removing dust on PV modules and reducing dust density. According to the mechanism of the dust deposition process, particle size, particle incident velocity, and surface adhesion have important effects on dust deposition. It was found that of all the factors that affect the efficiency of photovoltaic module production, there are outdoor factors such as altitude, dust, humidity, temperature, wind speed, hail, and self-factors such as the tilt angle, material, quality, and maintenance of PV modules. This paper investigates the power generation performance of PV modules in a highly polluted environment, focusing on the effect of dust deposition on PV modules. Inhibiting dust deposition improves PV panel performance, promotes dust rebound and resuspension, keeps surfaces dry, and inhibits dust gelling. The above solutions can be achieved by covering the PV modules with a self-cleaning coating to adjust the surface adhesion. The super-hydrophilic coating is limited by weather conditions, and the super-hydrophobic coating is more suitable for the surface of photovoltaic modules. The high roughness structure of super-hydrophobic coatings makes it difficult for dust particles to deposit on photovoltaic modules. Super-hydrophobic coatings have the characteristics of low surface energy, which can promote the rebound and resuspension process of particles. The super-hydrophobic properties of the coatings keep the PV modules dry and inhibit the cementation of dust particles.

A super-hydrophobic surface mainly depends on its roughness to achieve self-cleaning. Water droplets that fall on PV modules roll quickly along the surface of the module to remove dust from the module. Super-hydrophobic coatings do not conflict with other dust removal methods, and are better if combined with other dust removal methods. However, super-hydrophobic coatings still face problems, such as insufficient mechanical strength, fast degradation rate, and disclosure, leading to super-hydrophobic failure, which requires further study and better solutions. The dust deposition mechanism, influencing factors, and self-cleaning methods were concluded in Figure 12.

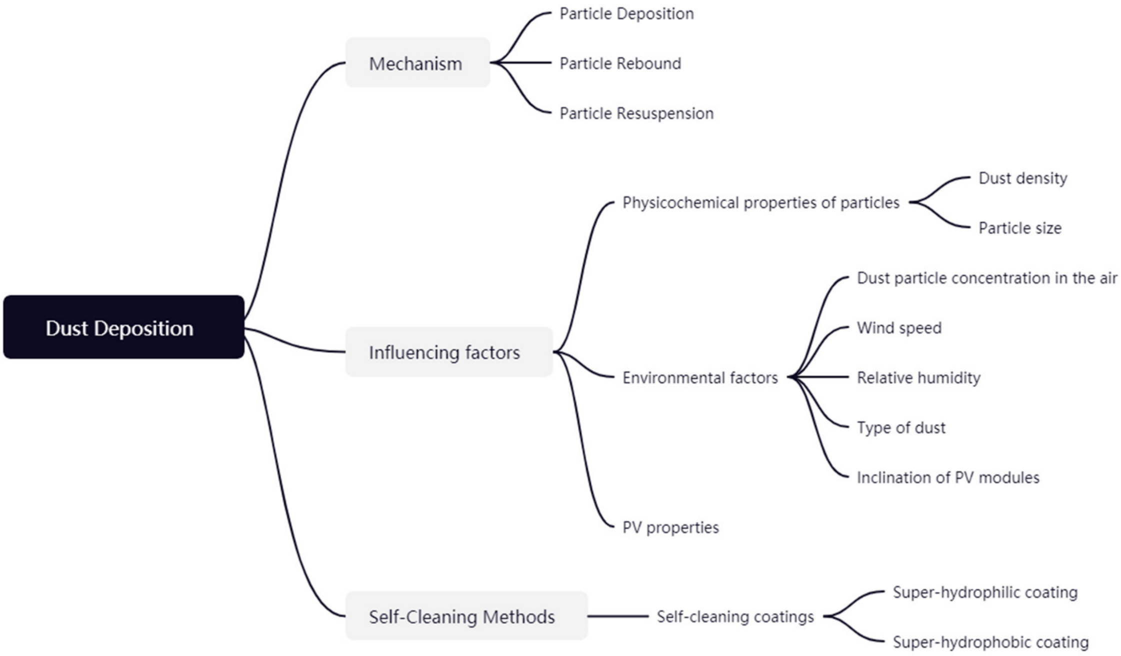


Figure 12. A flow chart that explains the dust deposition mechanism, influencing factors, and self-cleaning methods.

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Nomenclature

AFM	Atomic Force Microscope
CFD	Computational Fluid Dynamics
E	East
FEP	Fluorinated Ethylene Propylene
GHG	Greenhouse Gas
IR	Infrared Ray
N	North
NF	Nanofluid
NW	Northeast
PTFE	Polytetrafluoroethylene
PV	Photovoltaic
S	South
SE	Southeast
SEM	Scanning Electron Microscope
SW	Southwest
UV	Ultraviolet North

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