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Overview of Factors Affecting Dust Deposition on Photovoltaic Cells and Cleaning Methods

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Abstract

Dust deposition on the surface of photovoltaic (PV) cells poses a significant challenge to their efficiency, especially in arid regions characterized by desert and semi-desert conditions. Despite the pronounced impact of dust accumulation, these regions offer optimal solar radiation and minimal cloud cover, making them ideal candidates for widespread PV cell deployment. Various surface cleaning methods exist, each employing distinct approaches. Choosing an appropriate cleaning method requires a comprehensive understanding of the mechanisms involved in both dust deposition on module surfaces and dust adhesion to PV cell surfaces. The mechanisms governing dust deposition and adhesion are complex and multifaceted, influenced by factors such as the nature and properties of the dust particles, environmental climatic conditions, characteristics of protective coatings, and the specific location of the PV installation. These factors exhibit regional variations, necessitating the implementation of diverse cleaning approaches tailored to the unique conditions of each location. The first part of this article explores the factors influencing dust deposition on PV cell surfaces, delving into the intricate interplay of environmental variables and particle characteristics. Subsequently, the second part addresses various cleaning methods, offering an analysis of their respective advantages and disadvantages. By comprehensively examining the factors influencing dust accumulation and evaluating the effectiveness of different cleaning strategies, this article aims to contribute valuable insights to the ongoing efforts to optimize the performance and longevity of photovoltaic systems in diverse geographical contexts.

Keywords

Solar Energy, Dust Deposition, Cleaning Methods

1. Introduction

Massive energy demand and tangible climate change have prompted the development of modern renewable energy solutions and projects. According to [1] and [2], the increased interest in renewable energy sources is primarily due to the realization of resource exhaustibility, fluctuations in oil prices on the international market and a sharp increase in the emission of harmful gases into the atmosphere. Due to the perfect success of renewable energy, in Europe, renewable energy sources produced more than natural gas in 2022 for first time [3]. A particular growth is observed in solar energy, even if it is still significantly behind the wind energy in terms of the volume produced. From [4] works the advantage of solar energy is the independence of its conversion from moving objects and absence of particle and noise emissions into the atmosphere.

The amount of electricity produced by photovoltaic cells is directly related to the intensity and annual duration of solar radiation. These two factors are not evenly distributed over the earth (**Figure 1(a)** and **Figure 1(b)**) [5] and lead to the definition of zones where solar energy is more promising than in others. The most promising zones in terms of intensity and duration of solar radiation are also desertic or semi-desertic regions (**Figure 1(c)**). This is because in these regions the formation of clouds is reduced and many studies [6] [7] have shown the relationship between cloudiness and the amount of solar radiation that reaches the ground.

Additionally, these regions are also attractive for installing large solar power plants due to their low population and availability of free space. Based on the potential of solar energy, Kurokawa [8] estimates that installing solar energy

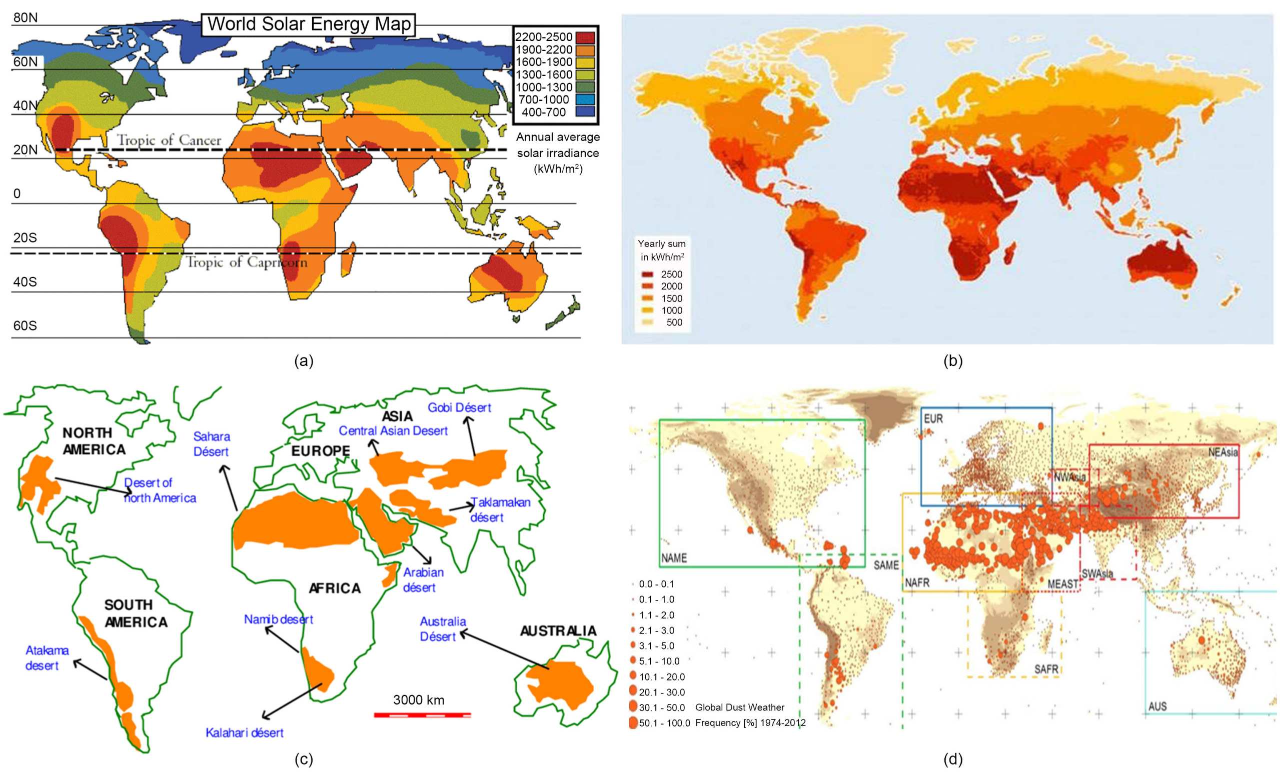

Figure 1. (a) Average annual solar radiation [14], (b) Global solar radiation map [15], (c) Location of the world's deserts [16], (d) Global atmospheric dust map [1].

systems in an area of 4% of the world's deserts, could easily meet the total energy demand in the world [9]. However, these estimates do not consider the problem of delivering the generated electricity to urban areas.

However promising regions are also particularly prone to dust deposition (**Figure 1(d)**). Dust deposition on the surface of solar modules leads to a decrease in their efficiency [1] [5] [10] [11] [12] [13]. Sayyah *et al.* [5] in their review showed that this reduction can be as high as 80% of the efficiency in some regions. In addition to lowering the efficiency, according to [13] non-uniform distribution of contamination on the surface of the module also lead to the creation of hot spots, leading to its destruction. From these works, it follows that to maintain the efficiency of large solar power plants, it is necessary to select a suitable module cleaning technique.

From the relationship between population growth in urban areas, energy demand and the space required to produce this amount of energy, large centralized solar power plants are not suitable for large population. Small local power plants are more efficient. Burger *et al.* [17] show that such power plants can provide the same electricity services as large, centralized power plants and due to their distributed and modular nature they are able to provide services where they are most valuable in the power system, making them more profitable. Although such power plants are not used in desert or semi-desert regions, they are also prone to dust deposition. Dust deposition on the surface of the modules is exaggerated by many factors and leads to different solutions to the problem of reduced efficiency.

In the first part of this study, we will describe factors affecting dust deposition on the PV cell surface and their specific impact on PV cell structure and work. In second part existing cleaning methods with advantages and disadvantages are discussed.

2. Factors Affecting Dust Deposition on the Solar Module Surface

2.1. Nature and Properties of Dust

From many studies [18] [19] [20] dust is the term for any material or particle present in the atmosphere with a diameter of less than 2000 μm, including solid organic and inorganic particles such as wood burning products, car and factory emissions, soil particles, volcanic emissions, microfibers, bacteria, fungi, plant pollen and limestone erosion products. Dust can be characterized based on chemical, biological, optical, and electrostatic properties as well as size, shape, and densities. Wu *et al.* [21] also noticed in their work that different dust properties also affect the electrical and thermal properties of PV modules in different ways.

Mainly the properties of dust particles depend on their size. Most studies categorize dust particles into different classes, which are generally defined as fine and coarse dust [19]. Adebiyi *et al.* [19] propose to classify dust based on particle size into fine (<2.5 μm), coarse (2.5 - 10 μm), extra coarse (10 - 62.5 μm) and giant (62.5 - 2 mm). Although the size of a dust particle is characterized by its radius or diameter, the population of dust particles is described by the dust size distribution, which is the distribution of the number of particles, their surface area, volume, or mass within a given range of diameters [19].

Optical properties describe the interactions between dust and light. They consist of absorption, light transmission, reflection, and emission. The optical properties of dust depend on the size, shape, refractive index, and chemical composition of the particles [22].

From [5] [22] [23], the absorption properties of dust reduce the amount of light reaching the surface of the module, which reduces the amount of electricity produced. By absorbing sunlight, dust also absorbs heat [24], which affects the production rate and can damage the module [22]. The absorption properties of dust depend on the amount of dust, chemical composition [25] [26] morphology and size of dust particles.

Limestone, carbon black and red soil are three common air pollutants with high absorption coefficients. Limestone and red soil are composed of various metallic constituents such as calcium, magnesium, iron, and aluminum oxides [27]. Their high uptake can be explained by the fact that metallic constituents absorb more than non-metallic constituents [22] [23].

Besides the chemical composition, the absorption is strongly influenced by the size and shape of the dust. Large particles absorb more than small particles [22], and non-uniformly shaped particles have lower absorption rates than uniformly shaped particles [23]. The combination of these factors leads to the fact that dust composed mainly of iron oxide (Fe_2O_3) has a higher absorption rate compared to dust composed mainly of silicon oxide (SiO_2) [28].

Light transmission, the property of dust to transmit light is also reflected in the efficiency of the module [22] [29] [30] [31]. Scientific studies [32] [33] have shown that the decrease in light transmission depends linearly on the dust mass. They also showed that small particles have a more significant effect on the light transmission coefficient than large particles because they are more uniformly distributed on the surface and reduce the amount of light passing through the gaps between particles [22]. Light transmission also depends on the light transmission of chemical constituents of dust. From [34] works, the chemical composition and density of dust also affect the reflection.

Radiation is the ability of dust particles to emit thermal radiation, which can affect the temperature of photovoltaic cells [22] [35]. It is directly related to the other optical properties. Increasing the operating temperature above 25˚C negatively affects the electrical efficiency of PV modules [36]. In the literature [37]-[45], many expressions of the effect of temperature on the performance are found using a large number of correlations [36]. Besides lowering the performance, the non-uniform distribution of heat on the module surface lead also to its damage [46]. The thermal effect of dust also depends on its composition. The work of

Abderrezek *et al.* [47] showed that dust with high thermal conductivity such as salt promotes heat dissipation, while dust with low thermal conductivity such as soil leads to an increase in surface temperature.

The chemical composition of dust can predict its dielectric constant based on the dielectric constants of each constituent from [48]. The works of Sharif [48] relying on the solution of the Looyenga model (1) [49], the mixture model proposed by Neelakantaswamy *et al.* (2) [50] and dielectric constants of dust components, they proposed theoretical dielectric constants. These theoretical constants deviate from the real ones by 5% in the Looyenga model and 15% in the Neelakantaswamy model [48].

$$\varepsilon_m^{\frac{1}{3}} = \sum_{i=1}^{n} v_i \varepsilon_i^{\frac{1}{3}} \tag{1}$$

$$\varepsilon_m = \prod_{i=1}^{n} \varepsilon_i^{v_i} \tag{2}$$

where ε_m is the dielectric constant of the mixture, ε_i is the dielectric constant of each component, v_i is the volume of this component.

Usually, the PV modules are mounted at some angle and, if the adhesion forces between the dust particles and the module surface are excluded, they should roll under the effect of gravity. The adhesion forces between the particles and the surface can be explained by the triboelectric effect and hence it follows that the dielectric properties of the dust particles also affect their ability to adhere to the surface of the PV cell, which allows the module surface to be cleaned using an electric field [51] [52] [53] [54] [55]. Electrification of the dust layer can also help to reduce the rate of gravitational settling, which can facilitate the transport of coarse dust over long distances [19] [56] [57] [58] [59].

Understanding the chemical properties of dust is necessary to predict and reduce its effect on the performance and temperature of PV cells [22]. The chemical composition of dust particles includes various materials such as: silicon oxide, carbon, iron, aluminum calcium carbonate and other minerals [22] [23]. The composition of dust particles accumulated on PV panels can vary depending on the location and environmental conditions [60]. The chemical composition of mineral or inorganic dust depends primarily on the nature of the soil, while organic dust depends on the fauna and flora. In populated areas and intermittent zones, dust may also include combustion products and exhaust gases [5] [61]. The dust components accumulated on PV panels in desert areas consist mainly of silicon oxide, clay, and silt [62] [63], and in coastal areas, salt [62].

It should also be noted that the chemical composition of dust includes soil particles from far locations. Such a phenomenon was observed in [64] [65] [66], where Saharan soil particles were found on the coast of America and in the Caribbean Islands.

2.2. Tilt Angle and Orientation of a Photovoltaic System

The tilt angle of a photovoltaic system plays an important role in its performance [67] [68]. It should be chosen in such a way to ensure optimum exposure of sunlight to the PV panels.

From [13] and [69] the tilt angle depends on the geographical latitude of the area. The orientation should be towards south for northern hemisphere territory and towards north for southern hemisphere territory. Also, the tilt angle depends on climatic conditions [69] and on the season [13] [70] [71]. In case of stationary installation, the tilt angle β can be determined by the formula:

$$\beta = (L \pm 10) \tag{3}$$

where L is the latitude of the installation location [5].

The maximum efficiency of the solar module is achieved at small tilt angles between the surface of the solar module and the direction of sunlight [13]. However, small tilt angle with respect to the ground is also more prone to dust accumulation like it's noticed on [13] and [71]. This phenomenon can be explained by the fact that, hence according to formula (4), the smaller the tilt angle, the more the surface of the panel faces upwards. The main mechanism of dust deposition on the surface S is gravitational forces [5], which are supplemented by triboelectric forces, which are responsible for the adhesion of dust to the surface of the module.

$$S = A\cos\beta \tag{4}$$

where S is the surface turned to the top, A is the area of the module, β is the tilt angle.

When the photovoltaic cell is placed vertically, the main mechanism of contaminant deposition is particle diffusion [5], which is supplemented by electrostatic adhesion forces. Gravitational forces on large particles are stronger than adhesion to the module surface and for this reason such particles do not adhere to the module surface.

The optimal angle increases not only the efficiency of the photovoltaic system and reduces the amount of deposited dust, but also to more efficient dust cleaning by wind or rainfall [5].

2.3. Ambient Temperature and Humidity

In his book, Pruppacher [72] gives the velocity of small particles falling under gravity simply as the finale velocity in Stokes flow with Cunningham's slip correction—(1 + αNKn). The velocity in Stokes flow is commonly used in viscous fluids where the Reynolds number is below one. Despite this fact, many works [66] [73]-[79] use this model to describe the motion of dust particles.

$$V_s = \frac{2(1 + \propto N_{Kn})r^2 g(\rho_p - \rho_a)}{9\mu_a} \tag{5}$$

where V_s is the deposition velocity, r is the radius of the particle, g is the gravitational constant, ρ_p is the density of the particle, ρ_a is the density of the medium, in our case air and μ_a is the dynamic viscosity among.

The dynamic viscosity also depends on temperature according to Sutherland's Formula [80]:

$$\mu_a = \mu_0 \frac{T_0 + C}{T + C}\left(\frac{T}{T_0}\right)^{\frac{3}{2}} \tag{6}$$

where μ_a is the dynamic viscosity at a given temperature, μ_0 is the reference viscosity at some reference temperature, T is the given temperature, T_0 is the reference temperature in Kelvin, C is the Sutherland constant for the gas whose viscosity is to be determined.

It follows that the deposition rate is affected by the ambient temperature. It also follows from formula (6) that the particle size affects the deposition rate.

When humidity increases, the particle adhesion forces increase, which leads to an increase in particle size and hence affects the deposition rate [81].

High humidity can also cause moisture condensation, which occurs when the temperature of the PV panel is below the dew point temperature of the ambient air [82]. In this case, water vapor in the air can condense on the photovoltaic cell's surface, forming water droplets. Dew formation promotes dust settling on the flat surfaces of the collectors, while vaporization, on the other hand, enhances dust adhesion to these surfaces [83]. This adhesion of dust to the surface is also called "cementation" and occurs due to dissolution or re-solidification of soluble dust components, which enhances the adhesion of dust particles to the surface like in [84] [85] [86] studies.

On the other hand, humidity may play an important role in the decay of electrostatic charge on dust particles [87] [88]. For example, Sayyah *et al.* [89] suggested that the electrostatic charge density of dust particles decreases by 15% when the relative humidity increases from 30% to 50%.

In addition to the problems associated with dust deposition, high humidity can also lead to poor performance. When dew forms, the droplets can scatter and absorb sunlight, reducing the amount of sunlight reaching the photovoltaic cells [90]. High humidity can also lead to corrosion of electrical connections and potential failure of the PV system [82].

2.4. Wind Speed

From [91] wind speed significantly affects the performance of photovoltaic systems. The main reason for this influence is the amount of dust that collects on the module surface. Depending on the speed and particle size, wind can sweep or accumulate dust on the photovoltaic module surface [92]. The wind is more efficient in sweeping away larger sized particles while smaller particles from the module surface [93].

By moving the particles on the surface, the wind can scratch it [46]. These scratches lead to a decrease in the transmitted light and thus affect the performance of the module.

Wind speed affects the temperature of the module cooling it and increasing its performance [30] [94]. Wind also affects the relative humidity of the environment [95], which leads to a lower possibility of grouting and coarse particle formation.

2.5. Climatic Conditions

Dust deposition depends on many parameters such as temperature, humidity, and wind speed. The combination of these parameters and the amount of precipitation is defined as climatic conditions. They differ from one geographical region to another and from one season to another. The effect of climatic conditions on dust deposition on the surface of photovoltaic cells is seasonal in nature. The works of El-Nashar [96] show that in the United Arab Emirates, the monthly decrease in transmittance reaches 10% in summer and 6% in winter. Van der Does *et al.* [97] in their works cite the effect of climate on dust particle size.

Dust particles have also influence on the climatic conditions by changing the frequency of precipitation and the temperature of the environment. However, due to a variety of factors, there is still no unanimous agreement on heating or cooling the planet [98] [99] [100] [101]. Globally, fine dust tends to cool, while coarse and ultrafine dust aerosols warm, counteracting cooling. Given that atmospheric dustiness has increased substantially [102] [103] [104] and continues to increase [105] [106] the effect of dust on temperature will also affect the deposition rate.

In addition to the influence of climatic factors on the deposition rate of dust particles, they also influence the natural cleaning of solar modules. Natural module cleaning involves the cleaning of modules by wind or precipitation such as rain and melting snow [5]. In works [107] and [108], dust related productivity losses are more noticeable in seasons with lower rainfall [5]. In Hottel and Woertz [109] works, it is reported a case where the self-cleaning of the collector is due to snow melt.

2.6. Surface and Coating Characteristics

Surface properties also influence the soiling of photovoltaic cells. Glass or plastic is often used as protective plates in photovoltaic cells. In studies [5] [12] [110] [111], it is noticed that plastic cover plates accumulate more dust compared to glass plates. This can be explained due to their electrostatic properties. Polymer plates are also susceptible to UV related aging [5].

To reduce the effect of the surface on module dusting and to avoid other factors that could affect the performance of solar modules, many protective coatings have been developed. Although they are often based on polymer films treated surfaces have shown higher performance levels than untreated ones like it's showed [112]. Anti-reflective (AR), self-cleaning (SC) and multi-layer (ML) coatings are used as surface treatments. These coatings reduce the transmittance of the module, but their effectiveness becomes noticeable after some exposure time [112].

Hee *et al.* [113] report that photocatalytic, hydrophobic, and hydrophilic effects of various fillers are utilized as self-cleaning coatings.

3. Methods for Surface Cleaning for Photovoltaic Cells

Many different methods have been developed to solve the efficiency degradation due to dust deposits on the surface of solar modules, differing in both technological approach and application. Among them there are surface methods, mechanical methods, and climate dependent methods. These methods can also be categorized as passive or active methods.

3.1. Climatic Conditions Favorable to Cleaning

Rainfall is considered to be the most effective natural cleaning agent for removing contaminating particles from the surface of PV cells, thus restoring their performance from [5] [112] [114] [115] studies. This approach is particularly interesting as it does not need to extra cost [116]. Typically, photovoltaic system is installed at an angle, which facilitates the runoff of dirt from the surface. This cleaning method can be made more effective by coating the photovoltaic panels with a hydrophobic or hydrophilic coating. Such coatings can also work in very humid climates by depositing dew drops on the module surfaces. However, this method of cleaning is directly dependent on weather conditions, which makes it unreliable. In many countries where solar energy is interesting to be extracted, rainfall is rare because they are deserts or have semi-desert climates. This is due to their lower cloud cover and increased duration of sunshine. From [5] in low latitude regions with high annual rainfall, natural rain cleaning periodically restores the efficiency of PV cells.

Like rain cleaning of panels, works [5] and [117] report that wind cleaning depends on the tilt angle and orientation of the surfaces with respect to the wind direction. Wind cleaning of the module is particularly effective on large particles [118].

Snow, as well as dust, is a factor which can reduce the efficiency of transmittance reduction modules like it's showed in [119]-[125] and can also disable the photovoltaic module [126]. Despite these disadvantages, [109] reported that it also plays a restoring role, precisely during its melting.

3.2. Passive Cleaning Methods

Passive methods consist of modifying the collecting surface of a solar module to facilitate its cleaning or to minimize the adhesion of the dust layer to the collecting surface of the module [127]. In this way they improve the performance of solar photovoltaic devices. Coatings with hydrophobic, hydrophilic, or photocatalytic effects are used for surface passivation.

3.2.1. Coatings with Hydrophobic and Superhydrophobic Effects

The hydrophobic effect refers to the tendency of a molecule or surface to avoid contact with water. The difference between the concept of a hydrophobic surface and a superhydrophobic surface is the angle of contact with water. In a hydrophobic surface, the angle is between 90˚ and 150˚, while in a superhydrophobic surface it is between 150˚ and 180˚. Superhydrophobic surfaces (**Figure 2(a)**) have self-cleaning properties due to their special surface textures and chemical composition that regulate wettability [128].

Lotus leaf is the first biological surface that inspired the superhydrophobic phenomenon [129]. The super hydrophobicity and self-cleaning property of lotus leaf are caused by the interaction of rough surface micro- and nanostructures. These surface structures consist of hierarchical arrays of microcapillaries, nano clusters and nanotubes, which are the roughness factor on the surface of lotus leaves [130] [131] [132].

Solar modules often utilize a superhydrophobic coating as a self-cleaning surface [15]. Since the contact angle with water is >150˚, self-cleaning surfaces have unique wetting protection properties, allowing water droplets to easily roll off and collect dust on the module surface (**Figure 2(b)**). This approach is particularly effective in high humidity environments. When humidity is high, dew forms on the module surface [82] which can result in cementation. By rolling off the surface water droplets do not have time to allow this process to occur.

Superhydrophobic coatings have a structure like micro pyramids on the surface, which makes them anti-reflective. [133] showed that due to their micro-nano anti-reflective structures, PV modules coated with superhydrophobic films have higher transmittance.

Such superhydrophobic anti-reflective coatings are suitable for outdoor applications [15]. Superhydrophobic coatings are much more effective in cleaning the module surface than simple hydrophobic coatings [134]. In [135], a 5% improvement in efficiency was observed for modules coated with a hydrophilic anti-pollution coating. When using superhydrophobic coatings, the solar module is usually positioned at an angle to allow water droplets to flow off under the effect of gravity. Such coatings combine well with other cleaning methods that utilize water.

From [130] and [135] the big disadvantage of superhydrophobic coatings is their short lifetime. In [136], a decrease in the contact angle of water droplets with the surface of the module was observed for only two weeks from the beginning of the test under real conditions.

3.2.2. Superhydrophilic Coatings

The superhydrophilic effect refers to the tendency of a molecule or surface to interact with water. A hydrophilic surface has an angle of less than 90˚, while a superhydrophilic surface has an angle of less than 5˚ (**Figure 3**). In contrast to the hydrophobic effect, a thin water film forms on the surface of a hydrophilic coating, which dissolves contaminants and flows off the surface of the module under the effect of gravity. This approach is particularly effective in the case of cementations.

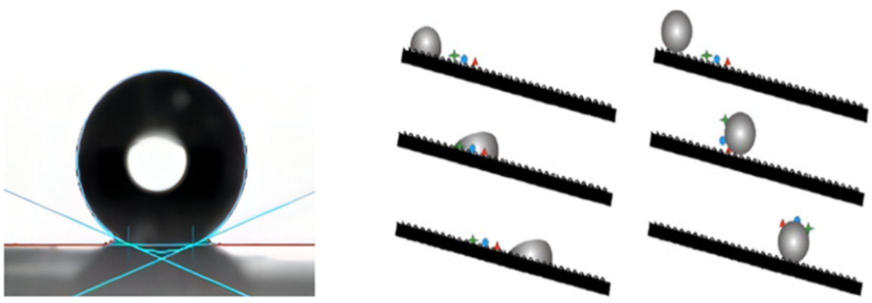

Figure 2. (a) Water droplet on hydrophobic coating [128]; (b) Water droplets roll off substrates with conventional hydrophobic surface (left) and self-cleaning superhydrophobic surface (right) through dust particles [134].

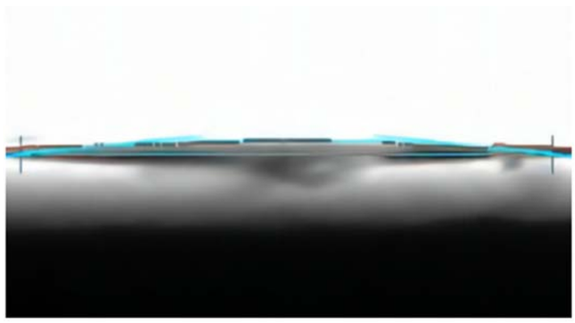

Figure 3. Water droplet on a hydrophobic coating [128].

It was shown in [128] that under natural deposition conditions, the deposition mass reduction ratio of a superhydrophilic coating is only 8.1%, while for a superhydrophobic coating it can reach 85.8% due to the surface microstructures and low surface energy. This is because the high surface energy of the superhydrophilic coating may favor dust deposition. However, after water spraying, the remaining dust mass ratio for the superhydrophobic surface is only 16.5%, while it is 18.6% for the superhydrophilic surface. The self-cleaning mechanism of the superhydrophobic coating is such that most deposited dust particles are removed from the glass samples as the liquid drops roll off. However, the self-cleaning mechanism of superhydrophilic coating is to break the liquid film and dissolve the dirt [128].

The effectiveness of hydrophilic coatings is particularly successful when combined with rain or with an artificial water source due to dispersion over the entire surface. These droplets wash away dust rather than collecting them together [131]. Due to the need of water for cleaning solar modules by this method, [131] consider its efficiency is reduced in promising regions where rainfall is limited.

The efficiency of hydrophilic coating can be improved by using an automated mechanical vibration system [137]. The results of the study [137] showed a 12.94% decrease in the efficiency of photovoltaic panels with hydrophilic coating and mechanical vibration system while the efficiency of photovoltaic panels with only hydrophilic coating decreased by 24.46%.

Many superhydrophilic coatings contain titanium dioxide TiO_2 [138]. Under different conditions of surface UV light illumination, TiO_2 films can exhibit hydrophobicity and superhydrophilicity [139]. The wettability can be reversibly altered by alternating surface illumination with UV light and storage in the dark. This unique property is believed to be due to the synergistic effect of the photosensitivity of the surface and the geometric structure of the films [139]. The superhydrophilic effect as well as the photocatalytic effect is found in the crystalline form of anatase [140]. Hydrophilic coatings containing titanium dioxide have an additional property: they can break down chemically adsorbed dirt when exposed to sunlight or UV light [141].

Works [142] [143] showed that to achieve improved hydrophilic properties of the film, a suitable geometric surface must be selected. The preparation method can play a significant role in preparing a suitable geometric surface to improve the hydrophilic properties of TiO_2. To achieve superhydrophilicity, many studies have usually used sol-gel [142] [144] [145] [146] or sputtering [147] [148] as the preparation method.

Hydrophilic coatings containing titanium dioxide can also be improved by polymeric dispersants such as polyethylene glycol [140]. In such coatings, the hydrophilic properties are not only related to the properties of titanium dioxide but also to the properties of the polymer.

3.2.3. Coatings with Photocatalytic Effect

To clean the surface of a solar module coated with a hydrophobic or hydrophilic coating, it is necessary to use a water source. This source can be rain or an artificial water source. In another approach, improving the efficiency of photovoltaic panels is achieved by using photocatalytic coatings to utilize incident solar radiation and self-clean the panel surface. The photocatalytic effect is the ability of the coating to decompose ambient contaminants such as volatile organic matter or nitrogen oxides under the effect of ultraviolet (UV) radiation. This decomposition results in the formation of water droplets (**Figure 4**). Titanium oxide (TiO_2) or zinc oxide (ZnO) is often used as a photocatalytic agent.

When activated by UV irradiation, titanium (TiO_2)-treated surfaces react with moisture and oxygen from the environment [149], providing photoinduced superhydrophilicity, self-sterilization and antimicrobial ability [150] [151] [152]. In [153], TiO_2/SiO_2 composite thin films were deposited on a photovoltaic module by sputtering to increase the generated electrical power through self-cleaning. It was shown in [113] [154] that such coatings have little effect on the module's ability to absorb radiation and their ability to clean the surface is directly related to the climatic conditions.

Photocatalytic coatings are well compatible with hydrophobic and hydrophilic coatings. Such combinations are used to protect solar modules in countries with humid climates but are not effective in countries with dry climates. Water droplets formed by photocatalysis evaporate before cleaning occurs, which is more likely to lead to cementations.

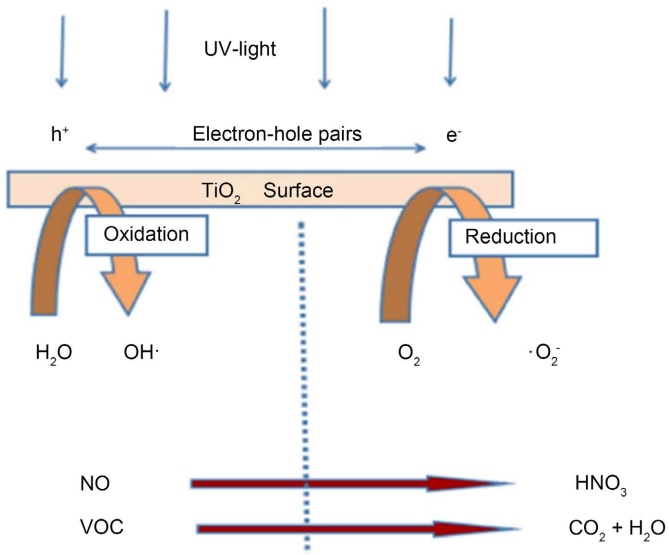

Figure 4. Principle of photocatalysis [150].

In addition, coatings containing TiO_2 are considered promising because they can contribute to the cleaning of air near PV plants by photocatalytic oxidation of gaseous pollutants such as volatile organic compounds and NO_x nitrogen oxides [51] [52] [155].

3.2.4. Coatings with Antistatic Effect

Coatings with antistatic agents can also be used to clean modules from dust deposition. An antistatic agent is a compound used in the treatment of materials or their surfaces to reduce or eliminate the buildup of static electricity, usually caused by triboelectric effects.

An antistatic agent can be a conductor. Its role is to make the surface or the material itself non-conductive. Indium tin oxide can be used, for example, as a transparent antistatic coating. Other possibilities are conductive polymers and graphene. The antistatic agent can also be a surfactant: its role is to absorb moisture from the air. Molecules of this type of antistatic agent have hydrophilic and hydrophobic parts; the hydrophobic side interacts with the surface of the material, while the hydrophilic side interacts with moisture in the air and "captures" water molecules.

In photovoltaic cells, antifouling effect can be achieved by containing tin oxide and platinum (**Figure 5**). Tin oxide has many free electrons, which reduces the electrical resistance. The low electrical resistance of the surface prevents the attraction and adhesion of fine dust and particles hovering in the air. In [151] and [152] antistatic coating, together with hydrophilic and photocatalytic effect is used to effectively remove almost all dust particles. This coating also contains platinum. This superconducting metal enhances the effect of tin oxide. This antifouling effect also works for inorganic contaminants such as exhaust gases, coal ash, yellow sand and iron powder which cannot decompose the powder, and which cannot be decomposed by the photocatalyst [152].

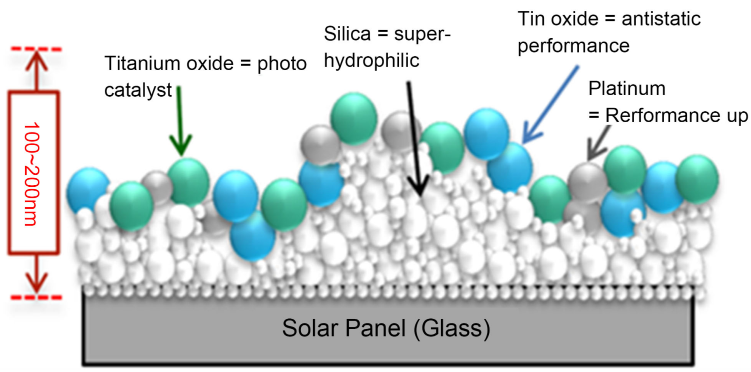

Figure 5. Coating structure on the surface of the solar module [152].

However, the use of platinum to enhance the efficiency of such a coating makes it expensive. An alternative to this approach could be a coating based on electrically conductive polymers.

3.3. Active Cleaning Methods

Under active methods of cleaning the surface of a solar module are considered methods in which external intervention is necessary. This kind of intervention can be natural, mechanical, or manual.

3.3.1. Manual Cleaning Methods

Manual cleaning methods are the most affordable and common methods of cleaning photovoltaic modules. Their efficiency does not depend on natural conditions and are often used as complementary to natural cleaning methods. The frequency of such cleaning is inflated by the time of year and location. In [156], the authors suggested cleaning once a week during dry periods and daily washing in cases of heavy dust accumulation to increase efficiency.

Various tools and methods are available for cleaning the photovoltaic panel manually by the operator. A cleaning kit is the most common manual cleaning tool that includes several extension poles, carrying bags, brushes, rags, hose connections, and more. Many companies manufacture brushes and hoses for solar panel cleaning, and they can be easily found in the market [157].

This method cleans the panel effectively, but as the size of the solar power plant increases, manual cleaning becomes impossible as it increases the operational cost and requires a lot of labor. In addition, manual cleaning often scratches the coating, which in turn leads to lower efficiency.

Usually, simple water is used to clean the modules by manual method [131]. However, in case of long time between cleaning, dust spots accumulate as residues, forming firmly adhered dust layers that cannot be removed without mechanical cleaning with detergents [158].

3.3.2. Mechanical Cleaning Methods Using a Robotic System

The robotic system is the most used technology compared to all other technologies discussed above because it has a wide range of applicability in both small and large PV systems. The robotic system consists of activators, actuators, gears having a specific motion over the module surfaces and is a virtual operator that cleans the module even much better than manual cleaning. Advances in 3D printing, nanotechnology are helping to create very sophisticated robots that can work as efficiently as a human does [157].

Recent developments in automation are making the cleaning job even easier so that the complexity between the robot and the operator is reduced. The integration of automation into a robotic system has given the robot the ability to make its own decisions and perform actions when needed, reducing human-machine interaction time and humanitarian assistance throughout the cleaning process. The use of microcontrollers and programmable logic controllers to facilitate the photovoltaic panel cleaning process can be seen in most cleaning robots [155] [159].

A disadvantage of robotic cleaning system is the uses a fraction of the energy produced. In addition, small grains of sand can become lodged in the mechanism and scratch the surface, resulting in reduced efficiency. An additional disadvantage of a robotic system is the need to replace various parts, which increases the cost of this technology.

3.3.3. Tracking Cleaning Methods

Tracking refers to the automated change of the tilt angle of a solar module. Usually, the tilt angle is changed during the day to ensure optimum module performance based on solar radiation. Changing the angle affects not only the efficiency of the module but also its cleaning. Studies [160] have shown that cleaning combined with tracking can increase the efficiency of a solar panel by 50%.

Variable tilt angles in solar systems using tracking can make more convenient the cleaning role of gravitational forces or natural cleaning agents to remove settled particles from the surface of collectors [5] [110] [131].

The efficiency of tracking cleaning can be improved by using robotic cleaners as they move unrestricted over a given surface and a large area can be scanned with a single robot [161].

The main disadvantage of tracking cleaning is the wear and tear of the mechanisms required to move the module and the energy required for this movement and tracking the sun.

3.3.4. Mechanical Cleaning Methods Using an Electrostatic Field

Dry dust can be controlled by applying an appropriate electric field to the dust particles on the surface of the module. This dust particle charging phenomenon is an electrostatic concept in which charged dust particles are bound together to form a standing wave type electric curtain, such that at any point there is an electric field with amplitude and direction oscillating at a given frequency. The frequency of oscillation is set so that the dust particle moves along the electric field line to one of the edges of the module, thereby cleaning the surface. Uncharged particles that have not had time to form an electric curtain are soon charged by the polarization or electrostatic induction process and hence removed from the module [51]. The electrodynamic shield is one type that utilizes the same principle of standing wave type electric current. Instead, a high-voltage three-phase electric current source is used to generate a traveling wave with strong forward energy [52].

This cleaning mechanism requires a dry surface of the surface module, which will avoid any binding of dust to the module based on vapor. dust particles to the module, and it has been suggested that such systems can be used where humidity is extremely low, and precipitation is almost negligible.

According to a study [51] [52] [53] conducted on concentrated solar power plants, it has been reported that their applicability is limited to locations where the relative humidity is less than 60%, and such a system is expected to have 90% efficiency in recovering the reflectivity lost due to pollution. Air humidity can also affect the performance of module cleaning using electrostatic field due to dust cementation and destruction of electrostatic charge carried by dust particles [81].

In studies [162], it was similarly shown that the efficiency of dust removal from the module using an electrostatic field decreased as the dust particles remained on its surface longer.

Unlike other methods commonly used to clean solar surfaces, electrostatic field cleaning technology is an active and automated cleaning method that does not require water or manual labor [89] [163] [164]. This cleaning system is effective in deserts, in space, and on other planets. However, it uses part of the electricity produced by solar modules, which reduces its efficiency.

3.3.5. Mechanical Cleaning Methods Using Vibrations

Recently, vibration-based panel cleaning methods have been gaining popularity [165]. In this method, vibration modules are placed under the photovoltaic cells. They drive the entire surface and roll the dust particles. This method also increases the effectiveness of hydrophobic coatings for module cleaning.

Although no studies have been conducted to date on the effect of this cleaning method on the structure of the solar module, it is implied that it may reduce its lifetime. This is justified by the fact that vibrations can accelerate the growth of defects and micro cracks in the structure.

3.3.6. Mechanical Cleaning Methods Using Water

Currently, water-based cleaning methods are the most used for cleaning solar collectors [131] [166] [167]. Water is sprayed over the module surface periodically or on the signal of sensors checking the degree of surface contamination. This cleaning method is usually enhanced by a hydrophobic or hydrophilic coating. In addition to cleaning, it helps to cool the solar module, resulting in higher efficiency.

Summarizing the most effective cleaning methods, washing by spraying purified water is the most effective cleaning method [168]. However, this method requires a large amount of water, which is rare in countries with dry climates [169].

3.4. Comparison of Cleaning Methods

The diversity of dust and the multitude of factors influencing its deposition have given rise to a variety of cleaning methods for photovoltaic cells. Choosing the most suitable cleaning approach requires careful consideration of the operational area's climatic conditions and the specific characteristics of the encountered dust. In this context, Table 1 systematically outlines the respective advantages and disadvantages of the various cleaning methods.

Table 1. Advantages and disadvantages of solar module cleaning methods.

Method	Type	Advantages	Disadvantages
Rain	Natural	- Highly effective - Does not require additional costs - Increases the effectiveness of passive methods	- Not predictable as it depends on climatic conditions - Rare in promising regions
Dew	Natural	- No additional costs	- Can leads to cementation - Possible corrosion of the module - Low efficiency in dry regions
Snow	Natural	- No additional costs	- Lowers transmittance - Can damage the module
Wind	Natural	- Effective on coarse dust	- Ineffective on fine dust
Hydrophobic coating	Passive	- Increases the effectiveness of climate-controlled cleaning methods - Compatible with water-assisted cleaning - Avoids cementation - Increases transmittance	- Short lifetime
Hydrophilic coating	Passive	- breaks down grouting - increases the effectiveness of rain cleaning methods	- Enhance dust deposition
Photocatalytic coating	Passive	- Does not need a water source - Decomposes contaminants	- Does not work in dry hot region
Antistatic coating	Passive	- Reduces dust accumulation	- High cost
Manual cleaning	Active	- Efficient cleaning - Can be monitored and adapted depending on the type of contamination	- High labor costs - Risk of scratching the surface of the module
Robots cleaning	Active	- High efficiency - Suitable for all plot sizes - Automatic adaptation - Reduces the need for labor	- Use of part of the energy produced to operate the robots - Risk of scratching the surface of the module - Wear and tear of parts
Tracking cleaning	Active	- Improving the efficiency of natural cleaning methods	- Parts wear
Electrostatic cleaning	Active	- Effective in dry climates - Can be used in environments without water such as space or other planets	- Use of part produced by energy - Does not work in humid environment due to cementations
Water cleaning	Active	- Efficient cleaning - Lowering of module temperature - Dissolution of grouting	- High demand for water resources
Vibration cleaning	Active	- Increases the efficiency of hydrophilic cleaning	- Possible damage to the module

The effectiveness of each cleaning method is a crucial parameter, evaluated in conjunction with the economic feasibility of implementation and its impact on the structural integrity of the photovoltaic system. This comprehensive analysis provides insights into the multifaceted criteria influencing the selection process.

The ranking presented in **Table 1** encompasses not only the efficacy of the cleaning methods in mitigating dust deposition but also considers their cost-effectiveness and their influence on the structural integrity of the photovoltaic system. By critically examining the advantages and disadvantages within the context of these key considerations, this section aims to guide practitioners and researchers in making informed decisions tailored to the specific operational environment of photovoltaic installations.

4. Conclusions

The implementation of cleaning methods in the realm of photovoltaic installations proves to be a crucial strategy, providing substantial benefits from both an energy efficiency and structural preservation standpoint. In some cases, the use of only one cleaning method is not sufficient. Such a phenomenon, for example, is observed in the case of cementations, where a combination of cleaning methods with water, passive cleaning methods and cleaning with robots or vibrations is effective for cleaning.

In regions most conducive to solar energy, where the efficacy of water-based methods is undeniable but hindered by excessively dry climates. So, it is necessary to develop water-free, passive cleaning methods emerges as an unavoidable necessity. Conversely, humid climates offer a conducive environment for systems capable of preventing or dismantling cemented deposits, with photocatalytic coatings emerging as a promising avenue.

The continual evolution of existing cleaning methods, geared towards increased efficiency and reduced operational costs of solar modules, reflects the industry's ongoing commitment to promoting ever more effective technological solutions. This pursuit of efficiency and cost-effectiveness speaks to the broader goal of maximizing the performance and sustainability of photovoltaic systems on a global scale.

In summary, the judicious adoption of cleaning methods proves to be a pivotal lever, propelling energy efficiency forward and preserving the structural robustness of photovoltaic modules. This occurs within the framework of a comprehensive vision aimed at securing the future of solar energy in the context of a sustainable energy transition.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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