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Review Article

Soiling mechanics of solar photovoltaics: A review

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ABSTRACT

The widespread deployment of solar energy, while promising sustainable and renewable power generation, is affected by various factors, with soiling being a significant concern. This review provides an in-depth exploration of the complex mechanisms underlying the soiling of solar photovoltaic (PV) surfaces, which has become a pressing concern in the face of the rapid expansion of solar energy deployment worldwide. The deposition, accumulation, and detachment processes, including rebounding, resuspension, and cementation, are examined in detail, highlighting their interplay with various environmental factors and installation parameters. Emphasis is placed on the critical role of airflow dynamics, such as wind speed and direction, in influencing soiling rates and adhesion forces. Moreover, the impact of geographical location and climatic conditions on soiling mechanisms is thoroughly analyzed, considering factors like dust particle characteristics, surface roughness, and moisture content. Although research has advanced understanding, comprehensive studies integrating all soiling variables are still needed, highlighting the need for further investigation.

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INTRODUCTION

The deployment of alternative renewables is growing exponentially in response to energy security issues. Solar energy is among these renewables, with large installations being established each year at a scale of gigawatt capacity. Solar energy, particularly through photovoltaic technology, is a key sustainable and cost-effective alternative to fossil fuels for generating clean energy [1, 2]. However, soiling of solar photovoltaic (PV) and thermal surfaces has become a major area of concern, particularly because regions with high-quality solar irradiance also tend to experience significant dust prevalence. Dust accumulation on solar collector surfaces is increasingly worrisome due to its detrimental effects on the performance and reliability of solar PV and thermal collectors. Initially neglected, soiling has garnered attention as studies increasingly recognize its significant impact on performance, shifting focus from only studying the reliability, efficiency, and costs [3].

The increasing installation of solar photovoltaic (PV) and thermal collectors has highlighted soiling as a major threat to their performance. The impact of soiling is dependent on several factors, including the installation location, environmental conditions, installation geometry, as well as the chemical and physical properties of dust particles. Additionally, in analysing soiling, it is crucial to consider

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variables including dust particle size distribution and surface roughness [4]. The distribution of dust particles and pollutants varies globally based on regional conditions and the specific location influences the type and quantity of dust present [5]. Contaminants such as dust from agricultural and industrial emissions, plant debris, pollen, fungi, bird droppings, algae, mosses, bacterial biofilms, and mineral dust deposits are examples of location-dependent particles that can obstruct and scatter sunlight, thereby impacting the overall efficiency of solar photovoltaic (PV) cells [6]. Regions experiencing extended dry spells are more susceptible to adverse effects compared to those with frequent rainfall. Similarly, areas with high dust particle concentrations face increased risks of soiling and consequent power reduction. Humid and cold areas exhibit the lowest dust levels. Conversely, humid environments, common in many European and North American nations, experience soiling that can reduce power generation by up to 25% [7]. In contrast, arid regions with elevated PM_{10} concentrations, such as those in the Middle East and North Africa (MENA), and some parts of India and China, possess significant photovoltaic (PV) potential but face considerable soiling losses of up to 70% [7–10].

The installation geometry is another crucial factor influencing the soiling of solar panels. Panels located near the equator require a low tilt angle (approximately 0°), making them more prone to dust accumulation. Conversely, panels situated farther from the equator, such as in Europe, require a higher tilt angle, rendering them less susceptible to soiling [11]. For instance, Enaganti et al. [12], examined the impact of dust accumulation on surfaces with low-iron glass positioned at three different angles: vertical, horizontal, and the local tilt angle. Their results indicated a strong dependency of dust deposition on the tilt angle.

Environmental factors such as wind speed and dust particle characteristics are critical in the dust deposition process on solar PV surfaces, with wind serving as a mediator for dust transport [13]. Larger dust particles and higher dust density significantly increase deposition rates [14, 15]. Analyzing the impact of wind speed on dust deposition is complex, as factors such as dust particle size and density also play significant roles. However, general observations indicate that higher wind speeds are associated with reduced deposition, whereas lower wind speeds tend to enhance deposition [16]. The accumulation of dust on solar PV panels can be influenced by the direction of the wind. Consistent wind in one direction may lead to uneven dust accumulation, with one side of the panels accumulating more dust than the other [17]. Both wind speed and direction affect the amount of dust settling on PV surfaces, and the dispersion of dust across the solar PV surface is primarily determined by wind direction [17, 18].

Soiling on solar collectors causes significant performance losses, particularly in arid regions and other areas with prolonged periods of dry weather. These regions are characterized by airborne dust and minimal precipitation, aggravating the dust buildup on solar panels thereby diminishing their efficiency [19]. To qualify as a dust particle for soiling purposes, the particulate matter should have a diameter of less than 500μm [20]. The deposition of dust particles on the PV surface creates an obstruction that diminishes the incident sunlight reaching the solar cells, thereby lowering the total energy output of the PV system and resulting in reduced efficiency in power generation [21]. Moreover, the presence of dust alters the temperature of PV modules, elevating operational temperatures. This thermal effect exacerbates efficiency reduction, given that PV cells generally exhibit superior performance under cooler operating conditions. In some circumstances soiling has been reported to actually reduce performance in PV systems by up to 70% [22, 23].

Three main processes occur when a dust particle interacts with a collector surface: deposition, accumulation, and detachment [24]. Deposition refers to the process where dust particles make contact with the collector surface. Accumulation occurs when these particles remain on the surface after some particles have detached. Detachment involves two actions: rebound, which is an immediate particle detachment after deposition, and resuspension, which is the detachment of particles after some residence time on the collector surface. Dust accumulation on solar panels occurs due to the adhesion of dust particles to the panel surface, influenced by various forces acting between the dust particle and the panel. These forces include gravity, capillary, van der Waals forces, and electrostatic forces [25, 26]. Gravity pulls particles towards the panels, van der Waals forces attract particles due to molecular interactions, electrostatic forces arise from charge imbalances between particles and panels, and capillary forces can draw moisture and dust together, enhancing adhesion and accumulation of dust particles on the surface over time.

In the solar PV industry, soiling is primarily correlated with performance losses in solar panels, typically interpreted in terms of reduced transmittance resulting in a drop in generated power [27, 28]. Literature has shown that the performance loss attributed to soiling is directly proportional to the amount of soiling on the collector surface. This accumulation lowers the optical performance of the collector surface, consequently diminishing the energy harvested from the solar system [20, 29]. In this study, unless specified otherwise, the term «surface» is used to refer to both solar PV and solar thermal collector surfaces. Furthermore, soiling is the buildup of dust and other unwanted particles on these solar surfaces.

Figgis et al. [27] reviewed literature on soiling mechanisms in desert regions, with a particular focus on research conducted in Qatar. However, findings from studies conducted in desert environments may not be directly applicable to other climates. Therefore, it is crucial to offer a comprehensive review of soiling mechanics with a broader scope, encompassing regions that experience soiling in different ways compared to desert environments. Moreover, recent advancements in the PV industry have revealed that the balance of adhesion forces differs significantly from the conventional understanding due to the high system voltages present in the contemporary solar systems. Modern solar PV power plants with high system voltages have shown an increase in electrostatic forces affecting dust adhesion on solar panels due to the high system voltages involved. Recent research highlights that these electrostatic forces generated by solar panels› high voltages can be 1 to 2 orders of magnitude stronger than both van der Waals and capillary forces in attracting and adhering dust particles [30]. Consequently, in contemporary studies, the adhesion forces that previously prevailed as the primary factor in solar surface soiling are no longer dominant in certain circumstances. For instance, Moutinho et al. [3] emphasized that while electrostatic forces may appear not as important as capillary and van der Waals forces in theoretical computations, the scenario differs in real-world conditions. In environments where PV systems are subjected to elevated voltages, the electrostatic forces generated may surpass the combined magnitude of both Van der Waals and capillary forces. Given the variability of soiling mechanics, which is situational, it is imperative to explore different soiling mechanisms while considering the factors unique to each situation examined in the study. Previous research has confirmed that the fundamental physical understanding of adhesion has been explored. However, there still remains a gap in solar PV applications where the adhesion mechanism has yet to be fully explored, as noted by studies [31, 32].

In the past decade, critical work aimed at understanding soiling processes has been reported [32]. Clarity and thorough analysis are necessary regarding the impact of variables affecting soiling mechanisms on solar collectors. For example, certain studies have suggested that due to oversimplification by theoretical approaches, there is inconsistency in assessing the impact of relative humidity. Furthermore, clarity is also needed regarding dust deposition processes, as some reports present conflicting information on the role of surface roughness. Moreover, there is a need for clarity regarding dust deposition processes, as certain reports present conflicting information on the impact of surface roughness, particularly when terms like «smooth» or «rough» are employed. While some studies suggest that surface roughness encourages dust deposition, leading to greater accumulation on such rough surfaces compared to smooth surfaces [33], others indicate that rough surfaces may experience lower adhesion forces compared to smooth surfaces [34]. Therefore, a more thorough analysis is necessary to consider the relative differences in surface roughness and the size of dust particles under study. The concept of true contact area becomes crucial in understanding the adhesion between particles in such contexts [34]. For instance, when a small particle is deposited on a surface with high roughness where the asperities are larger than the particle itself, it becomes trapped and deposited, regardless of whether the surface appears visually «smooth» or not. Conversely, if the dust particle exceeds the size of the surface asperities, the adhesion forces are reduced, resulting in less expected deposition.

The current study aims to review literature concerning the mechanics of solar collector soiling across diverse environments, including arid, semi-arid, tropical, sub-Saharan, and other areas where such reviews remain limited. Special attention is given to understanding dust particle deposition, accumulation, and adhesion. The study explores various adhesion mechanisms on solar surfaces of different types and surface textures. Previously, fewer studies were conducted on this topic, often focusing on a single climatic area. However, there has been a noticeable increase in research efforts in recent years, resulting in a wealth of new knowledge and insights. There are questions about whether deposition and adhesion have the same meaning or if they are technically different. Furthermore, this study seeks to offer clarity on the use of these terms as they pertain to soiling mechanisms.

IMPACT OF SOLAR COLLECTOR SOILING

The phenomenon of dust buildup on solar panels causes a reduction in the transmission and absorption of sunlight, thereby diminishing the overall energy output of photovoltaic systems [35]. When solar irradiance encounters a dust particle on a solar panel, some of the irradiance is either reflected or absorbed by the dust particle, resulting in losses in transmittance and reducing the total irradiance reaching the solar cell. Studies indicate that these transmittance losses, influenced by factors such as exposure duration and natural events like dust storms, typically range from minimal levels, approximately 2% to 10% [36, 37], to significant levels, potentially reaching up to 80% [8, 9, 38].

Dust particles, comprising organic matter, hydrocarbons, metals, fibres, and oxides, directly affect the solar PV modules› power production and efficiency [39]. This decrement in energy generation arises from the obstructive nature of dust and dirt particles, which impede the penetration of sunlight onto the solar panel surfaces, consequently impinging upon the efficiency of energy conversion processes. Notably, regions characterized by arid environmental conditions experience heightened rates of soiling, exacerbating the extent of energy losses incurred [40]. Moreover, the impact of soiling extends beyond mere reduction in energy output, as it perturbs the uniform distribution of sunlight across the solar panel surface, thereby instigating disparities in cell temperatures, further attenuating the efficiency of energy conversion mechanisms. The impacts of soiling on solar collectors is summarised in Table 1 [41-46].

Table 1. Summary of the effects of soiling on solar collectors

Research findings	Reference
Dust deposits on solar PV modules can harm performance, especially in dusty, low-rainfall areas.	[39]
Dust types include fly ash, bird droppings, cement, and rice husk samples.	[39, 41]
Huge transmittance and efficiency losses up are encountered due to soiling.	[42]
Soiling results in an inverse relationship between efficiency, solar irradiance, and module temperature.	[39]
Increasing the particle quantity amplifies the deposited weight, consequently diminishing transmittance.	[43]
Frequent cleaning is required to reduce efficiency losses.	[39, 40]
In the dust correlation models, future studies should take into account the effects of rain, dust patterns, and soiling ratio factors.	[39]
Although less recognized, dust plays a significant role in influencing the performance of PV installations. Although it is less well known, dust has a significant impact on PV generation performance.	[20, 44]
Soiling reduces PV collector module temperature.	[45]
Hard shading due to bird dropping, leaves and dirt patches have a severe negative impact on PV performance.	[42]
Rainfall primarily cleans larger dust particles but it has minimal to no effect on smaller dust particles	[9, 46]

Soiling in solar PV systems not only reduces efficiency and impacts cost-effectiveness over the lifespan but also leads to reversible optical losses and permanent degradation of both PV modules and CSP collectors [28, 47]. Soiling in solar PV systems results in several long-term effects, including the formation of a permanent cemented dust layer, hot spots, and corrosion. This soiling can irreversibly damage solar panel surfaces and significantly reduce the lifespan of system components. Additionally, it can cause permanent degradation of PV modules and mirror materials, along with reversible optical losses. Omitted cleaning can lead to practically irremovable cemented dust layers, lichens, and fungi, while harsh cleaning methods can scratch or abrade anti-reflective coatings (ARCs) or corrode glass surfaces [48, 49].

Under partial shading caused by soiling such as bird droppings or leaves, unshaded cells are constrained to operate at the shaded cell›s current level, which forces current through it leading to the formation of hot spots. This causes accelerated aging of the surrounding materials like the encapsulant and backsheet, diminishing the panel›s lifespan [50] and potentially compromising both panel safety and installation integrity. Efforts should be made to reduce uneven soiling and both preventative and corrective maintenance methods should be considered to prevent hot spots from significantly impacting the system.

Environmental conditions significantly influence the energy output of PV systems, contributing to various forms of degradation including corrosion, discoloration, delamination, and breakage [51–53]. Corrosion degradation, a long-term concern for solar panels, often arises from abrasive actions such as sand particles scratching surfaces during dust storms or improper cleaning methods. Alternatively, chemical bonding of particulate matter over time can also lead to damage during removal efforts. For example, Piliougine et al. [54] analyzed the degradation of single-crystalline silicon modules over 21 years in the field in Spain. They found that the PV power degrades annually by 0.9%. The study attributed this degradation primarily to a significant increase in series resistance caused by corrosion in the bus bars and interconnection ribbons.

The long-term effects of soiling on solar panels can have economic implications that potentially diminish the effectiveness of solar PV energy over time. Reversible soiling can reduce overall power generation by up to 80% [55]. Studies have shown annual global economic revenue losses ranging from 4 to 7 billion Euros [28] due to soiling. Permanent damage can lead to partial performance or complete destruction of the power plant. For example, while discoloration may decrease power generation, it typically does not halt it entirely, whereas aging and hotspots can render the solar installation unusable, resulting in significant investment losses [56].

Soiling Mechanics

The mechanisms underlying dust deposition and resuspension on solar collectors primarily depend on airflow characteristics which are impacted by the installation geometry on the collector surface [24]. For a comprehensive analysis of the soiling mechanisms of solar collectors, it is essential to examine each individual variable and assess its contribution to soiling. However, analysing soiling in outdoor conditions poses significant complexity, particularly when utilizing computer simulations, given the variability of environmental conditions, which are location-dependent. Figure 1 illustrates the main cycles of the soiling mechanism on solar photovoltaics [57].

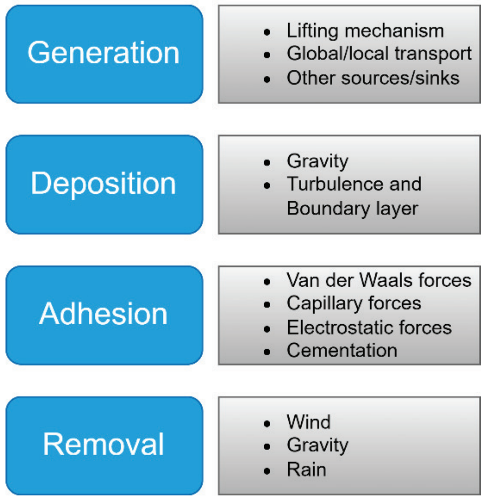


Figure 1. The four primary stages of soiling mechanisms on solar photovoltaics include dust generation, deposition, adhesion, and resuspension [From Picotti et al. [57], with permission from Elsevier].

In the absence of wind, soiling primarily depends on gravity and is proportionate to the collector›s tilt angle›s cosine [27]. On the other hand, studies conducted in desert environments have shown that all deposited particles on a surface may be detached when wind speeds of at least 4m/s are experienced [58].

During the soiling process, influenced by factors such as location, environmental conditions, installation geometry, and the chemical and physical properties of dust particles, gravity and inertia play primary roles in depositing large particles with diameters in the order of tens of microns, while turbulent deposition is characteristic of smaller particles. After deposition, dust adhesion depends primarily on various adhesion mechanisms including gravity, electrostatic forces, capillary action, and van der Waals forces, which maintain persistent contact between particles and the surface [59]. Additionally, there exists a threshold corresponding to a specific minimum quantity of dust deposition known as the dust deposition density on the solar surface, beyond which further deposition may not lead to significant additional performance reduction. The buildup of dust particles, where some settle on top of others, contributes to the deposited mass without necessarily causing further performance loss beyond this threshold [60].

Effect of Installation Geometry

Solar installation geometry holds significant importance in soiling and factors such as fixed or tracking installation, tilt, orientation relative to wind direction, and wind speed define the installation geometry. Gravity›s impact on deposition is largely influenced by the collector tilt angle [61, 62], whereas inertial deposition and particle detachment are affected by both the tilt and orientation (azimuth) of installation. At high tilt angles, rebounding is a common characteristic that minimizes dust settling on the solar collector surface. Sites with higher wind speeds and greater module tilt angles observe a lower deposition rate, leading to a smaller impact on the reduction in performance [63]. This phenomenon could be attributed to the following factors: when the tilt angle is high, more wind turbulence is created on the surface, which tends to accelerate wind speeds around the solar panel. This increase in wind speed, combined with the influence of gravity on steep surfaces, leads to reduced deposition as particles rebound or resuspend, resulting in lower overall dust accumulation on the PV surface. Additionally, a low tilt angle avoids partial natural cleaning caused by the sliding of larger dust particles on a slope [64]. In addition, when a solar panel faces away from the wind, less deposition occurs due to the lack of direct interaction between dust particles and the surface. Tracking solar systems on the other hand experience

Table 2. Summary of impact of installation geometry

Installation Parameter	Impact	Reference
Tilt (°)	• High tilt angles reduce soiling while lower or horizontal tilt angles increase soiling. • Tilt angles close to vertical configurations promote deposition through diffusion, characterized by fine particles.	[27, 65]
Orientation/ Azimuth (°)	• Tilting towards the wind direction results in more dust deposition. • Due to the three-dimensional air flow, it is more difficult to analyse the impact of orientation with regard to wind direction.	[27, 61]
Height (m)	• Dust concentration exponentially decreases with altitude. • Installation at high altitudes significantly reduce dust deposition while installations close to the horizontal position increase soiling.	[29, 33, 66, 67]
Tracking	• Tracking configurations experience less soiling compared to non-tracking configurations	[46, 65]
Multiple arrays	• Front rows experience more soiling than rows located at the back.	[68]

reduced dust accumulation due to the facilitation of gravitational forces and natural cleaning mechanisms, like wind and rain, which effectively remove deposited dust from the solar collector surface. The impact of installation geometry is summarised in Table 2 [65-68].

Sedimentation is the primary soiling mechanism in calm conditions, with soiling mass proportional to the tilt angle›s cosine [27, 61]. Sayyah et al. [29] found that gravitational pull is proportional to particle diameter, causing larger particles to deposit at higher velocities at lower (or horizontal) tilt angles. For small particles, as the tilt angle increases, the particle›s angle of incidence also increases, deviating from the flow streamlines and causing deposition [24]. In another study, dust deposition distribution on a collector surface was analysed by Figgis et al. [24] and they showed that between 0° and 10°, deposition increases with distance from the leading PV edge, while at higher tilts, it gradually decreases, shifting maximum deposition closer to the leading edge of the collector surface.

Figure 2. Uneven soiling observed on a PV array in Doha, Qatar, influenced by prevailing north-westerly winds. The north and west-facing sides of the PV array show distinct patterns due to the sweeping effect of these winds [From Figgis et al. [27], with permission from Elsevier].

Impact of Wind Direction and Speed

Wind effects on solar collector soiling are complex, with wind playing a dual role of both depositing and removing dust particles from solar collector surfaces [27]. There are indications that stronger winds have a cleaning effect compared to slower wind speeds, which favour more deposition [33]. This is because particles typically adhere to the surface when striking at low speeds. Conversely, high wind speeds force dust particles to impact surfaces, resulting in plastic deformation and increased adhesion force, which depends on the particle type and chemical composition.

The effects of wind are considered in relation to other variables influencing soiling. Windy weather implies more dust carried by the wind, increasing the probability of dust settlement depending on wind speed. While low-speed winds facilitate dust settlement, high-speed winds have the opposite effect by blowing off dust and aiding in cleaning [64]. This is attributed to the turbulent nature of high wind speeds, which accelerates wind speeds around the solar panel, inhibiting deposition. Additionally, high wind speeds can resuspend previously deposited particles, further reducing overall dust accumulation. Particles suspended in turbulent wind streams can be deposited through various mechanisms, including inertial deposition, gravitational settling, and Brownian diffusion. Fluid turbulence is a key enabler of inertial deposition, while gravitational settling typically occurs with larger particles where the influence of gravity is significant. In contrast, Brownian motion affects smaller particles, where gravity is insignificant, leading to deposition when these particles come into contact with a surface.

Despite the general conclusion that higher wind speeds increase particle deposition [69], wind speed›s impact is complex and influenced by tilt, azimuth, location, particle sizes, and density [70]. Dagher and Kandil [14] found that dust deposition rates decrease with higher wind speeds, increase with larger particles or higher densities above 2 m/s, and have a critical particle size at lower speeds, with a maximum deposition rate of 10.8% at 2 m/s and 150 µm. Wu et al. [16] noted minimal dust deposition at 1-3 m/s, reduced deposition over 5 m/s, and found that wind direction has little effect on deposition, though dust accumulation increases over time. The direction of the wind and PV surface positioning determine dust accumulation, with consistent wind directions causing more dust on one side [17]. Figure 2 shows the impact of wind direction on the soiling patterns of solar PV surfaces [27].

Jiang et al. [71] studied the wind-cleaning effect on solar photovoltaics by means of the particle resuspension theory,

Table 3. Effect of wind speed and direction

Parameter	Impact	Reference
Wind speed	• Turbulent flows are characterised by significant dust particle removal and reduced deposition. • High wind speeds up to 50m/s are ineffective in removing particles of diameter less than 50µm on a horizontal surface. • Inertia dominates deposition at higher wind speeds.	[24, 29, 63, 72]
Wind direction	• More deposition on collectors facing the wind direction.	[73]

considering hydrodynamic force, adhesion force, and rolling detachment model effects. They observed that wind effectively removes large particles but struggles to clean small particles due to the requirement for a large shear velocity for detachment. Therefore, large particles removal on a collector surface is easier due to a smaller magnitude of the required wind velocity in comparison to smaller particles. The effects of wind direction and speed are summarised in Table 3 [72, 73].

Several factors determine whether dust settles on a surface, including collector geometry, surface moisture condition, the amount of dust already accumulated, dust size, shape, elemental composition, wind speed, direction, turbulence, and numerous other factors. Inertial deposition, or sedimentation, occurs when fluid flow causes turbulent deposition of particles on the solar collector, typically for atmospheric coarse particles. Increasing flow velocity leads to rebound and hence less deposition at higher wind velocities.

Location and Dust Particle Characteristics

The geographical location greatly influences the chemistry and concentration of dust particles, notably PM_{10} levels in the environment. Understanding various particle sizes significantly affects the accuracy of deposition models and different locations exhibit distinct soiling characteristics due to variations in factors like dust particle size, shape, and chemical composition. Solid aerosols and dust particles adhere strongly to surfaces, with the bonding mechanism dependent on dust properties, contact surface area, prevailing environmental conditions, and other factors. The way dust particles and solar collectors interact is determined by several variables, including the antecedent particle charge, surface hardness, roughness of both the surface and particles, presence of organic matter or soluble salts, surface cleanliness, humidity, wind, and temperature [65, 74–76].

Experiments showed that increasing dust deposition density reduced solar system output by up to 26% as dust density rose from 0 to 22 g/m² [78]. These findings highlight that higher dust densities can lead to losses potentially reaching 70% [77]. Additionally, the tilt angle of solar panels, influenced by latitude within +/- 10 degrees, affects soiling rates, with 0° tilt accumulating maximum dust via gravitational settling [78], while higher angles aid in natural dust removal. Table 4 summarises the effect of location and dust particle characteristics [79-82].

The disparity in size, shape, and elemental composition also results in distinct light absorption and scattering characteristics [60]. According to Figgis et al. [27], the shape of dust particles is asymmetrical, contrary to the general assumption of spherical shape in soiling studies. In aerosol science, the aerodynamic diameter (d_a) is used to represent the diameter of an equivalent sphere with the same fluid mechanical behavior as the dust particle. Other quantities include the sphere of equivalent mass (d_e) and the sphere of equivalent projected area (d_{pa}). These quantities can be converted using shape information [83, 84].

Particle image analysis determines the circularity of dust particles, a geometric attribute indicating smoothness or roundness computed from equation (1), where P is the particle›s perimeter and A_p is the projected area [85]. Higher circularity values indicate uniformity, enhancing aerodynamic efficiency and longer-range transport. Lower circularity values show irregular shapes, impacting aerodynamic characteristics and dispersion patterns. Understanding dust particle circularity is therefore, crucial for understanding atmospheric dynamics and environmental processes.

Petean and Aguiar [34] found that larger particle diameters significantly increase adhesion force between powders

Table 4. Location and dust particle characteristics

Parameter	Impact	Reference
Geographical location	• Dust chemistry is determined by location. • Arid regions are characterised by sand particles.	[32, 79]
Dust particle size	• More performance deterioration is caused by fine dust particles compared to bigger particles. • Small particles are deposited by turbulent eddies. • Large particles are the primary contributors to soiling. • Larger particles result in either lower or higher adhesion forces depending on the dust particle being studied. • Large particles deposit by gravity.	[80, 81]
Dust particle shape	• Smooth particles and sphere-like shapes have a larger contact area. • Adhesion force is not affected by particle shape on rough surfaces. • Adhesion force is decreased by convex particle structures, high Young's modulus, irregular shapes, and low surface energy.	[34, 82]
Particulate matter concentration	• Increased PM_{10} levels lead to higher soiling rates. • PM_{10} is dependent on the location.	[72]

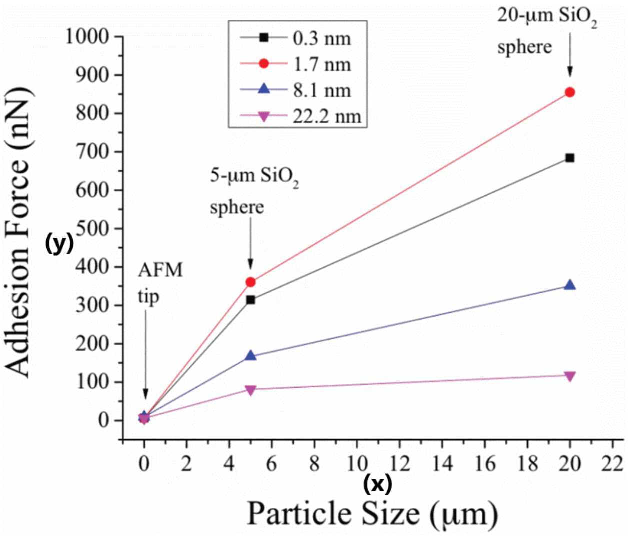


Figure 3. The relationship between adhesion force and particle size with varying collector surface roughness [From Moutinho et al. [3], with permission from authors]. The figure illustrates the relationship between adhesion force and particle size for varying levels of particle surface roughness, showing how lower surface roughness of the collector surface generally increases adhesion force for smaller particles.

and surfaces. Salazar-Banda et al. [81] confirmed that as particle size increases, adhesion force also increases and follows a log-normal distribution, highlighting the impact of dust particle size on the force of adhesion as shown in Figure 3. Dust from different locations have different elemental compositions. For instance Alnasser et al. [86], found that 50% of Iraqi dust is composed of silicon oxides, with white cement, sand, and gypsum causing the most significant loss. Similarly, Mehmood et al. [87] found higher calcium (Ca) and lower sodium (Na) levels in Saudi Arabian dust while Chen et al. [88] reported SiO_2 and $CaCO_3$ as the primary dust composition in East China. El Boujdain et al. [89] discovered that wind speed, relative humidity, ambient temperature, and dust aerosol optical depth are the main factors affecting the performance of solar reflectors, all of which vary based on location. Many studies have concluded that dust composed of materials with high carbon content has the most detrimental effect on performance reduction [90–92].

$$C = \frac{4\pi A_p}{P^2} \tag{1}$$

$$F = Cv_{d,e} \tag{2}$$

$$F = \sum_{i=1}^{n} (c_i v_{d,i}) \tag{3}$$

The deposition velocity (v_d) of dust particles depends on their size. Figgis et al. [27] proposed two equations for determining deposition velocity: one for all aerosols suspended in the air (equation 2) and one for different size ranges (equation 3). Both equations use F (kg/m^{2}s^1) for deposition flux rate and C (kg/m^3) for atmospheric particle concentration. Equation (3) is more accurate but requires specialised equipment such as the rotary impactor.

Relative Humidity, Rain and Moisture

Moisture plays a crucial role in soiling mechanics and when surfaces and materials come into contact with water, they can undergo both chemical and physical changes. These changes can include softening, phase change, and solubility, which can lead to complex adhesion behavior. The collection of dust on photovoltaic modules can be strongly impacted by the dew formation. While dew assist dust particles to surface adhesion, it can also clean the collector surface by causing dew droplets to flow to the lower edge of the collector surface. As humidity tends to increase soiling, rain can have both cleaning and soiling effects on surfaces. Rain exhibits minimal cleaning effect on micro dust particles (2–10 µm), whereas it notably cleans larger particles like pollen (approximately 60 µm) [93]. A summary of the effect of relative humidity (RH) and moisture on dust accumulation is provided in Table 5 [94-96].

As the relative humidity increases, atmospheric aerosol particles are prone to absorbing water. This means that dust adhesion is facilitated by the increased relative humidity as shown in Figure 4. The absorbed water then acts as an adhesive between the particle and the surface [94]. Relative humidity significantly affects the attractive forces between surfaces and fine particles of the order of 10µm [97]. On the other hand, Moutinho et al. [31] found

Table 5. Summary of the effect of relative humidity and moisture on soiling

Parameter	Effect	Reference
Adhesion	• Relative humidity promotes dust adhesion. • Dry conditions promote less dust adhesion. • RH is the main cause of capillary adhesion.	[94]
Rebound and resuspension	• RH suppresses particle rebound and resuspension. • Moisture does not affect particle deposition rate.	[95, 96]

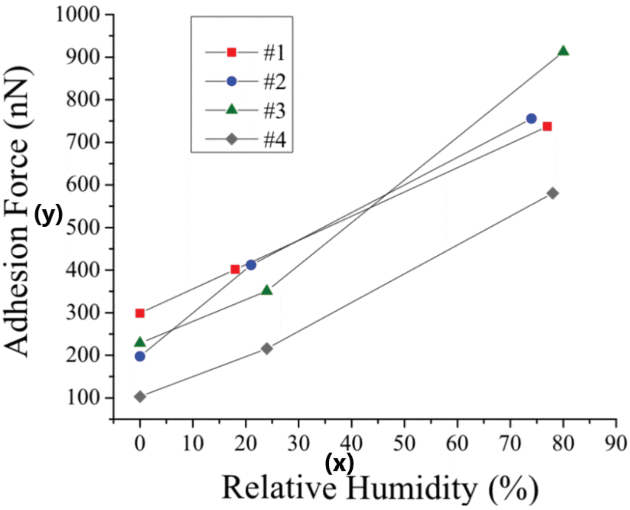


Figure 4. Relative humidity (RH) impact on adhesion force between dust particles and a glass substrate, indicating that higher RH levels generally increase adhesion force [From Moutinho et al. [3], with permission from authors].

that at lower relative humidities, van der Waal forces dominate adhesion forces, whereas higher relative humidities enhance capillary forces due to the thickness of the water layer getting sufficiently thick to cover the asperities on the surface. As relative humidity decreases, the adhesive properties between dust particles and surfaces diminish, resulting in reduced dust retention on surfaces. Javed et al. [72] reported that relative humidity and PM_{10} concentration have a notable impact on the daily change in clearness index. The daily change in clearness index drops as relative humidity increases up to 60%. High relative humidity intensifies PV soiling, as it promotes soiling rate due to gravitational settling and particle adhesion. Pouladian-Kari et al. [98] combined the effect of inverting the collectors at night with dew formation to minimize soiling. The study demonstrated that gravity can effectively remove low dust from PV collector surfaces, even with little dew formation overnight.

Collector Surface Characteristics

Surface characteristics of solar collectors depend on their optical properties and surface roughness. Flat plate collectors and PVs can use both beam and diffuse irradiance, while concentrated solar power systems use only beam irradiance. Soiling causes different efficiency losses on collectors depending on optical and roughness characteristics. Surface roughness affects adhesion forces by reducing the contact area, limiting particle-surface interaction. Adhesion forces decrease with increasing roughness, and true contact area is critical in determining particle adhesion forces [34]. Increasing surface roughness reduces capillary forces by preventing complete meniscus formation at the particle-surface contact point [99].

Studies demonstrate that asperities smaller by three orders of magnitude than the diameter of dust particle significantly lower the adhesion force to a small percentage of its expected value for smooth surfaces [100]. The magnitude of the force diminishes proportionally to the square of the distance apart, but only when roughness changes are smaller than the particle. Asperities greater than dust particles have no effect on adhesion. In the presence of adsorbed water, adhesion decreases with increasing surface roughness, particularly when the height of the asperities approaches the thickness of the adsorbed moisture film. Gorb et al. [101] investigated the impact of roughness patterns on adhesion under high loads. Their study revealed that rough walls exhibited higher adhesion forces compared to flat walls. Specifically, structures featuring pillar patterns characterized by high aspect ratios and radii demonstrated the highest pull-off forces.

$$rms = \sqrt{\left(\frac{32\int_0^r y^2 r_1 dr_1}{\lambda^2} k_p\right)} = 0.673r \tag{4}$$

$$F_{ad} = \frac{A_{12}R}{6H_0^2}\left[\frac{1}{1+\frac{R}{1.48rms}} + \frac{1}{\left(1+\frac{1.48rms}{H_0}\right)^2}\right] \tag{5}$$

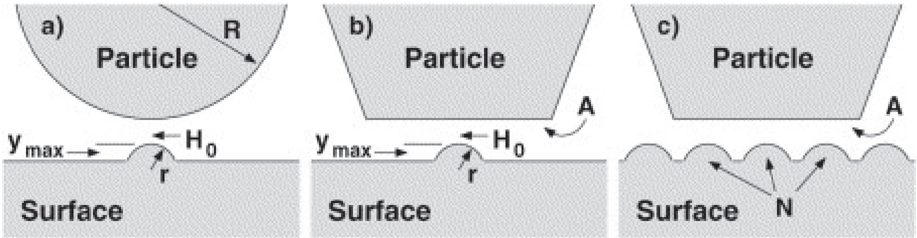
$$r = 1.485rms \tag{6}$$

$$A_{12} = \sqrt{(A_1 A_2)} \tag{7}$$

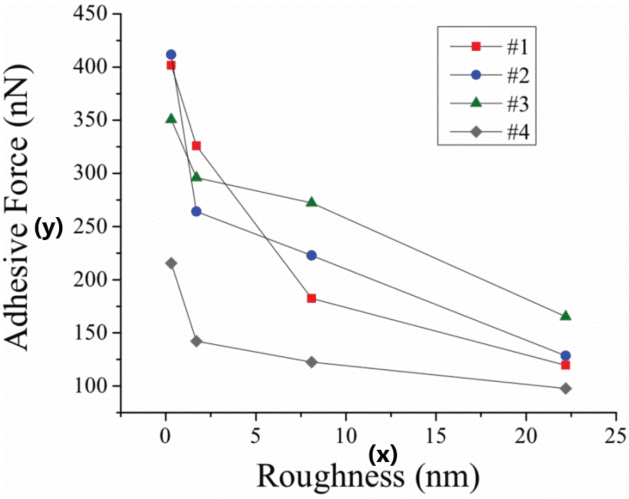
Where, $r_1 = rsin\alpha$, $y = rcos\alpha$, $\lambda = 4r$ and for close-packed spheres $k_p = 0.907$ being the surface packing density.

Table 6. Hamaker constants for dry-air outdoor materials

Material	Hamaker constant [J × 10–20]	Reference
Silica	10.38	[104]
Cementitious materials	0.1–0.9	
Basalt	11.06	[105]
Limestone	10.07–10.33	
Granite	7.33–8.42	



(a)



(b)

Figure 5. (a) Illustration of the particle adhesion to a surface asperity [From Katainen et al. [103], with permission from Elsevier]. (b) Adhesion force dependency on glass substrate roughness in which increased roughness generally decreases the adhesion force [From Moutinho et al. [3], with permission from authors].

Van der Waals forces are more impacted by surface roughness than electrostatic forces. However, in some cases, surface roughness can increase electrostatic forces if soiling occurs under dry conditions [102]. Rabinovich et al. [100] developed an adhesion model based on Rumpf's model (Fig. 5(a)) [103] that considers surface roughness and the root mean square (rms), which is a statistical approach implemented to calculate the average magnitude of the dust particle sizes, and it is calculated using equation (4). For a dry and rough surface, equation (5) is used to calculate adhesion forces. The effective Hamaker constant (A_{12}) is obtained by computing it between the materials (1 and 2) in a vacuum. The dust particle radius is R, and the asperity radius is r. The separation distance (H_0) is usually 0.3nm on nanoscale surfaces. The approximate values of A are provided in Table 6 [104, 105] and in van der Waals forces, the Hamaker constant is smaller for water than for air [106]. Figure 5(b). shows the correlation between the adhesion force and surface roughness. Mehmood et al. [87] found that dry mud on glass and polycarbonate surfaces had different frictional, cohesion, and adhesion work values. Kumar et al. [107] showed that adhesion force increases proportionally with dust particle size and decreases with surface roughness, but increases for particles smaller than the asperities.

Soiling Analysis

Soiling analysis entails studying the impacts of dust accumulation on solar thermal collectors and PV modules› performance and efficiency. This analysis encompasses various attributes, such as the characterization of dust particles, measurement of transmittance and reflectance, evaluation of temperature rise due to soiling, and assessment of power output degradation over time. Experimental studies, field observations, and computational modelling techniques are employed to accurately quantify the influence of dust on solar collectors.

Studies have been undertaken in a bid to analyse soiling on solar collectors using different approaches in different geographical locations and this has been achieved through, experimental work [108], simulations [61] and machine learning approaches [109]. The experiments have involved wind tunnel tests and outdoor experiments, while simulations have been carried out using CFD [110]. Furthermore, researchers have developed models to analyse the impact of different variables on soiling, including exposure time, dust particle size, shape and composition, installation geometry, wind speed, and direction. For example, Figgis et al. [24] conducted wind tunnel experiments to examine how tilt angle affects soiling of a tracking PV solar system. In order to reduce soiling effects in photovoltaic (PV) power plants, the study looked into the possibility of using horizontal single-axis trackers and varying the tracker tilt angle. The results show that maximum accumulation happens at a 22° tilt away from the wind, whereas maximum deposition happens at a 45° tilt towards the wind. The study suggested storing 1-axis PV trackers at their maximum tilt towards the wind to reduce soiling at night.

A study by Velásquez and Ezcurra [111] analyzed dust levels in photo-voltaic solar plants using satellite data in assessing the impact of dust soiling on a large-scale PV plant spread across 400 hectares. In a different study, Ovrum [112] presented experimental results showing a significant relationship between dust deposited on solar panels and topsoil in arid locations, with notable differences in the chemical and visual appearances of module dust and topsoil from vegetated areas. It was discovered that the amount of iron oxide, albedo, and particle size distribution all affect how much sunlight is transmitted through a layer of dust. The study proposed a standard technique for collecting and assessing dust samples at potential solar power plant locations, incorporating methods such as squeegee and water spray for dust collection, while for particle size distribution the suitable technique is the Focused Beam Reflectance Measurement (FBRM), and, ImageJ for albedo determination, and, X-ray diffraction (XRD) approach for assessing iron oxide content. These approaches can be used in model development for estimating sunlight transmission based on dust density.

Yap et al. [113] used image-processing methods to quantitatively analyze dust and dust accumulation on solar photovoltaic panels in tropical regions. The study focused on quantifying dust and solar photovoltaic (PV) soiling. Various image-processing techniques were explored, including colour histograms, statistical models, image matching, binarization, and texture matching. These techniques were applied to captured PV images to accurately quantify dust and soiling levels. The results experimentally demonstrated the suitability of the proposed methods in accurately analyzing dust and soiling and providing a valuable tool for monitoring and maintaining PV system efficiency in tropical regions. Tripathi et al. [109] investigated the PV panel performance under varying levels of dust deposition using different machine learning approaches. By quantitatively analyzing the impact of varying sizes of dust pollutants on PV panel performance, the study made use of several machine learning approaches to model and predict the degradation in PV panel efficiency. Table 7 outline the different analysis approaches used for soiling of solar collectors including Photovoltaic (PV), Concentrating Solar Thermal (CST), Concentrating Photovoltaic (CPV), Evacuated Tube Collectors (ETC) and Concentrating Solar Power (CSP) [114-128].

Table 7. Approaches used in soiling analysis

Approach	Collector type	Reference
Simulation	PV	[114–117]
Experimental	PV, CSP, CPV, ETC	[118–123]
Artificial Intelligence	PV	[124, 125]
Chemical analysis	PV	[126]
Optical or Image analysis	PV, CST	[127, 128]

Dust Deposition and Adhesion

The attraction caused by intermolecular forces between two solid substances that share a contact surface is known as adhesion [34]. When two solids are in contact, an interface is formed and they can experience adhesive forces (F_{ad}) such as capillary (F_c), electrostatic (F_e), gravitational (F_g) and van der Waals forces (F_v) as shown in Figure 6. Table 8 highlights the interdependency between surface characteristics and dust particles, and, dust deposition and adhesion force [129].

$$F_{ad} = F_c + F_e + F_v \tag{8}$$

Adhesion forces can be computed analytically using the Derjaguin, Muller, and Toporov (DMT) and the Johnson, Kendall, and Roberts (JKR) models to produce results closely matching experimental data. For instance, Petean et al. [34] computed adhesion forces as shown in Figure 7 and in the process observed that the surface energy of mica varies depending on the measurement conditions, with approximately 4500 mJ/m^2 in a vacuum and about 300 mJ/m^2 in ambient laboratory atmosphere. Their study found that adjusting the surface

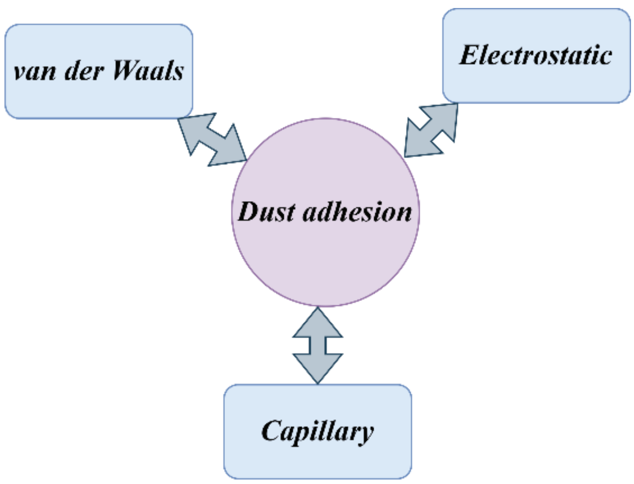


Figure 6. Forces involved in the dust adhesion mechanism include van der Waals, electrostatic, and capillary forces.

Table 8. Dust deposition and adhesion

Parameter	Impact	References
Adhesion force	• Adhesion force is the sum of F_c, F_e, F_g and F_v. • The physical and chemical qualities of materials determine the magnitude of these forces. • Small dust particles are affected by F_c, F_e and F_v. • F_g is significant for particles larger than 500 µm.	[129]
Particle and surface characteristics	• Large particles have higher adhesion forces.	[82]

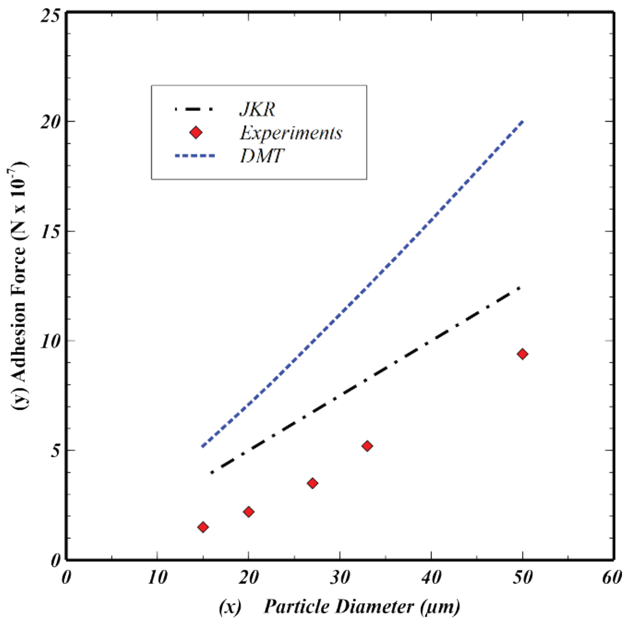


Figure 7. Comparison of the experimental results and the DMT and JKR models in determining the characteristic adhesion force vs. the particle mean diameter [From Petean and Aguiar [34] with permission from Elsevier].

energy value allowed the JKR and DMT models to produce results closely matching experimental data.

Differences in adhesion characteristics between smooth and rough surfaces have been investigated in the academic literature. Sun et al. [82] proposed a mathematical model aimed at quantifying adhesion between rough walls and particles, particularly relevant in engineering contexts. Their findings suggested that larger particles tended to contact more asperity peaks, resulting in heightened adhesion forces. Additionally, analysis via Atomic Force Microscopy (AFM) indicated a notable increase in adhesion force, ranging from 20 % to 60 %, despite a doubling of particle sizes. This phenomenon was attributed to the suppression of adhesion force in relation to wall roughness. In a similar study, You et al. [130] developed a multiscale-roughness model to calculate adhesion influenced by both capillary and van der Waals forces, drawing from the DMT and JKR models. The efficacy of these models was confirmed through validation via AFM experiments.

The deposition and adhesion of dust particles on the solar module surface adversely affect output characteristics by reducing the energy conversion efficiency [131]. Dust particles cause transmittance loss, reducing the amount of solar irradiance incident on the collector surface. Additionally, dust adhesion increases the operating cell temperature, making the soiled PV surface hotter than a clean one leading to a reduction in the energy generated [132]. Cleaning is necessary to restore proper energy conversion efficiency, but this process can leave residual detergents or scratches, potentially causing permanent degradation to the solar PV module›s performance. Implementing anti-reflective coatings, automated cleaning systems, electrostatic dust removal, improved module design, regular maintenance, and environmental adaptation can mitigate these adverse effects of dust on solar PV module efficiency.

Van der Waals forces

The van der Waals force, produced by the movement of electrons, induces attractive forces between materials in a dry environment. This force is ten times [34] stronger than the electrostatic force and is effective only at short ranges, especially for particle radii less than 50µm [33]. Van der Waals forces are dependent on distance and are active when materials are in close contact due to dipole interactions between particles or molecules [133]. Dust particles on solar surfaces create van der Waals forces due to their proximity to the glass surface.

Studies suggest that high humidity boosts dust adhesion through van der Waals forces [134] and other adhesion mechanisms dominate beyond this threshold. The van der Waals forces include dispersion, orientation, and induction forces. The van der Waals forces can be calculated using equation (9), where the Hamaker constant is A (J) and the strength of the van der Waals force is represented by A, and is dependent on the types of particulate material and the substrate in the contact medium. A can be represented by equation (10) and in air, it is typically given an approximate value of 10^{-19} J.

Isaifan et al. [99] conducted a study on the van der Waals forces in a desert environment in Qatar. The dust particles in this environment are composed of silica which contains a higher amount of calcite. For this study, a Hamaker constant of 8.45 x 10^{-20} was used for calcite particles in contact with a glass surface in air, and 1.03 x 10^{-20} in water. The separation distance was taken as 4A°. The study found that the van der Waals forces were 324nN in dry air and 39.4nN in humid air. The distance *(d)* between the particle and a surface varies from 0.35 to 0.4 if they are considered to be smooth. However, in cases where nanoscale roughness is present, d is calculated using equation (11), where σ (nm) is the surface roughness and R (m) is the radius of the particle.

$$F_v = \frac{AR}{6d^2} \tag{9}$$

$$A_{12} = \sqrt{A_{11}A_{22}} \tag{10}$$

$$d = 1.817\sigma \tag{11}$$

Capillary forces

The adhesion forces between dust particles and solar surfaces are mostly determined by capillary forces. These forces are a type of intermolecular forces that arise from the interaction between liquid molecules and a solar collector surface. Capillary forces become active when moisture is present, as water molecules establish a thin film of liquid on the glass surface, promoting adhesive forces between the dust particles and the glass surface. Research has demonstrated that van der Waals and capillary forces are highly dependent on surface roughness due to their limited range. This is due to the reduced particle-surface contact as surface roughness increases.

Van der Waals forces act on a limited number of contact points between the surface and particles, while capillary forces require more water to fill surface irregularities. Moutinho et al. [3] found that capillary forces dominate in high relative humidity but are not applicable to higher surface roughness values due to large asperities preventing the development of a continuous water meniscus. Capillary forces may still be present in dry conditions if there is a small amount of moisture on the solar surface due to condensation or cleaning.

The force resulting from surface tension (F_{st}) and the force resulting from the pressure differential between the water meniscus and the air (F_{mc}) combine to form the capillary adhesion force [31]. Studies have shown that the capillary force exhibits a direct proportionality to the particle diameter and assumes significance for diameters exceeding 10μm [135]. The capillary force between a planar surface and a spherical particle can be computed utilizing Equation (12), where R and γ respectively represent the dust particle radius and the surface tension of water-air. The contact angle of water on the substrate is represented by θ. The adhesion force and surface tension in this relationship is not linked to relative humidity, despite studies showing a correlation. This approximation is valid as long as the contact angle is minimal and the film thickness is far less than the sphere›s radius. Rabinovich et al. [97] proposed a modification to equation (12) to account for the impact of relative humidity. The new equation (13) takes into consideration the separation distance (z) and the equilibrium radius of the meniscus (r) as shown in equation (14) [97]. The latter equation uses V to represent the molecular volume of water (18.03 mL/mol), κ as Boltzmann›s constant (1.38 x 10^{-23} m^2Kg/s^2K), Na as Avogadro›s number (6.022 x 10^{23} atom/mol), T as the absolute temperature (K), and P/P_s as the relative humidity. It›s worth noting that particle adhesion on glass surfaces increases slowly with RH between 60 to 70% RH, and then increases rapidly [136].

$$F_c = 4\pi R\gamma cos\theta \tag{12}$$

$$F_c = 4\pi R\gamma cos\theta\left[1 - \frac{z}{2rcos\theta}\right] \tag{13}$$

$$r = -\frac{V\gamma}{N_a\kappa T ln\left(\frac{P}{P_s}\right)} \tag{14}$$

In their study, Isaifan et al. [99] applied the model by Rabinovich et al. [97] to investigate the dependency of capillary forces on relative humidity. They used a temperature of 29 °C and a relative humidity of 72 % and calculated a capillary force of 1951 nN using an air surface tension of 71.2 x 10^{-3} N/m and a Kelvin radius of 1.56 nm. The study found that capillary forces accounting for 95 % of the total adhesion forces was the dominant adhesion forces, while van der Waals forces contributed only 2 % under the humid conditions studied. The study also revealed that for particles smaller than 500μm, the gravitational adhesion force can be disregarded as it is negligible.

Electrostatic forces

Electrostatic forces (F_e) are also a substantial variable in the soiling of solar collectors. When dust particles collide [99] or come into contact with the collector surface, friction generates an electrical charge, resulting in the creation of electrostatic forces between the panel and the dust particles. This process causes a coulomb force [135] and makes a strong adhesion between the dust particles and the solar surface. In arid regions, the dust particles are characterized by electrostatic charges resulting from the erosion process, which contributes to the electrostatic adhesion forces [29].

Tribo-electrification is a phenomenon that occurs on non-conductive materials, especially glass surfaces, when materials become electrically charged due to frictional contact with different materials. Equation (15) computes the electrostatic force, where ε is the dielectric constant, q (C) is the dust particle charge, ε_o is the permittivity of free space, and l is the separation distance between charge centres (2R). Table 9 provides the relative permittivity of common materials encountered in soiling studies [137].

$$F_e = \frac{q^2}{4\pi\epsilon\epsilon_o l^2} \text{ [99]} \tag{15}$$

Table 9. Relative permittivity of common outdoor materials at ambient temperature [137]

Material	Relative permittivity [ε/εo]
Glass	3.7–10
Alumina	9.3-11.5
Bakelite	3.5-5.0
Calcium	3.0
Graphite	10 - 15
Silica Sand	2.5-3.5

In a study by Isaifan et al. [99], the electrostatic force of dust particles was determined using extrapolated data by Deputatova et al. [138]. The study revealed that humidity has a significant impact on electrostatic forces under experimental environmental conditions. This is attributed to the presence of moisture which effectively nullifies Coulomb attraction.

Investigations by Jiang et al. [30] explored the effect of elevated DC voltages on solar panels and their effect on dust adhesion. The findings revealed that high voltages enhanced adhesion force of dust particles by amplifying the electrostatic attraction, surpassing the strength of van der Waals and capillary forces by 1 to 2 times. Additionally, when dust particles are charged, the electrostatic force was measured to be three times stronger than the afore-mentioned forces. In another study by Jiang et al. [139], when the voltage is set at -100V, the van der Waals forces are five times weaker than the electrostatic force. This results in atmospheric dust sticking to the surface of solar PV, leading to a decline in array performance.

Gravitational force

Equation (16) provides the calculation for the gravitational force that acts upon a spherical particle and a solar collector surface. This force is determined by the dust particle's density, denoted as ρ, and the gravitational acceleration (g). Isaifan et al. [99] examined the dust density in the Qatar desert environment and determined that it was 882.7kg/m^3. From this, they calculated the gravitational adhesion force to be 0.0018nN. It is important to note that gravitational forces can cause larger particles to dislodge from the solar collector surface, particularly at higher tilt angles.

$$F_g = \frac{4}{3}\pi \rho g R^3 \quad [99] \tag{16}$$

The phenomenon of soiling can be attributed to sedimentation, inertial, and Brownian motion. The deposition caused by sedimentation is driven by gravity, while that caused by inertial motion is due to flow turbulences. The extent to which these mechanisms affect soiling depends on the ratio of viscous to inertial forces acting upon dust particles, which is determined by factors such as particle size and wind speed, as stated in reference [27]. Small particles of ≤ 1μm diameter remain suspended longer due to Brownian motion. Medium-sized particles deposit by gravity under calm conditions and by inertia under turbulent conditions [27]. Large particles with sizes of ≥100μm are primarily deposited due to gravity and tend to settle faster than smaller particles, regardless of flow characteristics.

Experimental Adhesion Force Measurement and Analytical Adhesion Force Computation

Experimental adhesion force measurement

The measurement of adhesion forces can be accomplished either experimentally or by analytical models. The use of the Atomic Force Microscope (AFM) for the measurement of adhesion forces has been widely embraced in experimental studies. In addition, methods such as the Centrifuge Technique and electric field separation have been implemented. Particles with known mass and size

Table 10. Summary of research findings on experimental force measurements and analytical force computations

Findings	References
• The centrifuge technique uses centrifugal force to detach particles from a substrate. • The centrifuge technique allows for the simultaneous analysis of several particles' interactions with a substrate.	[4, 82, 141]
• For stability purposes, the centrifuge machine's rotational speed is restricted.	[34]
• The centrifugal force in a centrifuge counteracts the direction of adhesion force, causing particles to separate from the substrate when the centrifugal force exceeds the adhesion force.	[140]
• AFM measured values are sometimes notably lesser than those calculated by the JKR model.	[142]
• AFM experiments indicate that particle adhesion could either increase or decrease due to surface roughness.	[143]
• Real surfaces possess anisotropic asperities and exhibit irregular shapes deviating from theoretical models like the DMT and JKR models.	[144]
• Analytical models have limitations as they require an estimation of surface energy, which varies and depends on the source.	[145]
• Rough wall models have been proposed to analyse non-contact adhesion for nanoscale roughness and contact adhesion for large roughness.	[146]

distribution are positioned within the centrifuge, where the centrifugal force acts to dislodge them from the substrate [140]. Angular velocity, denoted as ω (rad/s), is monitored before and after each step, while the number of dust particles remaining attached to the surface is tallied. By progressively increasing the angular velocity until all particles detach from the substrate, the adhesion force (F_{ad}) can be computed using equation (17) where s (m) is the distance between the rotor axis and the substrate, and m (kg) is mass of the particle. Table 10 outlines the key findings on experimental adhesion force measurements [141-146].

$$F_{ad} = ms\omega^2 \tag{17}$$

Analytical adhesion force computations

Analytical adhesion models have been developed in the literature, including those proposed by Derjaguin et al. [147] and Johnson et al. [148]. These models, which involve elastically deformable solids arranged in sphere-plane or sphere-sphere configurations, aim to calculate the force involved in separating the solids. Equations (18) – (21) outlines the alnaytical models where W_a is the work of adhesion, and R is the reduced radius of the two dust particles in the case of a sphere-sphere contact or the particle radius in the case of a sphere-plane contact. The work of adhesion (W_a) can be expressed using the Dupre equation, where γ_1 and γ_2 represent the surface energies of two dissimilar solid particles, and γ_{12} is computed using equation (21).

$$Fad = \frac{3}{2}\pi R W_a \tag{18}$$

$$F_{ad} = 2\pi R W_a \tag{19}$$

$$W_a = \gamma_1 + \gamma_2 - \gamma_{12} \tag{20}$$

$$\gamma_{12} = |\gamma_1 + \gamma_2| \tag{21}$$

Petean et al. [34] suggested a model to adjust the theoretical DMT and JKR values to match experimentally measured values. In their study, two materials were examined, and work values of 0.0918 J/m^2 and 0.1175 J/m^2 were reported for cellulose ester membrane and microcrystalline cellulose respectively. The model developed takes the form:

$$F_{ad} = k_m W d_p \tag{22}$$

$$k_m = k_t k_c \tag{23}$$

Where kt is equal to π for the DMT model and $3\pi/4$ for the JKR model. kc represents a correction factor used to align analytical results with experimental findings, with values determined to be 0.052 and 0.050 for the JKR model for cellulose ester membrane and microcrystalline cellulose, respectively.

Sedimentation

Figgis et al. [27] highlighted in their review that dust deposition through sedimentation occurs primarily with medium to large particle sizes under low wind speeds, while inertial deposition is associated with higher wind speeds. They also noted that the physical dust particle attributes, such as size, shape, and density, govern the sedimentation processes. The tendency of a dust particle to be deposited under the influence of gravity is characterized by its deposition velocity v_d (m/s), as shown in equation (24), where F and C are respectively the deposition flux rate to a surface (kg/m^{2}s) and the particle concentration in the atmosphere (kg/m^3). Larger particles, due to gravitational action, have higher deposition velocity values and a greater tendency to deposit compared to smaller particles. For large particles, the deposition velocity is provided by their Stokes terminal velocity v_s, given by equation (25), where ρ, g, and d, are respectively the dust particle density, acceleration due to gravity, and the particle diameter, while the dynamic viscosity of air is μ (kg/ms) [149].

$$v_d = \frac{F}{C} \tag{24}$$

$$v_s = \frac{\rho g d^2}{18\mu} \tag{25}$$

In case of small particles with the Renolds number less than 1, the Stokes regime applies. However, at certain critical sizes, transition flow regimes are experienced due to the quick falling of particles. In these circumstances, a separate terminal velocity equation is applied, and in desert regions, especially in the Middle East, where the dust particle density is 2700kg/m^3, the critical size is 60μm [27]. In most cases, dust particles on PV collectors are larger than this size and the stokes velocity is used instead. Soiling by sedimentation may be eliminated or reduced by covering or tilting the surface.

Inertia Deposition

Inertial deposition relies on airflow characteristics, including flow velocity and associated turbulence. When atmospheric airflow interacts with surfaces, such as solar arrays characterized by surface roughness, turbulence occurs. This turbulent airflow leads to a velocity component toward the surface, causing particles to eventually impact and deposit onto the surface [27].

In wind tunnel experiments, turbulence causes considerable deposition compared to gravity and other deposition mechanisms. Figgis et al. [27] highlighted in their review that inertial deposition is proportional to the frictional velocity (u*) and is characterized by higher wind speeds. Studies have demonstrated that the friction velocity (u*) and the dust particle size, are correlated to inertial deposition velocity as depicted in equation (26). Similarly, Kim et al. [150] formulated a comparable model (equation 27) for inertial deposition, wherein the flow eddy Stokes number

(S_e) serves as the exponent, exhibiting good agreement with the empirical model outlined in equation (26) where v_i is the inertial deposition velocity.

$$v_i = 1.12u^* e^{-\left(\frac{30.36}{d}\right)} \tag{26}$$

$$v_i = u^* 10^{-\left(\frac{-2.8}{S_e}\right)} \tag{27}$$

Mitigating soiling attributed to inertial deposition involves managing wind flow characteristics, which influence dust deposition. This can be accomplished by siting solar collectors in regions with favourable wind regimes or positioning them in elevated areas exposed to higher wind speeds [27].

Particle Rebound, Resuspension and Cementation

Rebound

Rebounding describes the phenomenon where a particle bounces off a collector surface and becomes re-entrained in the air immediately after deposition. This occurs when there are weaker adhesion forces between the particle and the surface, than the kinetic energy of the dust particle, leading to particle rebound [151]. Therefore, mid-sized dust particles, possessing enough inertia to separate from eddies but lacking sufficient energy that exceeds adhesive forces, are more likely to cause soiling [27]. While this concept is widely accepted, experimental confirmation is lacking according to Figgis et al. [27]. They noted that rebounding results in a decrease in the net deposition velocity, particularly for particles around 30μm in size. Figure 8 displays the projected deposition velocity of a dust particle [152], and a summary of rebound and resuspension of particles is provided in Table 11 [153].

Bateman et al. [96] noted that increasing relative humidity decreases particle rebound, with higher humidity levels associated with larger minimum rebounding particle sizes. Moreover, they found that hygroscopicity reduces rebound, with ammonia particles showing reduced rebound at 20% RH reaching the lowest rebound at 70% RH, while

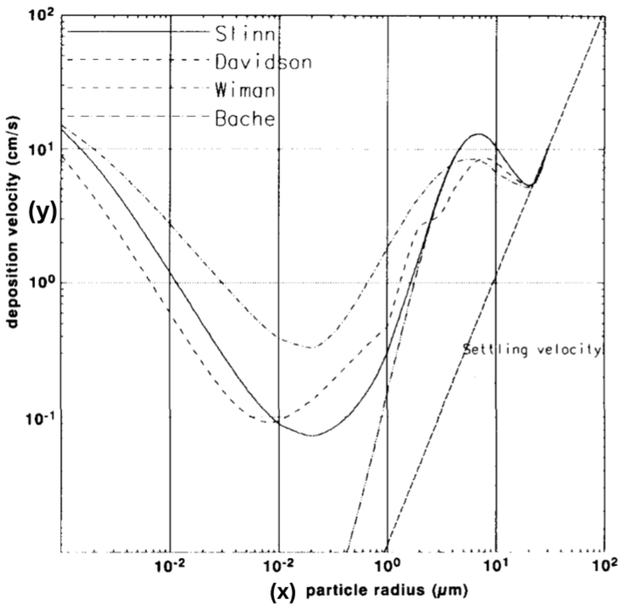


Figure 8. Predicted particle deposition velocity versus particle radius showing how the speed at which particles settle on a surface changes with particle size [From Ruijrok et al. [152], reproduced in terms of the Creative Commons CC BY license].

hydrophobic polystyrene exhibited a decreased rebound at RH above 50%, reaching a minimum at a relative humidity of 95%. Despite numerous studies on rebound phenomenon, there is no broadly adopted model to describe rebound quantitatively under arbitrary conditions [27].

Resuspension

Resuspension refers to particles being re-entrained into the airflow after residing on a surface. It occurs when the hydrodynamic or fluctuating forces overcome the surface force of adhesion, detaching the particles from the collector surface and suspending them back into the air flow. Turbulent airflow near a surface can generate lift and drag

Table 11. Summary of rebound and resuspension

Phenomenon	Characteristics	References
Rebound	• Large sized dust particles have a more likelihood to rebound while smaller particles have less likelihood for rebounding. • Significant only for particles larger than 10μm. • Rebound increases with increasing wind velocity. • RH reduces rebound at low flow velocities.	[97]
Resuspension	• Significant only for particles larger than 10μm. • Caused by turbulent flows in the viscous sublayer. • Resuspension does not occur in the viscous sublayer typically within 100μm of the collector surface.	[153]

forces, potentially leading to the re-suspension of particles. Turbulent eruptions in the viscous sublayer of the airflow are thought to contribute to the resuspension of dust particles. Resuspension is influenced by four main forces acting on the particle: the lift force, adhesion force, drag force, and gravity as shown in Figure 9. Aerodynamic forces cause resuspension, with particle detachment occurring through sliding, rolling, or lift-off mechanisms.

The lift-off force is typically considered negligible in resuspension processes and rolling is more prevalent than sliding, particularly for small particles. Rolling occurs when the moment resulting from the force of adhesion (F_a) is surpassed by the moment generated by the drag force [151, 154]. The lift force (F_l) becomes active when it surpasses both the adhesion and gravity forces. Conversely, the drag force (F_d) must exceed the combined adhesion and gravity forces subtracted from the lift force multiplied by the friction coefficient. These force relationships are depicted in equations (28) and (30), where u_1 represents the coefficient of friction, and y denotes the horizontal distance between two non-deformable particle asperities. Rolling is the most probable method of resuspension, followed by sliding, with direct lift-off being the least likely scenario [155].

Equation (30) computes the drag force (F_d) in Stokes flow acting on a sphere at the centre of a surface, where ρ represents the air density and a correction factor (f) accounts for the presence of the surface, typically set to 1.7009. This formula is applicable to dust particle sizes and wind velocities commonly encountered in photovoltaic soiling [156, 157]. Aerodynamic forces acting on a dust particle are expressed in equation (28) [151], $C_{l,d}$, ρ_a, A_a, and v denote the lift or drag coefficient, air density, cross-sectional area of the particle perpendicular to the flow, and air velocity, respectively. λ represents the molecular mean free path in gas and at ambient conditions it typically considered as 0.07μm.

$$F = 0.5\frac{C_{l,d}}{C_c}\rho_a A_a v^2 \tag{28}$$

$$C_c = 1 + \frac{2\lambda}{d_p}\left[1.257 + 0.4e^{\left(-1.1\frac{d_p}{2\lambda}\right)}\right] \tag{29}$$

$$F_d = 1.5\pi\rho f d^2 (u^*)^2 \tag{30}$$

$$F_l > F_a + F_g;\ F_d > \mu_1(F_a + F_g - F_l);\ \frac{F_d d_p}{2} + \frac{y(F_l - F_g)}{2} > F_a y$$

Particle resuspension models are commonly categorized into energy and force approaches [151, 157, 158]. In the force approach, resuspension occurs when the aerodynamic force surpasses the particle›s adhesion force. Turbulent flow plays a crucial role in these models as it causes velocity fluctuations, determining resuspension based on peak instantaneous velocity [154]. In contrast, the energy approach suggests that particles can overcome adhesion through vibration energy. The particle will not amass energy to overcome adhesion if the time interval between turbulent flows exceeds the particle›s vibration period, as it cannot dissipate the energy generated by the turbulent flows [159].

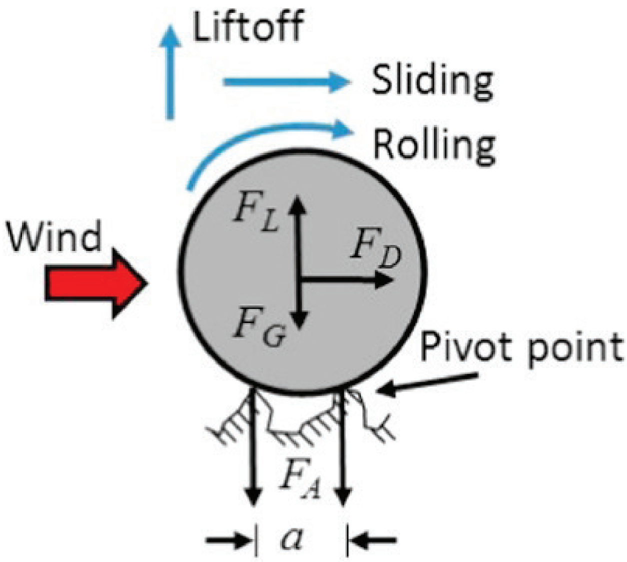


Figure 9. Resuspension forces acting on a dust particle encompass the impact of wind and resulting resuspension mechanisms, including liftoff, sliding, and rolling [From Brambilla et al. [155], with permission from Elsevier].

In the immediate surrounding of the collector, there exists a thin viscous sublayer where turbulent flows are suppressed [160]. Turbulent forces affect particles beyond this layer, which extends approximately 5 times the dimensionless quantity $y^+ = \frac{yu^*}{\nu}$ where y represents the distance from the surface, ν is the fluid's kinematic viscosity, and u^* is the frictional velocity. This viscous sublayer is typically within 100μm of the surface [153]. Hence, in regions where particles are within 100μm, turbulence›s influence on particle detachment diminishes. Smaller particles exhibit a higher ratio of adhesion to detachment forces, typically causing surface soiling by particles finer than airborne particulate matter [27].

Cementation

Cementation occurs through repeated cycles of condensation and drying on a surface, driven by both physical and chemical processes, resulting in robust dust particle adhesion to the surface [27, 161]. Cementation involves the dissolution and subsequent precipitation of material, influenced significantly by the composition of dust particles settling on the PV module. Particle deposition and dew formation, essential for cementation, are significantly influenced by environmental parameters [162]. Condensation of water on solar surfaces, combined with deposited dust containing certain elemental compositions, and elevated temperatures, triggers a chemical transition resulting in the formation of a firmly adhered, cemented layer of dust particles on the surface [163, 164].

In humid conditions, water present on the surface partly or completely dissolves soluble fractions of deposited dust. This process includes the dissolution of salt deposits like NaCl or gypsum, as well as the hydrolysis of silicates, carbonates, or glass [165]. In the drying process, the dissolved materials precipitate thereby forming solid bridges between nonsoluble fractions or insoluble particles and the PV surface which enhance particle adhesion [166]. However, the literature has not yet detailed the intricacies of the cementation process regarding the soiling of solar panels. Therefore, critical equations describing the cementation process are currently unavailable, highlighting a need for further study in this area. Cementation can lead to strong adhesion of soiling on PV modules, often requiring significant manual effort or advanced mitigation processes such as surface coatings to prevent accumulation in the first place [27].

Valerino et al. [122] observed that moisture facilitates the formation of cementation products through precipitation reactions occurring within the droplets on the collector surface, with carbon and salt masses being the most prevalent components. Furthermore, In Qatar, Ilse et al. [166] found that the cycle of water droplet formation and drying in form of dew contributes to soiling patterns by rearranging dust particles. This accelerates dust accumulation, forming line-like structures within a day of exposure. Microstructural analysis proved that a needle-shaped material known as palygorskite enhance the cementing effet of dust particles deposited on the collector surface.

Current Soiling Mitigation Approaches

Soiling significantly diminishes the efficiency and performance of solar panels by obstructing the amount of sunlight reaching the photovoltaic cells. Consequently, addressing soiling has emerged as a pivotal area of research and technological innovation within the solar industry. Recent literature highlights various advanced approaches in anti-soiling technology aimed at minimizing dust accumulation and optimizing energy production efficiency. Recently, superhydrophobic transparent coatings have garnered considerable interest in the solar energy sector because of their straightforward preparation, cost-effectiveness, self-cleaning capabilities, and high efficacy in preventing dust adhesion to surfaces [167]. A superhydrophobic surface substantially reduce the rate of dust deposition even in the absence of water, attributed to its low surface energy and surface microstructure. Superhydrophobicity imparts surfaces with self-cleaning properties, characterized by a water contact angle (WCA) exceeding 150° and a contact angle hysteresis (CAH) below 10° [168, 169]. This means that water droplets easily roll off the surface upon contact, effectively cleansing it.

Superhydrophilic coatings have emerged as promising solutions for mitigating soiling on solar panels. Surfaces are classified as superhydrophilic when their contact angle (CA) with water approaches 0° [170]. Unlike superhydrophobic coatings that repel water, superhydrophilic coatings attract water molecules, promoting the formation of a thin water film that effectively cleanses the surface [171]. This self-cleaning mechanism occurs as water spreads evenly over the surface, carrying away dust particles and other contaminants. Additionally, the high affinity of superhydrophilic surfaces for water helps in maintaining transparency and optical properties, crucial for maximizing solar panel efficiency.

Electrodynamic screens represent a promising technology for mitigating dust accumulation on solar photovoltaic (PV) panels [172]. These screens operate by generating electric fields that effectively repel dust particles from settling on the panel surface. By creating a charged environment, electrodynamic screens can prevent dust buildup without requiring physical contact or the use of water [13, 170]. This non-contact approach not only reduces maintenance costs associated with cleaning but also minimizes water consumption, making it environmentally sustainable. Moreover, electrodynamic screens are adaptable to various environmental conditions and can operate autonomously, adjusting their cleaning frequency based on real-time dust accumulation data.

Autonomous or robotic cleaning systems provide rapid cleaning for solar panels [173], offering high efficiency and sometimes incorporating features for self-recharging. However, they require periodic part replacement and maintenance to ensure reliable operation. Another concern is the potential for repeated cleaning to cause damage to the panel surface over time [174] as well as the shodow effects cast by the cleaning robot [175]. Therefore, while autonomous or robotic cleaning systems offer efficient maintenance solutions, careful consideration of their operational and environmental implications is essential for maximizing their effectiveness and longevity in solar energy applications.

Other contemporary soiling mitigation techniques explored in the literature include advanced anti-reflective coatings designed to reduce surface reflection and enhance light absorption, thereby minimizing dust accumulation [176–178]. Additionally, self-cleaning glasses [179] have been explored in literature and they utilize specialized coatings that leverage natural elements like ultraviolet light to break down organic matter and facilitate the easy removal of dirt and debris from solar panel surfaces. These innovative approaches aim to maintain optimal efficiency and prolong the lifespan of solar energy systems amidst environmental challenges.

Potential Areas for Further Studies

While a substantial amount of work was undertaken in understanding the dynamics of soiling on solar energy systems, several areas warrant further investigation to enhance understanding and develop effective mitigation strategies. One potential avenue for future research is the exploration of advanced cleaning techniques that are both cost-effective and environmentally sustainable. Further study in cementation in the context of soiling on solar panels is crucial, as the current literature lacks detailed understanding and critical equations of this process. This area of research could significantly advance the ability to mitigate and manage soiling effects effectively on photovoltaic modules. Additionally, more studies are required to explore the long-term effects of soiling on the structural integrity and longevity of solar panels and collectors. Furthermore, research into the development of predictive models that consider a broader range of environmental factors, such as humidity and temperature variations, could provide valuable insights into soiling dynamics. Moreover, investigating the impact of emerging technologies, such as bifacial modules and novel surface coatings, on soiling susceptibility and mitigation strategies could open new avenues for optimizing solar energy system performance. Finally, collaborative interdisciplinary research efforts involving experts from various fields, including materials science, engineering, meteorology, and environmental science, could lead to comprehensive solutions for mitigating soiling effects and maximizing the durability and efficiency of solar energy systems.

CONCLUSION

Soiling presents a substantial challenge to solar energy systems, impairing their performance and reliability through dust accumulation on collector surfaces. Recent research highlights the complex interplay of factors such as dust particle size distribution, surface roughness, and environmental conditions in influencing soiling mechanisms. This review comprehensively examines literature related to soiling and the mechanics of soiling of solar PV collectors. It specifically explores the impact of solar collector soiling, detailing the mechanics such as types of deposition and adhesion forces, the influence of installation geometry, environmental conditions, dust physical properties, and collector surface characteristics. The review also delves into factors that facilitate soiling, deposition mechanisms, and dust adhesion on solar collectors and the review also discussed various techniques for measuring adhesion forces. The study has uncovered crucial conclusions essential for the research community in the field of soiling of solar PV panels. It highlighted the lack of standardized terminology in describing soiling on solar PV surfaces. For instance, the term «soiling mechanisms» has been broadly used in literature to encompass various variables and processes, including environmental factors, installation geometry, deposition mechanisms, and adhesion mechanisms. This underscores the necessity to differentiate these concepts into clearer terms such as soiling variables/factors, deposition mechanisms, and adhesion mechanisms. This study aimed to address these knowledge gaps and explore emerging research areas to advance the understanding of soiling phenomena in solar energy systems. The study provides an overview of soiling mechanics in solar photovoltaic (PV) across different climatic and environmental conditions. The following conclusions were drawn:

The *adhesion forces* between PV surfaces and dust particles highlight the interdependency of surface characteristics and dust particles, necessitating detailed studies on how surface roughness influences their contact area, beyond simplistic descriptors like «smooth» and «rough.» The review emphasizes scenarios where different adhesion forces dominate in the adhesion mechanism: for instance, electrostatic forces prevail in high voltage applications and dry weather conditions, while capillary forces are predominant in humid and wet conditions. Gravitational forces, on the other hand, exert influence primarily on large-sized dust particles. The study also confirms that these forces can be effectively modeled using the Derjaguin, Muller, and Toporov (DMT) and Johnson, Kendall, and Roberts (JKR) models, which are consistent with experimental findings.

Sedimentation predominates as the primary soiling mechanism under low wind speeds, particularly involving medium to large-sized dust particles, whereas higher wind speeds promote inertial deposition. *Wind direction* adds complexity to soiling dynamics, with surfaces facing the windward side experiencing more soiling compared to those facing away from the wind direction. Wind exerts a dual influence on solar collector soiling, acting both as a depositor and a cleanser of dust particles from surfaces. Stronger winds typically facilitate cleaning compared to lower speeds, where particles adhere more readily. For small particles, high wind speeds may enhance adhesion forces by causing high particle impact with the collector surface. The *spatial distribution* of dust deposition is influenced by tilt angle, wind direction, and proximity to ground or structures, underscoring the importance of comprehending these factors for optimizing solar collector performance and mitigating soiling effects.

Geographical location plays a significant role in shaping the chemistry and concentration of dust particles, thereby impacting soiling rates on solar collectors. Factors including dust size, shape, and composition, alongside environmental variables like wind, humidity, and temperature, dictate the interaction between dust and collector surfaces. *Fine dust particles*, owing to their larger surface area, cause more performance degradation, while larger particles contribute primarily to surface soiling.

Moisture, especially in the form of dew, is a crucial factor in understanding soiling mechanisms on photovoltaic (PV) modules. Dew facilitates both the adhesion of dust particles to surfaces and aids in surface cleaning by directing droplets downwards. As relative humidity increases, atmospheric aerosol particles absorb water, thereby enhancing dust particle adhesion through capillary forces. Dew formation is a critical factor in the cementation process, leading to the formation of a difficult-to-clean layer on the surfaces of PV collectors. Mitigation strategies such as inverting collectors at night combined with dew formation have been explored to effectively reduce soiling effects

The *optical properties* and surface roughness of solar collectors are critical factors affecting their efficiency and susceptibility to soiling. Surface roughness limits particle-surface interaction, reducing adhesion forces and consequently decreasing soiling. Surface roughness primarily affects van der Waals forces, particularly in dry conditions and adhesion force increases linearly with particle size but decreases with surface roughness, except for particles smaller than surface asperities. The impact of surface roughness should be studied in relation to dust particle size, as mere descriptions such as «smooth» and «rough» do not fully elucidate the surface area in contact between the surface and the dust particles. Concentrated solar power (CSP) mirrors experience higher soiling effects and energy losses compared to photovoltaic (PV) systems. *Gravitational forces* influence particle deposition, with larger particles settling faster. Sedimentation and inertial deposition contribute to dust accumulation, and these may be mitigated by proper siting or coverings.

The *statistical analysis* of environmental parameters› impact on soiling has not been explicitly studied, with existing studies presenting general outcomes rather than specific contributions of these parameters to soiling. The literature lacks coherence due to the absence of targeted experiments analyzing the exact influence of these parameters. Additionally, much of the reported experimental work did not control these parameters, making it challenging to determine their precise contribution to soiling under such conditions.

NOMENCLATURE

A	Hamaker constant
A_a	Particle cross-sectional area perpendicular to the flow (m^2)
A_p	Projected area (m^2)
C	atmospheric particle concentration (kg/m^3)
C_c	Cunningham correction factor
$C_{l,d}$	Lift or drag coefficient
d	Distance between particles (µm)
d_a	Aerodynamic diameter (µm)
d_e	Sphere of equivalent mass (µm)
d_{pa}	Sphere of equivalent projected area (µm)
F	Deposition flux rate (kg/m^2s^1)
F_{ad}	Adhesion force (N)
F_c	Capillary forces (N)
F_d	Drag Force (N)
F_e	Electrostatic force (N)
F_g	Gravitational force (N)
F_l	Lift force (N)
F_v	Van der Waals force (N)
H_o	Separation distance, (µm)
k_c	Correction factor to align analytical results with experimental findings
k_p	Surface packing density for close-packed spheres
l	separation distance between charge centres (µm)
M	Mass of dust particle (g)
Na	Avogadro›s number (6.022 x 1023 atom/mol),
P	Perimeter of dust particle (µm)
PM_{10}	Particulate matter of 10µm diameter or less (µm)
$PM_{2.5}$	particulate matter of 2.5µm diameter or less (µm)
q	Dust particle charge (C)
R	Dust particle radius (µm)
r	Asperity radius or equilibrium radius of the meniscus
s	Distance between the substrate and the rotor axis (m)
S_e	Stokes number
T	Absolute temperature (K)
u*	Frictional velocity (m/s)
N	Molecular volume of water (mL/mol)
v_d	Deposition velocity (m/s)
v_i	Inertial deposition velocity (m/s)
W_a	Adhesion work (J)

Greek symbols

γ	Surface tension of water-air (N/m)
γ_1, γ_2	Surface energy (N/m)
ε	Dielectric constant,
ε_o	Permittivity of free space,
θ	Contact angle between water and a substrate (°)
K	Boltzmann›s constant (1.38 x 10-23 m^2Kg/s^2K)
λ	Molecular mean free path in gas (µm)
μ	Dynamic viscosity of air ($kgm^{-1}s^{-1}$)
ρ	Density of the dust particle (kg/m^3)
ρ_a	Air density (kg/m^3)
σ	Surface roughness (nm)
ω	Angular velocity (rad/s)

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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