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# Dust Effect on Solar Energy Systems and Mitigation Methods

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**ABSTRACT**

Solar energy systems present a potential solution to global challenges in energy production and addressing environmental issues. However, such systems' performance could deteriorate in harsh weather conditions, which may lead to short- and long-term degradation. Particular attention should be paid to dust accumulation affecting both types of solar systems: Photovoltaic (PV) and Concentrated Solar Power systems (CSP). This review discusses the influencing factors affecting dust accumulation and the dust impact on solar systems. The comparison of dust accumulation effect on both technologies is then assessed. The reported dust accumulation studies showed more performance deterioration in CSP systems than in PV systems. In both cases, dust accumulation leads to a drop in optical characteristics resulting in a loss of energy yield. Potential mitigation methods and their advantages and disadvantages are also reviewed. It is concluded and recommended from the review analysis that dust accumulated on solar systems should be considered in the design and operation phases to define appropriate cleaning methods and frequencies.

## 1. INTRODUCTION

The energy demand is increasing globally following population growth and technological development. The very fast increase in electricity demand has contributed to raising more environmental concerns, including global warming and climate change. To overcome these challenges, renewable energy could be used to provide a clean and sustainable energy source. Solar energy is the most abundant energy, which can generate electricity directly using the Photovoltaic (PV) process or indirectly through a thermodynamic cycle [1]. In the United Arab Emirates, solar technologies are viable solutions for electricity generation using both PV and Concentrated Solar Power (CSP) because of the high irradiance level in terms of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI), which are above the minimum required values [2]. However, due to the harsh weather conditions, implementing solar technologies in the UAE must overcome other challenges to maintain a high performance.

One of the main challenges is dust accumulation in the solar system, which could significantly influence the performance and lifetime of these systems. Dust accumulation is a complex phenomenon due to the interaction of various weather conditions and solar surface characteristics [3]. Dust particles settled on the front surface of the solar collector (PV and CSP) could block the solar rays causing an essential loss in optical properties and power generation [4]. For instance, a high concentration of dust settled on the solar PV modules could deteriorate the transmissivity of the upper glass layer and lead to a decrease of more than 50% of output power without cleaning [5]. Similarly, dust particles deposited on the CSP mirrors can interfere with the solar rays in their double trajectory to the concentrator and dramatically decrease its reflectivity [6]. The long exposure time of CSP mirrors without cleaning could deteriorate their cleanliness by up to 73% [7].

Therefore, it is essential to understand the factors that could affect dust accumulation in solar systems and the potential impact on the performance of a solar system, particularly in regions with harsh environmental conditions. This work reviews the factors affecting dust accumulation and the dust impact on solar PV and CSP systems. It also shows a comparative assessment of the effects of dust on both solar systems. In addition, cleaning methods are discussed with more emphasis on self-cleaning methods.

## 2. DUST PROPERTIES AND FACTORS AFFECTING DUST ACCUMULATION

Generally, dust comprises the aerosol and fine particles of solid matter that are discharged, transported, and deposited (dry and wet) with an average size of less than 500 μm. Dust emissions are essential for sustaining the energy balance of the earth's climate [8]. The direct/indirect radiative equilibrium of dust with the atmosphere includes scattering or/and absorption of solar radiation [9]. Natural or artificial sources could produce solid particles. The storms holding the dust particles affect the local area and export the dust to areas miles away [10]. Industrial structure sites are the most common artificial sources of dust.

Contrary to natural dust sources, artificial dust sources act locally. However, artificial dust sources produce fine dust particles that are more harmful in various ways. The source of dust is the leading factor in the dust deposition density and all different dust side effects.

The storms striking arid or semi-arid areas are the primary natural source of dust [11]. Approximately 2000 million tons of dust are discharged worldwide annually. About 75% of the dust emission is deposited over dry land and 25% over water [8]. Even though dust accumulation occurs naturally, it is a very complex phenomenon, as many terrestrial conditions and locations control it. The world map for dust deposition could be divided into four different zones depending on the dust density [12], as shown in Figure 1. It can be seen that zone 4, including the Middle East North Africa region (MENA), has a more significant level of dust, and special attention should be given to this region to reduce its impact on the performance of solar energy systems.

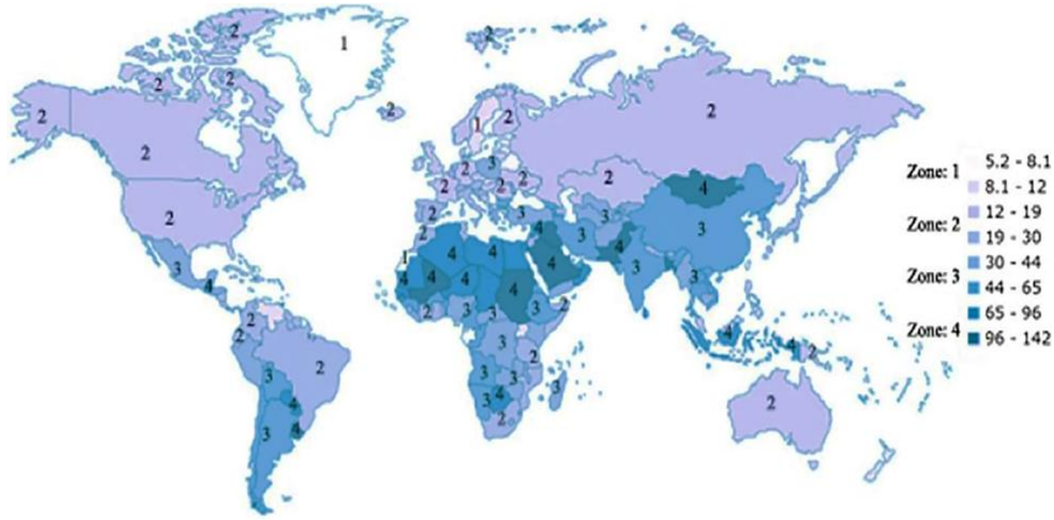


**Figure 1.** Dust world map [mg/m$^3$] [12]

Several literature studies were directed to consider the global dust cycle using satellites, ground observations and numerical models [9]. Rigorous research in the literature suggests that dust deposited on terrestrial solar power systems is due to the dust cycles [13-16]. As dust accumulation affects the solar system's optical properties, it considerably drops its photocurrent yield and reduces its power to a large extent. The dust particles' physical and elemental structure properties greatly influence the optical characteristics of dust accumulation [17, 18]. Various assessments have been conducted to study the dust optical properties and their accumulation challenges on solar systems [8, 10, 19, 20]. Bose et al. [21] designed an artificial chamber to study dust deposition under near actual conditions. The study findings reveal that the transmittance of the model screen could be decreased from 85% to 35%. This means the amount of solar radiation could be dropped by 50% when the dust accumulates, devoid of any timely countermeasure. Zarei et al. [10] conducted the most recent and comprehensive review that discusses and summarizes the experimental studies performed worldwide to study the impact of dust on PV systems.

Furthermore, various authors indicated that humidity is a significant factor that affects the adhesion of the dust particles to the top surface of a PV module due to capillary force. When the relative humidity is low, the particles drop with low kinetic energy, but the liquid bonds formed between the dust particles and the surface at high relative humidity would require higher kinetic energy. Maghami et al. [22] widely reviewed and assessed the critical cause of dust accumulation. These authors discussed the dust characteristics, such as nature, dimension, mass, and profile, which play a significant role in dust accumulation. Figure 2 summarizes the different factors that affect dust accumulation. Dust accumulation is a function of environmental conditions such as wind, temperature, moisture, dust characteristics, humidity and precipitation, as well as fixing issues such as tilt angle, alignment, height and location of the installation site. Real dust particles are complex multi-phase mixtures of compounds with their properties. The variation of their properties due to the inhomogeneity, phase structure and composition of different materials has a major effect on dust aggregates or dust agglomerates. Many current research studies have therefore been devoted to exploring dust deposition with varying characteristics on the optical transmittance of the solar systems. Table 1 summarizes the principal research methodologies and findings regarding dust characteristics considering the accumulation effects on the solar system's optical properties.

**Table 1.** Dust characteristics considering the accumulation effects on solar system's optical properties

| Authors | Study | Optical analysis | Main findings |
|---|---|---|---|
| Bose et al. [21] | An artificial chamber to study the dust deposition under near actual conditions. Assessing the change in optical properties (transmittance, reflectance, and absorbance) | Optical properties are measured before and after the dust deposition using V-750 UV-Visible Spectrophotometer | -The transmittance of the model screen could be decreased from 85% to 35%.<br>-The amount of solar radiation could be dropped by 50% when the dust accumulates devoid of any timely countermeasure |

| | | | |
|---|---|---|---|
| El-Shobokshy and Hussein [17] | Experiments were conducted using a solar simulator as a light source. Size distribution analysis using an optical microscope. Five dust types prepared in the laboratory were used: a) three limestone particulates with different classes. b) two cement and carbon particulates) with different physical properties | Samples of each test dust were collected on a piece of glass and examined under an optical microscope with a suitable magnification so that all particles could be clearly detected | -The fine dust particles significantly affect the PV system performance more than the coarse ones. -Fine dust particles are more sticky than coarse particles, and they typically accumulate and tend to be distributed uniformly as it shields most of the surface area. - The dust has significant variations in the dust refractive index values depending on the region and weather conditions |
| Piedra and Moosmuller [19] | Field experimental work to assess the power losses due to dust deposition | The use of discrete dipole approximation for particle optics calculations | -The absorption losses are dominant when the particles are small and have a relatively sizeable imaginary part of the refractive index |
| Aïssa et al. [23] | A comprehensive study of the structural, optical, and magnetic characteristics of the dust particles collected directly from in-field solar modules was set up in Doha, Qatar | Olympus (IX73) optical microscope. The objective lens of 40X magnification was used. Scanning electron microscopy, X-ray diffraction, atomic force microscopy, Raman, FTIR, UV-Vis and were also used to characterize the dust particles | - The effect of dust accumulation on the optical transmittance of a transparent substrate led to a reduction of up to 26%, leading to a considerable drop in the PV power output |
| Zhao et al. [24] | Study of the impact of seasonal dust accumulation on high-concentration photovoltaic/thermal systems | The sample's transmittance and the system's thermoelectric performance were performed. SEM, EDS, XRD, and a laser particle analyzer were used to study the dust particles collected from the surface of the Fresnel lens | With every 1 $g/m^2$ rise in dust density, the optical transmittance of the Fresnel lens declined by 2.73% |

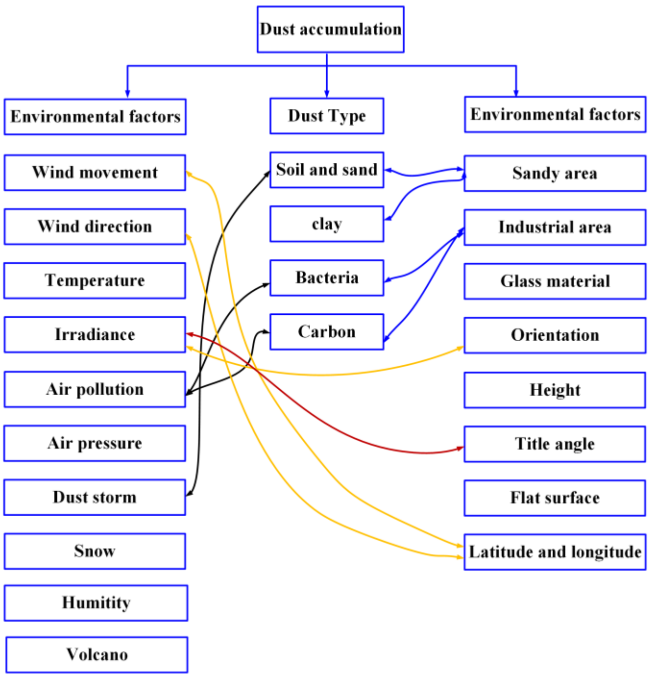


**Figure 2.** Causes of dust accumulating on the surface of solar systems [22]

### 3. DUST IMPACT ON SOLAR PV SYSTEMS

Dust accumulation on solar PV systems tends to block the solar rays from reaching the solar cells, reducing efficiency and power output. In general, dust deposition on solar PV modules may influence the optical, electrical, and thermal characteristics [11]. Without cleaning, the drop in the PV power may decrease the reliability of these systems and increase the operation cost [25]. Over the past decades, various research works have been conducted on the impact of environmental factors on PV performance, including soil deposition. Most of these studies targeted the effect on the electrical characteristics such as output power and electrical efficiency, while other studies were concerned with the optical losses, particularly transmission losses due to dust deposition. Other studies were conducted under controlled indoor conditions to observe the power deterioration with the dust accumulation [26-28]. Table 2 presents a review of selected published works on the effect of dust on PV systems in different regions highlighting the percentage of performance drop.

**Table 2.** Briefing of selected articles on the dust effect on PV performance

| Author | Location | Duration of Analysis | Module Setting | Dust Concentration | Target Parameter (s) | Rate of Reduction by Dust [%] |
|---|---|---|---|---|---|---|
| Cabanillas and Munguia [29] | Hermosillo and Sonoro, Mexico | 90 days | Optimum angle | 1.4-2.4 g/m$^2$ | Electrical power | 4–7% reduction in maximum power |
| Guan et al. [30] | Chang'an District, Xi'an, China | 8 days | Tilt angles of 30° and 35° | 5.06-12.64 g/cm$^2$ | output power and transmittance | 6.31-20.62% |
| Adinoyi and Said [5] | Dhahran, Saudi Arabia | 8 months | The tilt angle of 26° | 6.18 g/m$^2$ | output power | 50% |
| Ndiaye et al. [31] | Dakar, Senegal | 1 year | N/A | N/A | Electrical parameters; V, I, P, and FF | Poly:18-78% Mono: 23-80% |
| Tanesab et al. [32] | Perth, Western Australia | 1 year | The tilt angle of 32° | 0.038-0.17 mg/cm2 | Power output transmittance | 4-6% |
| | Nusa Tenggara Timur, Indonesia | 1 year | The tilt angle of 15° | 0.168- 0.37 mg/cm2 | Power output transmittance | 12.36%-15.16% |
| Song et al. [3] | Sharjah, United Arab Emirates | 7 months | The tilt angle of 25° | 0-5.44 g/m$^2$ | The power loss of the PV | 0.29-12.7% |
| Piliougine et al. [33] | Malaga, Spain | 10 months | The tilt angle of 21° | N/A | Transmittance and current | 3.3% |
| Juaidi et al. [34] | Nablus city, Palestine | 7 months | the tilt angle of 25° | N/A | The power loss of the PV | 9.99% |
| Mostafeoui et al. [35] | Adrar, Algeria | 6 months | The tilt angle of 27.88 ° | 1.05-4.86 g/m$^2$ | Electrical parameters; V, I, P, and FF | 29-31% |
| Alawasa et al. [36] | Oman | 16 months | Tilt angle 5° | N/A | Variation of daily produced energy (normalized yield in kWh/kWp) | 9.5- 45.6%, |
| Diop et al. [37] | laboratory conditions for Dakar Region | -- | Tilt angle 0° | 3.3 g/m$^2$ | current-voltage (I - V) characteristics of photovoltaic panels | efficiency decreases by 50% |
| Wang et al. [38] | Shanghai | 3 weeks | The tilt angle of 22° | 2.199 g/m$^2$ | the output voltage of the PV module | 5.546 to 35.226% |
| Khodakaram-Tafti and Yaghoubi [39] | Iran | 8 months | tilt angles of 0°, 15°, 30°, and 45° with an azimuth angle of 0° | 440 μg/m$^3$ | The hourly average output power | 20.7% to 58.2% |
| Jaszczuret et al. [40] | Poland | three consecutive weeks | β=15°, β=35° | -- | module temperature and power output | 2.39% and 2.26% |

**Table 3.** Briefing of selected articles on the dust effect on CSP performance

| Author | Location | Duration of Analysis | Mirror Material/ Application | Dust Concentration | Target Parameter (s) | Rate of Reduction by Dust [%] |
|---|---|---|---|---|---|---|
| Zhao et al. [45] | Hohhot, China | 48 days | Silver-plated and aluminum-plated/ linear Fresnel collector | 0.16 -2.5 g/m$^2$ | Cleanliness factor | 23.5% |
| Azouzoute et al. [46] | Morocco | 11 weeks | Silvered glass | 0.2-0.8 g/m$^2$ | Dust accumulation loss | 39% |
| Bouaddi et al. [7] | Agadir, Morocco | 12 weeks | Silvered glass Aluminum | N/A | Cleanliness factor | 73% |
| Merrouni et al. [44] | Oujda, Morocco | 12 weeks | Silvered glass | N/A | Reflectivity drop | 28% |
| Hachicha et al. [47] | Sharjah, UAE | 3 months | Silvered glass | 0-5.44 g/m$^2$ | Specular reflectivity Thermal efficiency | 63% drop in reflectivity 36% drop in efficiency |
| Wu et al. [48] | Hohhot, China | 30 days | Silvered glass/ parabolic trough collector | 0-1.48 g/m$^2$ | Cleanliness factor | 15% |

## 4. DUST IMPACT ON CONCENTRATED SOLAR POWER SYSTEMS

Similar to PV systems, dust accumulation may deteriorate the performance of Concentrated Solar Power (CSP) systems. Moreover, suspended particles like aerosols in the atmosphere could significantly attenuate the radiation reaching the concentrator [41, 42]. The impact of dust settlement on CSP systems is identified in the optical characteristics of the concentrators/mirrors used in these technologies. The specular reflectivity of CSP mirrors is the main parameter affected by dust [43]. The severity of dust deposition on CSP depends not only on the local weather conditions but also on the mirror material. Compared to PV systems, the impact of dust on CSP performance is more severe due to the interaction of incident radiation with the dust particle in a double trajectory through the CSP mirrors [44]. Selected studies on dust effect on CSP systems are summarized in Table 3.

## 5. COMPARISON OF DUST ACCUMULATION EFFECT ON CSP AND PV TECHNOLOGIES

Only a few studies have simultaneously assessed and compared dust accumulation's impact on PV and CSP systems. Bellmann et al. [49] presented an experimental programme to determine and compare the optical losses in CSP and PV due to dust accumulation. Their results showed 8 to 14 times higher optical losses for CSP compared to the PV under the same level of dust accumulation. Azouzoute et al. [46] evaluated the impact of dust on solar glass samples and mirror samples of hybrid CSP/PV plants. The authors reported that the dust accumulation losses in mirror samples were three times more critical than in glass samples. Abraim et al. [50] used dust accumulation sensors to evaluate the dust accumulation effect simultaneously on PV and CSP over one year. Based on the metrological data, they simulated the PV and CSP plant performance using commercial software. The numerical results showed a reduction in the annual yield due to dust accumulation 8 times higher for CSP than for PV. Hachicha et al. [47] conducted an experimental and numerical study of the dust accumulation effect on CSP and PV systems over a period of 3 months. It was found that the dust effected the power of CSP 3 to 5 times more than that of PV technology. Table 4 illustrates the main findings of studies that compared the dust accumulation effect on PV and CSP technologies.

**Table 4.** Summary of recent investigations comparing the dust accumulation loss between CSP and PV technologies

| Author | Location | Type of Dust | Methodology | Duration of Analysis | Target Parameter (s) | Key Findings |
|---|---|---|---|---|---|---|
| Bellmann et al. [49] | Southern Portugal | Rural area | Experimental and Modelling of optical dust accumulation losses | 9 weeks | The efficiency factor "cleanliness," ξ | Approximately 8 to 14 times higher dust accumulation loss for CSP technologies compared to PV |
| Azouzoute et al. [46] | Morocco | Rural area | Experimental | 3 months | The optical efficiency of mirror and glass | The dust accumulation loss reached up to 35%<br>Dust accumulation losses are 3 times more critical in CSP than in PV |
| Abraim et al. [50] | Morocco | Rural area | Experimental And Modelling | 1 year | The optical efficiency of mirror and glass<br>Energy yield | - The annual energy loss due to dust accumulation is about 8 times higher for CSP than PV<br>- The total annual energy loss due to dust accumulation, considering a monthly cleaning frequency, is equivalent to 17.76% and 1.95% for CSP and PV, respectively |
| Abraim et al. [51] | Morocco | Rural area | Experimental | 1 year | Soling loss | Dust accumulation effect for CSP mirrors with an annually averaged dust accumulation rate 5 to 6 times higher than for PV<br>The maximum dust accumulation loss was recorded during the dry period |
| Hachicha et al. [47] | UAE | Urban area | Experimental and modeling | 3 months | Optical losses<br>Power dust accumulation loss | The power dust accumulation losses are 3 to 5 times higher in CSP than in PV technology |

## 6. MITIGATION METHODS

Remarkable research progress has been made to address the dust challenges and develop innovative countermeasures over the past three decades [52]. Many comprehensive literature reviews were conducted on the power loss of the solar panel and the mitigation of these losses [11, 16]. There are numerous cleaning approaches for reducing the impact of dust accumulation on the surface of solar systems. Jamil et al. [53] summarized and classified the mitigation methods into two main categories: a) natural and b) artificial cleaning, as shown in Figure 3. The natural methods have the benefits of no cost however are controlled by the weather conditions and are mainly effective for coarse dust particles.

Like natural cleaning, passive cleaning techniques could clean PV panels by up to 70% without any operation cost and external power. However, passive cleaning methods have a limited lifespan, and coating may reduce the optical performance of solar systems. On the other hand, manual cleaning could effectively minimize dust deposition on solar systems; however, it requires a workforce and vast amounts of water. It is, therefore, very challenging to rely on manual cleaning for large-scale solar power plants, even though it is among the best cleaning methods. Electrodynamic, mechanical and robotic cleaning are more practical and faster for broad areas and huge solar plants. However, these methods consume a lot of power and the operation cost is relatively high. Furthermore, these technologies could make safer scratches on the top surface of the energy system.

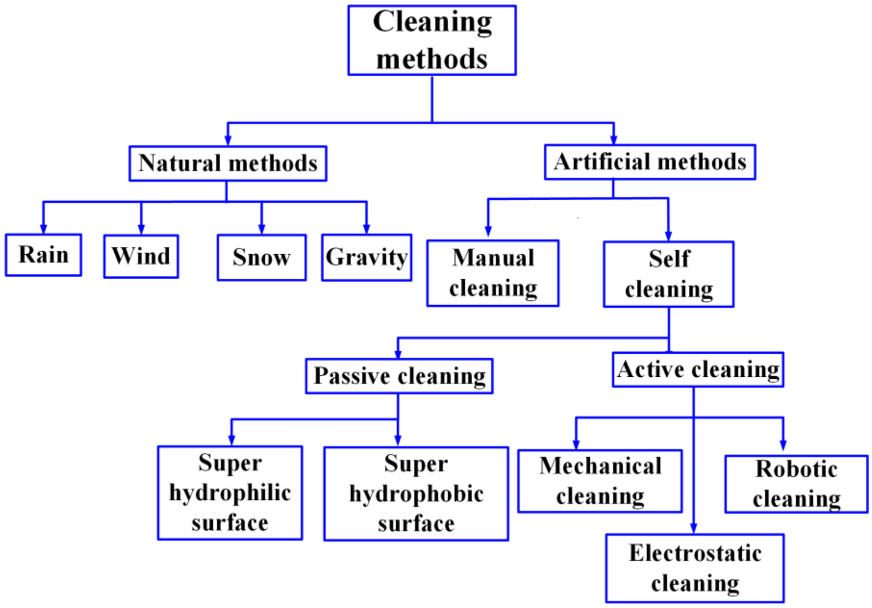


**Figure 3.** Classification of different types of cleaning methods [53]

**Table 5.** Briefing of selected articles on dust-accumulation mitigation methods

| Author | Cleaning Methods | Mechanism/Materials | Key Findings |
|---|---|---|---|
| Fan et al. [56] | Robotic cleaning | A rolling brush and negative pressure dust removal | An increase in the PV efficiency from 11.06% to 49.53% |
| Kawamoto [57] | Electrodynamic cleaning system | A detachable cleaning device that uses electrodynamic force | 80% of dust was removed for softly deposited dust but low performance for strong adherence |
| Zhong et al. [58] | Super-hydrophilic coating | Two-layer structures composed of $TiO_2$ and KH550 | The generated power increased by 4.3% using the super-hydrophilic coating with a pH value of 0.34 |
| Zhang et al. [59] | Super-hydrophobic coating | Organic silicon resin, ethanol, and $SiO_2$ nanoparticles | PV efficiency is improved using the super-hydrophobic coating by 3.7%, 2%, and 2% when the tilt angle is 30°, 45° or 60°, respectively |
| Yadav et al. [60] | Mechanical cleaning | Light-dependent resistor mounting structure, motor with a driver circuit, wiper, and power supply unit | A cleaning efficiency of 97.8% has been reported using the proposed cleaning system |
| Şevik and Aktaş [61] | Natural and manual cleaning | Using rainfall and rainwater harvesting | The effect of rain on array efficiency varied from 0.31% to 0.94%. After manual cleaning, the average efficiency increased by 4.95% |

Anti-dust accumulation and self-cleaning coatings are gaining much attention for solar applications by modifying surface properties and water mobility. Consequently, seeking a sustainable performance of solar energy systems requires incorporating sophisticated self-cleaning technologies. Hence, the role of self-cleaning coatings to maintain enough cleanliness and improve the ability to endure the terrestrial factors over time without reducing the optical transmittance of the glass material is of great concern. Various materials are used to manufacture and apply as self-cleaning coatings [54]. Two categories of self-cleaning coatings are developed to make the solar surface more resistant to dust: hydrophobic (water-repelling) and hydrophilic (water-attracting). Although both types can help reduce dust accumulation in solar systems, hydrophilic coatings are unsuitable for arid regions with low precipitations [55].

Selected works on using mitigation methods to clean solar systems and their main findings are presented in Table 5. Even though there are several mitigation practices, there is no typical effective mitigation method for cleaning PV or CSP technologies. It varies on the ecological circumstances of the site. In practice, selecting the most appropriate mitigation method depends on various factors such as site conditions, resource availability, solar system capacity, expectation, and cost.

## 7. CONCLUSIONS

Dust accumulation is one of the main challenges that need to be addressed to avoid deterioration of the performance of solar energy systems. This phenomenon depends on dust characteristics, properties, location and environmental parameters. Both solar energy technologies: PV and CSP, are affected by the dust deposited on the front surface, although dust accumulation losses are more pronounced in CSP mirrors due to the interaction of the dust particle with the solar rays in its double trajectory. Dust accumulation not only influences the performance of solar energy systems but also reduces the lifetime of these systems. Therefore, it is essential to clean these systems with a particular frequency to minimize the impact of dust on their performance and lifetime. Although there is no unique cleaning method, as it depends on the site and weather conditions, periodic cleaning is recommended for moderate dust accumulation. In addition, it is essential to optimize water usage and adopt recycling if water is used for cleaning, especially in a region where water is scarce. Preventive approaches, such as passive methods (coatings) or active (electrodynamic screens), are recommended. The economic feasibility and lifetime of such solutions need to be further investigated.

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## NOMENCLATURE

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|---|---|
| CSP | Concentrated Solar Power systems |
| DNI | Direct Normal Irradiance |
| GHI | Global Horizontal Irradiance |
| MENA | Middle East North Africa region |
| PV | Photovoltaic |