Solar Photovoltaic Panels Dust Mitigation Methods: A Review

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Abstract

The global expansion of solar photovoltaic (PV) systems necessitates efficient maintenance strategies to sustain energy yield. Dust deposition on PV modules is a critical issue, particularly in arid and semi-arid regions, as it reduces light transmission and causes significant power losses. This review examines the impact of dust on PV performance and evaluates cleaning approaches, including electrostatic removal, super hydrophobic and super hydrophilic coatings, surface acoustic wave (SAW) technology, robotic systems, and manual methods. Electrostatic and SAW technologies provide contactless, water-free cleaning, while hydrophobic coatings promote passive dust shedding. Robotic systems offer scalable solutions for large plants, whereas manual cleaning remains common but labour- and water-intensive. Challenges include coating degradation, high capital costs, and limited effectiveness against fine or sticky particles. Integrating dust mitigation with sustainability goals—such as water conservation and reduced manual labour—is essential. Future work should focus on hybrid methods, cost reduction, and long-term durability, ensuring PV reliability and supporting solar energy's role as a sustainable resource.

Keywords: *Photovoltaic (PV) Cleaning, Solar Panel Efficiency, Hydrophobic coatings, Electrostatic cleaning*

1. INTRODUCTION

The depletion of fossil fuels and the associated increase in carbon emissions have drawn significant attention toward renewable energy sources [1].Current dependency on fossil fuels can be reduced by utilizing solar energy for power generation[2]. The variability in renewable power generation makes forecasting difficult for optimal balancing [3]. Solar energy, with its abundant availability and clean nature, offers a significant advantage as a source for electricity generation [4] Energy experts predict that by 2050, over 50% to 80% of global electricity could be generated from renewable energy sources [5]. The annual average Global horizontal solar irradiation (GHI) ranging from 1897 $kWhm^{-2}$ to 2286 $kWhm^{-2}$ [6]. When there is increase in the PV cell temperature, there is reduction in photovoltaic units efficiency [7]. Green pollution free, small regional limitation and inexhaustible are the main advantages of solar energy [8].

1.1.Factors affecting Solar PV panels performance

Electricity generation from solar radiation relies on the photovoltaic effect [9], where solar cells convert sunlight into electrical energy. Optical loss due to soiling is a key contributor to efficiency degradation [10]. Output performance depends on following parameters: Cell surface temperature, temperature coefficient, equivalent series resistance, irradiation intensity and equivalent parallel resistance[11]. Dust accumulation rate of polycrystalline panels(10.5 g/m^2) is higher than that of cadmium telluride panels(8.4 g/m^2)[12]. Reference [13] shows that in Levelied cost of energy (LcoE) there are alterations due to soiling and rise in solar cell temperature. The dust collected from the solar module in USA and Egypt, it was observed that 75% of the dust was quartz silicates (SiO_2) and 20% was feldspars ($NaAlSi_3O_8$, $CaAlSi_3O_8$, KAlSi3O3)[14].

1.2. Solar Radiation

Solar photovoltaic energy is derived from solar radiation. Under standard test conditions, monocrystalline typically convert only 15% to 18% of the incident solar radiation into electricity[15].A Solar portable module analyser was set up to draw the I-V curve by collecting data from real operating conditions(ROC) with varying temperature and Solar irradiation[16]. Bifacial photovoltaic modules and cells are capable of producing electricity from both their front and rear surfaces, unlike conventional solar technologies that generate power solely through the front side. [17]. Valuable insights are provided for companies to enhance the durability, lifetime, and manufacturing processes of PV panels [18]. Soiling losses can causes efficiency losses ranging from 25% to 30% [19]. The Soiling Loss Index (SLI) refers to the decrease in solar irradiance incident on photovoltaic (PV) cells within a module, caused by the build up of dust, dirt, or other particulate matter on the panel surface. [20]. Reference [21] experimented in Dhahran that a Solar PV module which was not cleaned for 6 months reduced its output by 50%. Mass deposition rates (1–50 $mg/m^2/day$) and corresponding optical transmittance losses were quantified, showing temporal variations influenced by site conditions and module tilt angle. [22]. The composition of dust was estimated by converting Al, Ca, Si, Fe, K and Ti to Al_2O_3, CaO, SiO_2, Fe_2O_3, K_2O and TiO_2 [23]. Reference [24] founds the relationship equation between deposited particles mass and the reduction in transmission as

$\Delta\tau = 34.37\ \mathrm{erf}(0.17\omega0.8473)$.

1.3 Impact of Dust Accumulation on Solar PV Panels

Dust accumulation on the surface of PV panels is a key factor influencing energy conversion efficiency, as it can significantly reduce the actual power output [25]. In Algeria, eight weeks of uncleaned outdoor exposure resulted in an 8.41% power loss relative to a cleaned photovoltaic panel. [26]. In Qatar the dust accumulation rate, DAR, in two month duration reached around 100 mg $m^{-2}d^{-1}$[27]. Reference [28] shows that when there is 5% drop in the transmittance power generation drop will be around 6-7%. Reference [29], concludes by their experimentation that during heavy soiling conditions the daily loss is 1% . The average power reduction on PV panels due to different types of dust deposition is as follows: natural dust causes a 2.72% drop, fly ash results in a 13.16% drop, and coal ash leads to a 15.82% drop[30].

1.4 Various cleaning methods of Solar PV panels

To maximize power output from installed Solar PV systems, it is essential to develop efficient cleaning methods that minimize human intervention [31]. Environmental factors such as wind and glass covers can help reduce the build up of dust particles on the panels [32]. Manual cleaning is effective for rooftop of houses and not suitable for larger solar plants [33].

1.5 Significant Contributions of This Paper Compared to Existing Reviews

*Timely Analysis of PV Cleaning Methods: This paper provides a comprehensive and up-to-date analysis of

photovoltaic (PV) cleaning methods, addressing the latest challenges and advancements through a holistic approach.

*Outlook on Future Scope: The paper outlines future directions and potential advancements in PV panel cleaning

technology, offering insights into how cleaning practices can evolve to meet future demands.

Dust deposition on photovoltaic modules induces partial cell shading, reducing light transmittance and power yield. In Baghdad, performance losses reached 6.24% per day, 11.8% per week, and 18.74% per month under direct solar exposure. [36,37]. As shown in Figure 1 both active and passive dust mitigation methods are discussed in this study. Reference [40] concludes that without cost effective cleaning technique, economic and huge energy losses would be inevitable for solar energy PV plants. The PV panels would give their best performance when the ambient temperature is minimum and solar irradiance is maximum [41]. The most reliable method to maintain the cleanliness of PV panel surfaces is to regularly clean the panels, particularly in regions where dust levels are exceptionally high in the atmosphere [42].

Among various types of dust, ash dust caused the highest reduction in output voltage, with a 25% decrease compared to clean panels [43]. Different factors contributing for dust accumulation are explained [38]. A deep belief network (DBN) model was developed to quantify dust accumulation on PV panels, enabling condition-based cleaning to minimize cost and maximize output. [44].

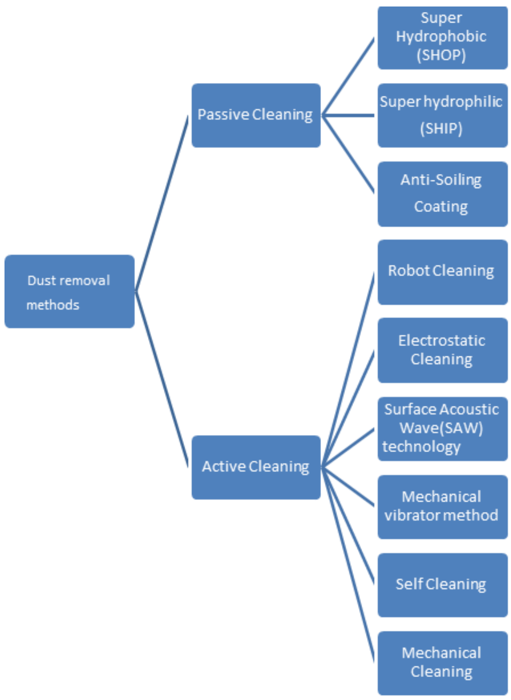

Figure 1 Mitigation strategies for PV panel cleaning system

2. ELECTRICAL SCREENS

The electrostatic cleaning technology can effectively remove dust accumulation, especially in arid regions. Unlike mechanical cleaning methods, which can cause scratches, scars, or surface damage due to intense water pressure or brushes, electrostatic cleaning is a non-contact technology that avoids these risks. Since electrostatic cleaning is automated, it does not require manual labour. Additionally, this method eliminates the need for water, making it a more sustainable option for cleaning PV panels in areas where water is scarce. The principle of electrostatic cleaning is illustrated in Figure 2 [45]. This method is particularly effective in arid, dry, and desert regions [46].

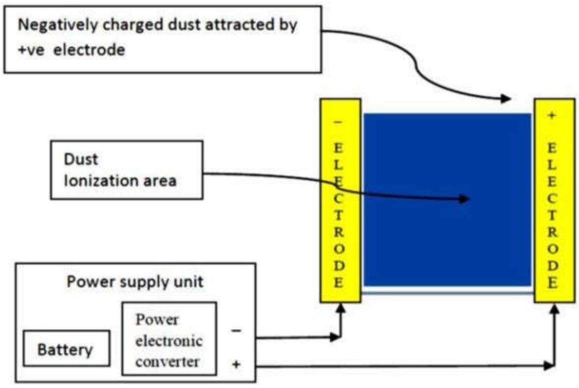

Figure 2 Solar PV panel cleaning using electrostatic principle [45]

3. SURFACE ACOUSTIC WAVE (SAW) TECHNOLOGY USED FOR CLEANING

Surface Acoustic Wave (SAW) and Micro-Electro-Mechanical Systems (MEMS) analyze methods for cleaning solar panels. In the passive method, dust particles are encouraged to slide off the surface by reducing the friction forces or adhesion. Active cleaning employs piezoelectric actuators with multi-contact SAW technology to dislodge dust from PV panel surfaces. [47]. Through the interaction of the SAW, dust particles were successfully removed from the panel surfaces. SAW technology is largely used in particle channellings and precise surface cleaning. The 90dB sound intensity which accompanies SAW is not desirable for continuous cleaning systems [48].

4. SUPER HYDROPHOBIC PLANE (SHOP)

Hydrophobic coatings on PV panels minimize surface adhesion, enabling water droplets to roll off rather than remain attached. Figure 3(a) illustrates how water droplets roll down from the PV surface, which is tilted at a certain angle, similar to how a ball rolls down a slide [49]. PTFE and FluroSurf are hydrophobic anti-dust coatings, which are fluorine-based [48]. UV-induced PV surface degradation can be mitigated using durable coatings or weather-resistant glass. The cleaning method is moderately effective during rain, but it becomes inefficient during dry periods. Dust does not stick to the surface; however, either water or rainfall is needed to remove the dust [49].

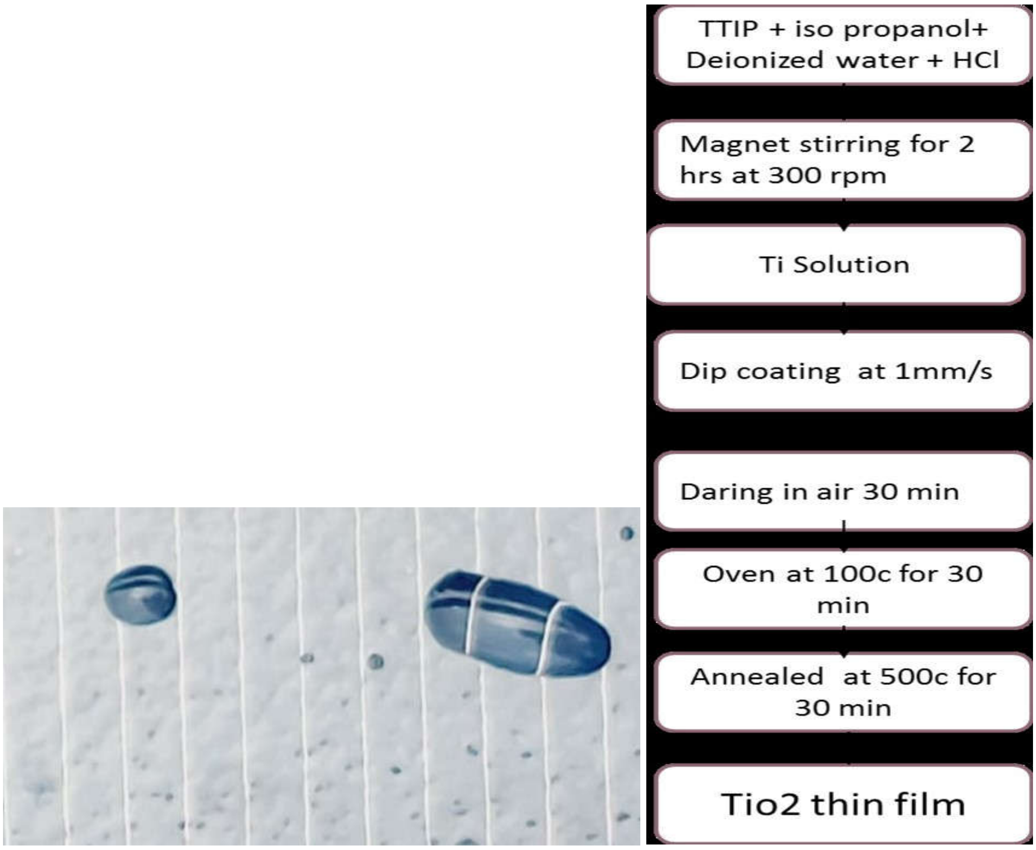

Figure 3 (a) Super hyperbolic Coating

(b) A graphical flowchart summarizes reactions and coating process[50]

5.SUPER HYDROPHILIC PLANE(SHIP)

SHIP can be fabricated using a nano-patterned glass surface and a titanium oxide (TiO_2) nano-film. This method is employed for soiling mitigation with the help of a tailor-made hydrophilic surface [46]. Figure 3(b) discuss that how TiO_2 coating can be done.[50]. While most studies have highlighted the self-cleaning attributes of this method in reducing dust accumulation on PV surfaces, many studies have failed to provide quantitative evidence on the restoration of PV panel efficiency following cleaning [49]. Mechanical vibrator is used on solar PV surface for cleaning the accumulated dust. They utilized wind energy to generate mechanical vibrations. Mechanical vibration applied to PV panels reduces dust adhesion by overcoming particle–surface forces[32].

6. AUTOMATED SOLAR PANEL CLEANING SYSTEM

Automated, waterless PV cleaning systems are vital for enhancing energy yield and ensuring sustainable, cost-efficient maintenance. A notable increase of 35.4 kWh was observed, over the course of month, cleaning resulted in 9.05% increase in energy output (kWh) [46]. To evaluate the effectiveness of the solar panel cleaning robot, a power plant was assessed by comparing two adjacent areas, each containing 40 panels. The results indicate that panels cleaned by the robot experienced a 3.40% increase in electricity production[39].

Figure 4 Automated Solar Photovoltaic Panel Cleaning System

Table 1 Various characteristics of Solar Photovoltaic Panel Cleaning methods

Methods	**Working**	**Energy Consumption**	**Water consumption**	**Advantage**	**Disadvantage**	**Remark**	**Reference**
Electrical Screens	Charges dust particles by generating electric field on the panel	High voltage required	Nil	• Waterless operation • No moving parts • Effective in arid/desert climates • ~90% dust removal in 2 min • Faster than conventional methods • Low power demand	• UV-induced screen degradation • High voltage requirement (≈15% efficiency loss) • Ineffective for wet or cemented dust • Limited removal of fine particles	• Works best in dry climatic conditions • UV protection improves efficiency • Weather proof polymer or glass enhances durability	[46], [35], [49]
Super hyper phobic (SHOP)	•Hydrophobic surface/coating requires no external power • Functions as a protective barrier against contaminants• Water forms spherical droplets due to high contact angle • Droplets roll off, enabling self-cleaning action	Nil	Only rainy water required	• No power is required	• High UV exposure may cause cracks • Efficiency not yet proven in different environments	• Works well in rainy conditions • Less effective in dry climates.	[46], [21], [49]

Super hydro philic(SHIP)	• Super-hydrophilic surfaces are developed using nano-films of titanium dioxide or chemical coatings • Such surfaces create a thin water film that minimizes contact angle • The water layer acts as a medium between dust particles and the PV surface, reducing adhesion	Nil	• Shows moderate cleaning efficiency during rainfall • In arid or dry climates, periodic manual/automated washing is necessary to remove deposited dust	• Provides self-cleaning like SHOP surfaces • UV-induced photocatalytic effect decomposes organic contaminants • Inorganic coating enhances durability compared to polymer-based SHOP • Maintains functionality over longer periods	• UV exposure degrades coating, increasing dust deposition • Moderate cleaning efficiency during rainfall • Requires periodic washing in dry climates.	• Reported to have self-cleaning effect reducing dust deposition • Lacks quantitative data on PV efficiency recovery	[46], [21], [49]
Auto mated cleaning	• Robot employs a vertical brush moving horizontally across PV rows • Integrated water spray system assists in cleaning • Fully autonomous operation for panel maintenance.	Robot needs to be charged	Water based and non- water based cleaning both are there, so it depends	• Water-based robots used in water-rich regions • Non-water robots preferred in water-scarce areas • Low water consumption with non-water systems • Minimal human intervention required	• Panels must be firm and smooth for robot movement • Manual placement needed between panel arrays • Higher maintenance cost	In robot cleaning manual intervention is very much minimized and for the larger solar farms robots are helpful.	[39], [34], [45], [46]

Surface acoustic wave cleaning (SA W)	Piezoelectric actuators generate vibrations These induce surface acoustic wave (SAW) propagation on PV glass covers	Sound waves need to be generated	Nil	PV surfaces require sensitive cleaning Rough mechanical methods may cause damage Can reduce panel efficiency and lifespan	• SAW cleaning less effective for particles <0.2 mm • Smaller particles have higher adhesion forces	• Hybrid cleaning combines acoustic, electrostatic, and hydrophobic methods • SAWs remove larger particles • Electrostatic cleaning effective for finer particles	**[47]**
Sprinklers	Water-based cleaning employs pressurized water jets as the primary medium for removing contaminants from photovoltaic (PV) panels	Power required to fill the water tank, to supply water	More water required	Cleaning is done properly	• High water consumption • Unsuitable in water-scarce regions • Significant water wastage • Cleaning often done at noon/after sunset • Wet surface dries slowly, attracting more dust.	• Improves PV performance • High cost for large-scale installations • Operating cost rises in water-scarce regions	[39], [49]

7. CONCLUSION

Various characteristics of Solar Photovoltaic Panel Cleaning methods are analysed in Table 1. The efficiency of Solar PV panels is significantly influenced by dust accumulation, which remains a critical challenge for maximizing solar energy output. Advanced techniques like electrostatic cleaning and Surface Acoustic Wave (SAW) technology offer innovative, non-contact solutions for arid and dusty environments, while super-hydrophobic and super-hydrophilic coatings provide passive cleaning methods with moderate effectiveness. Mechanical vibration systems powered by renewable energy sources like wind, as well as automated water-free cleaning systems, present sustainable and cost-effective alternatives for maintenance. Manual cleaning, is labour- intensive, water-dependent, and less feasible for large-scale operations. Automated systems and advanced coatings emerge as promising solutions for enhancing PV efficiency while reducing environmental and operational costs.

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