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A Comprehensive Review of Solar Panel Cleaning Systems and Their Impact on Electric Conversion Efficiency

Yogesh N. Nandanwar[1*], Pramod V. Walke[1], Amol D. Pitale[1], Ashish S. Raut[1], Amol Shrikant Chaudhary[1], Swapnil Shedmake[2]

[1] Department of Mechanical Engineering, G H Raisoni College of Engineering, Nagpur, India.

[2] Design Engineer, Safran Engineering Service, Bengaluru, India.

*****Correspondence: yogesh.nandanwar@raisoni.net

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Abstract: The global transition toward renewable energy has positioned photovoltaic (PV) systems as a cornerstone of sustainable power generation. However, the efficiency of solar PV modules is significantly compromised by soiling—the accumulation of dust, dirt, bird droppings, and other contaminants on panel surfaces. This review synthesizes findings from recent literature to examine the multifaceted impact of soiling on PV performance and evaluate the effectiveness of various cleaning methodologies. Soiling-induced power losses range from 5–35% globally, reaching up to 50–65% in arid and desert regions. The adverse effects extend beyond optical obstruction to include thermal stress, hotspot formation, and accelerated material degradation. In this paper, cleaning techniques are classified into conventional techniques such as manual, water-based, brush/wiper systems and advanced techniques such as robotic systems, superhydrophobic coatings, electrostatic screens, and ionic wind technologies. Special emphasis on emerging waterless and contactless technologies tackling water scarcity challenges in prime solar regions. The review concludes that although superhydrophobic coatings provide passive self-cleaning with 90–96% transparency and water contact angles above 150°, the long-term durability is still a problem. Electrodynamic screens have dust removal efficiencies of 80–90% at dry conditions, but their performance decreases at high humidity. Robotic cleaning systems may boost energy yield by 9-35% with a large capital expenditure. The paper concludes with a call for integrated approaches that combine multiple technologies, as well as future research directions in self-healing coatings, predictive cleaning powered by artificial intelligence, and hybrid systems to optimize the trade-off between cleaning frequency, water consumption, and energy gain.

Keywords: Photovoltaic module efficiency; self-cleaning coatings; superhydrophobic surfaces; electrostatic dust removal; robotic cleaning

1. Introduction

1.1. Global Context of Solar Energy

The last decade has seen unprecedented growth in the renewable energy sector, with solar photovoltaic (PV) technology being a major contributor to the global energy mix. According to the International Renewable Energy Agency (IRENA), solar energy is expected to grow the fastest in terms of global renewable capacity during the period of 2020–2050, with the total installed capacity exceeding 8500 GW by 2050 [1,2]. This growth is driven by declining costs, with solar PV costs falling to 0.118 USD/Wp in 2024 from 0.228 USD/Wp in 2023 (representing a 50% reduction), and enabling policies worldwide [3].

These advances notwithstanding, PV systems operate always below their theoretical efficiency limits. Solar cells in the laboratory can reach efficiencies of 20-25%, but real efficiencies in the field are usually 10-18%. This is due to various environmental and operational factors [4,5]. Among these factors, soiling, the accumulation of dust, dirt, pollen, bird droppings and industrial pollutants on the panel surfaces, has been identified as the second most significant cause of energy yield reduction after solar resource variability [6].

1.2 The Soiling Problem: Magnitude and Mechanisms

Soiling is one of the main sources of uncertainty in the production of PV energy. Soiling annual power losses are between 5–25% in the world with more drastic consequences in arid and semi-arid zones. [7,8]. Table 1 summarizes reported soiling losses from various geographical locations.

Table 1. Reported PV efficiency losses due to soiling across different regions

Location	Reduction in PCE	Time Period	Reference
Bahrain	40%	1 year	[9]
Egypt	65.8%	1 year	[10]
India	13%	1 month	[11]
Iraq	40%	1 year	[12]
Kuwait	60%	6 months	[13]
Qatar	10%	6 months	[14]
Saudi Arabia	50%	6 months	[13]
USA	23%	16 months	[15]

The soiling mechanism is the results of several physical processes. Dust particles with diameters of 1–100 μm can stick to the surface of a panel under the effect of van der Waals forces, capillary forces (in humid conditions), and electrostatic attraction. [16,17]. Under dry conditions, the van der Waals forces dominate, while the capillary forces considerably improve the particle adhesion at the relative humidity levels of 40–80%[18]. The fine particles (<10 μm) are particularly problematic because they form dense layers that resist natural removal by wind or rain. [19].

The aim of this review is to give a comprehensive analysis of the current state of solar panel cleaning technologies and their impact on photovoltaic efficiency. Specific objectives are: (1) quantify the effects of soiling on the PV electrical, optical and thermal performance; (2) classify and assess existing cleaning methodologies; (3) critically assess emerging waterless and contactless technologies; (4) identify research gaps and propose future directions.

2. Soiling: Mechanisms, Parameters, and Performance Impact

2.1 Dust Properties and Deposition Mechanisms

The severity of soiling is critically affected by the physical and chemical properties of the dust particles. Detailed characterization studies in different regions indicate that the dust particles are predominantly silica (SiO_2 , 37-80%), calcium oxide (CaO, 3-31%) and aluminium oxide (Al_2O_3 , 8-16%) with varying amounts of carbonates, sulphates and metal oxides.[20-22].

Particle size distribution is very important for their deposition behavior. Particles of 2.5–10 μm diameter are most effective in covering surfaces of PV modules whereas particles <50 μm show a positive correlation between particle size and accumulation rate [23,24]. Fine particles (<10 μm) are difficult to remove, and require wind speeds above 150 m/s to resuspend after cementation [25].

The adhesion forces governing dust deposition can be expressed as [26]:

$$F_{adh}=F_{vdw}+F_c+F_e$$

where F_{vdw} is the van der Waals force, F_c is the capillary force, and F_e is the electrostatic force. At dry conditions van der Waals forces dominate. Above relative humidity of 40% capillary forces are significant due to the formation of liquid bridges between the particles and the surface. [27].

2.2 Key Parameters Influencing Soiling

2.2.1 Tilt Angle and Orientation

Tilt angle of PV modules is an important factor for dust accumulation Studies show that dust deposition density decreases from 15.84 g/m² to 4.48 g/m² as the tilt angle increases from 0° to 90° [28]. In horizontal orientation (0°) dust tends to collect in the middle of the panel, and in vertical panels it tends to collect at the bottom edge [29]. Water droplet runoff during rain or dew events enables self-cleaning patterns at tilt angles larger than 30° [30].

2.2.2 Humidity and Temperature

Relative humidity influences soiling in two ways. At moderate humidity (40-80%) capillary effects increase adhesion forces up to 80%, which promote dust retention [31]. On the other hand, at very high humidity (>90%) surfaces become flooded, thus reducing the capillary forces, and potentially helping natural cleaning [32]. Thermophoretic forces also influence soiling, with lower surface temperatures favoring dust deposition and higher temperatures favoring resuspension [33].

2.2.3 Wind Speed and Rainfall

Wind is a cleaning agent and a dust-transporting agent. Low wind speeds (<3 m/s) are conducive to gravitational settling and dust accumulation, while at high wind speeds (>6 m/s) natural cleaning can occur through aerodynamic shear [28]. The high winds intensify deposition during dust storms. Rainfall can provide a natural cleaning effect, but only heavy rainfall (>20 mm) can remove dust. Light rainfall can worsen soiling by turning dust into mud which sticks firmly [34,35].

2.3 Impact on PV Performance

2.3.1 Optical Effects

The light transmission through the PV cover glass is reduced by the dust accumulation with the absorption and scattering mechanisms. At low to moderate loading, transmittance decreases roughly linearly with dust density, with transmission loss rates of 0.5–2% per g/m^2 of deposited dust [36,37]. Non-uniform soiling results in more severe losses than uniform distribution and the power loss can be twice that of uniform soiling [38].

The spectral dependence of soiling is important. Smaller particles (<10 μm) preferentially attenuate shorter wavelengths (300–500 nm) while larger particles scatter light more uniformly across the visible spectrum [39]. Light absorbing particles (e.g. soot, iron oxides) are more efficient than non-absorbing mineral dust [40].

2.3.2 Electrical Effects

The main electrical effect of soiling is the reduction of the short-circuit current (Isc), because the incident photons are prevented from reaching the solar cell. The uniform soiling does not have a strong impact on Voc, but can reduce under non-uniform soiling conditions due to mismatch losses [41]. Maximum power (P_{max}) reductions of 33 – 43 % have been reported at dust densities of 3.45 g/m^2 depending on dust composition [42].

The degradation of fill factor is mainly ascribed to the increased series resistance due to non-uniform illumination and hotspot formation. Localized shading caused by dust accumulation on the surface may reverse bias the shaded cells. The cells will dissipate power as heat, and they may be permanently damaged [43].

2.3.3 Thermal Effects

Soiling causes changes in the thermal characteristics of PV modules. The dust layers increase thermal resistance and reduce heat dissipation from the module surface. Soiled panels were reported to have temperatures 3–12°C higher than clean panels [44,45]. This temperature rise results in a V_{oc} reduction (generally 0.3–0.5%/°C) and an increase in the degradation of encapsulant materials [46].

There is a problem of hotspot formation. Under non-uniform soiling, shaded cells can reach temperatures above 80 °C while neighboring cells run at normal temperatures (∼45 °C), creating thermal stresses that can lead to cell cracking, solder bond failure and accelerated encapsulant discoloration [47].

3. Classification of Solar Panel Cleaning Methods

Cleaning methods are generally classified into traditional (manual, water-based, mechanical) and advanced (robotic, coating-based, electrostatic, airflow) methods. The full classification scheme is depicted in Figure 1.

3.1 Conventional Cleaning Methods

3.1.1 Manual and Water-Based Cleaning

By far the most usual method is to clean manually with water, detergents and soft brushes or cloths. This method is effective for loose dust but has significant disadvantages: high labor costs (~2000 INR per event in India), high water consumption (0.5–4 L/m² per cleaning), scratching of the surface and safety hazards for rooftop installations [48,49].

Water-based sprinkler systems have potential for automation, but require 2–4 L/m2 per cleaning and pressurized water supplies [50]. Studies demonstrate that cleaning with pressurized water containing surfactants can improve PV efficiency by 3–12% compared to clean bare panels, but efficiency gains diminish over time due to rapid dust re-accumulation [51].

3.1.2 Brush and Wiper Systems

For cleaning with a brush to remove dust and bird droppings that have adhered, nylon or silicone rubber or microfiber brushes work well. Efficiency improvements of 30–35% over uncleaned controls have been reported for brush-cleaned panels [52]. But improper brush selection can lead to micro-scratches on the surface of the glass, which over long-term use can decrease transmittance by 2-5% [53].

Wiper systems, like automobile windscreen wipers, have a water-free alternative. Linear piezoelectric actuators can move wipers on panel surfaces at forward speeds up to 117 mm/s, providing cleaning with minimal water [54]. However heavy soiling is a problem for wiper systems and the blades also have to be replaced regularly .

3.2 Advanced Cleaning Technologies

3.2.1 Robotic Cleaning Systems

The most advanced traditional option is robotic cleaners that are automated. These systems combine brushes, microfiber cloths, air blowers, and sensors for thorough cleaning with minimal human input. Commercial systems have reported dust removal efficiencies of 80-99% with cleaning times of 7-10 minutes per panel [55,56].

Ecoppia's water-free robots clean 99% of dust using microfiber and airflow, keeping optimal power output without water, and are used at multiple solar farms in the Middle East [57]. However, the initial capital cost (~$15,000–20,000 per unit) and ongoing maintenance requirements limit the widespread adoption [58].

3.2.2 Superhydrophobic and Superhydrophilic Coatings

Passive self-cleaning coatings have attracted considerable interest in research for maintenance-free operation. Superhydrophobic lotus leaf effect-based coatings can reach water contact angles (WCA) >150° and sliding angles <10°, which causes water drops to slide away from the surface with dust particles [59].

The Cassie-Baxter model describes the wetting state of superhydrophobic surfaces [60]:

$$\cos\theta^{*} = -1 + \phi_s(1 + r\phi\cos\theta_{eq})$$

where θ^* is the apparent contact angle, ϕ_s is the solid fraction, $r\phi$ is the roughness ratio, and θ_{eq} is the equilibrium contact angle on a smooth surface.

Recent advances in transparent superhydrophobic coatings have achieved transmittance of 90–96% while maintaining WCA >150° [61-63]. Table 2 summarizes representative studies.

Table 2. Representative transparent superhydrophobic coatings for PV applications

Coating composition	Method	WCA (°)	Transmittance (%)	Durability	Ref.
SiO_2/PDMS	Spin-coating	158	80	450°C stability	[64]
PMMA/SiO_2	Dip-coating	174	85	380°C, UV stable	[65]
PDMS/Zn-SiO_2	Spray-coating	117	>90	7 weeks, 0.4% loss	[66]
TEOS/ODTMS	Sol-gel	168	90	30 tape cycles	[67]
PTFE	AACVD	168	92	12 mL water impact	[68]

Superhydrophilic coatings mainly based on TiO_2 work on a different mechanism. TiO_2 shows photo-induced superhydrophilicity (WCA <5°) and photocatalytic activity for the degradation of organic contaminants under UV irradiation [69]. Hydroxyl radicals (OH) and superoxide radicals (O2−) are produced in the photocatalytic reaction and oxidize organic pollutants to CO2 and H2O [70]. However, the wide bandgap (3.2 eV) of TiO_2 limits its activation to UV light (∼5% of the solar spectrum) but its activity can be extended in the visible range by doping with metals or non-metals [71].

3.2.3 Electrodynamic Screen (EDS) Systems

Electrodynamic screens use electric fields to repel charged dust particles without physical contact. The system is composed of parallel transparent electrodes (usually ITO, FTO or AgNW) embedded in a dielectric layer. Application of a multi-phase AC voltage results in travelling waves that transport the charged particles to the edge of the panel [72,73].

The electrostatic force on charged particles is given by [74]:

$$F_e = q_p E$$

where q_p is the particle charge and E is the electric field strength. For spherical dielectric particles, the saturation charge follows the Pauthenier equation [75]:

$$q_{ps} = 4\pi\varepsilon_o R_p^2 \left(\frac{3\varepsilon_r}{\varepsilon_r + 2} \right) E_c$$

EDS systems achieve dust removal efficiencies of 80–90% in dry conditions with power consumption <0.2 Wh/m² per cleaning cycle [76]. However, performance degrades under high humidity (>60% RH) and for particles <10 μm diameter [77]. Field tests in Saudi Arabia showed cleaning efficiency dropping from 98% in laboratory settings to ∼32% after 458 days of outdoor exposure [78].

3.2.4 Ionic Wind and Airflow Cleaning

Ionic wind generators based on corona discharge produce airflow by colliding ions with neutrals. Using a wire-plate electrode configuration (wire radius 100 µm, spacing 3 cm) at -25 kV, air velocities of ∼2 m/s are obtained, achieving cleaning efficiencies up to 95% with power consumption of ∼20 W [79,80].

The electrohydrodynamic (EHD) force driving the ionic wind is [81]:

$$F_{EHD} = \rho_c E$$

where ρ_c is the space charge density. Numerical modeling shows that the Coulomb force dominates particle motion inside the blower, while drag and gravitational forces govern transport outside [82].

Another method that does not require water is the use of airflow cleaning with compressed air or drone propellers. It has been shown that cleaning with compressed air can restore 30–36% of the lost power. Cleaning with drones can reach 69% dust removal efficiency with horizontal flight patterns [83,84].

3.2.5 Ultrasonic and Vibrational Cleaning

Vibration based cleaning utilizes inertial forces to break particle adhesion. The dust removal rate was 90% in 60 s with a power consumption of 261 W for piezoelectric actuators working at 2–3 kHz [85]. The critical acceleration for particle detachment depends on the adhesion forces and on the particle mass [86]:

$$a_{crit} = \frac{F_{adh}}{m_p}$$

Chladni patterns in which nodal lines steer particles to particular points have been employed to clean dust from the solar panels of the Mars rovers without high voltage supplies, using vibration [87].

4. Comparative Analysis of Cleaning Technologies

4.1 Performance Metrics

Table 3 presents a multi-dimensional comparison of cleaning technologies based on cleaning efficiency, cost, water consumption, energy use, and durability.

Table 3. Comparative analysis of solar PV cleaning technologies

Technology	Cleaning Efficiency	Water Usage (L/m²)	Energy Consumption	Cost (relative)	Durability	Automation Level
Manual water cleaning	Moderate (60-80%)	0.5-4	Low (labor)	Low (operational)	N/A	None
Water sprinkler	High (80-95%)	2-4	Moderate	Moderate	N/A	Semi
Brush cleaning	High (85-95%)	0-0.5	Low	Moderate	Mechanical wear	Semi
Robotic systems	Very high (90-99%)	0-1	Moderate (2.1 Wh)	High (capital)	Good	Full
Superhydrophobic coating	Moderate (60-80%)	0 (passive)	None	Low-moderate	3-5 years	Passive
Electrodynamic screen	High (80-90%)	0	0.2 Wh/m²	High	Limited	Full
Ionic wind	High (85-95%)	0	20 W	Moderate	Good	Full
Ultrasonic vibration	High (90%)	0	261 W	Moderate	Good	Full

4.2 Cost-Benefit Analysis

The economics of cleaning technologies depend on local conditions such as electricity tariffs, water costs, labor rates and soiling rates. The levelized cost of cleaning for a typical 50 MW utility scale plant in a high-soiling region (daily efficiency loss of 0.2–0.5%) ranges from 0.07–0.33 Euro/W for tracking systems to 0.36–1.89 Euro/m2/year for hydrophobic coatings [88,89].

A data-driven predictive cleaning scheduler, the Opti-Clean framework, demonstrates that optimized cleaning can reduce cleaning frequency by 88.89% while maintaining energy yield, with annual savings of £44,000 in cleaning costs for a 24 kW system [90]. The aim is to minimize the total cost [91]:

$$\min\left[C_{total}(n) = n.C_{clean} + \rho\sum_{t=1}^{T}\left(P_{\max} - P_{actual}\left(\mathrm{t},\mathrm{D}_t\right)\right)\Delta T\right]$$

5. Challenges and Future Directions

5.1 Current Limitations

5.1.1 Coating Durability

Superhydrophobic coatings have been successful in laboratory applications, but durability under field conditions is a major concern. Accelerated ageing tests show that the coating performance is degraded by UV exposure, temperature cycling and abrasion by windblown sand in 3-5 years, which is much shorter than the 25-year PV module lifespan [92,93]. Five-year field studies in different climates show no significant improvement in dust removal of coated modules over uncoated controls, with degradation mechanisms that differ by location (fungal contamination in humid areas, mechanical abrasion in arid regions) [94].

5.1.2 EDS Performance Gaps

Electrodynamic screens work well in the laboratory, but perform poorly in the field. The performance reduction with repeated use, the difficulty in removing water-soluble binder particles, and the inhomogeneous dust deposition leading to inconsistent cleaning are still to be solved [95]. The efficiency of EDS is also dependent on the tilt angle of the panel with an optimal angle being >20° [96].

5.1.3 Water Scarcity vs. Cleaning Requirements

The maximum amount that water-scarce areas are those with maximum solar irradiance, the arid and semi-arid regions. The adoption of conventional water-based cleaning requires 7000–200,000 L per MW per wash, which is not sustainable in desert environments [97]. This paradox is the reason for the urgency to develop effective waterless technologies.

5.2 Emerging Research Directions

5.2.1 Self-Healing and Bio-Inspired Coatings

A promising direction is the development of self-healing superhydrophobic coatings that can restore the surface structure after damage. Superhydrophobicity can be recovered in polymer brushes and fluorinated ionic liquid-infused slippery surfaces after mechanical abrasion or chemical damage [98,99]. The insensitivity to abrasion, instead of surface-only features, of bulk material properties of phase-separated glass coatings with interpenetrating nanostructures [100].

5.2.2 AI-Driven Predictive Cleaning

Machine learning models can combine environmental data (PM2.5, PM10, wind speed, humidity) with PV performance metrics to help achieve optimized cleaning schedules. Random Forest and Decision Tree regressions succeed in obtaining R2 values of 0.96–0.997 for the prediction of power losses due to soiling [90,101]. Multi-modal deep learning frameworks with visible and infrared images can classify soiling severity with an accuracy of 88.27% [102].

5.2.3 Hybrid and Multifunctional Systems

Multiple cleaning mechanisms are integrated for synergistic advantages. Superhydrophobic coatings combined with EDS reduce the voltage for dust removal by decreasing the adhesion forces [103]. Dual-layer coatings combining antireflective and self-cleaning properties achieve transmittance >98% with WCA >150° [104].

5.2.4 Standardization and Testing Protocols

There are no standard testing protocols to compare across studies. Recent efforts have developed sequential laboratory test methodologies that simulate natural soiling processes (deposition, cementation, dew cycles) to predict field performance [105]. Accelerated ageing standards (IEC 61215, IEC 62788-7-3) exist to assess durability, but they need to be developed for some cleaning technologies.

6. Conclusions

This exhaustive review of solar panel cleaning systems and their impact on the efficiency of photovoltaic power generation leads to the following conclusions:

- Soiling severity varies dramatically by location with annual efficiency losses of 5–25% worldwide and 40–65% in desert areas. The strongest van der Waals and capillary adhesion forces are responsible for the most persistent soiling by fine particles (<10 μm).
- No single cleaning technology optimally addresses all operating conditions. Conventional water-based cleaning is highly effective, but unsustainable in water-scarce regions. Robotic systems are better cleaners but require a large capital investment. Passive coatings are maintenance free but suffer from durability limitations.
- Superhydrophobic coatings represent the most promising passive solution, WCA >150° and transmittance >90% by suitable nano structuring. The critical challenge limiting its widespread adoption, however, is long-term durability under UV exposure, temperature cycling and mechanical abrasion.
- Electrodynamic screens demonstrate excellent dry-cleaning capability (80–90% efficiency) but require further development to address performance degradation under humid conditions and with fine particles.
- Data-driven predictive cleaning optimization can reduce cleaning frequency 80-90% at the same energy yield, with significant economic benefits (40-45% reduction in soiling related losses).
- Future research should prioritize self-healing coating materials, AI-enabled predictive systems, hybrid cleaning technologies, and standardized field-testing protocols to bridge the gap between lab demonstrations and commercial deployment.

Moving to sustainable solar energy does not just mean efficient photovoltaic cells, but also novel maintenance techniques that maximize energy output with less resource use. The most promising path ahead to optimize PV performance under various environmental conditions is to use integrated approaches combining passive anti-soiling surfaces with intelligent, data-driven cleaning scheduling.

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Conflicts of Interest

The author declares no conflicts of interest.

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