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Research Article

Research progress and development trends in photovoltaic desertification control and photovoltaic dust removal technologies

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Abstract. Against the backdrop of the global energy transition, photovoltaic (PV) power generation has expanded rapidly worldwide. In China, the integration of photovoltaic systems with desertification control has generated substantial environmental and economic benefits, contributing simultaneously to renewable energy development and ecological restoration. However, severe dust accumulation on PV installations in desert regions significantly reduces power generation efficiency, increases maintenance costs, and shortens system lifespan, creating major operational and environmental challenges. Consequently, there is an urgent need to develop efficient and sustainable dust removal technologies that can improve power generation efficiency, conserve scarce water resources, and minimize environmental impacts in desert environments. This study systematically reviews recent advances in photovoltaic desertification control and dust mitigation technologies for PV power plants located in deserts, Gobi, and other barren lands. First, the development of PV-based desertification control technologies is reviewed, and their environmental and ecological achievements are summarized. Second, the mechanisms of dust accumulation and their impacts on PV performance are examined, with particular emphasis on the influence of environmental factors such as wind speed, humidity, dust characteristics, and panel tilt angle. Third, existing dust removal technologies—including robotic and mechanical cleaning systems, as well as coating-based and non-contact cleaning technologies—are comprehensively reviewed and critically discussed. Finally, future research directions and technological trends in PV desertification control and dust mitigation are presented to support the sustainable development of photovoltaic energy systems and environmental protection. This review provides valuable insights for researchers, engineers, and PV plant operators by improving the understanding of dust accumulation mechanisms in desert photovoltaic systems, evaluating advanced robotic and autonomous cleaning technologies, identifying emerging self-cleaning solutions, and highlighting strategies for enhancing the long-term efficiency, reliability, and sustainability of large-scale desert PV installations.

Keywords: photovoltaic power station, PV desert control, dust accumulation, dust removal technology, robotic cleaning, self-cleaning coating

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1. Introduction

Against the backdrop of the global energy transition, photovoltaic (PV) power generation has entered a phase of rapid exponential expansion. According to statistics from China's National Energy Administration, China added 277.57 GW of newly installed PV capacity in 2024, representing a year-on-year growth of approximately 28.3% (Wang, 2025). By the end of 2024, China's cumulative installed PV capacity had reached 886 GW (Fig. 1a). Globally, new PV installations in 2024 reached 530 GW—a 35.9% increase year-on-year—with China accounting for 52.4% of this total (Fig. 1b). Global annual PV installation capacity is projected to continue rising rapidly in the coming years. Photovoltaic sand prevention and fixation represent an innovative practice in China's coordinated strategy for renewable energy development and ecological governance. By combining ecological, economic, and social benefits, this approach holds profound significance for environmental restoration. Photovoltaic panel coverage effectively reduces surface wind speeds, thereby minimizing sand movement and preventing wind erosion. Furthermore, the shade provided by the panels lowers ground temperatures and reduces soil water evaporation, indirectly enhancing soil moisture and creating favorable conditions for plant growth. Many PV projects adopt a "power generation above, ecological restoration below" model. Drought-tolerant plants cultivated beneath and between the panels form localized ecological oases; their root systems stabilize shifting sand, while decomposing organic matter gradually improves soil quality and restores desert ecosystem functions. Most large-scale PV power plants in arid regions are situated in deserts characterized by frequent sandstorms, sparse vegetation, and harsh environmental conditions. Dust accumulation on PV module surfaces severely reduces light transmittance, diminishing the effective solar radiation received by the panels and degrading their photoelectric conversion efficiency. Ultimately, this leads to significant power output losses. Consequently, the impact of surface dust accumulation on power generation has gained increasing attention from plant operators, and module dust cleaning techniques have become a focal point for researchers and engineers alike. This growing focus stems from the critical need to maintain optimal energy yield in challenging environments where natural dust deposition poses a

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persistent operational hurdle (Parsay et al., 2025). Therefore, this study systematically reviews recent research progress in PV desert control and dust removal technologies for solar power plants in desert and wasteland regions. First, advances in PV desert control technologies are reviewed, and key achievements are summarized. Second, the mechanisms of dust accumulation and methods for evaluating efficiency losses under various environmental factors are analyzed. Third, cleaning technologies—including robotic/mechanical systems as well as self-cleaning coatings and non-contact methods—are evaluated in detail. Finally, future research trends in PV desert control and dust removal technologies are outlined to support the sustainable development of solar energy and ecological protection.

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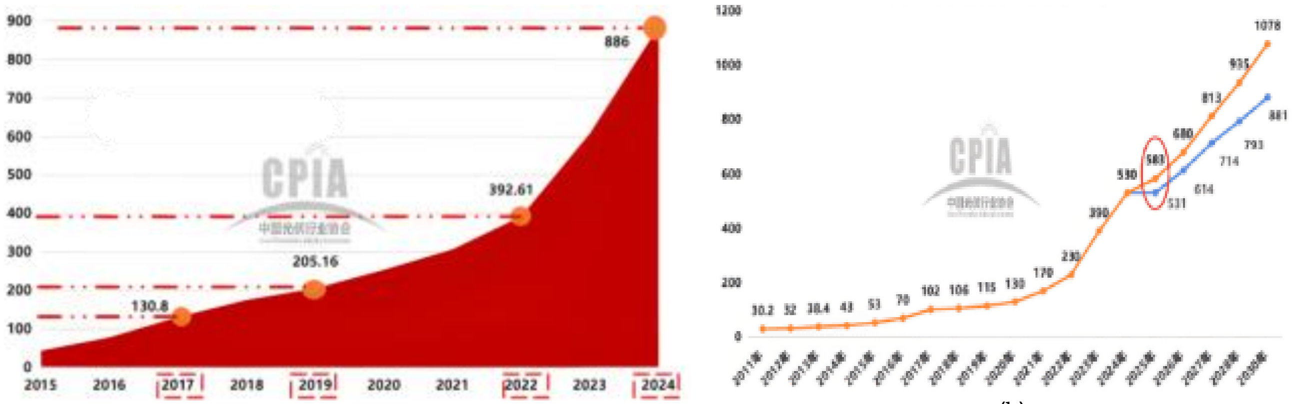

(a) (b)

Figure.1(a). Installed capacity of China's photovoltaic power (GW), (b) Annual global photovoltaic installation capacity (GW)

2. Progress and achievement of photovoltaic desert control

The large-scale construction of PV power stations in regions with superior solar and thermal conditions, low-cost land, and arid to semi-arid climates has spurred the development of PV-based sand control and fixation technologies. The establishment of renewable energy mega-bases in deserts, gobi, and barren lands integrates PV power generation, desertification control, and water-saving agricultural technologies. This model leverages the abundant solar resources in deserts to produce green electricity while employing multi-scale spatial layouts of engineering and ecological measures to combat desertification and improve the ecological environment.

2.1 Progress of photovoltaic desert control technology

Wang et al. (2017) evaluated three desert industry models in the Kubuqi Desert using Data Envelopment Analysis (DEA). Their results indicated that the PV power generation integrated utilization model and the ecotourism model achieved the highest comprehensive input-output efficiency. Based on these findings, the authors identified key operational challenges in the "Kubuqi Model" and proposed future development strategies and countermeasures for desert industries. Guo et al. (2017) reviewed various ecological and engineering approaches in the Kubuqi Desert, including plant-engineering sand control, comprehensive sand-fixation forest protection, composite intercropping, sand and photovoltaic industry models, the Engebe model, the Sichuan Road cutting and zoning management model, and the Fengshui Ridge model. The authors highlighted that aerodynamic disturbances caused by PV infrastructure can trigger secondary wind-and-sand hazards—such as severe surface erosion and inter-panel sand accumulation—which urgently require targeted mitigation strategies. Chang et al. (2018) investigated the ecological roles of PV power stations in the desert and Gobi regions of the Hexi Corridor, analyzing their contributions to desertification control and sand stabilization. The study revealed that PV infrastructure in arid landscapes fulfills critical ecological functions through three primary mechanisms:

- Solar Energy Conversion and Thermal Regulation: By converting solar radiation and regulating thermal balance, PV systems attenuate the thermodynamic drivers of sandstorms and aeolian sand flows.
- Windbreak and Sand Barrier Effects: PV arrays act as physical barriers, suppressing wind erosion and stabilizing mobile sand dunes.
- Rainwater Harvesting for Vegetation: System infrastructure facilitates localized rainwater interception, increasing soil moisture availability to support plant growth in hyper-arid conditions.

Dang et al. (2019) examined the topsoil (0–5 cm sediment layer) of a PV power station on the southern margin of the Kubuqi Desert to assess how PV infrastructure influences wind-driven sediment particle size distribution. The sediments beneath the PV array consisted primarily of fine and medium sand. The physical blocking effect of the panels increased the proportion of ultrafine and fine sand while reducing medium sand content. Sediment characteristics on the windward side fluctuated significantly, featuring a higher deposition frequency, a smaller average particle size than on the leeward side, and a overall trend toward coarse granularization. Consequently, protective measures—primarily focused on the windward boundary—are essential to prevent coarse granularization and inter-panel sand accumulation. Wang et al. (2019) investigated critical engineering aspects of desert PV power plants, including site selection, structural design planning, scientific management, and ecological rehabilitation. The authors demonstrated that integrating these design factors promotes vegetation recovery, improves soil quality, and enhances microclimatic conditions in desertified areas. Zhang et al. (2020) conducted field surveys and sample collection across typical desert and Gobi PV power stations in the Hexi Corridor to evaluate plant species diversity across different spatial zones (beneath panels, between panels, and outside arrays). Their research mapped the spatial patterns of plant diversity, illustrating how infrastructure placement modulates localized ecological dynamics in fragile ecosystems.

Wang et al. (2020) selected five established PV bases in the desert–Gobi regions of the Hexi Corridor, using adjacent natural desert vegetation as a baseline reference. They performed a comparative analysis of the spatiotemporal variation in solar radiation utilization and solar energy conversion efficiency between PV arrays and native vegetation. The results demonstrated that large-scale solar conversion by PV facilities significantly alters surface temperatures and thermal balance. This thermal regulation stabilizes surface energy fluxes, serving as an effective mechanism to mitigate sandstorm initiation and development in arid zones. Shi et al. (2020) investigated the impact of reed sand barriers deployed within PV power stations on wind speed, sand transport volume, and particle size distribution. Their findings confirmed that reed barriers significantly reduce near-surface wind speeds, suppress aeolian sediment transport, and efficiently intercept and redistribute drifting sand. This dual windbreak and sand-stabilization approach provides a cost-effective protective measure that balances ecological restoration with infrastructure protection in sandstorm-prone regions.

The Dalate Photovoltaic Base in the Kubuqi Desert exemplifies the synergistic integration of solar power generation and desertification control. By embedding environmental remediation into energy production, the project fulfills a dual mandate of renewable energy generation and ecosystem restoration. Sand stabilization and ecological rehabilitation serve as operational prerequisites for infrastructure stability in harsh, windy environments. In turn, sustained PV project operations generate a positive spillover mechanism for green benefits, including enhanced regional biodiversity, increased carbon sequestration, and favorable microclimate regulation (Chanchangi et al., 2020). To analyze near-surface aeolian sand transport dynamics under structural disturbances from PV arrays, Tang et al. (2021) conducted field measurements at a 200 MW PV power station in the central Kubuqi Desert. They quantified sand transport rates across uncovered mobile dunes (upwind control areas) and specific structural zones within the array interior. By assessing the overall sand-blocking efficiency and airflow heterogeneity across varying wind speeds and directions, the study elucidated post-deployment sediment transport dynamics, offering a mechanistic foundation for optimizing secondary sand hazard prevention strategies.

Yao et al. (2023) explored potential water sources supporting weed growth in desert–Gobi PV power plants in northwestern China, analyzing the mechanisms driving the "bidirectional canopy effect." In summer, PV shading significantly lowers surface soil temperatures, reducing weed evapotranspiration demand. In colder seasons, the thermal insulation of the panels retains shallow soil moisture and prevents deep freezing, thereby sustaining ruderal vegetation survival year-round. Yao et al. (2022) conducted a microclimatic analysis at the Gulang Zhenfa PV Power Plant in Gansu Province, quantifying differences in air temperature, wind speed, and solar radiation inside versus outside the PV array. In the sandstorm-prone Hexi Corridor, PV arrays reduced temperatures at a 10-meter height during spring (the peak sandstorm season), effectively weakening convective uplift forces and mitigating the thermodynamic drivers of sandstorm formation.

Finally, Wu et al. (2024) synthesized research on the ecological, environmental, and biodiversity impacts of solar energy projects. To maximize green benefits and mitigate environmental risks, the authors recommended: Rigorous site selection and scientific project planning; Enhanced design for biodiversity conservation, material recycling, and solid waste management; Robust environmental impact assessments (EIAs), soil erosion control programs, and ecological restoration initiatives; and Expanded development of rooftop PV, floating solar installations, and agrivoltaic technologies.

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(a) (b)

Figure.2 (a). photovoltaic power in sand areas (initial installation) (b) photovoltaic desert control results (In a few years)

2.2 Current achievements of photovoltaic desert control

The development of photovoltaic (PV) industries in desert and Gobi regions not only generates substantial economic benefits but also plays a crucial role in ecological restoration and desertification control. As illustrated by the comparison between Figures 2a and 2b, areas that were once barren deserts have gradually been transformed into vegetated landscapes after several years of PV operation. Given China's vast desert and Gobi resources, the potential for further PV expansion is considerable. PV-based desert restoration is expected to become the third major approach to sand control, complementing afforestation and mechanical sand barriers.

a. Large-Scale Demonstration Projects

- Kubuqi Desert: The PV ecological project developed by Elion Group has restored approximately 100,000 mu of desert land, increased vegetation coverage from 3% to 65%, and sequesters more than 200,000 tons of carbon annually.

- Talatan, Qinghai: Home to one of the world's largest PV industrial parks, covering 609 km², the project has reduced wind speed by over 50%, restored forage coverage to 80%, and successfully integrated photovoltaic power generation with sustainable livestock farming.

b. Technological Innovation and Integrated Development

Recent technological advances have enhanced the efficiency and sustainability of desert PV systems. Intelligent operation and maintenance (O&M), including drone-based inspections and robotic cleaning systems, have reduced maintenance costs while improving power generation under dusty conditions. Meanwhile, integrated ecological models—such as photovoltaic agriculture, livestock grazing, and water-saving systems—have been widely implemented in provinces including Gansu and Ningxia, promoting coordinated industrial and ecological development.

c. Economic and Social Benefits

By 2024, China's installed PV capacity in desert regions exceeded 90 GW, generating approximately 180 billion kWh of electricity annually and reducing carbon dioxide emissions by more than 250 million tons each year. In addition, PV-based desertification control has created employment opportunities for over 100,000 people in regions such as Inner Mongolia and Xinjiang, contributing to rural revitalization. Many local households have increased their income through power plant maintenance and agricultural activities beneath PV panels.

d. Policy Support and Global Significance

The Chinese government has introduced a series of policies to regulate land use for PV ecological projects and accelerate the development of renewable energy bases in deserts, the Gobi, and other arid lands. China's successful experience has also been recognized by the United Nations Convention to Combat Desertification (UNCCD) as a model for sustainable desert restoration, providing valuable technical references for countries in Africa, the Middle East, and other regions affected by desertification.

The integration of photovoltaic systems with ecological restoration demonstrates that renewable energy development can simultaneously enhance energy security, mitigate climate change, restore degraded ecosystems, and promote sustainable socio-economic development. China's large-scale desert PV projects provide a successful model for balancing environmental conservation with clean energy production.

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3. Dust accumulation effects and efficiency loss assessment

In desert regions, such as the Middle East and North Africa (MENA) and the deserts and Gobi areas of northwestern China, large-scale photovoltaic (PV) power plants are among the most important infrastructure projects. Post-construction maintenance of PV power plants in these regions is a critical factor determining their efficient operation. Among these challenges, dust accumulation on the surface of PV modules significantly constrains the power generation efficiency of photovoltaic stations. Consequently, PV module dust removal technology stands as a vital technical solution for improving operational efficiency in such power plants (Cui, Y.Q., Sun, J.H., Xiao, J.H. 2021.].

3.1 Quantitative analysis of dust types and efficiency loss

Chanchangi et al. (2020) reviewed the effects of dust accumulation on photovoltaic (PV) performance and corresponding mitigation strategies, with particular emphasis on Nigeria, a region characterized by high solar energy potential but severe dust contamination. The review examined dust generation mechanisms (e.g., sandstorms and industrial emissions), transport and deposition processes (including dry and wet deposition), and the influence of particle size, chemical composition, and meteorological factors such as humidity and wind speed on PV efficiency. The authors highlighted that Nigeria's proximity to the Sahara Desert substantially increases PV performance losses due to frequent sandstorms and seasonal dust events, emphasizing the need for region-specific studies to optimize cleaning strategies. Said et al. (2024) conducted a systematic review of dust-induced PV performance degradation and cleaning technologies under diverse environmental conditions. Their analysis demonstrated that daily energy losses caused by dust deposition range from 2.8% to 50% across regions including the Middle East, Asia, and Australia. The severity of contamination depends on particle size, ambient humidity, and geographical characteristics. Furthermore, mathematical models confirmed that electrostatic dust removal and self-cleaning technologies provide effective, water-efficient alternatives to conventional cleaning methods, particularly in arid environments. Kazem and Chaichan (2019) performed a year-long field investigation of environmental factors affecting PV soiling and cleaning efficiency at six locations in northern Oman. The results showed substantial efficiency losses in industrial areas (e.g., Sohar) and high-traffic urban environments (e.g., Muscat), where fine particulate matter (PM) and chemical pollutants accumulated on PV surfaces. Conventional water cleaning was insufficient in highly polluted areas, requiring sodium-based cleaning solutions, whereas water alone was adequate in low-pollution locations such as Shinas. The study also found that humidity and nocturnal condensation promoted salt crystallization, producing persistent residues, while wind and rainfall contributed to natural cleaning. Jiang et al. (2018) developed a particle resuspension model to investigate wind-induced dust removal from flat PV surfaces. By integrating adhesion, hydrodynamic drag, and rolling detachment models, the study quantified the minimum shear velocity and corresponding wind speed required to remove particles ranging from 0.1 to 100 μm. The results indicated that particles larger than 1 μm can be readily removed by wind, whereas smaller particles remain strongly adhered to the surface. Dust composition had only a negligible effect on particle removal efficiency. Kayri and Tan Bayar (2024) proposed an artificial neural network (ANN)-based approach to predict long-term efficiency degradation of PV modules caused by clay, calcareous, and urban dust. Experimental results showed efficiency losses of 18%, 26%, and 28%, respectively, after one month of exposure, increasing to 67%, 77%, and 78% after six months. These findings identified urban and calcareous dust as the most detrimental contaminants. Yakubu et al. (2025) investigated the impacts of dust accumulation on PV performance by analyzing environmental variables (wind speed, humidity, and precipitation) and dust composition (e.g., coal, sand, and gypsum) across different climatic regions. The study reported efficiency losses ranging from 10% in temperate climates to 64% in coal-rich environments. It further emphasized the importance of installation parameters, including panel tilt angle and orientation, together with local microclimatic conditions, in determining soiling severity. Appropriate cleaning strategies and optimized system design were recommended to mitigate annual energy losses, which may reach 40% in arid regions.

Chanchangi et al. (2020) also conducted controlled indoor experiments to evaluate the influence of dust characteristics and PV cover materials on soiling behavior. Thirteen dust types, including charcoal, bird droppings, cement, and salt, were deposited on acrylic and low-iron glass surfaces. Charcoal caused the greatest reduction in short-circuit current (98%), whereas salt produced the smallest reduction (7%). Acrylic surfaces accumulated dust more readily than low-iron glass, and wet deposition resulted in stronger particle adhesion than dry deposition. Huang et al. (2022) investigated the role of organic matter in dust adhesion under condensation conditions using dust samples collected from five representative environments, including deserts and rooftops. Their results showed that anthropogenic activities significantly increased the organic content of deposited dust. Organic compounds, together with condensed moisture, formed interfacial films that enlarged the contact area and enhanced adhesion to silica-based PV glass through hydrogen bonding. Hachicha et al. (2019) examined the effects of dust accumulation on PV performance under the climatic conditions of Sharjah, United Arab Emirates. Dust density exhibited a linear negative relationship with power output, with approximately 1.7% power loss per 1 g m^{-2} increase in dust deposition. Outdoor experiments showed power reductions of 37.63%, 14.11%, and 10.95% at panel tilt angles of 0°, 25°, and 45°, respectively. After five months of exposure, dust density reached 5.44 g m^{-2}, resulting in a 12.7% reduction in power output. The study confirmed that both dust characteristics and meteorological conditions jointly determine PV performance degradation. Zaghba et al. (2024) combined experimental measurements with numerical simulations to evaluate the effects of dust deposition and sandstorms on PV power plants in arid environments. Comparisons between clean and dust-contaminated systems demonstrated substantial monthly reductions in energy yield, conversion efficiency, and performance ratio, highlighting the cumulative impact of dust under desert conditions. Lenka et al. (2024) investigated the effects of eight different dust types, including ash, laterite, cement, and sand, through combined indoor and outdoor experiments. Dust accumulation reduced light transmittance and caused partial shading, leading to significant power losses. Under irradiance levels of 500–1000 W m^{-2}, ash produced the greatest indoor power loss (39.21%), whereas laterite caused the smallest reduction (8.32%). Outdoor experiments identified laterite, sand, and brick dust as the most influential contaminants under natural exposure.

Zhao et al. (2021) investigated particle deposition mechanisms and their influence on PV soiling. By analyzing particle collision dynamics, the authors proposed an energy-based deposition criterion and developed a numerical model that was subsequently validated through experiments. Their results demonstrated that dust accumulation has a greater impact on optical transmittance than on electrical conversion efficiency. Song et al. (2025) experimentally investigated the effects of partial shading caused by dust and external obstructions on PV energy output and module temperature. The study demonstrated that the location of shading significantly influences system performance, with central and lower-panel shading producing the largest power losses and highest thermal risks. A quantitative model relating shaded area, power loss, and temperature rise was proposed, highlighting the implications of dynamic shading for PV reliability and fire safety. Hu et al. (2025) developed a numerical model incorporating multiple dust deposition mechanisms. The model integrated adaptive descriptions of temperature, humidity, capillary forces, surface roughness, and rainfall dynamics into a three-dimensional particle deposition framework, providing a more comprehensive simulation of PV soiling under realistic environmental conditions. Guo et al. (2024) investigated the dual mechanisms by which dust accumulation affects PV performance by simultaneously considering optical attenuation on the front surface and thermal regulation through the module backsheet. The study identified a critical cleaning threshold of 5.83 g m^{-2} for rooftop PV systems in Hohhot, demonstrating the interaction between solar radiation attenuation and thermal buffering, thereby providing guidance for intelligent cleaning strategies. Fountoukis et al. (2018) combined a 12-month field monitoring campaign with a three-dimensional aerosol dispersion model to evaluate the effects of desert dust on PV electricity generation. Although PM_{10} concentration showed only a weak correlation with efficiency loss, aerosol mass concentration and ambient humidity exhibited nonlinear relationships with output degradation. The study also demonstrated regional differences in dust distribution and suggested that floating PV systems could reduce dust deposition by approximately 28%. Paudyal and Shakya (2016) evaluated the influence of dry-season dust accumulation on off-grid PV performance in Kathmandu, Nepal. A five-month outdoor comparison between cleaned and uncleaned modules showed that dust deposition reduced module efficiency by 29.76%, with a final dust loading of 9.67 g m^{-2}. Meteorological observations revealed greater dust accumulation near the lower edges of PV panels, increasing the likelihood of hotspot formation. Regression models were developed to quantify the relationship between dust deposition density and PV efficiency loss..

3.2 Deposition dynamics and multivariate environmental correlations

Wan et al. (2024) systematically investigated the mechanisms of dust deposition on photovoltaic (PV) panels, including electrostatic attraction, van der Waals forces, and gravitational settling, as well as the effects of particle characteristics, wind speed, and humidity on the deposition process. The review further examined the impact of dust accumulation on the optical, electrical, and thermal performance of PV systems and evaluated various cleaning technologies, including robotic cleaning systems capable of improving power generation efficiency by up to 49.53%. The authors proposed an integrated mitigation framework combining real-time monitoring, performance loss prediction, and optimized cleaning strategies. Khalid et al. (2023) comprehensively reviewed dust accumulation mechanisms and mitigation techniques for PV systems. The study examined the influence of environmental factors, particularly rainfall and humidity, on dust mobilization and developed mathematical models to quantify efficiency losses. Various mitigation technologies, including electrostatic cleaning, hydrophobic coatings, robotic cleaning, and drone-assisted inspection, were critically evaluated. Both experimental and numerical analyses demonstrated that hybrid electrostatic-mechanical cleaning approaches offer considerable potential for improving cleaning efficiency while reducing operational costs. Xie et al. (2023) established outdoor PV test platforms with tilt angles of 0°, 30°, 45°, and 60° in Shenyang, China, to investigate soiling behavior under winter snow and summer dust conditions using SEM and XRD analyses. The study revealed that snow exerts dual effects on PV performance by simultaneously causing shading and promoting cleaning through snowmelt. Dust accumulation exhibited a positive correlation with power attenuation, resulting in approximately 2.6% power loss per 1 g m^{-2} increase in dust deposition. An empirical power-loss model was developed, identifying a 30° tilt angle as the optimal configuration for minimizing performance degradation. Yao et al. (2024) conducted field experiments across nine climatic regions in China to investigate the physicochemical characteristics of dust and its deposition behavior under different PV tilt angles. The authors developed a Dust Density Prediction (DDP) model to estimate dust accumulation and quantify its effects on module temperature and output power under controlled deposition conditions.

In addition, a Photovoltaic Output Power Prediction (POPP) model was proposed to improve PV performance prediction and operational optimization.

Zhang et al. (2023) investigated the effects of PV panel tilt angle and water-droplet impact height on dust removal efficiency. Experimental results showed that increasing the tilt angle from 10° to 40° enhanced dust removal by 10.62 mg per droplet, whereas increasing the droplet fall height from 0.5 cm to 10 cm at a 4° tilt angle improved dust removal by an additional 6.6 mg. Droplet impacts fragmented deposited particles and produced residual dust bands, while superhydrophobic surfaces exhibited a critical cleaning threshold beyond which droplets followed elliptical rolling trajectories. Zhao et al. (2021) investigated particle deposition mechanisms on PV surfaces and demonstrated that particle deposition increases with higher relative humidity and lower panel tilt angles because of enhanced kinetic energy dissipation during particle impact. Under wind speeds exceeding 7 m s^{-1} and particle diameters greater than 30 μm, the deposition rate initially decreased before increasing, providing theoretical guidance for optimizing PV tilt angles in dusty environments. Javed et al. (2021) conducted a two-year field investigation of natural soiling in Doha, Qatar, to evaluate the effects of desert dust on PV performance. The results revealed pronounced seasonal variations in dust-induced performance losses, with relatively lower soiling during summer due to stronger winds and reduced humidity. Dust composition and particle size were identified as the primary factors governing PV efficiency degradation. Elamim et al. (2024) investigated the effects of natural dust accumulation on polycrystalline, monocrystalline, and amorphous silicon PV modules under Mediterranean climatic conditions. Dust deposition reduced power output by 7.4%–12.35%, decreased maximum current by 11.6%–18%, and reduced glass transmittance by approximately 70%. Thermal analyses further indicated that accumulated dust acts as a heat-storage medium, increasing module operating temperatures. Zheng et al. (2024) systematically investigated high-speed airflow as a dust removal technique for PV surfaces. The study demonstrated that higher panel tilt angles (30° and 45°) significantly improved cleaning efficiency. Optimal cleaning conditions were achieved using airflow velocities of 5 m s^{-1} for 8 s and 10 m s^{-1} for 5 s, respectively. Cleaning efficiency increased with airflow velocity, exposure time, and decreasing particle size, achieving 100% removal of 10 μm particles under 10 m s^{-1} airflow within 5 s. Consequently, PV power output increased by up to 23.39% after cleaning. Boddupalli et al. (2017) investigated dust deposition on photovoltaic and concentrated solar thermal (CST) systems in India's Thar Desert. The study showed that dust accumulation on tilted PV panels and heliostat wake regions is strongly influenced by airflow-induced vortex structures, with neighboring installations intensifying localized dust deposition. Optimizing collector geometry reduced dust adhesion, while integrating cyclone separators into open volumetric air receivers (OVARs) significantly improved resistance to dust accumulation.

Despite extensive studies on PV soiling, important knowledge gaps remain regarding the coupled effects of dust transport mechanisms, climatic conditions, and panel orientation on dust deposition and natural cleaning processes in desert photovoltaic systems. Dust accumulation is governed by complex physical mechanisms, including airborne particle transport, electrostatic attraction, van der Waals interactions, and gravitational settling, all of which are strongly influenced by regional wind patterns and local microclimatic conditions. Wind speed plays a dual role by both removing deposited particles and transporting new airborne dust onto PV surfaces, whereas low wind velocities promote continuous particle accumulation. Relative humidity further modifies particle adhesion by enhancing capillary forces, allowing even small amounts of moisture in arid environments to bind dust particles into cohesive, cement-like deposits. In addition, PV panel tilt angle critically influences gravity-assisted self-cleaning, where inappropriate tilt angles create stagnation zones that favor dust accumulation, while optimized tilt configurations enhance natural wind-driven particle removal. Therefore, a comprehensive understanding of the interactions among dust transport dynamics, meteorological variables, and panel geometry is essential for developing effective dust mitigation strategies and improving the long-term performance of large-scale desert photovoltaic installations.

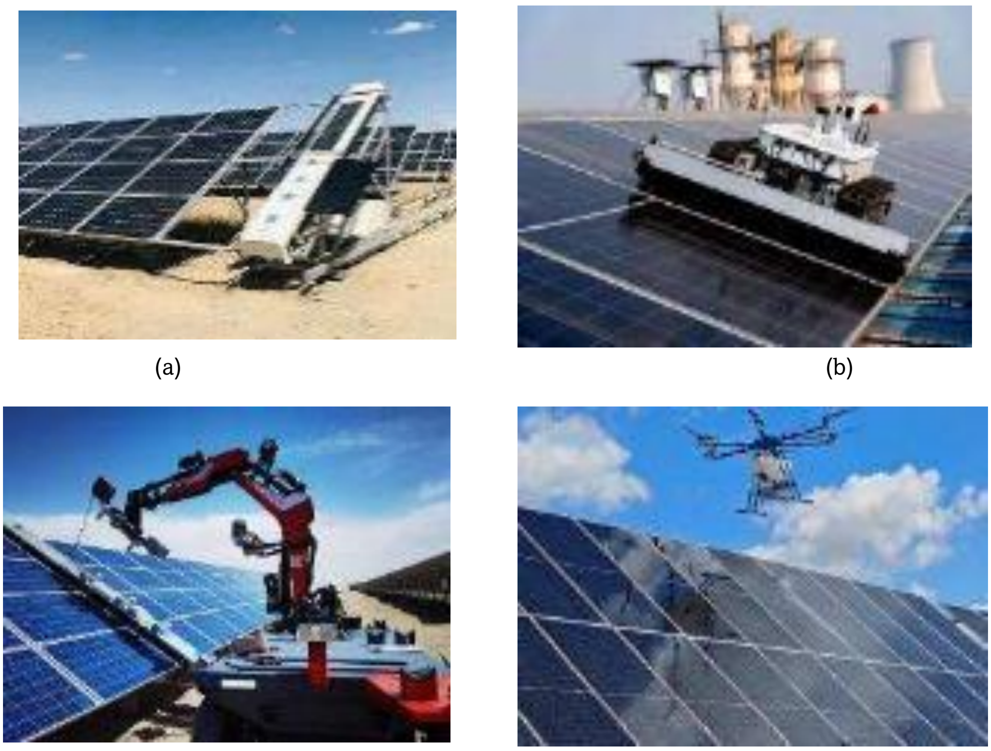
4.Cleaning technology development and optimization

In arid regions, large-scale photovoltaic (PV) power stations face prominent challenges of dust accumulation on components due to frequent sandstorms, which severely reduces power generation efficiency by decreasing light transmittance and shortening module lifespan. Current mainstream dust removal technologies include natural dust removal, high-pressure water washing, robotic cleaning, air-blowing/vibration techniques, and nano-coating self-cleaning solutions. However, the arid conditions and severe water scarcity in desert regions impose higher requirements for effective dust mitigation in large PV plants.

4.1 Robotic/Mechanical cleaning technologies

In recent years, mechanical cleaning technologies for photovoltaic (PV) systems—including waterless cleaning robots, tracked cleaning devices, and optimized vacuum-adsorption systems—have advanced rapidly and attracted considerable attention as sustainable solutions for mitigating dust accumulation in arid environments. Gandomzadeh et al. proposed a comprehensive four-dimensional framework for PV soiling management consisting of preventive measures, dynamic monitoring systems, active cleaning technologies, and intelligent multi-criteria decision-making models. Their analysis demonstrated that hybrid cleaning systems combining mechanical and electrostatic methods improve cost-effectiveness, while artificial intelligence (AI)-driven dynamic cleaning strategies further reduce operational costs. The study also highlighted the considerable potential of drone-based cleaning technologies for large-scale PV installations in arid and dust-prone regions. Patel et al. comprehensively reviewed the application of Electric Dynamic Shield (EDS) technology for dust removal from solar energy systems. The authors examined the operating principles of electrically generated dust transport and evaluated the influence of electrode geometry, alternating-current (AC) frequency, waveform characteristics, and electrode materials on cleaning performance. They also compared theoretical models describing particle charging through contact electrification and dielectric breakdown. Al Shehri et al. (2016) evaluated the effectiveness of nylon-brush dry cleaning through controlled dust accumulation and optical transmittance measurements. The results showed that nylon brushes effectively restored glass transmittance without causing permanent surface damage. However, residual dust remaining after cleaning reduced overall performance, making brush cleaning less effective than conventional water washing. Parrott et al. developed an automated dry-cleaning robot equipped with silicone rubber foam brushes. Daily automated cleaning limited PV efficiency losses to only 1.3%, outperforming weekly manual cleaning (5.8% loss) and monthly cleaning (10.9% loss). The low-cost brush system demonstrated excellent dust removal capability and wear resistance, providing a practical and sustainable cleaning solution for desert environments such as the Middle East. Cai et al. (2019) optimized the structural design of a robotic vacuum cleaning system to improve dust removal performance. Using orthogonal experimental design combined with computational fluid dynamics (CFD) simulations, sixteen combinations of inlet and outlet dimensions were evaluated to determine the optimal configuration. The proposed methodology achieved efficient structural optimization with a limited number of experiments, resulting in an energy-efficient robotic cleaning system. Kawamoto (2020) proposed an improved detachable electrodynamic cleaning system employing parallel grid electrodes to generate electrodynamic forces through high-frequency alternating voltage. The induced particle vibration transported dust through the electrode gaps, achieving cleaning efficiencies exceeding 80% under dry conditions. However, the performance decreased substantially when hygroscopic dust formed cemented deposits. To overcome this limitation, the author proposed optimizing cleaning schedules, electrode spacing, and auxiliary airflow.

Fan et al. (2022) developed a lightweight (2.6 kg) water-free cleaning robot based on negative-pressure adsorption for distributed PV systems in arid regions. The robot integrated a roller-brush sweeping mechanism with negative-pressure dust collection, effectively minimizing secondary dust dispersion. Experimental results demonstrated an average dust removal efficiency of 92.46%, restoring PV output by 11.06%–49.53%. Compared with manual cleaning, the proposed system significantly reduced water consumption while improving cleaning efficiency. Antonelli et al. (2020) developed an autonomous robot for cleaning PV panels in desert environments. The robot features a semi-tracked mobility system and dual counter-rotating spiral brushes that enable water-free cleaning. Its innovative design eliminates the need for guide rails or suction mechanisms while employing bidirectional brushing to prevent dust redeposition. A low-profile chassis further enhances operational stability on inclined PV arrays. Zhao et al. (2024) designed a vacuum-adsorption robot for cleaning PV panels under complex operating conditions. The robot incorporates an auxiliary mobile platform integrating locomotion and dust removal systems, allowing stable operation on panel inclinations ranging from 20° to 50°. Structural optimization and gas-solid coupling simulations demonstrated the feasibility of intelligent robotic cleaning for distributed PV installations. Mousavi and Farahani (2022) introduced the MFv01 autonomous PV cleaning robot, which combines dual rotating brushes with an integrated vacuum collection system to efficiently remove sand and airborne pollutants. Comparative evaluations showed that the robot outperformed manual cleaning, water-based cleaning, and superhydrophobic surface treatments, particularly under desert conditions, offering significant improvements in both cleaning efficiency and operational cost. Figgis et al. (2023a) investigated the shading effects of commercial cleaning robots on series-connected PV modules. Robot movement reduced string power output by approximately 80% for full-cell modules and 40% for half-cut cell modules installed in horizontal configurations, whereas vertically oriented modules experienced negligible performance losses. These findings support the use of vertical module layouts to minimize temporary shading during robotic cleaning. Figgis et al. (2023b) experimentally evaluated the vibration induced by robotic cleaning on six types of PV modules. Displacement measurements indicated that vibration amplitudes remained below 0.8 mm, substantially lower than those generated by natural wind loading. Nevertheless, larger PV modules exhibited greater structural deformation, suggesting that module dimensions should be considered in robotic cleaning system design. After years of technological development, photovoltaic cleaning robots can generally be classified into four major categories: rail-mounted PV cleaning robots, tracked PV cleaning robots, UAV-integrated cleaning robots, and automated guided vehicle (AGV)-based brush cleaning robots, as illustrated in Figures 3(a)–3(d). The technical characteristics, advantages, limitations, and typical application scenarios of these robotic cleaning systems are summarized in Table **1**.



(a) (b) (c) (d)

Figure 3. (a) Rail-Mounted PV Cleaning Robot (b) Tracked PV Cleaning Robot, c. UAV-Integrated Cleaning Robot, d. AGV-Based Brush Cleaning Robot

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Table 1. Robot type, Characteristics and application fields

Robot Type	Characteristics	Applicable Scenarios
Rail-Mounted PV Cleaning Robot	Moves along guide rails installed on PV panel frames Equipped with width/angle adaptive cleaning rollers matching photovoltaic strings	Large-scale utility PV plants (mountainous/water-based installations)
Tracked PV Cleaning Robot	Features crawler-type chassis structure Deploys single/dual-head rotating brush mechanisms	Distributed PV systems (residential/commercial rooftops)
UAV-Integrated Cleaning Robot	Utilizes UAV platforms for aerial operations Performs wet cleaning via carried reservoirs or transports track-based robots to panels	Maintenance in hard-to-reach PV arrays or emergency cleaning tasks
AGV-Based Brush Cleaning Robot	Combines autonomous guided vehicle (AGV) chassis with synchronized roller brushes Implements path planning algorithms for large-area coverage	Utility-scale solar farms requiring systematic surface maintenance

4.2 Coatings/Non-contact cleaning technologies

In recent years, non-mechanical cleaning technologies, including superhydrophobic coatings, electrostatic cleaning, and carbon nanotube (CNT)-based transparent conductive films, have undergone rapid development and emerged as major research directions for dust removal from photovoltaic (PV) systems. Rifai et al. (2016) investigated the kinetic behavior of dust particles on rotating polycarbonate disks for PV self-cleaning applications. The study analyzed ambient dust properties and demonstrated that increasing rotational speed significantly enhanced dust removal efficiency, with particle size being inversely proportional to the residual dust fraction. When the rotational speed exceeded the threshold value, the removal efficiency for micron-sized particles exceeded 90%, validating rotational dynamics as an effective passive self-cleaning mechanism for PV systems. Chen et al. (2019) experimentally investigated the relationship between PV surface morphology and cleaning efficiency. Their results identified surface roughness (Sa) and average peak-to-valley spacing (Sm) as the key parameters governing dust removal. Increased surface roughness together with an optimized Sm significantly improved cleaning performance. The study revealed a strong correlation between surface microstructure and particle removal efficiency, providing valuable guidance for the design of self-cleaning PV surfaces. Syafiq et al. (2022) comprehensively reviewed recent advances in self-cleaning coatings for photovoltaic glass. Wettability-based coatings were classified into hydrophobic and hydrophilic systems. Hydrophobic coatings utilize low surface energy together with micro- and nanostructures to minimize dust adhesion, whereas superhydrophobic coatings enhance rain-driven self-cleaning. In contrast, hydrophilic coatings generally employ photocatalytic materials to decompose organic pollutants while facilitating surface cleaning.

Niu et al. (2023) systematically analyzed the challenges associated with transparent superhydrophobic materials for photovoltaic applications. Although these coatings achieved optical transmittance of up to 91.1%, outperforming superhydrophilic surfaces, their practical application remains constrained by the trade-off between optical transparency and surface roughness, limited mechanical durability, and poor chemical resistance. Al-Salaymeh et al. (2023) compared electrostatic neutralization, manual cleaning, natural cleaning, and nano-coating technologies for PV modules operating under Jordan's arid climate. Two-week field experiments conducted in Amman revealed energy losses of 5.93%, 4.56%, and 2.33% for natural cleaning, electrostatic cleaning, and nano-coating treatments, respectively, demonstrating the superior performance of nano-coatings. Yadav et al. (2021) designed a low-cost automated dry-cleaning system employing silicone rubber blades controlled by a microcontroller. The wiper-based mechanism achieved a cleaning efficiency of 97.8% after ten cleaning cycles per day while consuming only 0.74 Wh day^{-1}. Validation experiments conducted over three weeks demonstrated that the proposed system is particularly suitable for small- and medium-scale PV installations in desert environments. Rahbar et al. (2022) proposed a self-cleaning approach that integrates a single-axis tracking (SAT) system with dew formation. During a 94-day experimental period, the proposed method exhibited only 5.9% efficiency loss, significantly outperforming fixed-tilt systems (33.2%) and conventional SAT systems (11.9%). Computational fluid dynamics (CFD) simulations further demonstrated that corrugated glass surfaces increased dew collection by 86% and water film thickness by 67%, thereby enhancing natural self-cleaning performance. Liu et al. (2024) developed an electrostatic dust removal technique using carbon nanotube (CNT)-based transparent conductive films. Experimental results demonstrated dust removal efficiencies exceeding 98.6%, restoring PV output to 94–97% of its original clean-state performance. The optimal operating humidity was approximately 70%, indicating considerable potential for practical electrodynamic cleaning applications.

In a related study, Liu et al. (2023) fabricated transparent conductive films based on single-walled carbon nanotubes (SWCNTs) for electrostatic dust removal. Even after accelerated aging tests, the films maintained dust removal efficiencies of 97.5–98.5% and restored 93.5–97.8% of the original power generation efficiency, demonstrating excellent long-term outdoor stability under high solar irradiation. Hariri (2022) developed a novel photovoltaic self-cleaning technology utilizing shape memory alloys (SMAs) driven by waste heat generated by PV panels. The proposed system exploits the thermomechanical properties of SMAs to convert residual thermal energy into mechanical motion, enabling autonomous cleaning without requiring external power. Yilbas et al. (2021) proposed a hydrophobic grid-assisted water-droplet rolling technique for PV surface cleaning. The hydrophobic grid reduced coating coverage while improving particle removal through droplet rolling and imbibition effects, thereby minimizing residual water droplets. Consequently, post-cleaning performance losses were significantly reduced compared with conventional hydrophobic coatings. Li et al. (2024) introduced a water-free electrostatic adsorption (ESA) cleaning technology for photovoltaic panels. Transparent indium tin oxide (ITO) conductive films were integrated with high-voltage electrodes to selectively remove dust particles through electrostatic attraction. The study clarified the underlying ESA mechanisms and provided both theoretical and experimental support for future industrial applications. Yan et al. (2025) numerically investigated dust accumulation mechanisms and the application of electrostatic barriers for suppressing particle deposition. Without electrostatic barriers, dust accumulation increased with the gravity-to-drag force ratio. The introduction of electrostatic barriers significantly enhanced particle capture through the combined effects of inertial collision and electrostatic attraction, reducing downstream dust deposition by approximately **90%**. Zhao et al. (2024) investigated the influence of self-cleaning superhydrophobic coatings on dust deposition under sandy environmental conditions. The effects of particle size, wind speed, and module tilt angle were systematically analyzed. The superhydrophobic coating effectively suppressed particle adhesion by reducing surface energy, thereby improving cleaning efficiency at higher tilt angles. Coated modules exhibited only **7.9%** efficiency loss compared with **9.8%** for uncoated modules. Guo et al. (2024) developed a transparent superhydrophobic coating possessing both self-cleaning and dust-repellent properties. The coating utilizes a porous microstructure to reduce the effective dielectric constant and minimize particle contact area, thereby weakening van der Waals interactions responsible for dust adhesion. Abrasion, acid-base resistance, and sand impact tests demonstrated excellent long-term durability, highlighting its considerable potential for passive photovoltaic cleaning applications. Bhaduri et al. (2023) evaluated four commercially available hydrophobic anti-soiling coatings designed for water-free photovoltaic cleaning. The study demonstrated that degradation of hydrophobicity, quantified by increasing roll-off angles, was positively correlated with repeated cleaning cycles. Furthermore, the anti-soiling performance declined significantly once the roll-off angle exceeded the tilt angle of the photovoltaic module. Zimmermann et al. (2024) systematically investigated nano-engineered sol-gel coatings for dust-resistant photovoltaic applications. Their results demonstrated that all tested coatings effectively reduced the deposition of particles larger than **10 μm**. Under wind-driven cleaning conditions, smoother coating surfaces exhibited superior particle removal efficiency, whereas rougher coatings retained a greater proportion of fine particles. These findings indicate that optimizing surface morphology is essential for balancing optical transparency, dust repellency, and long-term cleaning performance in photovoltaic applications.

5. Conclusion and future outlook

This study systematically reviews advances and trends in PV desertification control and dust removal technologies. Currently, integrated PV desert control and sand stabilization within China's new energy development and ecological management have achieved remarkable ecological and environmental benefits, which are bound to exert a global influence in the future. Post-construction maintenance of PV power plants in desert regions is a critical factor determining their operational efficiency. Dust accumulation on the surface of PV modules significantly constrains power generation efficiency. Consequently, module dust removal technology serves as a vital solution for improving overall power plant performance. Intelligent PV cleaning robots have seen significant progress; through large-scale commercial applications, they have greatly enhanced dust removal efficiency, reduced operational costs, and supported environmental protection goals. Meanwhile, self-cleaning surface coatings ensure the prolonged cleanliness of module surfaces, pushing this technology into the initial stages of large-scale implementation.

5.1. Development trends of PV desert control and sand stabilization

At the R&D level, intelligent PV operation (e.g., AI monitoring, self-cleaning coatings) will optimize sand control efficacy and enhance power generation efficiency. The integration of novel materials with energy storage systems will improve adaptability to extreme environments. Concurrently, advancements in sandy land ecological restoration—such as drought-resistant plant gene editing and water-saving drip irrigation systems—will boost vegetation survival rates. Application models will expand into diversified "PV+" scenarios, evolving from pastoral–agricultural synergies to integrated "desert control + industrial development + carbon sink" systems, spurring emerging industries like green hydrogen production and ecotourism. Policy mechanisms will prioritize cross-regional ecological compensation systems and desert carbon trading markets to incentivize corporate and social capital participation. Industrial collaboration will integrate wind–solar–storage bases with China's Western Development and Rural Revitalization strategies, creating multi-energy complementary green energy economic belts. Globally, China will lead technology exports and joint projects under the Belt and Road Initiative, fostering international cooperation in PV-driven desertification control to align with climate goals. Leveraging technological innovation and policy evolution, this field will become a pivotal contributor to China's blueprint for global ecological civilization.

5.2 Development trends of PV dust removal technologies

Dust removal technologies for photovoltaic power plants are rapidly advancing toward becoming more intelligent, efficient, and sustainable. While mainstream methods such as mechanical cleaning, water washing, and surface coatings are widely used, they face drawbacks including high water consumption, short material lifespans, and elevated maintenance costs. Future developments will concentrate on three key technological pathways: first, AI and IoT-enabled smart monitoring systems that leverage precise dust-detection modules to dynamically schedule cleaning robots; second, innovative material applications—such as nanocoatings and photocatalytic self-cleaning technologies—that significantly enhance anti-fouling capabilities and extend service life; and third, breakthroughs in contactless cleaning technologies combining high-frequency vibration devices with drone-mounted directional airflow jets to achieve daily dust removal rates exceeding 98%. These innovations will accelerate lifecycle cost reductions and efficiency improvements in PV plants, driving the global transition toward green energy..

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The corresponding author states that there is no conflict of interest.

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