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Article

Transition from Manual to Robotic Cleaning for Large Photovoltaic Systems: Review of Innovation Technologies

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ABSTRACT

With the growing trend toward renewable energy, especially high-capacity solar power plants are currently being installed, and their number is expected to increase in the future. Therefore, automated photovoltaic (PV) cleaning using robots is imperative to maintain their efficiency and prevent economic losses resulting from dirt accumulation. Dust on PV is a major challenge, reducing their efficiency by 20% to 40% in desert and arid regions. The use of robots to clean PVs has become an innovative and effective solution to improve performance and reduce operating costs. Cleaning robots are capable of removing dust with an efficiency of up to 99% without requiring large quantities of water, making them ideal for areas affected by water scarcity. Furthermore, these robots address the challenges of human labor required to clean large areas, as they can clean hundreds of square meters per day with less effort and faster than manual methods. This review focuses on three distinct types of robotic cleaning systems: rail-mounted systems, on-panel crawling robots, and aerial systems. Studies show that the use of robots can improve energy production by up to 49% compared to traditional methods in specific studies under extreme soiling.

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GRAPHICAL ABSTRACT

1. Introduction

With the global trend toward sustainability and a reduction in reliance on conventional energy sources, solar energy systems have experienced tremendous growth in recent years. Photovoltaic (PV) panels have become essential components in various solar energy applications. These branches include hydrogen production [1, 2], solar desalination [3, 4], solar heaters [5, 6], irrigation [7, 8], and domestic uses [9, 10].

However, these systems face numerous challenges, most notably the accumulation of dust and dirt, which is one of the most significant factors negatively impacting the efficiency of solar cells. Studies have shown that dirt accumulation can reduce PV productivity by up to 40%, making cleaning a necessary operational task. In this context, brush-based robots have emerged as an innovative and effective solution to overcome this problem.

Thanks to their technological advancements, these robots offer brush-based cleaning techniques that precisely remove dust while maintaining the integrity of panel surfaces. These techniques are not only an alternative to costly manual cleaning but are also more efficient and sustainable, particularly in large-scale solar farms.

Previous studies on PV cleaning have reviewed various cleaning techniques aimed at enhancing the efficiency of PVs and reducing losses due to dust and dirt accumulation. The most common method is hydro-cleaning, where water is sprayed onto the surface of the panels to remove dust and impurities [11, 12]. Despite its high effectiveness, this method faces significant challenges in water-scarce areas.

Additionally, compressed air cleaning techniques have been used, where powerful jets of air are directed to clean surfaces [13, 14]. This method is suitable for dry areas but may not be effective at removing sticky dirt. Studies have also included vibration-based techniques, where devices generate vibrations on the surface of the panels to remove dust. This method has shown promising results, but it needs to be improved to avoid negatively impacting the panel structure. Furthermore, some

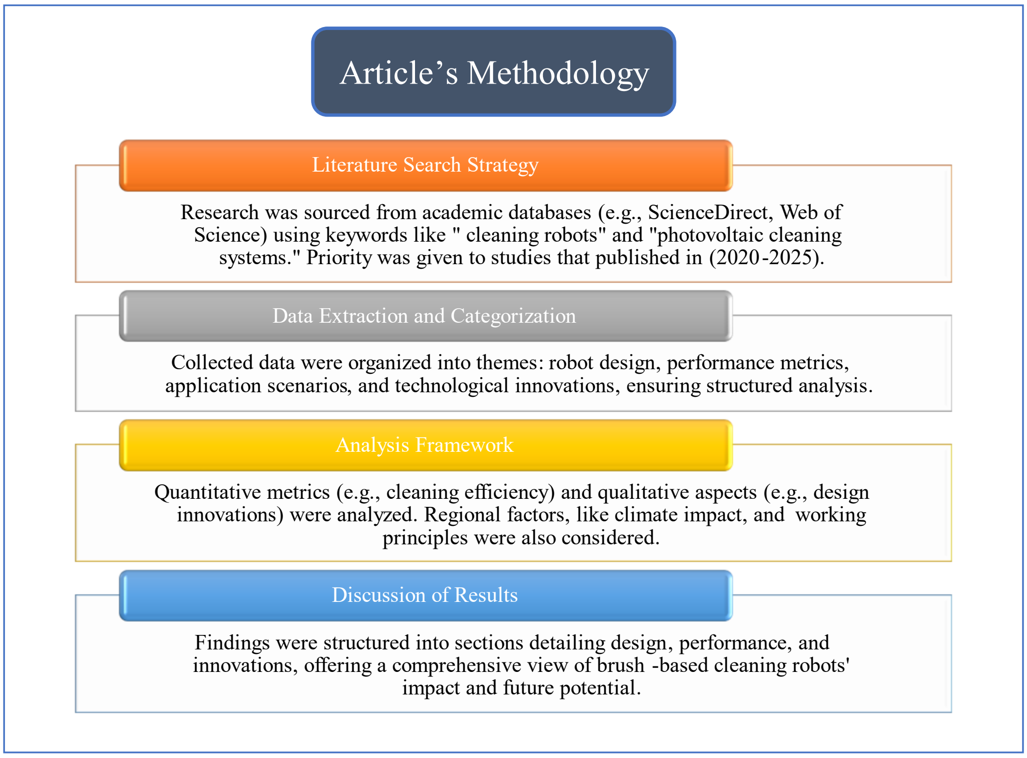
unconventional solutions have been studied, such as the use of self-cleaning coatings, which
rely on materials that prevent dust adhesion but face limitations related to cost and coating lifespan [15-18].

Several publications have addressed solar tracking systems, which rely on continuously orienting PVs toward the sun throughout the day to maximize solar radiation [19]. These systems include single-axis tracking [20], which aligns panels toward the sun from east to west, and dual-axis tracking, which provides higher accuracy by aligning panels along two axes (horizontal and vertical) [21, 22]. Studies have shown that these systems can increase energy production by 20% to 40% compared to fixed panels. Additionally, the literature has focused on the importance of smart monitoring and control systems, which rely on artificial intelligence and Internet of Things (IoT) technologies to monitor PV performance and analyze data in real time [23-25]. These systems enable the rapid detection of faults or performance degradation, contributing to improved maintenance and reduced waste. Furthermore, studies have included innovative modifications such as improving panel materials and using anti-reflective or dust-resistant coatings, which enhance the efficiency and sustainability of solar cells [26, 27]. All of these efforts demonstrate the growing role of advanced technology in improving the performance of solar energy systems and expanding their global adoption. Gandomzadeh, et al. [28] reviewed techniques for reducing the impact of dust on photovoltaic systems, categorizing strategies into prevention, dust monitoring systems, active cleaning, and decision-making strategies. Key findings include the effectiveness of superhydrophobic coatings, which reduce dust accumulation by 50%, and the development of hybrid cleaning systems that combine manual and mechanical cleaning to enhance efficiency. Moreover, it is essential to transition from static cleaning schedules to dynamic AI-based decisions, which can result in up to an 8% reduction in energy costs in large plants.

The importance of robotic cleaning lies in its ability to provide sustainable and more efficient solutions to problems associated with dust accumulation, particularly in desert and arid regions, which represent the largest sites for solar system deployments. The novelty of this technology lies in its integration of artificial intelligence and autonomous control systems, enabling precise monitoring of panels and continuous improvement in cleaning performance. These features make robots a promising tool for supporting the sustainability and efficiency of future solar systems. Therefore, the current review aims to highlight several robotic systems used for cleaning solar panels, including fixed-route robots, robotic arm-based systems, integrated flying robots, and autonomous robots. Recent technological innovations are reviewed, and the advantages and limitations of each type will be evaluated based on performance, efficiency, economic feasibility, and adaptability to diverse environmental conditions.

2. Methodology

The methodology of this study focuses on systematically collecting, analysing, and summarising research and developments related to robots for cleaning PV systems. To ensure comprehensive coverage, an extensive search was conducted in reliable academic databases, such as ScienceDirect, Springer, and Web of Science, using targeted keywords such as "cleaning robots," "PV cleaning technologies," and "PV cleaning automation" Priority was given to research published within the last decade to ensure relevance to current technological developments and industry practices. Inclusion criteria focused on studies and reports that provided quantitative data on cleaning efficiency, operational performance, resource consumption, and maintenance costs. Particular attention was paid to research that highlighted innovations in brush-based robots, particularly those designed for large-scale solar installations or harsh environmental conditions. Exclusion criteria excluded articles that focused on other cleaning mechanisms (such as water or air cleaning systems) or lacked sufficient technical details. Case studies were incorporated into the review to highlight real-world applications of brush-based robots. These studies provided insights into the effectiveness of systems in improving energy productivity, overcoming environmental challenges (such as excessive dust accumulation in desert areas), and reducing operating costs. Specific examples are included to demonstrate innovative solutions, such as the use of advanced brush materials, foldable designs for enhanced portability, and autonomous systems for remote or large-scale solar farms. The results of the analysis are organized into thematic sections, focusing on the operational principles and core components of brush-based robots, a comparative evaluation of performance metrics across different designs, and future development directions for technological innovations. This methodology, illustrated in **Figure 1,** ensures a comprehensive and well-organized review, providing valuable insights into the current status and future potential of robotic systems for solar cell cleaning.



.**Figure 1.** Sequential Flowchart of article’s methodology

.**Figure 2.** The transition from manual cleaning to robotics version

3. Cleaning Robots techniques

Cleaning robots for PV systems leverage various mechanical, pneumatic, and electromechanical mechanisms to dislodge and remove surface contaminants.

Their architectures vary widely, ranging from rail-mounted systems optimized for utility-scale arrays to rail-free crawling robots designed for commercial rooftops, and to aerial drone-based cleaners aimed at inaccessible or elevated installations. Cleaning modalities include rotary brushes, negative-pressure suction, vibrational actuators, water jet nozzles, and, more recently, dry electrostatic systems and compressed air-based units. Many modern systems incorporate sensors, autonomous path planning, and energy-efficient actuation to enhance precision and adaptability across different module geometries and tilt configurations. This section provides a detailed description of these robots for the transition from manual to robotic cleaning, as illustrated in **Figure 2**.

3.1. Rail-Mounted Systems

Rail-mounted cleaning robots represent one of the earliest and most structurally anchored approaches to automated PV maintenance. These systems utilise dedicated aluminium or steel rails, affixed parallel to PV module rows, serving as guided tracks for brush-equipped robots or nozzle carriers. The cleaning mechanism typically a roller brush or water spray system is integrated into a mobile carriage that traverses the rail in a controlled manner. Rail-mounted designs are particularly prevalent in large-scale utility PV plants with uniform, low-tilt module arrangements. Their movement precision enables full-coverage cleaning, making them effective for scheduled operations in dusty climates. However, the installation of rail infrastructure imposes considerable capital expenditure and structural constraints. These systems are best suited for arrays where high cleaning frequency justifies infrastructure cost, and where panel uniformity ensures uninterrupted rail alignment. Their mechanical simplicity, coupled with programmability, makes them reliable workhorses for plant operators prioritizing operational uptime. They offer high cleaning precision thanks to their controlled movement and are effective in large solar farms where tracks can be installed on a regular basis. However, track installation is required, which increases initial setup costs.

Khadka, et al. [29] designed and prototyped a smart solar PV cleaning system integrating a robotic unit and an autonomous decision-making module based on IoT. The robotic unit, equipped with a rotary cleaning brush and mounted on rails,

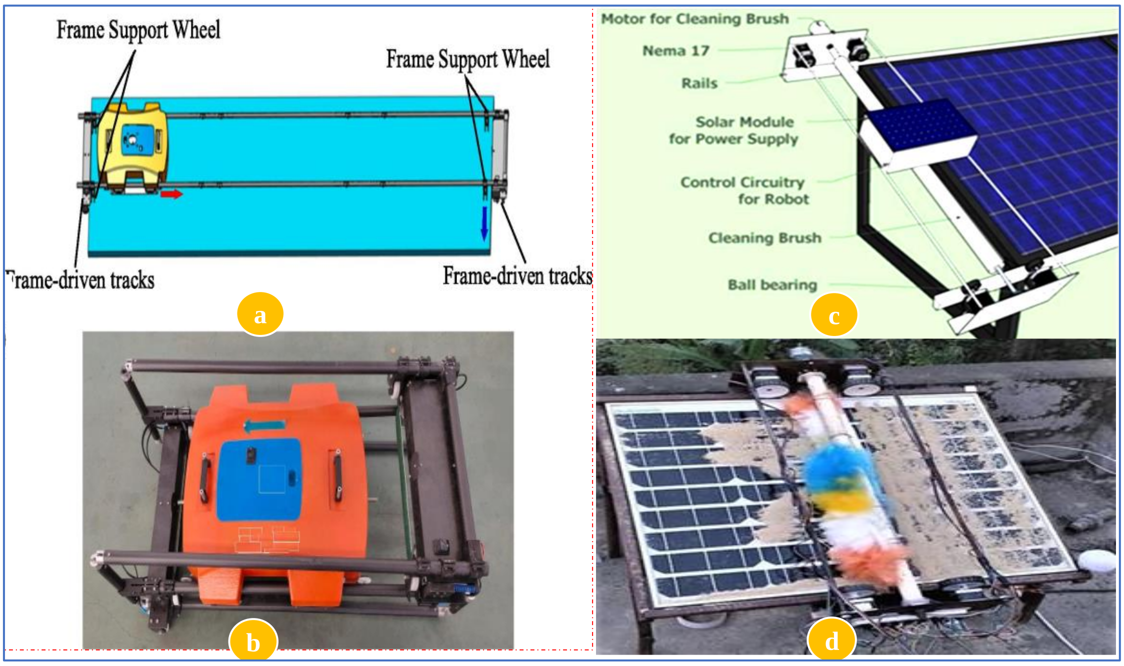


Figure 3. Rail-mounted cleaning robots design: a) and b) schematic and real photo Zhao, et al. [30] c) and d) schematic and real photo Khadka, et al. [29].

was tasked with physically cleaning the panels. It was powered by motors delivering torque values of 0.3189 Nm (lower part) and 0.1482 Nm (upper part) and operated on a 50-watt PV module inclined at 30°. The autonomous unit employed sensors to monitor light intensity, dust density, temperature, humidity, and output power. A regression model, trained on clean vs. dusty panel data, automatically triggered the cleaning action when efficiency dropped. The linear regression analysis revealed a significant performance gap: the clean panel had a slope of 0.67, whereas the dusty one had a slope of 0.33, indicating a nearly 50% degradation in power output.

Zhao, et al. [30] proposed a spiral-roller robotic cleaner optimised to navigate PV modules with varying tilt angles. A series of design iterations led to the identification of a 20° helix angle as optimal for maximizing brush contact and dust conveyance. The structural layout of the dust collection and transmission system was also refined to accommodate larger angular inclinations. Experimental evaluations confirmed the robot's effective performance across PV modules inclined at 20° to 50°, with power recovery rates reaching 27.8% under high soiling density. The system's mechanical adaptability and cleaning precision make it a versatile option for both residential and utility-scale applications.

Ghodki [31] developed a lightweight 520 g rail-mounted self-cleaning robot incorporating innovative infrared (IR) sensor technology. The system operates along a linear track fixed to the PV array and performs multiple functions, including early-morning, shadow-free cleaning, thermal monitoring of panel surfaces, and automated control of a PWM-driven robotic arm equipped with a silicone wiper. This multi-sensor platform enables precise, condition-based cleaning cycles while preventing excessive mechanical loading on the panels. Field trials conducted over a 73-day winter period demonstrated a 11.88% increase in energy yield, a 13.02% rise in module efficiency, and a performance ratio of 81.35%. The robot achieved a cleaning coverage rate of 1.86 m^2/s, using only 0.31 L/m^2 of water, and consumed 59.13 Wh per month, accounting for merely 9.1% of the total monthly recovered energy. Economically, the cleaning cost was calculated to be $1.84 per kWh, with an annualised cost of $95.57 per kWh per year, making it a cost-efficient alternative to conventional cleaning systems.

Figgis, et al. [32] conducted an extensive structural analysis to assess the mechanical impact of a commercial brush-type cleaning robot operating at ~7 Hz on six types of PV modules. The vibration and panel deflection data revealed that the cleaning process induced deflection amplitudes in the range of 0 to -1 mm. In contrast, natural wind loads typically caused deflections from +2 mm to -1 mm. Notably, the study found no correlation between vibration intensity and variations in glass thickness or frame material, suggesting that the cleaning-induced deflection remains well within mechanical tolerance limits and poses no structural risk to modern PV modules.

A robot-based automated cleaning system was introduced by Parrott, et al. [33]. The system is equipped with an innovative brush that is constructed from silicone rubber foam strands and is mounted on an aluminum core. The study illustrated that the robotic system, by employing this brush, was capable of significantly reducing the influence of dust on the energy yield of PVs, resulting in a higher energy production rate than when the panels were cleansed manually. The new brush demonstrated its potential for use in PV cleaning technologies by effectively removing grime at a low cost and without causing damage to the PVs' surface.

3.2. On-Panel Crawling Robots

On-panel crawling robots are mobile cleaning units designed to move directly over the surface of PV modules without the need for guiding rails or external infrastructure. They represent a flexible and scalable class of cleaning technologies, particularly well-suited to retrofitting existing PV arrays of various configurations. These robots typically rely on belt drives, wheels, or suction systems for traction and employ a range of cleaning mechanisms, including rotating brushes, vacuum suction, and vibrational mop heads. The core advantage of crawling robots lies in their adaptability to both residential and commercial PV installations, regardless of tilt angle or support geometry. Their lightweight design and low installation overhead make them deployable with minimal labor. Nevertheless, on-panel mobility introduces challenges, including traction loss on smooth or wet surfaces, the risk of panel deflection under concentrated loads, and difficulties in navigating obstacles. Despite these limitations, crawling robots strike a practical balance between cleaning efficacy and deployment flexibility, especially when designed with real-time navigation feedback and minimal energy draw.

Yang, et al. [34] presented a self-propelled, hydraulically actuated cleaning robot that integrates a crawler wheel drive with a three-point suspension system for automatic surface leveling **(Figure 4-a)**. The design was further enhanced through kinematic optimization using chaotic maps combined with an improved sparrow search algorithm, allowing for adaptive navigation across irregular module surfaces. The motion trajectory of the robotic arm was refined using a 7th-order non-uniform B-spline curve, which enabled smooth and efficient coverage. Simulation and experimental results demonstrated an 18.7% reduction in cleaning time along with improved dust removal efficiency, highlighting the robot's robustness and adaptability in variable terrain and its potential for deployment in challenging topographies.

Antonelli, et al. [35] developed an autonomous cleaning robot, as illustrated in **Figure 4-b**, to address the challenge of maintaining PV efficiency in arid conditions. The robot operates without water and utilizes ultrasonic sensors that are managed by an ARDUINO DUE platform to navigate. It also includes independent helical brushes. Optimal cleansing is achieved by the robot's autonomous adjustment of speed and direction. Its capacity to clean effectively under severe conditions while maintaining low power consumption was validated through field tests, rendering it a cost-effective solution for large-scale PV systems in arid regions. In order to mitigate the necessity for manual labor in PV array maintenance, Megantoro, et al. [36] created an intelligent mobile robot, as illustrated in **Figure 4-c**. The robot utilizes PID control to ensure stability while safely navigating PV arrays, which is facilitated by its gyroscope and proximity sensors.

Figure 4. a) Arm cleaning systems by Yang, et al. [34] , b) On-Panel Crawling Robotsby Antonelli, et al. [35], c) by Megantoro, et al. [36], and d) by Fan, et al. [37].

Cleaning durations were reduced to approximately 13 minutes as a result of autonomous operation, which illustrated cost savings and efficient energy consumption in PV system maintenance. This solution is particularly beneficial for large-scale solar installations, as it provides improved safety and efficiency. Fan, et al. [37] developed a compact robot that integrates a rotating brush with a negative-pressure suction system, designed specifically to minimise dust resuspension during operation (**Figure 4-d)**. Field tests on a 2 kW rooftop PV installation in northeast China showed that the system achieved a dust removal efficiency of 92.46% and improved PV system performance by 11.06% to 49.53%, depending on initial soiling density. The device's small form factor and waterless operation make it particularly well-suited for arid and dusty environments, where traditional water-based cleaning is logistically or environmentally impractical.

Other dry-cleaning robots were studied, utilising innovative technologies such as silicone rubber brushes and passive suction systems to prevent dust from flying during cleaning.

Deb and Brahmbhatt [38] developed and tested a novel PV cleaning mechanism to mitigate soiling losses affecting solar panel performance (Figure 5-a). The apparatus featured a rotating brush system driven by a DC motor, mounted on an aluminum frame designed to be lightweight and non-damaging. The cleaning process was evaluated over multiple cycles on a test PV array in Kuwait's dusty conditions. Experimental results showed a 10–16% improvement in power output post-cleaning and a significant reduction in surface dust density. The study concluded that frequent dry cleaning using this system could substantially maintain system efficiency, especially in arid climates with limited water resources.

These systems proved efficient in cleaning solar panels without damaging the anti-reflective coatings, which play a key role in improving solar energy absorption. Furthermore, the study demonstrated the potential for developing low-cost, portable systems suitable for small solar power plants, enhancing the spread of this technology in remote areas suffering from water scarcity [39].

Figure 5. a) Deb and Brahmbhatt [38] , b) Nahar Myyas, et al. [41] , c) Figgis, et al. [39] , d) Al-Rasheedi, et al. [40].

Al-Rasheedi, et al. [40] assessed the performance of two utility-scale PV technologies, thin-film (TF) and polycrystalline silicon (PC) operating under Kuwait's harsh desert conditions at the 11.15 MW Shagaya Renewable Energy Park (Figure 5-d). Over a 25-month monitoring period, both systems, sized at ~5.5 MW each, were evaluated using parameters such as final yield, performance ratio , and system losses. The findings revealed comparable annual reference yields (1805 kWh/kW for TF vs. 1810 kWh/kW for PC), similar power ratio values (80.0% for TF vs. 80.2% for PC), and system efficiencies of 10.42% (TF) and 13.02% (PC). Notably, soiling and high temperature were identified as significant performance degraders. Despite PC's better efficiency and smaller land use by 18.5%, both technologies were found to be technically viable for future GW-scale deployment under similar environmental conditions.

Nahar Myyas, et al. [41] explored and compared various PV cleaning techniques, including manual, semi-automated, and robot-assisted methods, with a focus on cost-effectiveness and water efficiency. Field experiments were conducted in dusty environments to determine the optimal cleaning frequency, effectiveness, and the impact on system performance. One key result showed that semi-automated truck-mounted systems reduced water consumption by up to 70% and labor cost by 50% compared to manual methods. Moreover, energy output improved by 15–25%, depending on the severity of dust accumulation. The study emphasized the importance of striking a balance between economic viability and operational performance when selecting cleaning methods for large-scale photovoltaic (PV) farms.

3.3. Aerial (Drone-Based) Systems

Aerial or drone-based PV cleaning systems represent an emerging frontier in automated maintenance, offering terrain-agnostic mobility and deployment flexibility. These systems utilize unmanned aerial vehicles (UAVs), typically multi-rotor platforms, equipped with lightweight cleaning modules such as rotating brushes, soft pads, or fine spray nozzles. Their ability

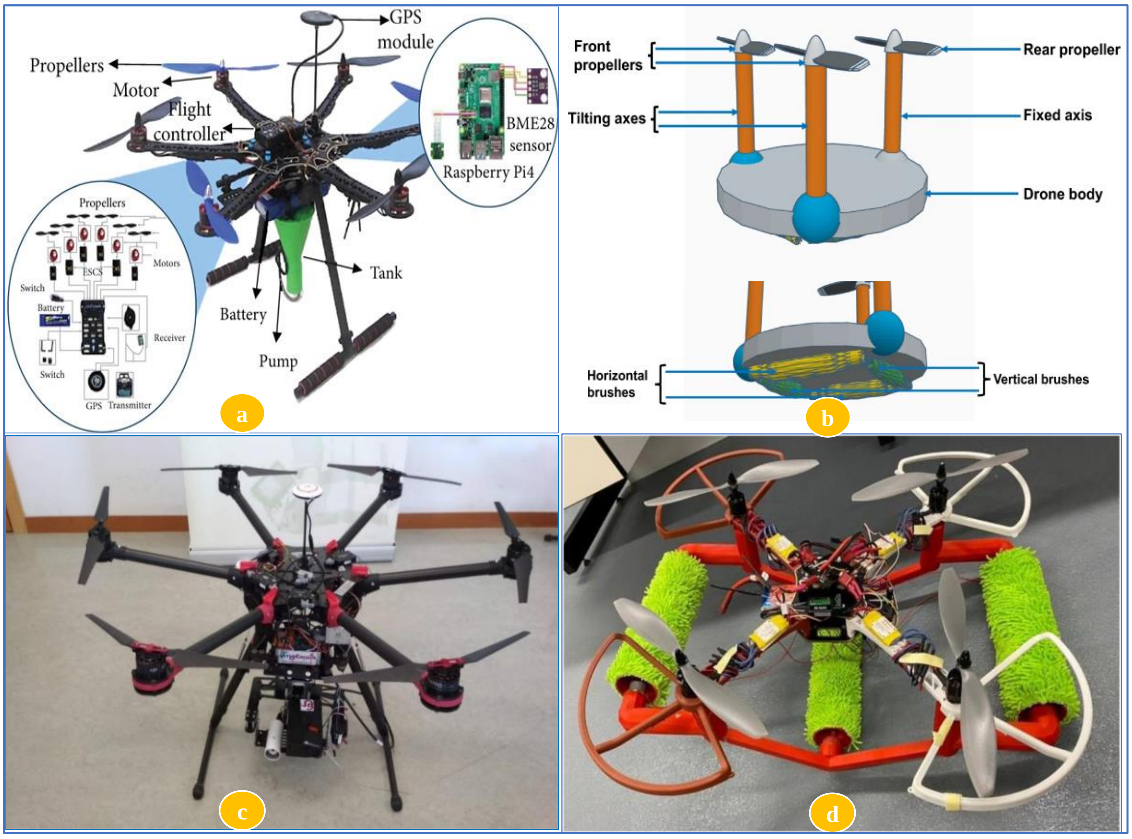


Figure 6 (a) drone version designed by Almalki, et al. [42], b) Chtita, et al. [43], c) Segovia Ramírez, et al. [44] and d) Sarkis, et al. [45].

to bypass ground obstacles and reach elevated or remote installations makes them ideal for industrial rooftops, floating PV arrays, and difficult-to-access solar farms. Unlike surface-bound robots, drones eliminate the need for mechanical contact with panel surfaces, thereby reducing the risk of inducing micro-cracks or damaging junction boxes. Cleaning is often executed in short bursts, constrained by flight time and battery payload capacity, making them more suitable for spot cleaning or rapid dust removal rather than heavy soiling. Integrating drone systems with optical or thermal sensors can enhance cleaning precision through real-time soiling detection. While still at low technology readiness levels (TRLs), drone-based PV cleaners hold promise as complementary systems in hybrid cleaning frameworks or as primary solutions in topographically complex environments.

Almalki, et al. [42] devised an autonomous quad-rotor drone that carries a one-liter water reservoir whose inner surface is coated to exploit the lotus effect. The aircraft utilises a MobileNet–VGG-16 convolutional neural network pipeline to locate soiled modules with 99% classification accuracy, and then executes a two-step cleaning cycle that sprays water for 23 seconds and applies the lotus coating for an additional 10 seconds. A single flight (approximately 30 minutes of endurance) can treat around 25 modules or 30 m², while one liter of fluid is sufficient for 70 m² of array area. Field measurements on the roof of Taif University revealed that the procedure increased the direct-current output of the cleaned string by 31% compared to its pre-cleaning state. The authors note that wind gusts and limited payload still constrain real-world deployment.

Chtita, et al. [43] advanced the concept with a three-rotor platform that combines light-detection-and-ranging, optical cameras and infrared sensors to map panel orientation and detect contamination. The control loop maintains a standoff of 5–10 cm, allowing four counter-rotating brushes (two vertical and two horizontal) to exert uniform pressure without scratching the glass. Although energy-yield tests are still pending, the authors detail a modular water-spray subsystem and closed-loop telemetry that promise fully autonomous operation under dusty, high-temperature conditions.

Segovia Ramírez, et al. [44] developed a novel Internet-of-Things-based platform for the aerial inspection of PV solar plants using thermal imaging captured by unmanned aerial vehicles. Their system automates the detection of critical faults such as hot spots, which appear as thermal anomalies on panel surfaces and are typically caused by damaged cells or defective interconnections. They implemented a two-stage image analysis pipeline using consecutive convolutional neural networks. The first network accurately detects the location and boundaries of photovoltaic modules with 99 % accuracy, while the second identifies thermal faults with 96 percent accuracy. The study, validated across three distinct solar farms with varying panel configurations and environmental conditions, demonstrates the platform's effectiveness in delivering reliable and real-time diagnostics, enabling faster maintenance interventions and minimizing system downtime.

Sarkis, et al. [45] proposed a hybrid aerial–terrestrial system for dispersed residential installations: the drone flies to each array, lands, and then rolls across the glass on four micro-fibre brushes. In laboratory path-following trials on a 1.70-m track the robot's mean heading error stayed below 5° and lateral deviation remained within 0.13 m, while the mechanism could negotiate roof pitches up to 25°; however the original paper does not publish power-gain data, so quantitative efficiency benefits remain to be validated in the field.

4. Discussions

Robotic systems used for cleaning solar panels have demonstrated significant progress in energy efficiency, economic feasibility, and environmental monitoring [46].

Table 1 provide a comprehensive comparative analysis of multiple reviewed research initiatives aimed at advancing robotic systems for the cleaning of PV panels. Track-based robots offer precise and methodical cleaning, making them suitable for large solar plants, but their rigid design and high cost limit their flexibility. Arm-based systems are highly flexible and adaptable to various shapes, but they incur high

Table 1. Summarized outline of articles related to cleaning robots in PV systems.

Ref.	System	Cleaning Principle	Power Demand	PV Gain / Efficiency Recovery	Observations
Figgis, et al. [39]	Shadow-impact evaluation of robot movement during daytime cleaning	Not applicable (assessment of moving robot's shading effect)	Not reported (focus on shading impact, not mechanical draw)	Worst-case energy loss from a single robot pass was 0.16 % of daily energy production.	Recommends robot operation during non-peak solar hours and using portrait orientation to minimize power losses from shadow
Ghodki [31]	Infrared sensor-based track-mounted cleaning	lightweight silicone wiper and PWM-controlled motor.	monthly energy consumption of 59.13 W	Increased energy output by 11.88% and panel efficiency by 13.02%. and.	Annual cleaning cost: $95.57/kWh/year.
Figgis, et al. [32]	Robotic cleaning system using a vibration	Linear horizontal dry brush actuated at 7 cycles per second	Power consumption not reported; experiment focused on vibrational behavior rather than energy draw	Cleaning efficiency not quantified; no direct energy gain reported	Panel surface deflections during cleaning were measured as 0.8 mm downward and 0.5 mm upward. while wind-induced displacement on rigid crystalline modules reached 2 mm, over 2.5 times higher than the robot's maximum.
Yang, et al. [34]	Tracked robot with three-joint hydraulic boom (seven-DoF trajectory)	Dry roller-brush; time-optimal path via improved Sparrow algorithm	*Not specified* (hydraulic actuation)	Trajectory time shortened 45 s → 36.6 s (18.7 %), raising cleaning throughput accordingly	Closed-loop angle control keeps joint error ≤ ±1.5°; climbs slopes ≤ 10° without detachment
Fan, et al. [37]	Water-free suction brush	Twin brush + centrifugal fan	15–75 W; 0.88 Wh panel^{-1}	11–49.5% PV recovery; 92.5% dust removal	8 kg; waterless; suitable for moderate tilts
Zhao, et al. [30]	Vacuum roller robot	Spiral helix + vacuum conduit	450 W; 2.5 Wh module^{-1}	10.6–27.8% PV recovery at 3–10 g m^{-2}	Effective for flat to 50° tilt; high throughput
Khadka, et al. [29]	Smart rail-based IoT system	Roller brush; cloud-triggered	12 V @ 2.5 Ah battery	~30–40% gain under dry dust	Regression model + Ubidots platform
Fan, et al. [37]	Water-free cleaning robot with rolling brushes and negative pressure suction	Fully mechanical dry cleaning with obstacle-crossing ability	Not numerically stated; lightweight and low-profile system	Cleaning efficiency averaged 92.46 %; photovoltaic output improvement ranged between 11.06 % and 49.53 %	Designed for water-scarce areas; field-tested on a 2-kilowatt rooftop installation in Northeast China
Parrott, et al. [33]	Guide-rail "E4" robot with silicone-foam brush (10 kW field array, Saudi Arabia)	Water-free rotating brush	*Not reported* (weight ≈ 36 kg)	Daily robotic cleaning prevents 1.5 % energy loss after 7 days and ≈ 5 % loss after 21 days compared with manual cleaning schedules	>1000 cleaning cycles caused no micro-cracks; lower output decay rate (0.25 % day^{-1}) on 45°-tilted panels
Megantoro, et al. [36]	Wheeled mobile robot for roof-top arrays (Indonesia)	Dry brush with PID-controlled path following	*Not reported* (average 13 min autonomous cycle)	Regional tests show dust causes ≈ 11 % output drop in 7 days; routine robotic cleaning eliminates this deficit	Robot stabilizes on track in 5.7 s; reduces labour, water use and safety risks
Antonelli, et al. [35]	Autonomous half-track robot with dual helical brushes (desert deployment)	Dry counter-rotating soft-brush sweeping	36 W total electrical load during cleaning (prototype measurement)	Continuous dust removal designed to recover the ≤ 80 % output loss caused by soiling; lab/field tests confirm full restoration after each pass	Rail-free navigation; ultrasonic localization; brush pressure kept low to avoid micro-scratches
Swain, et al. [55]	Self-powered dual-axis robot	Frame-mounted rotating brush	PV-sourced energy	PV efficiency increased from 62% to 83%	Fully autonomous, off-grid operation
Deb and Brahmbhatt [38]	Comparative review of water-free automated dry cleaners	Friction and air-blower based cleaning; various dry systems reviewed	Power consumption ranged between 30 and 150 watts	Energy yield increased by 10 to 35 %, depending on dust density and cleaning frequency	Concluded dry weekly cleaning gave best efficiency-cost balance; system sustainability high in water-scarce regions
Nahar Myyas, et al. [41]	Automated system with soft water jet, thermal sensors, and rainwater harvesting	Hybrid intelligent system with water injection and environmental feedback	Power not specified; includes controller, sensors, and pump	Prevented energy loss of 8.14 to 10.28 kWh /m^2 over 6 months; daily savings of 1.03 to 0.82 $	Environmentally adaptive; design enables both cleaning and passive rainwater collection for sustainability in desert climates
Mousavi and Farahani [56]	MFv01 suction robot	Dual brush + dry suction	≈100 W; ~2–3 Wh panel^{-1}	~5% weekly PV gain; monthly ~50%	1-year ROI; no rail required
Almalki, et al. [42]	Autonomous drone with artificial intelligence and lotus-effect surface coating	Hydrophobic water-based cleaning using drone-mounted system	Not numerically specified; drone-integrated pump and sensors	Power output improved by approximately 31 %; dust detection accuracy was 99 % using MobileNet-VGG16 convolutional neural networks	Prototyped and tested at Taif University rooftop; system reduced manual labor risk and enabled intelligent inspection
Chtita, et al. [43]	Three-rotor drone with rotating brushes and water spray system	Hybrid cleaning (mechanical and wet) with tilt-adjusted rotors	Solar-powered, autonomous; exact consumption not provided	Improved solar panel efficiency and extended operational lifespan; estimated 15–25 % daily gain under soiled conditions	Optimized water distribution and flow control based on sensor feedback; environment-responsive operation enhances cleaning precision

operating costs, making them suitable for narrow or hard-to-reach areas. Drone-integrated robots are portable and require minimal infrastructure, making them effective in unusual terrain, but they face capacity constraints and high costs. Autonomous rotating robots are lightweight and cost-effective, making them suitable for small solar systems, but their battery life and operational range are limited.

Further supporting the advantages of cleaning robots, studies highlight their potential to enhance energy output significantly, with increases in efficiency ranging from 39.05% to 62.11% after cleaning panels with high dust accumulation [47]. In large photovoltaic plants, soiling contributes to 3–4% energy losses, necessitating regular cleaning [48]. Cost-effectiveness is another benefit, with automated systems offering a net present value of $2383.71 and a payback period of 1.95 years [49]. Additionally, robots equipped with sensors and advanced deep-learning models optimize cleaning schedules, enhancing operational efficiency [50, 51]. However, there are associated risks, including potential abrasion of anti-reflective coatings, which can degrade panel efficiency over time [52]. Dust accumulation remains a critical factor, with performance losses ranging from 7% to 98.13% if untreated, though robots can improve efficiency by up to 49.53% depending on environmental conditions [53]. Economic considerations must also weigh initial investment and operational costs against the anticipated gains in performance. While soiling reductions preserve revenue, power generation losses exceed 50% in some regions without cleaning [54]. **Table 2** compares four major types of robotic systems based on their advantages, disadvantages, and movement types.

Table 2. Advantages and limitations of cleaning robots based on movement types.

Movement Type	Advantages	Limitations
Rail-Mounted	Accurate path, ideal for flat utility plants	Requires permanent rails; complex installation
Crawling (Rail-Free)	Flexible, portable, low CAPEX	Slippage risk, panel strain, navigation errors
Aerial / Drone	Terrain-flexible, no physical contact, fast setup	Low payload, battery-limited, affected by weather

5. Conclusions and Future Directions

This study addressed the challenges related to dust accumulation on solar panels and its negative impact on solar energy production efficiency, especially in arid regions that suffer from high dust concentrations and frequent sandstorms. Several robotic systems used for cleaning solar panels were analyzed, including fixed-route robots, robotic arm-based systems, integrated flying robots, and autonomous robots. The advantages and disadvantages of each type were evaluated based on performance, efficiency, economic feasibility, and adaptability to diverse environmental conditions. The results showed that modern robots, particularly those designed for dry cleaning and integrated systems, can increase solar energy efficiency by up to 49.53% in some cases, achieving a cleaning rate of up to 92.46%. This demonstrates the effectiveness of these systems in reducing energy losses due to dust accumulation, which can reach 99% in critical situations. Furthermore, it was confirmed that robotic systems provide more sustainable and economical solutions compared to traditional cleaning methods that require large amounts of water and consume significant time and effort. Additionally, recent studies indicate that the use of robots can improve energy productivity by up to 15% and reduce operating costs by up to 30% annually. They also address the challenges associated with the availability of human labor, especially in remote locations or with difficult environmental conditions. The results showed that robotic systems are economically viable, with some recording a net present value of up to $2,383.71, accompanied by a payback period of less than two years. Environmentally, robotic systems reduce water consumption in cleaning operations, making them a sustainable option, particularly in areas experiencing water scarcity. Studies have confirmed that the biggest challenge lies in balancing cleaning efficiency with reducing resource consumption and operating costs, which has prompted the search for innovative solutions such as robots that combine efficiency and economy.

Robots also boast the ability to clean large areas efficiently and in a shorter time than manual or traditional methods, capable of cleaning hundreds of square meters per day without the need

Several future directions can be proposed to improve the performance, efficiency, and applications of robotic systems used for cleaning photovoltaic panels:

- Increasing the flexibility of fixed-path robots

Fixed-path robots offer high cleaning accuracy but are limited by their rigid design, which lacks the flexibility to adapt to different photovoltaic panel layouts. Future research could focus on designing modular track systems or robots capable of adapting to different panel positions. Smart sensors and AI-powered path-planning techniques could also be integrated to enhance flexibility while maintaining accuracy.

- Cost-reducing arm-based robots

Robotic arm-based systems offer high adaptability to different panel angles and heights, but they remain expensive to manufacture and operate. Innovations in the use of lightweight materials and energy-efficient motors, as well as shared power systems (such as integrating robotic arms with photovoltaic panels to draw power directly), could reduce costs and enhance commercial viability.

- Improving the Payload Capability of Flying Robots

UAV-based systems have the potential to clean remote and distributed installations, but they are limited by their small payloads, which reduce cleaning efficiency and operating time. Lightweight yet durable water tanks, advanced cleaning brushes, and hybrid power sources (such as solar-charged batteries) can be designed to increase operating range and reduce the need for frequent charging.

- Improving Battery Efficiency in Autonomous Robots

Autonomous rotating robots are an economical and compact solution, making them an attractive option for small panel systems. However, their short battery life limits their operating range. Research could focus on integrating advanced battery technologies, such as solid-state batteries or on-the-go solar charging systems, to enhance energy storage and extend operating life.

- Adaptation to Environmental Conditions

All types of robots face challenges in harsh environmental conditions such as high winds, sandstorms, and heavy rain. Future efforts should focus on robust designs that ensure stable operation in harsh conditions, such as reinforced structures, adaptive mobility systems, and weather-resistant components.

- Adaptive Cleaning Scheduling via AI

Integrate real-time soiling data, weather forecasts, and irradiance models using machine learning to trigger cleaning only when economically justified, reducing energy and water waste.

Specific Roles of Authors

Amr Elbrashy: Writing original draft, Writing review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Conflict of Interest

The author reports no financial or personal interests that could have biased the research presented in this paper.

Disclosure of Generative AI and AI Tools Used in Writing

The role of AI was limited to providing linguistic precision support without generating any content.

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