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Review Article

A comprehensive investigation of solar panel cleaning technologies: A review study

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ABSTRACT

This article explores the evolution and importance of photovoltaic (PV) panels, spanning from their inception to contemporary variations, emphasizing their critical role in addressing global concerns regarding climate change and carbon emissions. It underscores the necessity of maintaining clean photovoltaic panels to optimize efficiency and examines factors affecting dust accumulation and mitigation methods. The literature review highlights the substantial impact of dust accumulation on PV panel efficiency, documenting power output declines due to dust deposition globally. It also discusses the evolving landscape of cleaning methodologies, including robotic systems and surface treatments, to enhance solar PV performance in dusty environments. Dust's multifaceted role in environmental processes, affecting climate, atmospheric interactions, and human health, is acknowledged. The complexity of dust deposition on PV systems, influenced by various factors, underscores the challenge of maintaining optimal panel efficiency. The diverse characteristics of dust, including size, composition, adhesion, and density, complicate understanding and emphasize the need for comprehensive research. Various cleaning techniques, from traditional methods to advanced ones like electrostatic precipitators and coatings, are explored, addressing dust accumulation with considerations for water conservation and energy efficiency. Innovative dust mitigation approaches like super-hydrophilic and super-hydrophobic coatings are presented. This article provides a comparative analysis of solar panel cleaning methods, emphasizing their advantages and limitations, to aid in method selection based on installation needs and environmental conditions. It also delves into active and passive self-cleaning techniques, assesses automated cleaning systems, underlines the role of these methods in obtaining the highest efficiency of photovoltaic panels shows the different mechanisms by which these methods are built, and reviews the latest studies in this area.

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INTRODUCTION

The contemporary world faces numerous challenges, including climate change and global warming, resulting from carbon emissions from factories, automobiles, and power plants. The transition to renewable energy sources, such as solar energy, is crucial in addressing these concerns. Photovoltaic (PV) panels are essential in harnessing solar energy, but their efficiency is significantly reduced by dust accumulation [1].

Global governing bodies, such as the United Nations (UN), have recognized the pressing need to address the issue of climate change and global warming. In 2015, the UN organized a meeting that resulted in the Paris Agreement, which aims to limit the global temperature increase to well below 2°C above pre-industrial levels by the end of the century [2]. This agreement has spurred a series of measures taken by the international community to mitigate the effects of rising CO2 concentrations in the atmosphere. According to the agreement, the global temperature must be 2 degrees Celsius or lower by the end of the century. Methods for effectively reducing CO2 emissions, both at the source of production and through carbon capture techniques, have been identified. These methods include reducing energy consumption, increasing energy efficiency, using alternative energy sources, and implementing carbon capture techniques [3]. Renewable energy systems represent the first step in regulating energy consumption and industrial construction for energy alternatives [4]. Various renewable energy sources make significant contributions to the economy of energy production and form the basis of various projects. The most important sources today are solar, wind, and bioenergy [5]. With progress, we believe that all countries worldwide have taken significant strategic plans and steps to increase their share of renewable energy and reduce greenhouse gas emissions [6].

The annual amount of solar energy received by the Earth from the sun is approximately 1.73 * 1017 watt-hours [7]. Solar energy and solar heating are considered two ways to use solar energy to provide us with a better life. Now, the use of solar energy to directly convert it into electricity is widely recognized as a possible energy source. This is achieved through the photovoltaic (PV) effect, in which photovoltaic cells generate energy [1]. Typically, when light strikes a solar panel, the cells absorb two-thirds of the light, while one-third is reflected off the panel's surface. The front glass of the solar panel, which varies in thickness from 2 mm to 4 mm depending on the type of glass, is crucial for light transmission and protection. Maintaining the cleanliness of this layer is essential to optimize its properties, such as spectral transparency and light transmittance [8].

The complete conversion of light energy inside PV panels into electrical power does not occur due to a series of factors that affect the overall panel efficiency. Often, the effectiveness of panels is subject to factors such as dust accumulation, high temperatures, intricate details of the solar spectrum, panel orientation, and tilt angle [9].

The primary objective of this study is to investigate the effectiveness of various cleaning techniques and modifications in improving the efficiency and performance of photovoltaic (PV) panels. Despite extensive research on the impact of dust accumulation on PV panel efficiency, there remains a need for a comprehensive evaluation of cleaning methods that can reliably restore and maintain optimal panel performance. This study aims to fill this gap by thoroughly reviewing existing cleaning technologies, their advantages, limitations, and potential for enhancing PV system efficiency.

TYPES AND CHARACTERISTICS OF DUST AND ITS IMPACT

Dust is solid particulate matter that originates from the weathering of rocks. It is primarily composed of silicon but can also contain organic components. These organic constituents act as cohesive agents, binding the particles and facilitating their transport by wind, leading to agglomeration, and ultimately shaping the overall composition of dust. These organic elements may exert an influence on the behavioral traits of dust [10].

Dust particles play a crucial role in preserving the Earth's climate-energy equilibrium through both direct and indirect radiative engagements within the atmosphere [11]. The direct effects of dust in the atmosphere encompass the dispersion and assimilation of radiation [12], while the indirect interplay between dust and clouds pertains to the initiation of cloud formation by dust particulates [13, 14]. Dust also impacts the biogeochemical cycle by transporting nutrients to the oceans [15]. Additionally, inhaling dust can have detrimental effects on human health [16, 17]. The dust cycle encompasses the stages of particle release, atmospheric conveyance, and subsequent settling (both via dry and wet pathways) of particles, typically characterized by sizes below 500 μm. The dynamics of the dust cycle are significantly influenced by meteorological and climatic factors, particularly in arid regions [18]. On an annual basis, approximately 2000 metric tons of dust are globally emitted, with 75% being sedimented onto terrestrial surfaces and the remaining 25% dispersed over oceans [11], [19]. The deposition of dust on oceanic expanses can amplify carbon absorption and retention processes [20], its accumulation over landmasses can have implications for the efficiency of solar energy systems, as it can lead to the deterioration of photovoltaic panels over extended durations [21].

The characteristics of dust deposition on PV systems are determined by two primary interrelated factors: the inherent attributes of dust particles and the specific local surroundings. The local environment encompasses factors unique to the site, influenced by prevailing human activities, architectural traits (such as surface texture, alignment, and installation elevation), environmental elements (like vegetation type), and prevailing weather conditions. The qualities of dust particles (including their type, chemical and biological properties, electrostatic characteristics, size, shape, and mass) hold equal significance alongside their accumulation and aggregation tendencies. Similarly, the surface texture of the receiving PV surface also plays a critical role. A surface with adhesive qualities (manifesting as a rough, furry texture or exhibiting residue adhesion and electrostatic buildup) is more prone to amassing dust compared to a smoother surface with lower adhesion characteristics. Additionally, it is a well-established phenomenon that the presence of initial dust can attract or facilitate further deposition, thereby rendering the surface progressively more receptive to dust collection [22].

It becomes evident that the process of dust deposition is notably intricate and presents considerable difficulty in both practical management and comprehensive understanding, primarily due to the multitude of influencing factors involved.

Factors influencing dust settlement [22]:

- Dust Properties (includes dust type - chemical, biological, and electrostatic property, size, shape, and weight).
- Wind Velocity
- Glazing Characteristics (This includes the texture of the PV panel surface and coating characteristics)
- PV system tilt-angle and orientation (includes exposure movements of the sun and wind).
- Ambient Temperature and Humidity.
- Site Characteristics (This includes local vegetation. pedestrian and vehicular traffic, and air pollution).

PV systems are conventionally anticipated to be engineered for optimal energy production. The variables influencing the attainment of peak or maximum output can be classified into modifiable and unmodifiable factors. The adjustable factors offer opportunities for design adaptability in accordance with diverse installation prerequisites, while the unmodifiable factors necessitate inherent consideration as the default approach [22].

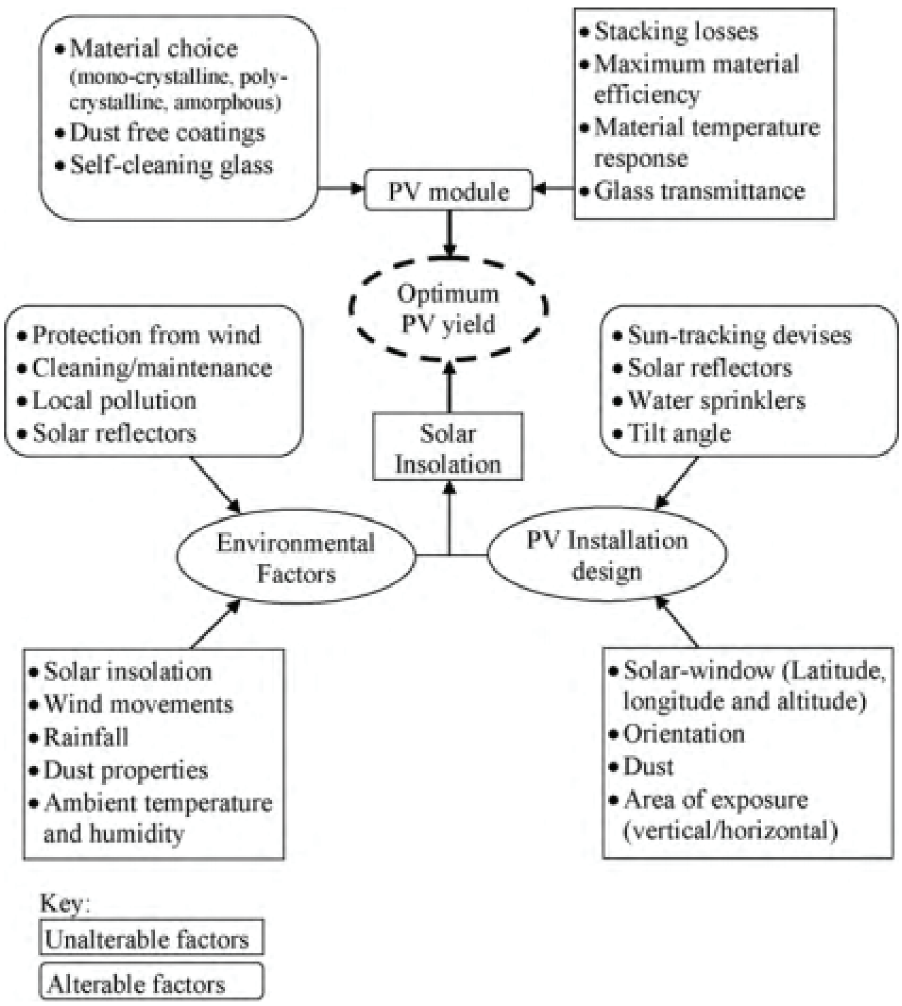

Figure 1. Factors influencing the maximum yield of a PV system are categorized into adjustable and unmodifiable factors. [From M. Mani and R. Pillai [138], with permission from Elsevier.]

PV modules have certain built-in traits that impact their performance. Figure 1 brings together these inner factors as well as external ones that affect them. It depicts how the module's inherent qualities interact with outside influences. By splitting factors into changeable and unchangeable groups, this model guides improving PV system output. It shows where strategic adjustments and careful decision-making during design and upkeep can boost efficiency.

Several types of dust and particulate matter can accumulate on solar PV panels. Some of the common types include:

- Inorganic Dust: This includes fine particles of minerals, metals, and other inorganic materials. It can come from various sources, such as construction sites, industrial areas, and urban pollution [23].
- Organic Dust: Organic particles, such as pollen, leaves, and dirt, can also settle on photovoltaic panels. These can come from vegetation, trees, and the surrounding environment [24].
- Airborne Particles: These are tiny particles suspended in the air, including pollutants like soot, smog, and fine particulate matter. They can settle on panels and reduce their efficiency [25].

The characteristics of dust play a significant role in determining its impact on solar panel efficiency. Some key characteristics to consider include [26-28]:

- Particle Size: Smaller particles can easily accumulate in the microscopic gaps between solar cells, affecting the panel's light absorption and energy conversion capabilities.
- Composition: The composition of the dust, whether organic or inorganic, can impact the ease of removal and the potential for chemical reactions with panel materials.
- Adhesion: Dust particles may have varying levels of adhesion to the panel surface. Strongly adherent particles might require more aggressive cleaning techniques.
- Density: The density of dust can influence how it distributes across the panel surface and whether it forms patches or even layers.

The influence of dust accumulation on PV panels is contingent upon prevailing weather conditions and particulate dimensions. Furthermore, the electrical output generated by PV panels experiences variability contingent upon geographical location, dust composition characteristics, and environmental temperature. Consequently, it is imperative to recognize that research findings derived in a specific country may not be universally applicable across diverse geographical regions [29].

The Significance of Studying the Effects of Dust Accumulation on Photovoltaic Panels

The issue of solar panel cleanliness emerges as a prominent concern in efforts to mitigate efficiency losses caused by dust particles. It has been observed that dust accumulation leads to a decrease in the electrical parameters of solar PV modules, thereby affecting the gains obtained from such modules. An experimental study conducted in Baghdad, Iraq, determined that there was a decrease in solar panel efficiency due to dust particles, resulting in a reduction of 6.24%, 11.8%, and 18.74% over one day, one week, and one month, respectively [30]. In Northern Oman [31], efficiency declines ranging from 5.5% to 18% have been documented in connection with dust accumulation. Similarly, in the climate conditions of Surat, India, the accumulated dust over eight weeks caused a significant 44.14% decrease in system electrical efficiency [32]. Furthermore, dust accumulation lasting five months in Lalitpur, Nepal led to efficiency reductions of up to 29.76% for dusty panels [33].

Based on observations in Northern Poland, it was found that the efficiency of PV modules decreased by approximately 25.5% on average due to naturally accumulated dust. Additionally, the daily maximum efficiency loss recorded for a silicon crystal module set at a 37° tilt angle reached 0.8%. A common trend emerged across the range of modules examined, indicating an average annual decrease of 3% in maximum power production [34].

In another study, the presence of dust accumulation resulted in a decrease in power production, reducing it from 15.43 W to 7.2 W for a 20 Wp PV module in outdoor conditions and from 4.354 W to 3.625 W in indoor settings [35]. Similarly, in Xi'an, Shaanxi, China, the relative power production ratio decreased by 79.38% due to dust accumulation [36]. Another study documented a power loss of 1.7% under the meteorological conditions of Sharjah, the United Arab Emirates [37]. Additionally, accumulated dust on a PV module in Tehran, Iran caused a significant power loss of 21.47% after a rainless period of 70 days [38].

Furthermore, experimental evidence demonstrates a noticeable impact of dust accumulation on photovoltaic systems. In the context of a 1.5 kWp grid-connected PV system in Perth, Australia, and a 50 Wp solar home system located in the Nusa Tenggara Timur region of Indonesia, monthly average power production decreases of 4.5% and 8% was observed, respectively. These reductions in power production contributed to lower production costs, calculated at 0.1768 $/kWh for the grid-connected PV system and 0.102 $/kWh for the solar home system [39].

Efforts have also been initiated to mitigate the effects of dust on solar energy production. It was observed that until 2009, only 10 relevant articles were published annually. However, over the subsequent 7 years, there was a notable increase in research contributions. In 2015 alone, 80 articles were published in various journals, reflecting a growing interest in this field [40]. This increased trend has led to greater emphasis on scientific outputs and an increased need for effective solar panel cleaning methods.

The current research literature unequivocally emphasizes that dust accumulation is a significant cause for concern, leading to substantial electrical and economic losses. Consequently, there is a compelling call for urgent action to address the losses incurred due to dust, aiming to optimize the output of PV systems. This driving force encourages the need for innovative and effective dust removal systems, although various methods for dust reduction have been presented, their effectiveness has been demonstrated to have limited effects on energy and power increases following the implementation of cleaning processes.

As time progresses, the surfaces of photovoltaic panels tend to accumulate various pollutants, including pollen, dust, dirt, and bird droppings. Typically, the buildup of such pollutants leads to an approximate reduction of 10-15% in solar output. Given that the operational lifespan of most photovoltaic panels is 30 years or more [41], a cleaning program is required to maintain continuous power production.

In a broader context, the operational efficiency of a PV panel is influenced by two fundamental vectors: first, inherent design features that are internal deliberation elements, and second, external factors that define the operational environment. Internally, the dynamics of PV panel operation are dependent on design parameters such as surface temperature, panel configuration, tilt angle, structural integrity of cells, and cell delamination, among other factors. Simultaneously, in an external context, the performance of a PV panel occurs under the complex interaction of a set of variables that include changes in humidity, dominant ambient air temperature, wind speed, levels of solar radiation, and the degree of shading affecting the panel surface, in addition to dust accumulation [42, 43]. Within this cluster of external influences, dust is positioned as a significant contributor to performance degradation, while other external factors synergistically facilitate the accumulation and dispersal of dust on the panel surface [44].

Numerous scientific studies have been conducted to address the challenges associated with dust and particulate matter for photovoltaic arrays [45, 47]. These studies have meticulously examined documented cases of reduced energy efficiency in existing solar energy facilities in various global regions. Additionally, a thorough examination has been undertaken, addressing key factors essential for the development of solar energy facilities. This includes the analysis of efficiency declines caused by pollution and the evaluation of efficient cleaning techniques tailored to diverse geographical conditions [48].

Methodology

This review examines different technologies for cleaning photovoltaic panels, focusing on their effectiveness, where they can be used, and their environmental impact. The researchers searched through various databases like Web of Science, Scopus, and Google Scholar, using keywords related to "photovoltaic panels", "dust buildup", and "solar panel cleaning methods". The selected studies were peer-reviewed articles, conference papers, and reports published between 2000 and 2023, giving a broad overview of the development of cleaning technologies and how well they work. The selection criteria were based on relevance to solar energy efficiency, specificity to dust-related performance degradation, and innovation in cleaning methodologies.

Data collected covered cleaning techniques, efficiency improvements, environmental factors, and operational settings. Structuring the review this way allowed a comprehensive look at current technologies. This structured approach ensures a comprehensive understanding of current technologies and identifies research gaps in solar panel maintenance strategies.

The experiments conducted as part of this study controlled several key parameters to ensure the reproducibility and reliability of the results. These parameters include:

- Dust type and composition
- Dust loading density on the PV panel surfaces
- Environmental conditions (temperature, humidity, wind speed)
- Panel orientation and tilt angle
- Cleaning method application protocols (frequency, duration, etc.)

The importance of these parameters lies in their direct influence on the efficiency of the cleaning techniques and the resulting impact on PV panel performance.

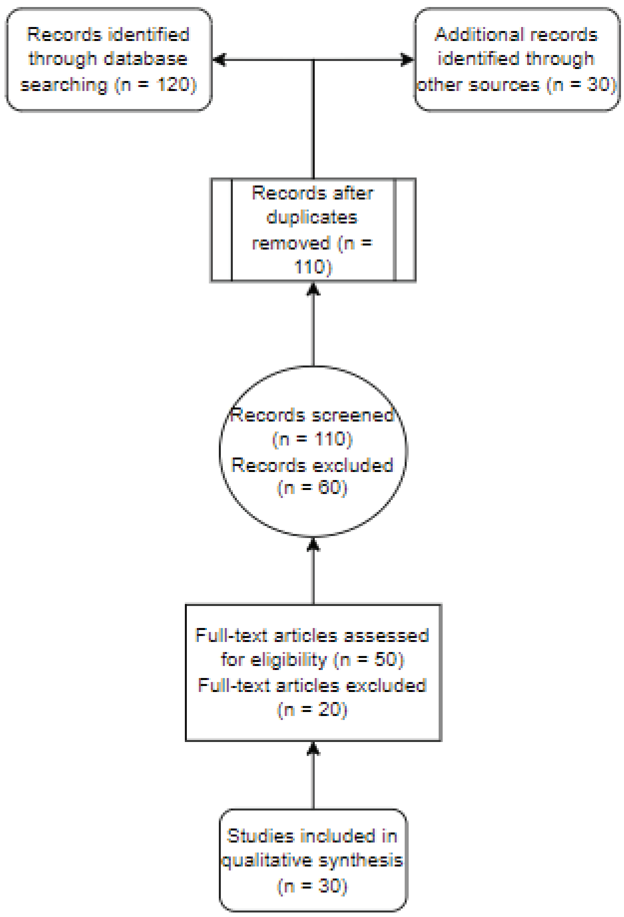

Figure 2. PRISMA flow diagram of the study selection process.

The PRISMA flow diagram (Figure 2) illustrates the study selection process for this systematic literature review. Initially, 120 records were identified through database searching (Web of Science, Scopus, and Google Scholar), and an additional 30 records were found through other sources, such as manual searching or reference list checking. After removing duplicates, 110 records remained for screening based on titles and abstracts. During the screening stage, 60 records were excluded, leaving 50 full-text articles to be assessed for eligibility based on the inclusion and exclusion criteria. Of these 50 articles, 20 were excluded for reasons during the eligibility assessment stage. Finally, 30 studies met the eligibility criteria and were included in the qualitative synthesis of this systematic literature review.

DUST CLEANING TECHNIQUES FOR EFFICIENT SOLAR PV PANELS

Revolutionizing Solar Panel Maintenance

In this section, we review effective cleaning methods and different technologies used for the cleaning process of photovoltaic panels, in addition to illustrating the efficiency added by this experimental research of the scientific community in this field. Assi et al. presented a novel method that takes advantage of the widespread use of air conditioning systems. The method makes use of the air circulation generated by air conditioner fans to eliminate dust from photovoltaic panels. This methodology was implemented across diverse geographical contexts, with prominence given to its application within the United Arab Emirates [49]. On a parallel note, Park et al. devised a passive strategy for PV module cleaning. Their design included a superhydrophobic panel structure that strategically encouraged the collection of rainwater and atmospheric condensation within micro-depressions on the glass surface. This localized pooling of water attracted particulate matter. Subsequent evaporation of the water left behind residuals requiring removal [50].

Lu et al. employed a linear piezoelectric actuator in tandem with wipers to effectuate the cleansing of PV modules. This configuration, characterized by its compact form and lightweight attributes, demonstrated efficacy in maintaining panel cleanliness [51]. In a parallel vein, Vasiljev et al. devised an ultrasonic cleaning system with the capacity to access minute crevices and challenging-to-reach surfaces, thereby penetrating regions conventionally inaccessible to alternative cleaning methodologies [52].

Parrott et al. enhanced the efficacy of cleaning procedures for PV systems by achieving a daily improvement of 0.25% through the utilization of robotic cleaning techniques. The robotic system, which featured a silicone rubber foam brush, effectively reduced the impact of dust accumulation on PV panels, resulting in increased power output [53]. Similarly, Du et al. formulated a distinctive nozzle configuration intended for dislodging dust from PV modules. Their design entailed a multi-stage expansion nozzle, engineered to cater to various climatic contexts [54]. In a parallel vein, Chesnutt et al. introduced an electrodynamic dust shield (EDS), which harnessed electrodynamic waves generated by electrodes affixed to the panel's surface to elevate and transport dust particles [55]. Deb & Brahmbhatt conceived an automated cleaning system devoid of water, designed for the removal of dust from photovoltaic panels. Furthermore, their work encompassed a comparative analysis of the energy capture efficiency achieved through this cleaning methodology [56].

Moharram et al. undertook a comparative investigation of cleaning techniques involving non-pressurized water and surfactants, with the latter proving to be more advantageous and efficient. In an analogous vein, the application of a nano-hydrophobic layer serves to level out micro-depressions, yielding a sleek glass surface that curtails water retention [57]. Demenkova et al. proposed a control system featuring sun-tracing algorithms validated through testing on mobile photovoltaic panels to ascertain the efficacy of the employed photovoltaic (PV) module [58]. Pan et al. empirically demonstrated the contrast between uncoated glass and nano-micro-structured coating on PV modules, highlighting the superior transmittance rate achieved by the nano-micro-structured glass after dust accumulation [59].

Diverse methodologies presently find application in the cleaning of PV panels, encompassing classical brush-based techniques, the use of compressed air to eliminate surface dust, reliance on natural precipitation for cleaning, as well as the integration of robotic systems designed for cleaning purposes. Within the realm of robot-assisted cleaning methods, the literature offers dry and aqueous cleaning modalities [60]. In the dry-cleaning paradigm, the method involves brush-based cleaning coupled with dust absorption, culminating in an associated power production enhancement of approximately 9% [61]. Conversely, the aqueous approach entails the application of water onto the PV panel surface, yielding inconsequential improvements in PV panel efficiency [62]. The findings from these investigations collectively underline the limited efficacy of employing solely non-pressurized water for PV panel cleaning. Instead, optimal outcomes are discerned through the adoption of pressurized water mechanisms or the mechanical cleansing of the PV panel surface through brushing actions [63].

Consequently, there exists a pronounced imperative to undertake investigations into the operational behavior of photovoltaic panels in dusty environments, a necessity driven by the quest for optimal utilization of panel functionality. Considering this perspective, the present article of review accentuates the ramifications of dust accumulation on the efficiency of PV panels and underscores the requisite for meticulously devised and efficacious strategies for dust removal. These methods hold the potential to enhance the operational proficiency of solar PV panels.

Table 1. A chronological evolution of dust accumulation modeling and prospective cleaning methodologies for photovoltaic panels [65]

Year	Cleaning mechanisms
1993	Degradation of PV Cell Performance due to Dust Deposition
2012	Waterless Cleaning Robot Utilizing Solar Power for Night Operations
2013	Electrostatic Cleaning with Transparent Electro-dynamic Shield
2014	UAV Robot Designed with Sprinklers, and Self-Cleaning Method with Translucent Nano-Coating
2015	Automated Cleaning System-Based Solar Tracker Module
2019	Modeling and Quantifying Dust Accumulation
2020	Dust Impacted PV Power Generation Using Bilinear Model
2022	Automated Cleaning with Wiper-Controlled Mechanism, and Hydrophobic Coating Utilizing Rainwater to Clean the Dust

Table 1 presents a chronological overview of the evolution of dust accumulation modeling and the development of various cleaning methodologies for photovoltaic (PV) panels. It categorizes advancements by year, spanning from 1993 to 2022, and details the specific cleaning mechanisms or models introduced in those years [64]. The progression reflects the solar industry's response to the critical issue of dust accumulation, which significantly impacts the efficiency and performance of photovoltaic panels. The table underscores the solar industry's evolving strategies to combat the challenge of dust accumulation on photovoltaic panels. From recognizing the problem to developing sophisticated automated and water-efficient cleaning technologies, and from empirical solutions to advanced modeling and predictive analytics, the advancements reflect a comprehensive and innovative approach to maintaining the efficiency and longevity of PV systems.

This study categorizes cleaning techniques for photovoltaic panels into two distinct classes: active and passive methods. Active approaches, represented by electrostatic and mechanical methods, require power for self-cleaning processes, whereas passive methods such as coating techniques operate automatically without energy consumption. The analysis encompasses the evaluation of six different cleaning systems: manual solar panel cleaning systems, electrostatic cleaning, robotic cleaning solutions, self-cleaning, automatic cleaning, and unmanned aerial vehicle (UAV)-based cleaning. It underscores the critical importance of selecting the most suitable system based on environmental parameters and non-environmental determinants. Furthermore, this analysis reveals significant variations in efficiency levels among these systems. Specifically, the electrostatic cleaning method demonstrates high efficiency ranging from 70% to 90%, while the effectiveness of coatings depends on the specific material used, potentially achieving high recovery efficiencies of up to 98% [66].

Building upon the groundbreaking advancements discussed, it becomes essential to juxtapose these innovative approaches with conventional cleaning methodologies that have been the backbone of solar panel maintenance. The transition from experimental solutions to time-tested practices underlines the evolutionary journey of solar panel upkeep strategies.

Existing Dust Cleaning Techniques

Solar power plants are typically engineered for an operational lifespan spanning 25 to 30 years. Nevertheless, the aggregation and buildup of dust, along with its various forms, can significantly diminish the optimal power generation capabilities of these facilities. As reported by [67], the accumulation of dust and particulate matter on photovoltaic panels can lead to energy losses of up to 7% annually in regions encompassing North America, Latin America, and the Caribbean. Moreover, in the Middle East, energy losses as substantial as 50% have been documented. This section delves into the potential mechanisms that can contribute to the effective cleaning of photovoltaic panels, all while preserving their inherent capacity for power generation.

Presently, a range of techniques are employed to clean PV panels, encompassing traditional approaches like manual brushing, air-based removal of surface dust through compressed air, application of coatings, and utilization of robotic cleaning systems. The prevalence of dust accumulation on the surfaces of PV panels within solar energy facilities is notably elevated, owing to the substantial volume of dust particles transported globally each year [68].

Numerous investigations have been undertaken to explore diverse methodologies involving water for the cleaning of PV panels. Moreover, substantial endeavors have been dedicated to the advancement of techniques that do not rely on water. These comprehensive inquiries are swiftly emerging as significant resolutions to enhance electricity generation and promote water conservation.

The exploration of solar panel cleaning techniques from the pioneering research presented in Section 4.1 to the established methods detailed in Section 4.2 highlights the solar industry's dynamic response to the challenge of dust accumulation. As we advance, it is imperative to foster synergies between these diverse strategies, combining the strengths of traditional practices with innovative advancements to craft

Figure 3. Manually cleaning PV modules.

holistic solutions that ensure the longevity and efficiency of solar energy systems.

Following an extensive review of numerous studies, the methods employed for cleaning can be broadly categorized as outlined below:

Manual solar panel cleaning systems

Historically, the task of cleaning was performed manually by individuals. Nevertheless, manual cleaning is associated with limitations, including potential employee injuries, potential harm to the panels, challenges in maneuverability, and inadequate maintenance practices, among others [69]. This approach necessitates frequent iterations and can consume a substantial amount of time. In cases where human intervention is essential for surface cleaning, the utilization of non-conductive materials such as brushes, cloths, and other implements is recommended to prevent electrical impairment and minimize the potential hazard of electric shock [70].

The volume of water utilized is influenced by the prevailing environmental circumstances. In regions such as the Middle East, the water consumption for cleaning large-scale PV power installations, such as megawatt-level PV power plants, is estimated at 0.5 L/m2 [71]. For manual cleaning in such contexts, challenges emerge in terms of higher labor requirements, prolonged cleaning durations, and the complexity of simultaneously addressing all panels comprehensively.

In addition to manual cleaning, a variety of approaches are available for the maintenance of solar cells, including natural cleansing mechanisms such as wind, rain, and snowmelt, as well as techniques involving water, hydrophobic and ultra-hydrophilic surface coatings, and the application of electrodynamic screens within photovoltaic cleaning processes [72].

Hence, diverse cleaning methodologies have been explored to address the limitations arising from the manual handling of photovoltaic panels. Some of these methods focus on optimizing and conserving water usage, while others aim to minimize electricity consumption. Additionally, certain approaches concentrate on efficiently cleaning a maximum number of panels. Various cleaning mechanisms have been studied with the overarching goal of identifying universal solutions that can contribute to achieving the highest possible efficiency for photovoltaic panels.

Figure 3 illustrates the fundamental process of manual cleaning, a prevalent method employed to maintain the efficiency of photovoltaic (PV) panels. In this image, a worker, donned in safety gear, is shown using a soft mop to gently remove dust and debris from the surface of the photovoltaic panels. The action captured here underscores the meticulous care required to avoid damaging the panels while ensuring they remain free of particulate matter that could impede sunlight absorption and, consequently, the panels' energy conversion efficiency.

Electrostatic cleaning

The techniques employed for dust elimination through electrostatic means are primarily rooted in the "Electric Curtain Concept," initially introduced by F.B. Tatom and NASA in 1967 and subsequently refined by Masuda at the University of Tokyo during the 1970s [73].

The electrostatic precipitator (ESP) effectively cleans and maintains the upper surface of the solar panel without necessitating any physical contact. Functioning as a filtration apparatus, the ESP operates by leveraging an induced electrostatic charge to extract minute dust particles from the solar PV panel's surface. The ESP's electrodes receive power through a relay system triggered by control signals, which are activated after assessing the panel's weight and comparing it against a predetermined threshold. Through the utilization of negatively charged electrodes, the ESP establishes an opposing charge on the dust particles present on the panel [74]. It is worth noting that this approach is ill-suited for the collection of gaseous pollutants and poses safety concerns for residential applications, as panel vibration might lead to a weakened attachment to the roof, potentially causing damage if dislodged [75].

Upon connecting the electrodes to a single-phase AC voltage, a standing-wave field is generated, as depicted in the figure. In the past, the prevailing understanding was that these standing-wave fields could elevate particles present on the curtain but were not capable of inducing overall particle transportation (Liu and Marshall 2010).

The provided research in Table 2 focuses on advanced techniques for maintaining the efficiency of solar photovoltaic (PV) panels through the development of innovative cleaning solutions. These studies introduce mechanisms such as transparent self-cleaning dust shields and electrostatic cleaning systems designed to combat the detrimental effects of dust, sand, and other particulates on solar panel surfaces. Utilizing principles like electrodynamic forces and alternating electrostatic fields, these technologies enable the effective removal of dust without necessitating water, thereby offering sustainable and low-energy solutions suitable for arid environments and large-scale solar installations. The emphasis is on improving solar panel performance through regular and automated cleaning methods, addressing challenges such as varying particle sizes, and adapting to different environmental conditions. Collectively, these approaches aim to enhance the reliability and efficiency of solar energy systems, particularly in regions prone to high dust and sand accumulation.

Table 2. Methods employed in electrostatic cleaning

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
R. A. Sims et al., [77]	Generated an electromagnetic field through electrodes positioned on the panel's surface	Transparent Electrodynamics Shield	Repels Dust Particles	Polarity of Particles	Higher voltages led to more effective powder removal, while signal frequency affected the speed of cleaning.
Hiroyuki Kawamoto and Takuya Shibata, [78]	Involved the application of a single-phase high voltage to parallel wire electrodes integrated into the cover glass plate of a solar panel	Electrostatic Force	High Voltage Applied to Parallel Wire Electrodes	Does not Require Water	The cleaning operation proved highly efficient in removing accumulated sand, recovering to 90% post-operation.
Surajit Mondal et al., [79]	The array of cleaning techniques discussed within this framework comprises electrostatic biasing	Electrostatic Biasing	Comparison with Other Techniques	Human intervention is required.	The study recommends using hybrid cleaning techniques and integrating sensors needed to monitor the parameters in solar stations.
Hiroyuki Kawamoto, [80]	They apply a high alternating current (AC) voltage to parallel grid electrodes on the panels, generating an electrostatic force that acts upon particles in proximity.	High AV Voltage Applied to Parallel Screen Electrodes	Low Power Consumption	Accumulation of Residual Dust	The system-maintained effectiveness at low panel inclinations, with 70% efficiency at 10°, and the measured power consumption was remarkably low.
Murat Altınta¸and Serdal Arslan, [81]	The electrostatic system, utilizing a negatively charged electrode and positively charged others, ejects dust particles by varying electric field density over the plate.	Electrostatic Cleaning	Self-cleaning of the solar panel	Particle Polarity and Water-Free Operation	The proposed electrode geometry of the N2 model significantly increased cleaning efficiency at the optimum voltage and frequency, reaching 75%.

Table 2. Methods employed in electrostatic cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Ying Liu et al., [82]	The development involved creating a unique, uneven electrode configuration for plasma generation aimed at discharging in damp conditions to remove stubborn and adhesive dust deposits.	Uneven Electrode to Discharge and Generate Plasma	Generates Plasma in Wet Conditions	It can work even in wet conditions	The study made important recommendations for effective utilization, understanding stability factors, analyzing cell wall characteristics
A.S. Al-Salaymeh et al., [83]	The study tests four cleaning approaches, including constant mopping, natural cleaning (wind and rain), coating with Ceracoat Glass Care photocatalysis, and electrostatic cleaning, without using water due to Jordan's water scarcity.	Electrostatic cleaning method with an EXAIR ionizer	Neutralizes static charge	Compressed air is used	Electrostatic neutralization showed substantial efficacy against dust accumulation. But paint proved more economical.
Amar Tilmatine et al., [84]	Utilized corona discharge plasma to generate an ionic wind, featuring a high-voltage electrode with parallel sharp needles and a grounded frame electrode	Solar panel cleaning device utilizing corona discharge plasma	The solar panel cleaning device utilizes a high-voltage electrode with parallel sharp needles	Generating an "ionic wind" through corona discharge	Achieving over 90% cleaning efficiency with low power consumption

Robotic cleaning solutions

Robot-based cleaning techniques represent contemporary and distinctive approaches that have significantly enhanced the efficiency of solar photovoltaic systems. These methods offer the advantage of utilizing both pressurized and non-pressurized water or compressed air, marking a substantial advancement in the integration of robots into the cleaning process. However, for robots to effectively navigate solar panel surfaces, it is crucial to establish a secure attachment mechanism. Two attachment systems have been devised to facilitate robot mobility on inclined surfaces: certain autonomous robots available in the global market struggle with solar panel cleaning due to their substantial weight. In such cases, designated starting points are allocated for the device to position itself without casting shadows on the panels, and the device is programmed to move systematically across each row of panels [85].

A range of robotic cleaning systems is available, offering autonomous, efficient, and versatile solutions for solar PV panel maintenance, with various features catering to different cleaning needs and scenarios.

Table 3 shows some previous studies' methods employed in robotic cleaning. The studies explore innovative robotic solutions aimed at enhancing the cleaning and maintenance of photovoltaic (PV) photovoltaic panels to optimize energy efficiency. These investigations delve into various automated systems ranging from modular, crawler-based robots to those controlled via Arduino technology, all designed to navigate and clean solar panel surfaces effectively. By addressing environmental challenges such as dust, dirt, and bird droppings, which notably diminish solar panel performance, these technologies strive to advance the efficiency and sustainability of solar energy production. The implementation of mechanisms like rolling brushes, water-efficient cleaning strategies, and adaptable modular designs demonstrates a significant improvement in solar panel efficiency post-cleaning, offering a promising alternative to conventional manual methods.

Self-cleaning

In recent years, there has been a growing interest among researchers and engineers in developing innovative techniques to enhance the efficiency of solar PV panels. This involves reducing the accumulation of dust on these panels and enhancing their ability to self-clean. Self-cleaning is a technique utilized for solar panel cleaning where coatings and materials like hydrophilic, hydrophobic, surfactant, etc. are used. This will allow us to develop a non-striking surface for water droplets that get rolled off while taking off dirt and dust from the photovoltaic panels. Scientists have explored super-hydrophobic coatings as a solution to counteract the drop in efficiency of solar PV panels caused by the buildup of organic and inorganic debris. These coatings offer several advantages, such as resistance to graffiti and corrosion [103]. Experiments conducted at the Assiut University Renewable Energy Laboratory in Egypt scrutinized the effect of hydrophobic SiO2 nanomaterial coatings on the efficiency of PV panels. The results demonstrated a significant enhancement in panel efficiency upon implementing this coating method [104].

A cost-effective and non-destructive technique for cleaning PV panels involves employing hydrophobic nano

Table 3. Methods employed in robotic cleaning

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Mark Anderson et al., [86]	This system is capable of both cleaning and maneuvering across the glass surface of a PV array, accommodating various angles ranging from horizontal to vertical orientations.	Portable Robotic Cleaning	Clean and Maneuver on the Glass Surface	Coordination with the Frame for All-Angle Cleaning	The project has successfully diminished manual labor and enhanced resource utilization.
Amit Kumar Mondal and Kamal Bansal, [87]	Characterized by four degrees of freedom (DOF) designed specifically for photovoltaic (PV) panels. This prototype is water-based and incorporates a combination of a sprinkler, an air blower, and a wiper for its cleaning mechanism.	4-DOF Cleaning Robot	Water-based Prototype	More Efficient on High-Powered Photovoltaic Panels	Implementing solar panel cleaning using SPCRA saved a 9.1% enhancement in efficiency.
V. Selvaganesh et al., [88]	Operated without water and employing brush-based cleaning, autonomously transitions between individual PV cells using a dedicated track system while aligning itself with the solar panel.	Micro-controller-Based Robot	Waterless Prototype	Requires track built for forward or backward movement.	The power output was improved, indicating a 93% enhancement in power output.
Manju B et al., [89]	Used an Arduino system, a rolling brush that moves in a perpendicular direction, motors, and rubber wheels, and operates without the use of water.	Automatic Solar Panel	Mechanism of Sliding Brushes	DC Gear Motor-Driven Technology	The system's advantages include low cost, ease of construction, and autonomy.
Brian Parrott et al., [53]	Highlighted that the employment of silicone rubber foam brushes by these robots, and don't utilize water in the panel-cleaning process.	Dry-Cleaning Robot System	Silicon Rubber Foam Brush	Does not Require Water	Solar panel cleaning has proven to be better than manual methods, as the automated method has proven to have significantly higher panel efficiency.
Nallapaneni Manoj Kumar et al., [90]	Introduced three distinct types of robots, each tailored to a specific method of panel fixation. The study proposed DCRs for integration with BIPV and BAPV systems	Dust-cleaning robots (DCRs)	Designed for Pitched, Horizontal, and Roofs	For Building integrated or applied PVs (BIPV & BAPV)	Addressing challenges such as energy consumption, stress on DCR, slipping, and autonomous operation.
Shibo Cai et al., [91]	Examined the mechanical properties of dust particles and theoretically established the correlation between pressure distribution and dust particle velocity to facilitate computational fluid dynamics (CFD) simulations.	Dust Cleaning Robot	Parameter Optimization	Built on CFD Simulation	The simulation results demonstrated symmetrical velocity distribution at the inlet, with higher velocities at the corners, indicating optimal dust-absorbing efficiency at those locations
Mohammad Hammoud et al., [92]	Experimented on a segment of a solar plant situated in Lebanon, during which the water-based robot cleaner prototype was utilized.	Water-Based Robot Cleaner	Increased Efficiency	Structure-Specific On-Wheel Device	The study demonstrated a significant increase in power generation efficiency, with an average increase of around 32.27%, the cleaning process resulted in a net benefit of $4287 in power generation.

Table 3. Methods employed in robotic cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Marcel Tômas Grando et al., [93]	Aimed to explore various solutions for cleaning photovoltaic panels, considering both their positive and negative practical aspects.	PV Cleaning Robots	Solar-Brush, UAV Robot Ecoppia E4, Wash Panel, NOMADD, Cleaning System	Comparison of Technologies	The study proposes innovative solutions, including the development of a manipulator robot with vertical movements on a fixed guide and the exploration of cable-driven robots.
K Chailoet and E Pengwang, [94]	Introduced a water-based cleaning system that involves the discharge of water through a miniature sprinkler, followed by the utilization of a spiral brush for panel cleaning, and ultimately deploying a rubber sweeper to eliminate the soiled water.	Modular Robot	Can Clean Various Lengths of Photovoltaic panels	An Activated Water Source	The tested solar panel cleaning robot demonstrated an approximate 3.40% increase in electricity production.
Omur Akyazi et al., [95]	Presented a robotic system comprised of a cleaning brush and motors attached to a frame, designed to move horizontally along the plane of photovoltaic (PV) panels for cleaning purposes without the use of water.	Waterless Cleaning Robot	Arduino Development Board	Coordinated Movement	The microcontroller-based SPCR system effectively reduces the impact of dust on PV panel output power
Ranganathan S et al., [96]	Aimed to regulate the temperature of photovoltaic panels integrated into hybrid vehicles. The system includes components such as a storage tank, a radiator temperature sensor, and water sprinkler jets.	Modular Mobility Robot	Clean and Maintain the Temperature of the PV Panel	Requires Silicon Chip	Results showed that cooling increased the power output, with a peak slightly higher than normal conditions reaching 12.9%.
Ghodki M. K. et al., [97]	The IR sensor plays a pivotal role in governing the configuration of the robotic arm, facilitating automated transitions between the cleaning, and charging phases.	Robotic Arm	IR/Sprinkler Based Cleaning	Coordination of Cleaning/ Charging Mechanism	A cleaning system resulted in an average energy increase of 11.26%, a PV module efficiency improvement of 13.63%, and a performance ratio increase of 85.2%.
Milin D Patil et al., [98]	Introduced a robotic cleaning system designed specifically for photovoltaic (PV) panels, the system's control is managed through the utilization of a deployed microcontroller.	Robot-Based Cleaner	Micro-controller Based Control	Stepper/ DC Motor Combination	Cleaning photovoltaic panels takes approximately 4.5 minutes, consuming 1.89Wh of energy, improving battery charging speed by 20%.
Nasib Khadka et al., [99]	This prototype leverages a cleaning robot and a cloud-based interface. the capability to clean the entire panel surface in a bidirectional manner using rotary brushes and it does not rely on water for cleaning.	Waterless Cleaning	Rotary Brushes-Robot-Based Design	Cloud Interface	Addressed the potential impact of dust accumulation on efficiency, especially in megawatt-scale production where even a 1% reduction could significantly affect the Internal Rate of Return (IRR).

Table 3. Methods employed in robotic cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Faridah Hanim Mohd Noh et al., [100]	They introduced a photovoltaic (PV) panel-cleaning robot operated via an Arduino microcontroller. The cleaning apparatus includes two coarse sponges, a water pumping system, and an Arduino control system to oversee the robot's mobility.	Arduino-Based Cleaning Robot	Water/Waterless Modes	Powered by Rechargeable Batteries	restored the solar photovoltaic output power to its maximum capacity after the cleaning process, with a notable 50% improvement in output current.
GEKKO Solar [101]	It presented a robot designed for water-based cleaning. This robot exerts constant pressure on the panels and utilizes demineralized water. It offers manual control from a remote location and boasts a cleaning capacity of 400 m2/hr.	Water-Based Cleaning Robot	Higher Cleaning Capacity	Used Demineralized Water	Capable of covering up to 400 m per hour, making it suitable for extended rooftop installations and adaptable for small solar farms with narrow panels
Manish Kumar Ghodki, [102]	They employed a pulse-width modulation (PWM)-based motor in conjunction with a silicon rubber wiper for wet cleaning operations. An embedded controller, specifically the IEEE 1149.1-based C8051F226DK, was integrated to oversee the cleaning process.	IR sensor	Temperature monitoring embedded controller	Wet cleaning	The developed device demonstrated a high cleaning rate, low cleaning time, and minimal water and energy consumption, along with lightweight construction.
Fırat Ekinci et al., [63]	A cleaning robot with pressurized water spraying fogging nozzles was employed for cleaning, and three different cleaning solutions were tested, considering the impact of solar panel temperature on performance efficiency.	3D printer generation	Improved power-embedded controller	Chemical solutions and electrical performance analysis	The use of Solution 1 with a cleaning robot achieved a 15% improvement over dusty conditions outperforming other solutions.

Table 4. Methods employed in self-cleaning

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Gaofa He et al., [73]	suggested using a self-cleaning nano-film on solar cell array surfaces, either employing a super-hydrophilicity film or utilizing a super-hydrophobic film. It serves as a point of reference in the exploration of self-cleaning nanofilm technology.	Translucent Nano-Film	Utilizes rainwater to Clean the Dust	Hydrophobic Hydrophilic Material	The best removal-dust strategy for solar cell arrays is an electric curtain.
Jaesung Son et al., [109]	proposed the development of durable, antireflective, and self-cleaning glass surfaces through a nanopatterning technique without chemical coatings. The effectiveness of the self-cleaning coatings is evaluated by monitoring contact angle (CA), optical transmittance, and photovoltaic performance over a 12-week outdoor testing period.	Types of Hydrophobic and Hydrophilic Materials	Analysis of Coated PV Panels	Contact Angle, Optical Transmittance, and PV Performance	The non-coated nanopatterned surfaces maintain superior self-cleaning, transparency, and solar cell performance.

Table 4. Methods employed in self-cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
K.A. Moharram et al., [57]	compared the effects of no cleaning, cleaning with non-pressurized water, and cleaning with water containing a surfactant. The cleaning is performed daily for 10 minutes with a controlled water flow rate of 12 L/min.	Anionic/Cationic Surfactant	Self-Cleaning	Non-Pressurized Water System	Daily cleaning with a surfactant mixture maintained a consistent efficiency of about 12%, demonstrating its effectiveness in preventing deterioration.
Hiroyuki Kawamoto and Takuya Shibata, [110]	employed a high-voltage, single-phase mechanism applied to parallel wire electrodes integrated into the cover glass plate of the solar panel.	Specialized Coating	Targets Dust Accumulation	Transmittance	The power consumption of the system was remarkably low. The system effectively removed accumulated sand, resulting in a power recovery of 60% to 90% after operation.
Zhong Hong et al., [111]	Glass sheets, serving as substitutes for PV panels, are cleaned and treated with KH-550 solution, then coated with 5% TiO2. This environmentally friendly coating, prepared with spraying technology or roller coating, aims to exhibit excellent super-hydrophilic properties, high stability, and corrosion resistance	Super Hydrophobic Coating	High Stability and Corrosion Resistance	KH550/Ti02	The coated glass has a perfect super-hydrophilic self-cleaning performance.
A. Syafiq et al., [103]	provided a comprehensive review of various self-cleaning methods for photovoltaic (PV) panels, with a particular focus on superhydrophobic coating-based approaches.	Hydrophobic Coating	Reliability and Low Cost	No Power Consumption	Passive coating methods provide benefits such as anti-adhesion and photocatalysis for dust removal
Saravanan V. S. and Darvekar S. K., [112]	explicated various cleaning methods for solar photovoltaic panels, including electrostatic cleaning, superhydrophobic coating, mechanical methods, microcontroller-based automatic cleaning, and self-cleaning nano domes	Electrostatic, Super Hyperbolic, Mechanical, Automated, and Self-Cleaning	Comparison Between Methods	-	Much research has been done on various solar photovoltaic panel cleaning methods; the best one is the Electrostatic cleaning method.
Osam H. Attia et al., [113]	This innovative cleaning device harnessed wind energy as its power source, converting it into mechanical energy. The mechanical vibrator generates a harmonic excitation force to effectively dislodge dust particles from the PV panels.	Mechanical Vibrator Mechanism	Harmonic Excitation	Vibrator Reliability	The study demonstrated the effective use of wind energy converted to mechanical energy, proportional to air velocities, for dust removal from a tilted solar panel surface.
Serkan Alagoz and Yasin Apak, [114]	employed surface acoustic wave technologies to facilitate the cleaning of PV panel surfaces.	Surface Acoustic Wave	Takes Angle of Panel into Consideration	Requires Gravity for Operation	Surface acoustic wave (SAW) application proves effective for cleaning PV panel surfaces, particularly in removing large dust particles (0.2 mm and above) on inclined panels.

Table 4. Methods employed in self-cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Edwin Babu et al., [115]	introduced an external mechanical vibration system designed for the cleaning of photovoltaic (PV) panels. In this system, a DC motor is positioned beneath the PV panel, and the revolution per minute (rpm) is adjusted to assess its effectiveness in removing dust.	External Mechanical Vibration System	Finite Element Vibration	Analysis Detection	Cleaning photovoltaic panels using mechanical vibration is economically viable for large solar farms and offers a waterless and manpower-saving alternative.
Hatem R. Alamri et al., [104]	applied a hydrophobic SiO2 nanomaterial coating. It employs a mathematical model and the particle swarm optimization algorithm to estimate the parameters of a PV panel.	Hydrophobic SiO2 Material	Comparison with Non-Coated Panels	Coating of Nanomaterial	Reducing dust deposition and improving resistance to mud formation, ultimately leading to a 15% increase in output power compared to dusty panels, a 5% improvement over manually cleaned uncoated panels, and a 10% reduction in panel temperature.
Raj Kumar Saini et al., [116]	Attention is dedicated to modern water-free cleaning techniques, particularly useful in water-scarce areas	Wireless data acquisition system	Water-based self-cleaning	Water supply	Highlighted the importance of adopting modern cleaning techniques, and appropriate cleaning frequencies.
Adel A. Ismail et al., [117]	involved the deposition of transparent mesoporous ZnO and TiO2 coatings on a SiO2 interlayer for self-cleaning PV cells under various weather conditions. The coatings are examined for their anti-soiling effect and power efficiency.	TiO2/SiO2 and ZnO/SiO2 films Coating	Low power consumption	Anti-soiling nano coating	The study demonstrated that TiO2/SiO2 nanocoating consistently outperformed ZnO/SiO2 and SiO2 coatings indicating its effectiveness in mitigating the impact of dust accumulation on solar cells.

coatings, which utilize nanofillers such as silica and titanium dioxide. These coatings augment the performance of solar PV modules, leading to a 15% increase in output power when compared to dusty panels and a 5% improvement compared to manually cleaned uncoated panels. Remarkably, these nano coatings remove dust without consuming additional energy [104]. Shielding PV surfaces from dust accumulation can be achieved by applying anti-dust coatings, including superhydrophobic and superhydrophobic films, with TiO2 coatings being widely used [73]. While superhydrophobic coatings have shown promise in dust removal and power enhancement [105], various studies indicate that coated modules generally exhibit lower daily soiling rates compared to uncoated modules [106], [107]. In regions with adequate rainfall, natural cleaning through precipitation can suffice [108].

Scientists have developed nanoparticle-based coatings to prevent dust accumulation on photovoltaic panels, particularly in harsh environments where heat, humidity, and pollution can hinder PV panel efficiency. These coatings repel dust and are easily cleaned with water, maintaining panel transparency and efficiency. It's crucial to note that

Table 5. Methods employed in automated cleaning

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Xiaolong Lu et al., [51]	In this system, a specialized wiper is affixed to the actuator, enabling precise and controlled dust removal through the application of optimal pressure to the panel surface.	Piezoelectric Actuator	Pressure Optimization	Lightweight Structure	The study suggests the potential integration of an optical dust sensor for smart and adaptive cleaning based on environmental conditions.
Piotr Vasiljev et al., [52]	They put forward a model for an ultrasonic cleaning system, characterized by the creation of an ultrasonic cavity within a thin moving water layer. To gauge the mechanical oscillations on the piezoelectric actuator, a laser vibrometer is utilized, thereby enabling the removal of dust from challenging areas	Ultrasonic System	Harmonic Analysis/ Interaction	Laser Accuracy	The proposed system exhibited effective cleaning, particularly in areas with thick water layers
Cong-Hui Huang et al., [118]	presented an innovative solar panel cleaning system equipped with an intelligent control system developed using LabVIEW.	Fuzzy Logic System	Determination of Solar Intensity	Accuracy of Output Voltage	Developed a cleaning device that improves the output current of the photovoltaic panels.
S. B. Halbhavi et al., [119]	The automatic cleaning system relies on LDR resistance changes to detect dust, triggering motor rotation for effective cleaning. Controlled by an 8051 microcontroller, the system employs a DC motor, a light-dependent resistor (LDR), and sliding brushes to facilitate panel cleaning.	LDR-Based Cleaning System	Built on Sliding Brushes	DC Motor Programmed by Microcontroller	Automatic cleaning has proved to be more economical and significantly less cumbersome, particularly in systems having many photovoltaic panels.
Z. H. Bohari et al., [120]	Involved in creating a Solar Tracking Robot utilizing Arduino's microcontroller to enhance solar panel efficiency through sun irradiance capture and renewable energy storage.	Solar Tracker Module	IR Sensor-Based Technology	Accuracy of IR Sensor	The project concluded that the solar tracker improves panel efficiency
V. A. Ballal and Prof. R. M. Autee, [121]	Proposed a PLC-based dual-axis solar tracker system utilizing photosensitive resistance for sunray detection, stepper motors for panel rotation, and PLC-controlled precise motor control.	Dual-Axis Solar Panel System	Sensor-Based Sun Tracking	Accuracy of Sensors	Experimental results show a 24% increase in energy gain for partly cloudy days
Ali Al Shehri et al., [122]	Explored the effectiveness of dry cleaning, particularly using Nylon brushes, in removing dust particles from the glass surface.	Brushed-Based Automated Cleaner	Nylon Brush-Based Dry Cleaning	Nylon Brush Material	The study recommends further research on cleaning technologies for coated glass. The brushing-induced defects, including scratches and dust clusters, were observed without affecting optical transmission

Table 5. Methods employed in automated cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
Syafaruddin et al., [123]	Utilized a wiper control mechanism powered by an ATmega16 microcontroller. The system involves spraying water on the panel surface and activating a wiper with a DC motor, controlled by limit switches.	Wiper Controlled Mechanism	Dual Mechanism	Power Consumption Capacity	Upon activating the cleaning system after movements up to a 17.55% efficiency ratio, and low and stable power usage.
Aditya Sinha and Ambuj Preet, [124]	Aimed to design an autonomous cleaning robot equipped with a solar tracker for efficient and cost-effective utilization of solar energy.	Automatic Solar Tracker	Tracing Photon Rays	Accuracy of Sun Tracker	The proposed system, integrated with an automatic solar tracker, minimizes overall expenditure by combining the cost of the cleaner with the solar tracker.
Dipankar Deba and Nisarg L. Brahmbhatt [61]	Introduced an innovative waterless cleaning apparatus designed for the efficient removal of soiling from PV panels. This device incorporates a brush attached to a movable frame, which traverses the entire PV panel surface.	Automated Water-Free System	Review of Yield Increase	Does not Require high-voltage Voltage Supplies	The proposed solution stands out by eliminating the need for liquid or high-voltage supplies, resulting in minimal maintenance costs. A notable 9.05% increase in energy yield when manufactured in bulk.
Nithin Sha Najeeb et al., [125]	It stands out due to its cost-effectiveness, energy efficiency, intelligent automation, and innovative design. Utilizing a Programmable Logic Controller (PLC). It included an air compressor, water pump, pressure regulator, and solenoid valves for automation, ensuring effective cleaning within a specified duration.	Air-Water Mixture Technology	Dust Cleaning and Cooling System of PV Panels	Reliable Stand-Alone Setup	A system utilizing an air-water mixture was deployed to clean and cool the panels revealing a significant 32% increase in power output from the cleaned panel during peak hours.
Nikhil Gupta et al., [126]	Suggested a model wherein a battery charged by the PV panel powers motors to clean the panels.	Cleaning Droid	Battery Charged by PV Panel	Functioning of Motors	By using the LDR and IR sensors it is more reliable for the robot to clean the solar panel
T.Mariprasath and K.Ramamohan Reddy, [127]	Proposed an automatic cleaning mechanism using an LDR, DC motor, and brush but lacked experimental data on efficiency improvement.	LDR-Based Cleaning	Energy Efficient Enhancement	2 cycles/day	The study emphasizes the utilization of MPPT techniques, particularly fuzzy-based MPPT, for optimizing solar PV performance.
Sai Manoj Katakam et al., [128]	Developed a semi-automatic self-cleaning mechanism that effectively removes dust deposits, utilizing minimal water and energy. The designed mechanism ensures regular and reliable cleaning, leading to increased power output	Automated Nozzle	Module System	Nozzle Placement	With the calculated average efficiency increasing by 1.2% to 3% after cleaning the panel.

Table 5. Methods employed in automated cleaning (continued)

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
N Sugiartha et al., [129]	Proposed a semiautomatic wiper control system as a preliminary design for cleaning solar panel surfaces, utilizing a DC motor, manual switch buttons, and water spray.	Semi-Automatic Water Spray Rotational	Wiper Control Built Solar Range of	System Panel Cleaning Wiper	Further prototype enhancements are needed for improved water spray distribution, optimal wiper repetition, and potential autonomous action via a microcontroller.
K. Jaiganesh et al., [130]	Suggested a novel Automatic Cleaning mechanism using Arduino without water, operating during non-sunlight hours to minimize shadow effects and input power, aiming to enhance solar panel efficiency and lifespan.	Water viper	Rooftop PV panel cleaning	Rooftop structure	Gave better performance and improves the system efficiency by 15–20%. The maintenance cost also is less because of no usage of water, and it will not create any electric short circuits or damage to the structure of the PV panel.
Ra'ed Nahar Myyas et al., [75]	Utilized an automated cleaning device designed to address high PV temperature and soiling factors. Rainwater is harvested through a gutter system, pumped to designated tanks, and utilized for cleaning solar cells.	Dust detection and cleaning	Solar and temperature control mechanisms	Rainwater harvesting	Supplied with a sustainable water source for various applications. It recycled 80% of cleaning water, automatic on/off functionality.

additional coatings should be applied judiciously, as they can reduce sunlight transmission, and regular cleaning remains essential for optimal PV module performance [75].

The compilation of research in Table 4 underscores innovative strategies for enhancing solar panel efficiency through self-cleaning technologies, addressing challenges such as dust and snow accumulation that significantly impede energy generation. Highlighted solutions encompass a variety of approaches, from employing natural forces and mechanical vibrations to innovative chemical coatings and nanoparticle applications. These methods aim to ensure continuous, efficient operation by maintaining clean panel surfaces without manual intervention. Particularly beneficial in environments with harsh weather conditions, these technologies offer cost-effective, sustainable alternatives to traditional cleaning methods, thereby ensuring photovoltaic panels operate at optimal efficiency while reducing maintenance requirements.

Table 4 provides an inventory of the technology utilized, outlining their respective characteristics and operational parameters within the domain of self-cleaning technology.

Automated cleaning

The maintenance and cleanliness of photovoltaic (PV) panels are of paramount importance to ensure optimal energy capture and efficiency, particularly in challenging environments prone to dust and dirt accumulation. To address this concern, numerous innovative automated cleaning systems and methods have emerged, offering efficient solutions for maintaining clean and high-performing PV panels.

Automated methods for cleaning photovoltaic panels are widely employed globally, utilizing a range of technologies, predominantly featuring robotics or motion sensors. Several research studies have explored the use of different substances, including chemicals and purified water, in these automated cleaning techniques.

Table 5 showcases an array of advanced methods and technologies designed for the automated cleaning and efficiency optimization of photovoltaic (PV) panels. The studies delve into various cleaning mechanisms, from simple mechanical systems to sophisticated automated, aimed at addressing the critical issue of dust accumulation which significantly affects solar energy production, particularly in arid and dusty climates. These mechanisms, which include the use of IR sensors, water sprays, mechanical wipers, and solar tracking systems, highlight the importance of maintaining clean panel surfaces and optimal orientation for peak performance.

Unmanned aerial vehicle (UAV)-based cleaning

Unmanned Aerial Vehicles (UAVs), a contemporary approach, are employed for the cleaning of photovoltaic panels. This technology enables the transport of cleaning

Table 6. Methods employed in UAV cleaning

Ref	Study Proposed	Technology	Characteristics	Operational conditions	Results
F. Grimaccia et al., [132]	Various methods for PV module monitoring, including visual detection, PV parameter measurement, and thermal and infrared cameras, are explored.	UAV-Based Cleaning System	Monitoring Applications for Energy Production	Analysis and Inspection of Sites	The UAS technology successfully identified various defects, including hot spots, micro-cracks, and burnt cells. Contributing to a 6–10% increase in overall performance while optimizing maintenance operations in PV plants.
M. Al-Housani et al., [133]	Involved in conducting experiments to determine the most suitable cleaning apparatuses for thin-film solar modules, evaluating their performance based on energy usage, efficiency, and cleaning time for different types of dust accumulation, and investigating the feasibility of equipping a drone with the various cleaning apparatuses.	Experimental Investigation Desert Climates	Comparison of Drone Retrofitting Techniques	-	Using Microfiber-based cloth wipers yields an average performance improvement of 7.7% for weekly cleaning in winter and 3.1% in summer and minimizing manpower costs through autonomous cleaning.
Marcel Tômas Grando et al., [134]	Presented the current state of the art in robotic technology for cleaning photovoltaic panels, identifying various solutions and their practical implications. They focused primarily on an extensive examination of various commercially available robotic systems designed for the cleaning of photovoltaic (PV) panels.	Review of Robots for Cleaning PV Panels	Cleaning Mechanisms	-	Highlighted the potential for optimizing cleaning methods tailored to different types of dirt.
Mohamed Mohandes et al., [135]	The study employs a multi-rotor drone, specifically the DJI SPARK, to inspect and clean photovoltaic panels, utilizing various flying patterns for dust removal. The research aims to evaluate the impact of blowing dust on panel efficiency based on electrical parameters and output power measurements over 5 weeks.	Drone Aerodynamic	Downward Thrust	-	Up to a 70% increase in panel output power for lower dust volumes.
Samer S. Sarkis et al., [136]	Proposed a novel solution for dust accumulation on small solar panel units using a hybrid drone that combines rolling and flying for cleaning.	Hybrid Drone System	Automated Brush Cleaning Method	Adequate for Small Solar Power Units	A novel hybrid drone prototype, capable of both rolling on the entire surface and flying between distributed small solar panel units

fluids and pneumatic pressure to clean photovoltaic panels, and it incorporates active sensors equipped with illumination sources and mapping cameras to ensure precise positioning. The autonomous capabilities of UAVs facilitate uninterrupted and continuous cleaning operations [131].

Table 6 focuses on innovative solutions for cleaning photovoltaic (PV) panels, crucial for maintaining efficiency in solar energy production, especially in areas prone to dust and debris accumulation like deserts. These solutions range from hybrid drone systems capable of rolling over and flying between photovoltaic panels for cleaning, to utilizing drones' aerodynamic forces for dust removal without direct contact or water. The overarching theme is enhancing solar panel efficiency through regular cleaning while minimizing water usage and manual labor, showcasing technological advancements in drone applications and automated cleaning systems tailored for challenging environments like Saudi Arabia, where dust significantly reduces solar panel output. These studies propose a shift towards automated, less resource-intensive cleaning methods to uphold solar energy's viability as a sustainable resource.

According to previous studies analyzed and summarized, effectiveness varies based on factors such as type, quantity of dust, local weather conditions, and specific cleaning techniques used. Technical selection depends on the environment, team design, and available resources. A range of methods can be used to optimize results, and ongoing research continues to refine these technologies to improve efficiency and sustainability. Furthermore, the ensuing table provides a detailed analysis of the merits and drawbacks associated with both systems and diverse technologies utilized for the cleaning of photovoltaic panels.

In summary, the choice of a cleaning method for photovoltaic panels depends on various factors, including the size of the installation, environmental conditions, available resources, and cost considerations. Innovative approaches like super-hydrophilic and super-hydrophobic coatings show promise for reducing maintenance needs

Table 7. Disadvantages and advantages methods for cleaning photovoltaic panels

Methods for Cleaning Photovoltaic Panels	Advantages	Disadvantages
Manual Solar Panel Cleaning Systems	· Cost-effective (no need for specialized equipment). · Suitable for small-scale installations.	· Labor-intensive. · Time consuming. · Potential risk of injury and damage to panels. · Significant water consumption may be a concern in certain regions.
Electrostatic Precipitator	· Cleans without physical contact. · Suitable for arid regions and environments with water scarcity.	· Not effective against gaseous pollutants. · Security concerns in residential applications.
Nanoparticle Coatings (self-cleaning)	· Increases panel efficiency. · Reduces dust adhesion. · Some coatings are self-cleaning. · Non-destructive and energy efficient.	· Periodic reapplication is necessary. · A decrease in solar conductivity may occur with certain coatings.
Automatic Wiper Cleaning Systems	· Mechanized and efficient. · Controlled water usage. · Suitable for medium-scale installations.	· Potential incomplete cleaning coverage. · Requires wiper replacement and maintenance. · Risk of damage to panels if not properly maintained.
Robotic Cleaning Solutions	· Efficient and multipurpose. · Suitable for both pressurized and non-pressurized water cleaning. · Can be employed for large installations.	· Requires a secure connection mechanism. · Initial setup and programming are necessary. · Acquisition and maintenance costs.
Ultrasonic Systems (self-cleaning)	· Soft and non-abrasive. · Effective for fine particles. · Can be used with appropriate cleaning solutions.	· Effectiveness may vary depending on factors such as dust type and quantity. · May not be scalable for large installations.
Unmanned Aerial Vehicle (UAV) based cleaning	· Easy Remote Control · Monitoring the daily activity of dust accumulation on photovoltaic panels · No need for a human operator.	· High maintenance costs. · The electronic component costs in an advanced drone are relatively expensive.

and enhancing panel efficiency. Robotic cleaning systems are efficient for large installations, while manual cleaning may be suitable for smaller setups. Electrostatic precipitators are valuable in arid or water-scarce regions. The selection should be based on a careful assessment of the specific needs and conditions of the solar panel installation.

DISCUSSION

The findings from the reviewed literature highlight the significant impact of dust accumulation on the performance and efficiency of photovoltaic (PV) systems. The reduction in power output and electrical parameters due to dust deposition can be substantial, ranging from 5% to over 40% in some cases, depending on the local environmental conditions and dust characteristics.

One of the key factors influencing dust's impact is the particles' size distribution. Smaller particles, ranging from 1 μm to 500 μm, tend to accumulate more readily in the microscopic gaps between solar cells, reducing light absorption and energy conversion efficiency. The composition of the dust, whether organic or inorganic, also plays a role in the ease of removal and potential for chemical reactions with panel materials. The adhesion characteristics of the dust particles to the PV panel surface are another crucial factor. Strongly adherent particles are more challenging to remove and may require more aggressive cleaning techniques, such as surfactants or electrostatic precipitators. The density of the dust can also affect its distribution across the panel surface, leading to uneven soiling and potential hotspots.

The maintenance and cleaning costs associated with different cleaning methods vary significantly. While cost-effective in small-scale installations, manual cleaning can be labor-intensive and time-consuming. Automated cleaning systems, such as robotic or water-based solutions, offer improved efficiency and reduced manual labor but require higher initial investments and maintenance costs. Self-cleaning approaches using hydrophobic or hydrophilic coatings can be more cost-effective in the long run but may have limitations in terms of their longevity and potential impact on light transmission.

Ongoing research and development in this field are crucial to address the challenges posed by dust accumulation and to develop more effective, sustainable, and cost-efficient cleaning strategies. Innovative approaches, such as the use of drones, electrostatic precipitation, and advanced coatings hold promising potential to enhance the long-term performance and reliability of PV systems, particularly in regions with high dust loads.

CONCLUSION

Cleaning photovoltaic panels is essential to maintaining efficiency and ensuring optimal energy generation, particularly in regions prone to dust accumulation and environmental contaminants. Various cleaning methods are available, each with their advantages and disadvantages. A wide range of cleaning methods exist for photovoltaic panels, including manual cleaning, vacuum cleaning, coatings with nanoparticles, electrostatic precipitators, robotic cleaning solutions, automatic wiper cleaning systems, and ultrasonic systems. The choice of cleaning method depends on factors such as installation size, environmental conditions, available resources, and cost considerations.

Despite the substantial potential for success in cleaning technologies and frameworks, their comprehensive implementation in real-world scenarios may encounter various serious challenges. These challenges arise from the integration of electrostatic, automatic, self-cleaning, and robot-based methodologies, leading to constraints in data transmission and power management [137], [138]. One significant gap identified is the lack of a unified standard for assessing cleaning methods' efficiency, which complicates the comparative analysis and decision-making process for solar panel operators. Additionally, there is a pressing need for research focusing on the environmental impacts of cleaning agents and the long-term sustainability of cleaning practices.

While this review highlights some gaps in current research, it's important to note that there's still a need for standardized ways to measure how well cleaning methods remove dust and how they affect the environment. As solar power becomes more popular, especially in areas with a lot of dust, it's becoming more and more important to find cheap, eco-friendly, and effective ways to clean photovoltaic panels.

Through a comprehensive review of the existing literature, we obtained a comparative understanding of the repair methods. This allowed us to identify several examples that have been used in different global regions, as well as some cleaning testing methods with widespread applicability so future research should focus on advanced materials science, mechanisms for the integration of production, and environmental sustainability to pioneer new cleaning technologies that can be easily integrated into solar energy systems. Furthermore, exploring predictive maintenance models, using data analytics and machine learning could revolutionize solar panel maintenance, maximizing energy production and reducing operating costs.

This study reviewed various solar panel cleaning technologies and assessed their effectiveness in maintaining PV efficiency. However, several limitations need to be acknowledged. First, the environmental conditions simulated in the experiments may not capture all real-world scenarios, particularly extreme weather events. Second, the cleaning techniques evaluated were limited to those reported in the current literature, and these methods' long-term durability and sustainability were not assessed. Future research should explore the performance of these cleaning approaches under diverse climatic conditions and over extended operational periods to further validate their effectiveness and practical applicability.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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