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Systematic Review

Solar Panels Dirt Monitoring and Cleaning for Performance Improvement: A Systematic Review on Smart Systems

Benjamin Oluwamuyiwa Olorunfemi *, **Omolola A. Ogbolumani** and **Nnamdi Nwulu**

Center for Cyber-Physical Food, Energy and Water Systems (CCP-FEWS), University of Johannesburg, P.O. Box 524, Auckland Park, Johannesburg 2006, South Africa
* Correspondence: ben93olorunfemi@gmail.com

Abstract: The advancement in technology to manage energy generation using solar panels has proved vital for increased reliability and reduced cost. Solar panels emit no pollution while producing electricity as a renewable energy source. However, the solar panel is adversely affected by dirt, a major environmental factor affecting energy production. The intensity of light falling on the solar panel is reduced when dirt accumulates on the surface. This, in turn, lowers the output of electrical energy generated by the solar panel. Since cleansing the solar panel is essential, constant monitoring and evaluation of these processes are necessary to optimize them. This emphasizes the importance of using smart systems to monitor dirt and clean solar panels to improve their performance. The paper tries to verify the existence and the degree of research interest in this topic and seeks to evaluate the impact of smart systems to detect dirt conditions and clean solar panels compared to autonomous and manual technology. Research on smart systems for addressing dirt accumulation on solar panels was conducted taking into account efficiency, accuracy, complexity, and reliability, initial and running cost. Overall, real-time monitoring and cleaning of the solar panel improved its output power with integrated smart systems. It helps users get real-time updates of the solar panel's condition and control actions from distant locations. A critical limitation of this research is the insufficient empirical analysis of existing smart systems, which should be thoroughly examined to allow further generalization of theoretical findings.

Keywords: photovoltaic panel; remote solar plant; automated cleaning; condition monitoring; internet of things; solar panels dirt; dirt detection; dirt accumulation and removal; device management; real-time monitoring and cleaning

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1. Introduction

In many industrialized nations, electricity generation is still dependent on fossil fuels. Although these fuels are very effective in energy quality, they are not suited for long-term use because the fossil fuel source will eventually run out someday. Furthermore, fossil fuels are a considerable threat to environmental balance and create numerous ecological problems such as global warming [1,2]. Therefore, the utilization of renewable sources must be accepted as soon as possible. A significant feature of renewable electricity generation is the infinite supply [3]. Compared to conventional fossil fuel technologies, renewable electrical energy sources have a more negligible effect on the environment, considering cleanliness.

Solar panel technology is becoming more popular as a renewable electricity generation due to the growing renewable energy request [4,5]. By the end of this decade, China's solar capacity is foreseen to reach 400 GW [6]. The cumulative installed solar capacity in megawatts between 2012 and 2021 is shown in Figure 1, based on the information provided by IRENA, International Renewable Energy Agency [7].

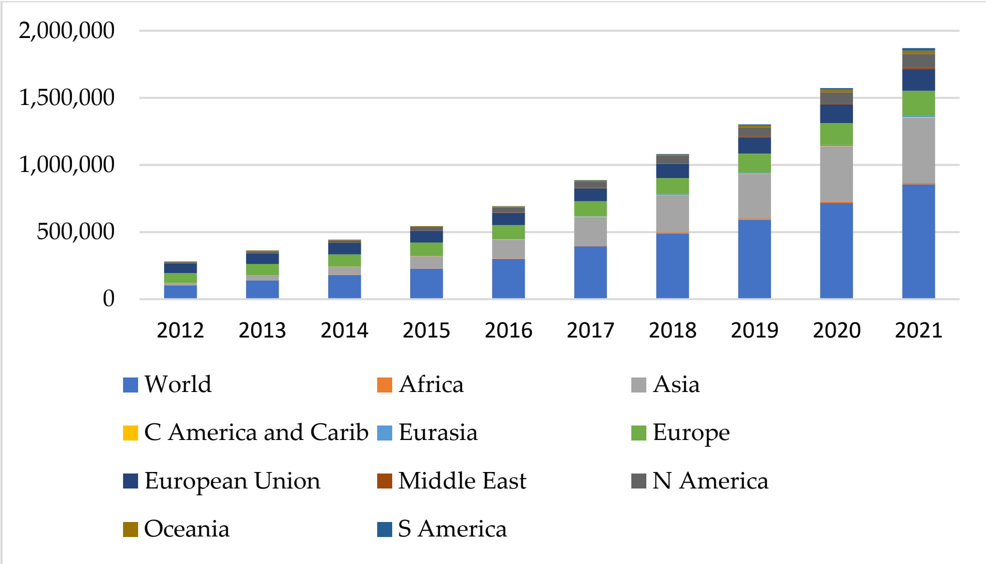

Figure 1. Cumulative installed solar capacity from 2012 to 2021 [7].

It is critical to appropriately manage solar power plants, aiming to optimize their performance and reliability for their continued use. The efficiency and stability of solar panels can be increased, while costs can be reduced [8]. Irradiation and temperature are the key environmental factors that determine the power output of a solar panel module. A decrease in the amount of irradiance and an increase in temperature decrease solar panel module efficiency [9]. Solar panels convert solar radiation into direct current electrical energy; it must constantly be exposed to the maximum amount of sunlight to maximize electricity productivity [10]. Nonetheless, irradiation decrease on the solar panel surface caused by shading due to dirt accumulation can be well controlled. This happens repeatedly and decreases the amount of sunlight reaching the panels [11]. Dirt accumulated on solar panels can include dust, snow, ice, and other organic waste [12]. Fine dust particles settle more deeply on the surface of solar panel modules, affecting their output performance more than coarse dust particles [13]. A controlled experiment conducted in [14], using spotlights to simulate solar radiation, found that the external irradiance resistance can reduce the photovoltaic performance by up to 85%. Rain can naturally wash away dust and sand, but moss requires proper cleaning [15,16]. Solar panel cleaning is one of the major challenges for solar power developers because cleaning the solar panel surface requires careful planning and resources (time, materials, and labor) and results in higher production costs. However, cleaning solar panels is an important task to ensure the long-term operational and financial success of a solar power plant [17]. Cleaning solar panels is necessary because it ensures that the solar panel surfaces are properly maintained to ensure efficient energy generation. It also prevents damage from accelerated aging or corrosion caused by weather conditions such as heavy rains, snow, hail, or high humidity [18,19].

The performance of a solar panel is mainly measured by its efficiency, which indicates how much electricity the panel produces compared to its maximum theoretical efficiency. For example, a solar panel with an efficiency of 20% means that it generates 20% more electricity than it could if left uncoated. An experiment on the cleanliness and tracking mechanism for the various conditions of a solar panel was carried out by [20]. The conditions examined are the fixed and clean panel, the dirty and fixed panel, the dirty and tracking panel, and the clean and tracking panel. Dust buildup on the solar panels' surfaces causes the efficiencies to decline even with installed sun-tracking. The high transmission rate of light on the cleaned solar panel causes an increase in efficiency [19]. Tracking a solar panel without cleaning is less efficient than keeping the solar panel fixed and cleaned, having an efficiency decrease of up to 50%. Dust deposition on solar panels reflects more loss in large-scale power plants in megawatts [21]. A 1% decrease in proficiency may meaningfully influence the Internal Rate of Return (IRR). In comparison, low-level dust accumulation might not significantly affect the production output of small-scale solar plants [22].

Solar panels are monitored with data acquisition systems, where the performance of the system is evaluated under real-world conditions [23]. Real-time monitoring and evaluation of dirt accumulated on solar panels are required to optimize the cleaning operation. Generally, monitoring dirt accumulation on solar panels can either be done online or offline [24]. Smart systems enhanced by internet connection are integrated into solar panel cleaning to improve the performance of autonomous cleaning methods. This will make the system intelligent to monitor the remote solar panel. It can detect dirty conditions and activate its removal from the solar panel surface without human control. Solar panel surface maintenance can be done at a fraction of the installation cost, and electricity generation improvements are possible [25]. There are several reviews on cleaning methods for the solar system, both manual and autonomous systems, but to the author's knowledge, none has considered a review of the different smart system approaches applied to solar panel monitoring or cleaning system approaches used in this study. Published research papers have been reviewed and analyzed. The study aims to conduct a literature review concerning the theoretical framework for smart systems as it relates to solar panel cleaning and remote monitoring to promote the concept of smart solar systems. Literature searches were conducted using specific keywords related to the paper's subject. Although there are many review papers in the literature concerning the concept of smart solar systems, there is a limited number of papers concentrating on the technology adoption aspect of smart solar systems.

1.1. Review of Solar Panels Automated Cleaning Techniques

The continuous cleaning and monitoring of solar panels after installation on a roof or at a remote solar farm is difficult [26]. Solar panels can currently be cleaned using a variety of techniques, including the traditional method of brushing away dust, coating processes, and robotic cleaning devices. This process has been automatized since cleaning with manual brushes and water is incredibly time- and labor-consuming and costly for industrial solar installations [27]. An automated cleaning system for solar panels is composed of an autonomous unit using sensors and controllers and a cleaning mechanism unit that can be watered or waterless. Solar panels can be cleaned using several methods of removing dirt [28,29]; they are robotic, heliotex, electrostatic, coating cleaning, vibrating cleaning, and forced-air cleaning. The review of the cleaning methods, listed in Table 1, compares each method's pros and cons.

1.1.1. Brush Cleaning

The brush cleaning method combines mechanical and electronic components to control the brush's movement as shown in Figure 2, for cleaning the solar panel either with or without water [38]. The turn-on and turn-off process is automated by sensing the current dust accumulation on the solar panels and comparing it with the set reference by the program. The electronic component supplies a signal to the motor for the cleaning system movement [39]. The system has to be robust with many types of complex procedures to be performed with greater precision, flexibility, and control than with conventional techniques [40]. Furthermore, the developed system improves the efficiency and output power of the solar panels as a result of improved performance [41].

Table 1. Comparison of various cleaning techniques.

Reference	Cleaning Technique	Merits	Demerits	Power Output Efficiency Compared to Clean Panels
[30]	Natural cleaning	No investment cost is involved.	Depends on the location's weather condition.	4%
[31]	Manual cleaning	Involves simple design.	Requires expensive materials and the use of human labor.	90.67%
[32]	Robotic cleaning	Effective and sustainable in all climates.	Requires complex construction.	99.5%
[33]	Heliotex cleaning	Effective for non-sticky dirt.	Requires a lot of water.	12.5%
[34]	Electrostatic cleaning	Effective for dry dust and requires no moving parts.	High voltage is required and design is costly.	3.35–11.5%
[35]	Hydrophobic and hydrophilic coating	Does not require water and labor.	Coating presence reduces screen efficiency.	6.62%
[36]	Vibrating cleaning system	Applicable for dry dirt in dry weather.	An external source is required to power the vibrating motor.	95%
[37]	Forced-air cleaning system	Applicable for dry dirt in dry weather.	An external source is required to power the air pump. Only removes small dust larger than 20 µm.	86.4%

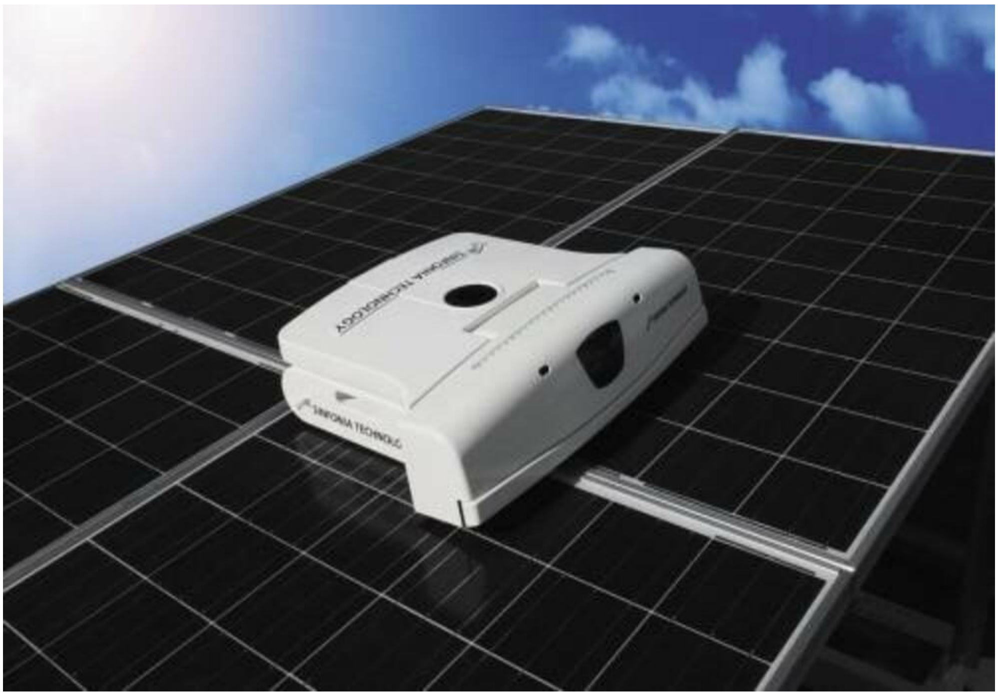

Figure 2. Robotic brush cleaning of solar panels [42].

1.1.2. Heliotex Cleaning

Heliotex cleaning involves spraying water onto the solar surfaces [43]. It is possible to program the cleaning system based on the environment whenever necessary. Further maintenance is not required, other than a periodic replacement of the water filter if it is blocked by sand and the top-ups of the cleanser. Pumps are connected via piping to a water reservoir, fixed to nozzles on the solar surface. The system is very effective and recommended for locations with no water deficiency due to the high amount of water consumed for cleaning [44]. Figure 3 demonstrates the heliotex method of cleaning. This system is not suitable for all situations [19].

Figure 3. Demonstration of the heliotex method of cleaning solar panels [45].

1.1.3. Electrostatic Cleaning

Another dust removal method is electrostatics cleaning, used on dry and dusty solar panels, as shown in Figure 4. In electrostatic precipitation (ESP), fine dust particles on the surface of the solar panel can be removed by induced electrostatic charges [46]. The solar panels are covered with transparent plastic or glass sheets of electrostatic charge material; when a high AC voltage is applied to the electrostatic material, the force acts on the dust close to it and causes the repository motion of the dust particles to shake off from the solar panel surface. The system can clean 90 percent of accumulated dust in less than two minutes [47]. A significant concern that limits the application of this method is safety. It would be unsafe since the solar panel would always remain charged even in showery weather. However, the dynamic motion of all the particles cannot be conveyed by fixed wire electrodes as experimented in [48].

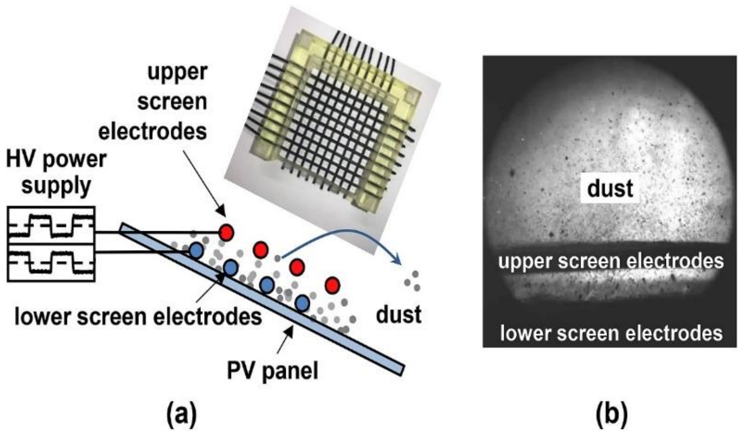

Figure 4. The electrostatic cleaning procedure Some dust particles pass through the hole in the upper screen electrode due to their inertia force and the alternating electrostatic field near the electrodes stirs up the dust particles, and a high-speed microscope camera was used to capture the results as shown in (**a**) and (**b**) respectively [49].

1.1.4. Coating Cleaning

The coating method is also a technique for cleaning solar panels using anti-soiling coating [50]. This method can be used with either a solid, liquid, or gas-based substrate. This method relies on the self-repellent action of the coating material to prevent dust particles from adhering to solar modules. Hydrophilic film and hydrophobic film are the two methods of coating cleaning [51]. The superhydrophobic coating surface method allows for self-cleaning PV panels. This has benefits, like preventing water damage and graffiti [44]. Water gets absorbed into the film in the hydrophilic and rinses the dirt away. On the other hand, the hydrophobic film repels water as it falls; due to its hydrophobic properties, water drops that reach the surface are pushed off quickly, picking up particles alongside. A specific cure time and evaporation of the solvent and drying of the nanoparticle base were required for the coatings to dry once applied as liquids with low viscosity [19]. Each of the coating samples had high transmission, low reflection, and low absorption properties in the ultraviolet (UV), visible (Vis), and near-infrared (NIR) regions.

The fundamental raw material for the coating cleaning is nano metal oxide particles and resin. The product is made by mixing chemicals [19]. Figure 5 compares a layer of hydrophilic coating causing a sliding motion to a rolling motion made by a hydrophobic coating. Despite their differences, both methods of self-cleaning serve the same end [52].

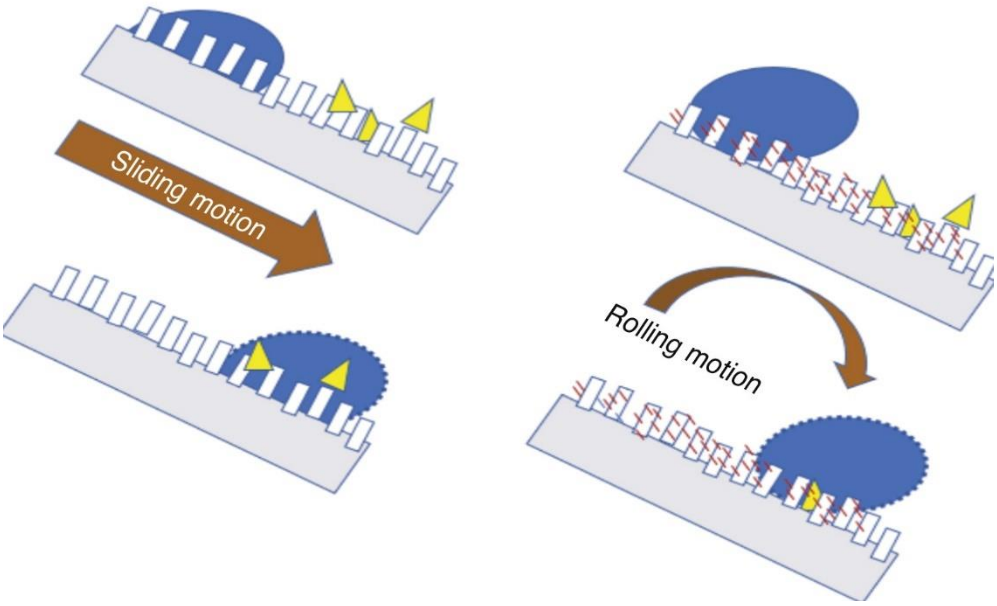

Figure 5. Droplets slide and roll during the self-cleaning process [53].

1.1.5. Vibrating Cleaning System

The vibrating cleaning method prevents solar panels from getting dirty and does not require water or manual labor [46]. To remove the adhesive force between dust particles and the solar panel surface, a mechanical vibrator attached to a panel produced harmonic excitation force. In [54], the wind energy is converted into mechanical vibration for dust removal from solar panel surfaces without consuming any energy from the solar system, thereby improving its efficiency. As vibration intensifies, the inertial force of vibration increases, which turns the dust particles' adhesion force into kinetic energy. External sources of power are usually needed to operate the vibrating motor in vibrating cleaning systems [36]. The panel's self-cleaning system is driven by a DC motor that is fastened to the rear sheet. Based on [55], a solar module was supported on four edges to simulate a system being excited by an unbalanced mass to induce vibrations (see Figure 6). As the DC motor's rotor reached the first natural frequency, a large amount of vibration was induced on the panel.

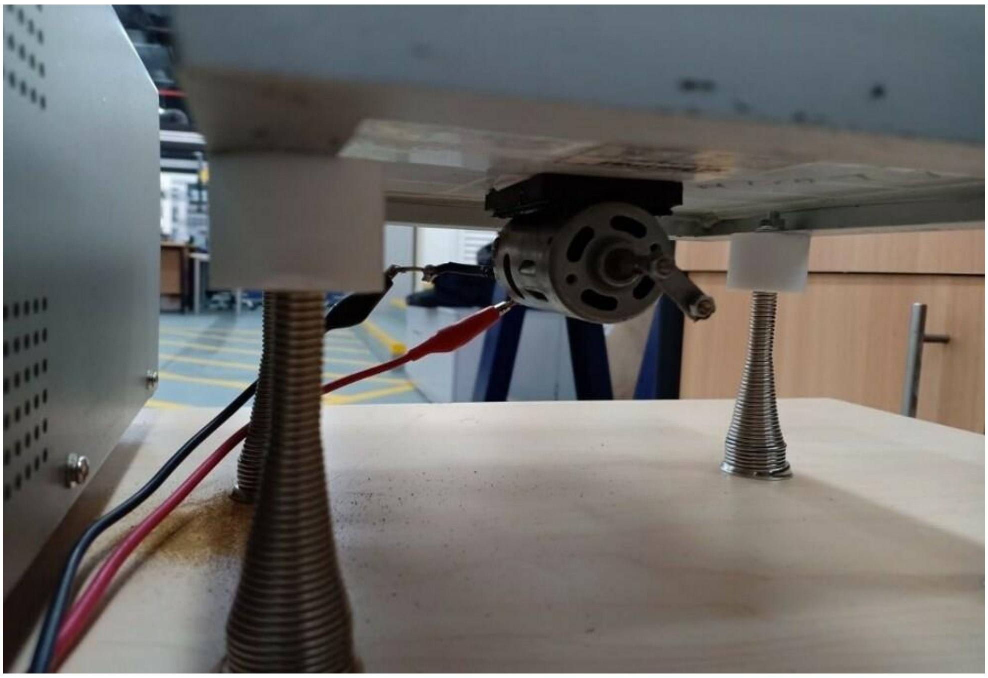

Figure 6. DC motor attached to solar panel rear for vibration cleaning [55].

1.1.6. Forced-Air Cleaning System

A forced-air cleaning system for solar panels can help to keep them clean and free of debris. This type of system uses a blower to force air through the panels, which can help to remove dirt, dust, and other debris, in addition to improving the efficiency and performance of residential and commercial solar panels. However, this method is only effective for removing dust blown by the air from solar panels [56]. Water is neither consumed nor directly contacted by the turbulent airflow generated by compressed air [37]. These results were used to construct a pilot cleaning and cooling system [37] that utilized a compressed-air unit composed of a compressor, air tank, airflow management valve, and nozzles with a thickness of 5 mm, see Figure 7. The compressor is powered by PV panels, and a valve controls the flow of compressed air from the tank to meet the needs of cleaning and cooling. A pipe assembly that can be moved around an installation as needed can transport air between the panels [19].

1.2. Evaluation of the Performance and Cost of Solar Panel Cleaning Techniques

Several studies may be done regarding cost–performance considerations after the cleaning technique is developed, implemented into use, and a cleaning frequency is defined. It is important to point out that various cleaning methods are dependent on market demands, with some common procedures employing natural, manual, mechanical, electrostatic, vibration, and coating processes. Different environmental variables and setups may be evaluated using the performance and cost. To assess the necessity for a self-cleaning system, a relationship analysis between soiling and its impacts on performance efficiency is required [57]. The amount of sunshine, dust concentration, and rain effects are a few examples of environmental variables. The effectiveness of each cleaning method and its costs may very well be forecasted for each circumstance using optimization models and machine learning. A configuration strategy and an investment plan will result from comparing the different circumstances.

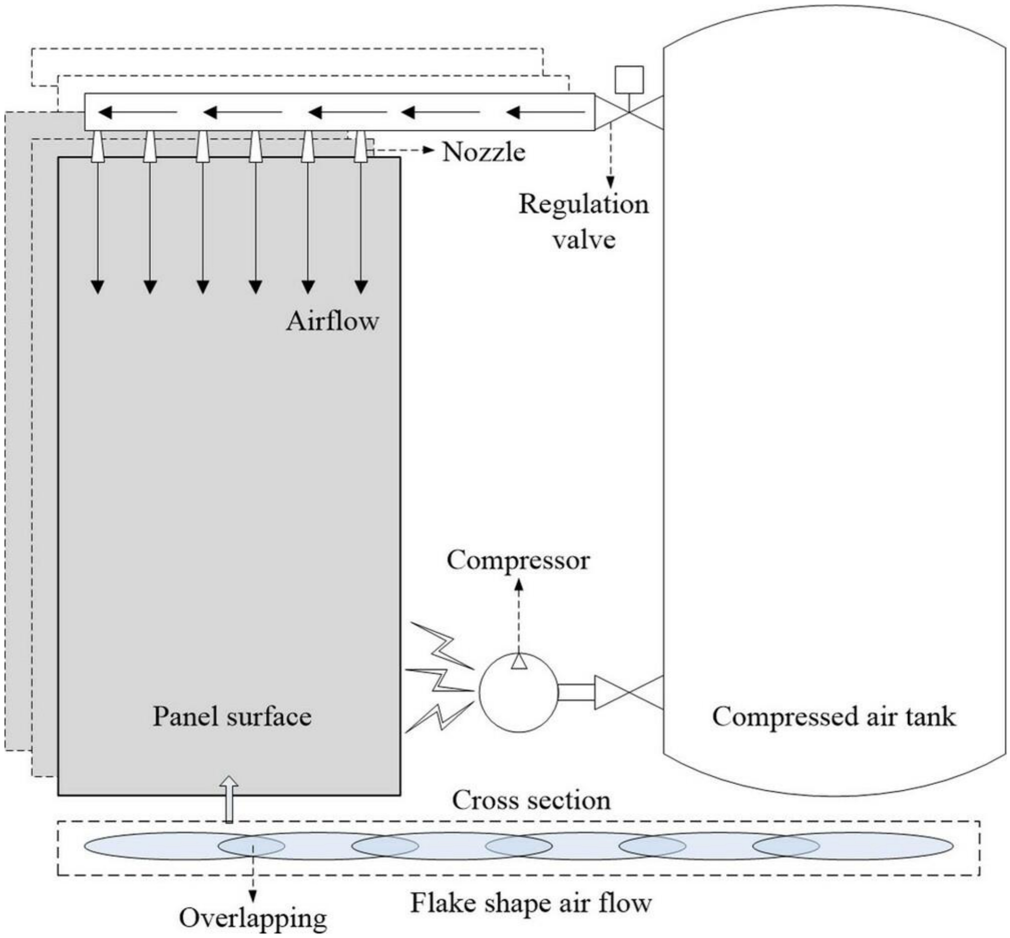

Figure 7. Regulatory mechanism for solar PV panel arrays using compressed air [37].

The configuration plan identifies the hardware and software modifications required to be made for the current platforms as well as the system architectural modifications that should be implemented. Some experts believe that the cost of restoring solar panels' capacity to capture energy should be determined exclusively using a satisfactory rate of return (ROI) [37]. The effectiveness of an integrated smart system for solar panel cleaning may be determined by this analysis [22]. The limitation of the ROI analysis is that they only evaluate the economic side of the problem. Reliability should be taken into account when determining how much to spend on solar panel cleaning methods because it is a major obstacle to effective monitoring and cleaning.

Based on the cleaning method analysis of various cleaning systems by [58], the electrostatic cleaning method is the most effective. Dust particles are removed from the surface without using water; however, spraying water on the photovoltaic cells during cleaning increases their efficiency. The economic viability of automatic self-cleaning mechanisms of solar panels is evaluated in [59] to determine their contribution to the total system cost. When comparing the power generation of PV modules with and without automated self-cleaning mechanisms, the findings reveal a difference of 35%. A domestic installation has a payback period of about five years while making an installation in a commercial setting will typically pay off after 2.25 years. Similarly, ref. [60] reported an efficiency increase of 30–33% in a solar panel array when a robotic cleaning system was used. A robot can also be programmed to fix panels of different sizes. Cleaning a complete array is extremely beneficial since the accumulation of dust on one panel can hinder the performance of the entire array. The fact that solar panel cells are usually connected in series makes it extremely important that they operate at maximum efficiency.

1.3. Review of Solar Panel Remote Monitoring

1.3.1. Condition Monitoring

It has been an important research topic to continuously check the condition of solar panels in remote areas and detect faults to provide stable power [61]. The status application captures and reports the operation, performance, and usage of the solar panel being monitored. With diagnostics applications, monitoring, troubleshooting, repairing, and maintaining networked devices are possible. IoT-enabled smart solar monitoring systems provide remote monitoring and recording. This platform monitors the solar system in real-time via the internet. Monitoring of parameters such as voltage, current, temperature, and humidity is performed by a smart solar panel cleaning system built with IoT. Solar panel performance is typically characterized by measuring the I–V curve under standard conditions (1000 W/m^2 solar irradiance and 25 °C temperature) [62].

In general, remote monitoring systems consist of three components: a sensing unit, a processing unit, and a display unit [63]. The sensing unit is located near the solar system to gather all relevant data to monitor system performance. The data from the sensing unit is carried to a processing unit using a wired or wireless (wireless sensor network—WSN) network, then to the display unit. These services are made possible by wireless sensor networks, which are cost-efficient to install, consume low power, and require little maintenance. Long-range features enable their deployment at remote sites [64]. Smart sensors are often used in a sensing unit so that the signals generated by a solar monitoring system can be handled efficiently before they are sent to a central processing unit. A plant health monitoring system utilizing IoT was proposed by [65], in which the sensors were embedded in the solar system and connected to the internet via wireless networks.

According to [66], the sensor values are crucial for determining a panel's output. A solar power plant's dirt condition can play a crucial role in monitoring the need for maintenance [22]. Despite the unpredictable nature of solar energy and the initial installation costs, research has been undertaken to discover the execution of solar energy optimization. To improve electrical systems reliability, the optimization method aims to minimize investment, operating, and maintenance costs and emissions [67,68]. Ref. [69] examined how the internet of things can be used to monitor solar panels and found its usage is crucial to the proper management of the solar system. Sensing hardware, data acquisition software, and block management modules measure data. This allows all the real-time data collection on the solar plant's electrical output variables to be viewed and stored within the block management. When the panel is not operating correctly, the smart system will offer suggestions, display errors, and send alerts when maintenance is needed.

1.3.2. Dirt Detection

Monitoring and cleaning solar systems have been studied extensively. Before the performance of the cleaning system, it can be challenging to predict the deposition rate of the organic and inorganic particles on the solar module surfaces. Therefore, to ensure that the cleaning system is as effective and efficient as possible and to make the best use of the energy yield, it is required to inspect the solar panels for dust. Besides analyzing dust effects and deposition rates, identifying the crucial information from the previous research is the purpose of this section.

A dirt detection mechanism on a solar panel was made by [39]. A weight sensor in the system continuously measures the dust. Upon receiving defined feedback from the sensors, the Arduino controller commands the dust cleaning. Solar panels are fitted with weight sensors that measure dust thickness according to changes in weight. The feedback for cleaning is that the panel weight goes more than the predefined value due to dust. A dusty solar panel will weigh more than one that is clean. The Arduino controller can reference the actual weight of the solar panel. In their findings, the continuous monitoring of the weight by the microcontroller through the load cell aids the dirt detection and cleaning of the solar panels. A mounting plate holds the load cell below the panel.

In 2019, ref. [70] developed an innovative system for monitoring solar panels' condition. Radiometric sensors are used in a condition monitoring system that links to an Arduino platform, and it works by analyzing the emissivity of a surface and recognizing a low value when the dust is present. A thermographic camera is employed for the radiometric sensor to provide reliable results. Unmanned aerial vehicles are designed to carry the system. With the Internet of Things, radiometric data can be sent to the cloud for analysis, and thermograms can be stored to be further processed. An actual solar panel measures sensor output and surface conditions from various angles and distances. Results from the radiometric sensor analysis show a high degree of accuracy, and dust is recognized in all set-ups. As part of a thermography analysis, it is found that there is consistency and regularity in the quantities. The average variation of each experiment determines accuracy. When the luminous emittance of the solar panel increases, the radiometer measures a higher temperature. The thermal images verify the results of this measurement using a radiometer sensor, the surface being measured is characterized by its temperature. Obtaining reliable measurements for thermal image processing requires knowing the surface characteristics and the ambient conditions, such as humidity, the temperature of the air, distance to an object, reflected temperature, and incident radiation [9].

A design and fabrication demonstration shows a prototype that cleans the panel's surface in [22]. The sensing unit was programmed with the regression model developed using a month's worth of data from spotless and dirty panels. By the regression model and the integrated sensing unit, the autonomous unit determines the optimal time for cleaning. The prototype autonomous unit monitors input and influencing parameters with direct or indirect impact on the solar farm's output power. They also investigated automatic cleaning in their study. Therefore, this system can determine if dust particles impact solar panels' power generation. In the prototype, the light intensity is measured with the TSL 2561 illuminance sensor, and sensors measure voltage and current to determine output power. The other manipulating parameters for solar panel output, such as temperature and humidity, are measured by DHT11 temperature and humidity sensors, whereas GP2Y1014AU0F dust sensors determine the dust density. The measured illuminance value and output power are stored in the cloud interface. Regression analysis of the processed data is carried out to determine the connection between input variables and power output.

Another study by [71] investigated robotic technology for removing solar dust from solar boards. The strategy proposes screening power generation on a mobile app and cleaning the solar surfaces in response. The input mechanism includes an Android switch unit, IP camera, voltage sensor, and current sensor in the experiment. IP cameras monitor solar panel cleaning and conditioning; it is internet-connected and displayed on a PC Windows system or an Android device. Images might be rather costly to transfer over the internet. A related study in [72] used smart cameras with "RGB" and "infrared" for night vision to continuously take pictures of solar panels. A real-time algorithm determines whether or not a panel needs to be cleaned based on the picture. An Advanced Reduced Instruction Set Computer Machines (ARM) processor, which will also be on the board, will process the incoming data and execute the algorithm. The intelligent system detects a dirty panel automatically and triggers a mechanism to clean the panel. As the panels become dusty or exposed to bird feces, but do not accumulate enough deposits to exceed the threshold, the energy drop is within the average fluctuation energy of clean panels. The dustier the panels become, the more the energy drop occurs, and the energy output can be increased by cleaning the panels. A typical cleaning interval can range from several months to less than a day, depending on weather conditions.

In the work described in [73], they used machine vision for solar power plants. A self-inspection cleaning device, fault detection systems, and combined power units using drone platforms for multi-image fusion contaminant recognition were researched. The autonomous detection and recognition function is achieved through an image recognition analysis. To collect images, an "infrared thermal imaging camera, a color visible light camera, and a black and white visible-light camera" are used; once the acquired image has been fused, it is processed. An infrared thermal imaging camera is combined with an image camera to create a visual image for inspection purposes. A recognition algorithm analyzes the image to identify hot spots and surface impurities generating fault inside the panel and pollution notification in the control system. According to [74], four generations of outdoor soiling loss monitoring systems were developed by the authors. In the fourth-generation soiling monitoring stations, a glass shutter is opened for 2 min (or less as necessary) approximately at solar noon to take Isc measurements on the clean cell. As the glass was open, the shunt voltage of this panel was also recorded. As a result of these measurements, it is possible to determine any soil accumulation on the glass surface. Positive gains occur due to thick soil layers at around 1%/mm, whereas positive gains are typically much lower than 0.2%/mm at thin soil layers. The design allows data to be sent via mobile networks from anywhere around the globe, enabling the monitoring of multiple sites.

An approach based on computer vision was presented for detecting soil and dust on solar surfaces in [75]. To sense dirt on the solar panel, physical features are extracted through the use of the Gray Level Co-occurrence Matrix (GLCM) method. Solar panel detection is the first step of the proposed solar panel classification method. A solar surface is discovered in an image. Its background is removed at this step, and the input image is stripped of extra information. By pre-processing the image, the effects of lighting can be minimized, while at the same time, fine details that represent dust and soil can be emphasized. The red, green, blue (RGB) image is converted to hue saturation value (HSV) during this process. This is followed by feature extraction, which converts the input image into a limited number of parameters. The final step in the proposed method is classification. A flexible camera orientation was used in this study to collect two hundred images under controlled conditions with variable lighting types. One-half of the collected images show clean and dry panels, while the other half shows dirty panels. Histogram equalization and a high pass filter are used to improve image contrast. The histogram equalization technique improves a picture's disparity. Based on the results of the tested images, the proposed method has a high recognition rate. It would be helpful to consider incorporating the shadow areas, broken panels, and wet panels into the pattern recognition stage in the future.

1.4. Device Management and Performance Analysis

As a device management system [76], a smart system for cleaning and monitoring can improve or enhance the solar panel's performance. In a system failure, the analyzed data are transferred to the cloud for predictive maintenance and cause assessment via the internet. In addition to using real-time monitoring data, historical data and trends can also be used to make comparisons [77]. Analytics applications such as predictive analytics, pattern recognition, and machine learning analyze data and trigger sequenced patterns of behavior based on data filtering, normalization, and transformation [78]. The site engineers can make future decisions based on historical data stored in this way. This prevents equipment failure. It also eliminates the need to keep track of upgrades and saves time and money.

The main aim of the monitoring system for the PV power plant is to transmit the data in a reliable, secure, and efficient manner. However, several issues significantly affect the performance of various monitoring technologies in terms of efficiency, range, data processing capability, sampling rate, and signal interference. There remains a clear link between dirt monitoring and dirt cleaning, especially under varying environmental test conditions [79,80]. The performance ratio of a photovoltaic system is the proportional rate between the instantaneous power generation and its rated power generation [9]. In existence are dirt accumulation monitoring and diagnostic systems, which do not take into account the instantaneous rate of dirt accumulation. It was not possible to quantify the cost of dirt contamination as there was no specific data available. The qualitative analysis revealed in this study is vital to evaluate smart system performance in monitoring and cleaning dirt from solar panels.

In an attempt to offer a systematization of the literature about optimizing the performance of smart systems monitoring solar panel cleaning, we investigated the variables and factors effective at producing the best outcomes in such systems. Parameters for the performance evaluation of solar panel monitoring and cleaning systems include the complexity of the system (hardware and software structure), the number of sensors required to provide reliable sensory feedback, the detection time for the system after an abnormal solar panel condition, and steps involved in the monitoring and cleaning action. The most important challenge in the dirt detection process is to counter the unique operating characteristics that result due to changing environmental conditions. Using environmental sensors such as weight and irradiance sensors to measure dirt accumulation rates is more susceptible to environmental effects. The complexity of these methods is lower, and they require high computational accuracy as well. In contrast, image detection is more reliable, requires less detection time, and is reported to be more robust in detecting dirt and shading on solar panels [81].

The remaining sections of the study give the methodology associated with the systematic literature review, and the results and conclusions. In conclusion, the study summarizes the results, implications, and limitations.

2. Methods

Scopus and Google Scholar were used as the fundamental database to retrieve the data for this study. Although additional sources were cited for this article, they were not included in the review, since they were only used to clarify the background of the topic. The Scopus database provides free access to STM (Scientific, technical and medical) journal articles and the references cited in those articles, research, and collection development can both be performed with the database [82]. Search topics included "solar panel", "monitoring", and "cleaning". The terms appeared in the titles, abstracts, and keywords of the publications. The period covered spanned from 2008 to 2022. Various types of publications were indexed, and the number of publications associated with smart solar panel monitoring, and cleaning was 45. According to the document types, the majority are journal articles (n = 25, 55.6%) and conference papers (n = 17, 37.8%). Similarly, conference reviews are few (n = 3, 6.7%). The Scopus database contains details about every publication, such as the publication year, the authors, their addresses, the title, abstract, the journal, subject categories, and references. This set of data from Scopus was exported for the analysis of publication output and growing trends, as well as geographical and institutional distribution and collaboration. The Scopus analysis feature was used to visualize the geographical and institutional distribution and collaboration, while VOSviewer was used to analyze and visualize author relationships, co-citations, and terms. VOS represents the similarity or relatedness between items according to their distance as accurately as possible [83]. This method of clustering topics into groups was used to classify them into different groups, where each group is denoted by a different color. The results section describes in detail how the visualizations were interpreted.

2.1. Search

The research scope was formulated at the intersection of the broad terms "solar panel performance improvement" and "remote monitoring and cleaning". The search string is composed of two main parts: (i) the smart solar system; (ii) the exclusions and limitations of the search scope. The structure of the search string used in the Scopus search comprises solar AND panel AND monitoring AND cleaning.

2.2. Eligibility Criteria

An overview of the hypotheses of the current study can be found in the preregistration on Open Science Framework (osf.io/rk8yj). The screening step in the evaluation process involves a deeper analysis of the publication's full-text analysis for potential research items, which is discussed accordingly. Scientific publications in the English language, including reviews, research articles, and open access documents, were considered. Moreover, the publication duplicate was checked by the EPPI-Reviewer.

After full-text analysis, two articles were excluded because they failed to meet the inclusion criteria, or did not meet the quality requirements since this review is focused more on the smart systems for solar cleaning and its implications. A total of 55 scientific publications entered the data collection phase. This is illustrated in Figure 8.

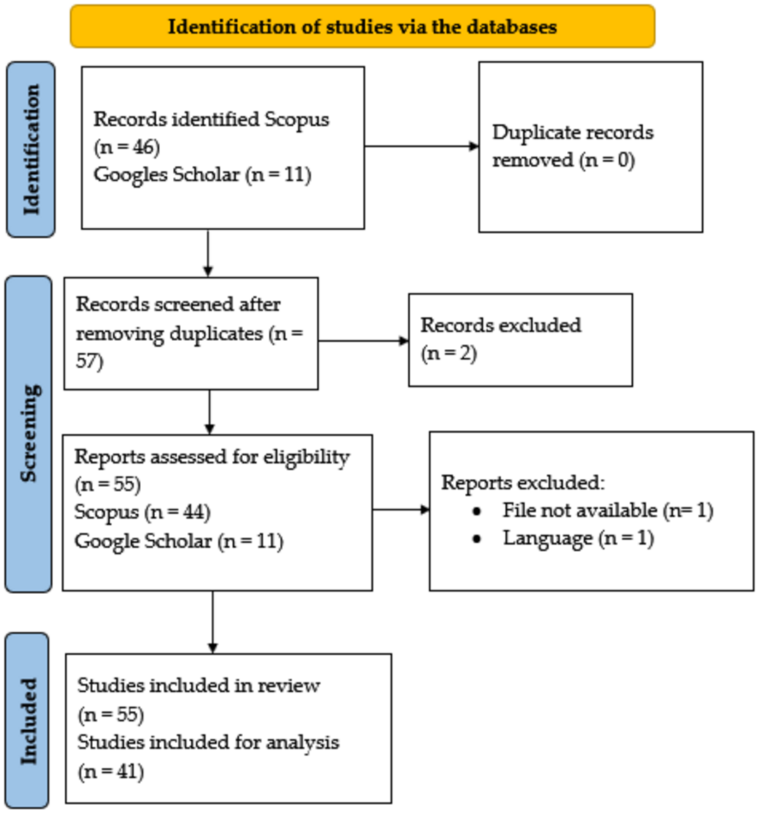

Figure 8. Process flow chart of the search.

3. Results

3.1. Overview of Selected Articles

Compared to other reviews on the monitoring and cleaning of the solar panel (e.g., [46,84]), the current review provides a relatively short bibliometric analysis. The bibliometric analysis was conducted following a systematic literature review (with PRISMA) that allowed the elimination of articles outside of the pre-defined scope (see Section 3) and work only with those within. Due to the lack of studies regarding the implementation of the Internet of Things in improving solar panel performance, the number of articles was significantly reduced during the filtering process (see Figure 8), resulting in only 41 papers for the bibliometric analysis.

3.1.1. Publication Output and Growth Trend

It is important to measure the number of publications of a scientific research discipline or subject to gauge its development trend. The number of smart systems for solar panel monitoring and cleaning publications has grown since 2008, as seen in Figure 9. In the year 2008, there was just one publication on smart systems for solar panel monitoring and cleaning. Until 2016, there were few publications on the subject (less than four publications each year). Every year since 2016 has had more than four in the number of publications, except for 2017, and 2019, when there has been a decrease. In 2020, there was a peak of publications (n = 11), followed by a downward trend (n = 4) in the first quarter of 2022.

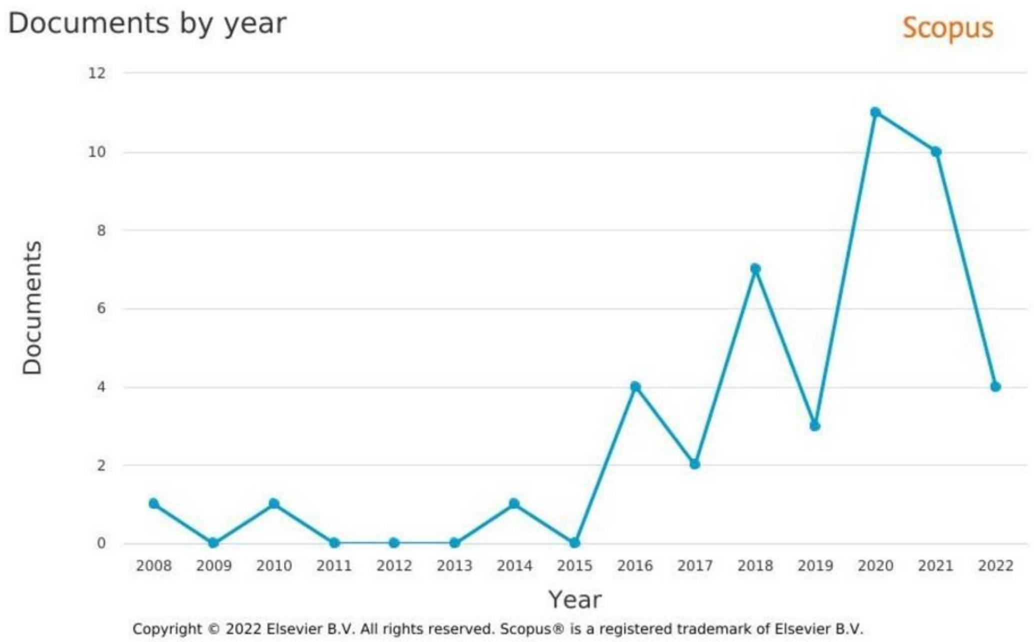

Figure 9. Publication trends related to smart systems for solar panels (between 2008 and 2022).

3.1.2. Authors and Their Collaboration

A total of 159 writers contributed to the 41 articles. Only a small set of prolific authors contributes to a considerable percentage of publications on a certain issue, which is consistent with observations in other subject areas. As shown in Figure 10, the subject areas of engineering and energy received the highest percentage of credit (22.0 percent each; approximately $n = 9/41$), while the computer science topic area accounts for 15.0 percent ($n = 6/41$). As a result of the multi-subject area publications, it can be stated that there is a lot of collaborative research in smart system technology.

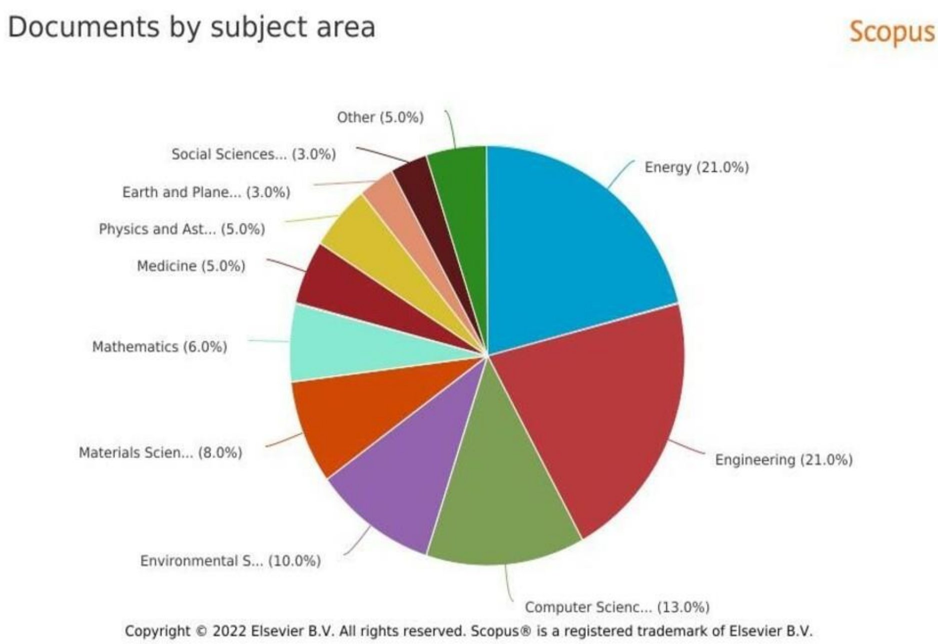

Figure 10. Analysis of subject area on smart systems for the solar panel.

One significant cluster of writers may be identified in the collaboration network in Figure 11. The average published for each of the principal researchers is in the year 2020. In terms of authorship, it is worth noting a potential bias: writers with the same name could not be separated from one another.

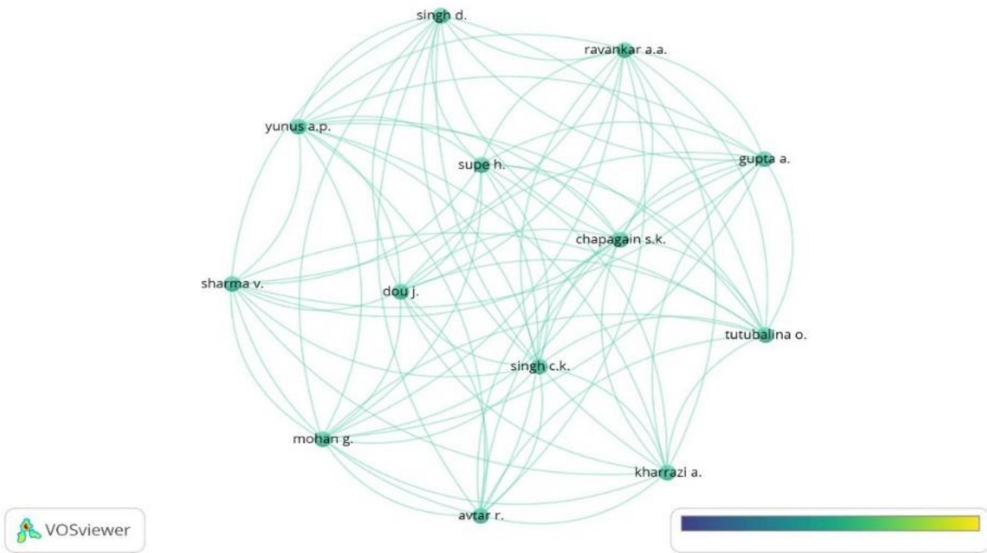

Figure 11. Author and co-citation visualization in the VOS viewer.

3.1.3. Geographical Distribution

One hundred and fifty-nine writers from various nations or territories contributed to the smart systems for solar panel publications. Elven are in India, six are in China, two are in Egypt, and one publication each came from Senegal, Morocco, and Algeria. Figure 12 depicts the global distribution of contributing countries and territories for the most productive solar panel research on smart systems technology. It is an economic investment to clean the module surfaces, but the investment must be offset by a sufficient increase in energy production [85]. Economic growth appears to encourage scientific and academic investment since the most prolific papers on smart systems for solar panel research are found in all of the world's major industrialized countries. A publication might be written by various writers from different nations or territories, or a single author can be affiliated with multiple countries or territories. When looking at the continents in Figure 12, a geographical discrepancy can be detected in the extension of the information on countries and territories. The depth of the color on the map represents the number of authors from each country.

3.2. Integration of Smart System for Solar Panel Monitoring and Cleaning

To keep solar panels clean, automatic connections and continuous monitoring are necessary. Smart solar monitoring and cleaning applications can overcome all of these challenges with robust and efficient cloud-based tracking systems that provide consistent and real-time monitoring from remote locations. As part of smart systems applications for solar panel cleaning, a key characteristic will be the combination of their essential functions in providing timely monitoring and device management as a solution for improving the efficiency of solar plants. Sensors and actuators would be integrated with different configurations to provide autonomous applications with a smart system that supports solar panel cleaning. Table 2 summarizes the focus of various journal papers on smart solar systems.

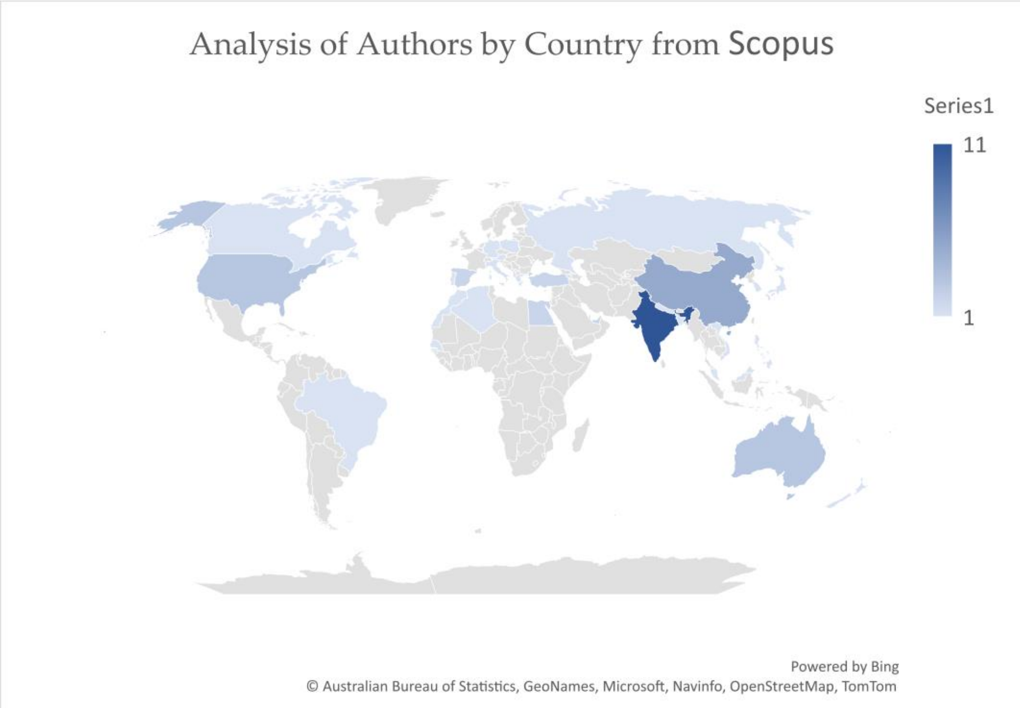

Figure 12. Geographical distribution of authors.

Table 2. Study characteristics.

S/No.	Author(s)	Year	Aim	Methodology
1.	Nalamwar H.S., et al. [64]	2017	The goal is to create and implement an IoT-based solar panel monitoring and control system.	The sensors and block management data acquisition system are placed in solar plants to collect as much data regarding the parameters of the plant as possible.
2.	Ravi K.K., and Jeswin J. [69]	2020	To explore how IoT would be implemented to monitor the various metrics related to solar panel efficiency.	A solar monitoring system that utilizes information stored in AWS to deliver actionable insights directly to clients in real-time is discussed.
3.	Abhishek P., et al. [61]	2015	To define the hardware and software required to effectively monitor solar panels continuously.	Wireless sensor nodes are used to gather and continuously store data while sending it to a central station. This collected data is then sent to the server via Ethernet.
4.	Papageorgas P., et al. [62]	2013	The purpose of this research is to provide an overview of the design process for a solar panel monitoring system.	Wired networking technologies are used to build the platform along with low-power wireless sensor nodes that have a short range. Solar panels are monitored remotely, and their performance parameters are sent to a coordinator.

Table 2. *Cont.*

S/No.	Author(s)	Year	Aim	Methodology
5.	Nur A., et al. [62]	2020	To build a solar panel dust monitoring system that accurately detects the presence and density of dust particles in real-time.	An IoT sensor was developed that could monitor dust accumulation, and the data was accessible online through smartphones and computers.
6.	Prutha M.B., et al. [65]	2018	The aim is to propose a remote wireless monitoring system to ensure the stability and efficiency of solar plants.	Sensors are used in the application for the Internet of Things (IoT), which is controlled by a CC3200 microcontroller with an ARMCortex-M4 processor and a Wi-Fi card.
7.	V. Kavitha and V. Malathi [66]	2019	To present an IoT-based solar energy monitoring system that collects and analyzes performance data to predict generation and handle unstable power generation due to environmental factors.	Blynk, as a software platform, was used together with a Wi-Fi-enabled CC3200 microcontroller featuring an embedded ARM processor. Based on this setup, the Blynk app enables real-time communication and upload of data to the cloud.
8.	Omar A., et al. [84]	2021	To analyze how solar energy systems are affected by regular operational factors and to optimize each factor's effect on the system.	A review of the main generic objectives of renewable energy system optimization was presented concerning technical, economic, social, and environmental sustainability factors.
9.	Mallikarjun G., et al. [46]	2017	To conduct a comparative study of several solar panel cleaning technologies, specifically to engineer a revolutionary new technology for dust separation using an electrostatic precipitator (ESP).	Weight-sensitive thresholds under the panel build up dust over time, and the algorithm detects the accumulation to determine whether the panel needs cleaning.
10.	Paredes-Parra, et al. [86]	2019	The goal is to provide solar power plants with a low-cost wireless system for communicating with remote areas using long-range (LoRa) technology.	The wireless communication solution is made up of the sensor layer and low power wireless area network (LPWAN) to bring a comprehensive monitoring system to the data exchange in an IoT environment.
11.	Nurhasliza H., et al. [87]	2019	To determine the most effective technology to clean solar panels, while remaining affordable and environmentally friendly.	The proposed technique uses a smartphone app to monitor power generation and clean the solar surface as needed using a robot.

Table 2. *Cont.*

S/No.	Author(s)	Year	Aim	Methodology
12.	Prasad A.A., et al. [88]	2022	To investigate a decrease in energy production by solar panels for the arid region of outer space in Australia.	Analysis of dust characteristics was performed using two reanalysis products, the Modern-Era Retrospective Analysis for Research and Applications, and the Copernicus Atmosphere Monitoring Service (CAMS), with satellite data were acquired by Himawari-8. The analysis was conducted over seasonal periods following natural sedimentation. It revealed significant reductions in the energy of up to 3%.
13.	Barker A.J., et al. [19]	2022	To apply a chemical coating to solar panels to protect the devices from sustaining damage, when the environment requires regular cleaning and disinfection.	Coatings technology was tested for glass cleaning and the incoming solar radiation was continuously monitored and logged to estimate power production capabilities and surface accumulation for each panel.
14.	Chen Y., et al. [89]	2021	To create a dust monitoring system for the increase in efficiency of solar panel generation.	The monitored real-time data include the weather, solar panel power generation, and surface images for automated aggregation by a microcontroller with transmission capabilities. Algorithms were used to process the imagery.
15.	Gupta V., et al. [90]	2022	To examine the self-cleaning of solar panels through a wireless system.	A wireless data collecting and monitoring system was used to create and test a PV system's performance. A fixed PV system with daily manual cleaning was compared to a suggested cleaning PV system for a month, and the efficiency of the proposed cleaning PV system was just 1.13 percent lower.
16.	Nattharith P., et al. [33]	2022	To create a mobile robot system for inspecting and maintaining solar panels.	An Arduino is used to control the robot while a Raspberry Pi provides an internet connection for remote users to control their cleaning system through the developed website. A webcam also gives a live stream during robot operation.
17.	Şevik S., et al. [91]	2022	To research ways on effective cleaning and maintenance of solar panels.	Thermal monitoring and snow load removal were experimented with on a connected solar panel to monitor power reduction due to dirt.

Table 2. *Cont.*

S/No.	Author(s)	Year	Aim	Methodology
18.	Sánchez-Barroso G., et al. [85]	2021	To determine the optimal period in which to clean photovoltaic panels installed at Dehesa subject to its specific environment.	Three cleaning schedules for monthly, quarterly, and semi-annual intervals were evaluated in comparison to comparable uncleaned controls.
19.	Narvios W., et al. [92]	2021	To create an Internet of Things (IoT)-based system to track, spot dust buildup, and remove dust from PV solar panel surfaces.	The dust sensor measures and detects dust on the panel. The cleaning system automatically activates when the amount of dust builds up to a certain point. The temperature and humidity sensor was used to keep track of the outside temperature.
20.	Shah M.d., et al. [93]	2021	To create a smart, Internet of Things (IoT)-based system that can spin the panel to track attributes and enable cleaning and output monitoring.	The IoT system used an Arduino Uno, a Wi-Fi module, and a smartphone to gather the data it needed for the application.
21.	Zeedan A., et al. [94]	2021	To compare output power and ambient dust density for solar panels.	Experimental data from long-term observations of various meteorological conditions and the output power of PV panels placed in Qatar University's Solar facility in Doha are used to quantify losses on solar panels.
22.	Priyadharshini N., et al. [95]	2021	To use a cooling mechanism to deal with the solar panel's temperature rising above the set point and the accumulation of dust on the panel.	Three sensors; temperature, LDR, and current are used to monitor the temperature rise and dirt on a solar panel.
23.	Pagani V.H., et al. [96]	2021	To suggest a soiling index modeling based on solar radiation and generated current for solar panel systems to establish the cleaning parameters.	The study was based on the modification of an existing mathematical model.
24.	Anilkumar G., et al. [21]	2020	To discuss potential strategies to reduce the impact of dust on the surface of solar panels.	An automated robot cleaning system was implemented using a low power wide area network (LPWAN) built on a network of ESP 8266 Node MCUs linked to a set of sensors.
25.	Jin L.C., et al. [97]	2020	To create a self-cleaning solar panel system that will increase power generation by eliminating accumulated dust from the glass surface of the panels.	The voltage, current, LDR, and IR sensors were used in the construction of the dust detecting system. The Arduino microcontroller then collected and analyzed the sensor data to launch an autonomous cleaning. For monitoring purposes, the data were also uploaded to the ThingSpeak and Blynk servers utilizing Internet of Things (IoT) technology.

Table 2. *Cont.*

S/No.	Author(s)	Year	Aim	Methodology
26.	Mohamed M., et al. [98]	2020	To achieve the optimized cleaning rate of solar panels with the least amount of energy losses and cost.	Investigated were the acquired soiling rate and cleaning PV scenarios to determine the impact of soiling density on the angle of incidence (AOI).
27.	Jaszczur M., et al. [99]	2020	To research the important factors that affect dust formation and how they interact.	Investigated were wind and rainfall as the main natural factors that affect dust buildup on solar panel surfaces and how they relate to one another.
28.	Azouzoute A., et al. [100]	2019	To research a novel method for measuring the reduction in glass transmittance on a solar panel.	The Brewster angle was utilized in the technique to assess the intensity of the reflected ray from the glass surface in the presence of various levels of dust deposition density.
29.	Arabatzis I., et al. [101]	2018	To determine how a self-cleaning solar panel with a photocatalytic and antireflective glass layer affects its effectiveness.	Utilizing UV spectroscopy and Methylene Blue's degradation as organic pollutants, respectively, the coating's optical and photocatalytic characteristics were assessed.
30.	Kama A., et al. [102]	2017	The aim is to propose a method for monitoring the performance of solar streetlights using a connected system.	A transmission mechanism and sensors are included in the proposed solar streetlight to enable real-time data collection on a distant server. The data are distributed to a Web server, where it can be viewed for monitoring reasons.
31.	Joglekar A.V., et al. [103]	2018	To propose online I-V traces for series-connected solar panels on-demand.	The I-V trace's shape analytics are utilized to identify the fault's nature and its location on a solar panel array.
32.	Nasib K., et al. [22]	2018	To demonstrate the design and construction of a solar panel cleaning prototype.	The system's prototype includes a cleaning robot and a cloud interface.
33.	Archana R., et al. [104]	2018	To develop a Smart Solar Panel Cleaning system with a primary focus on utilizing Internet of Things (IoT) technology.	The Internet of Things analyzes the solar panel's environmental factors and gives the user the ability to take appropriate action.
34.	Yousif A.A., et al. [105]	2020	To improve the efficiency of the system for cleaning and cooling solar panels.	An IoT device and a mobile application are used to remotely monitor and control the system through the internet.
35.	Mohammad A.J., et al. [106]	2015	To study and discuss the approaches and issues on solar panel dust removal.	The robot's control system is implemented using an Arduino microcontroller.
36.	Alireza G., et al. [28]	2015	To create an inexpensive automation system that can perform on-demand cleaning to maintain the effectiveness of solar panels connected in an array.	Data from individual panels were collected using wireless sensor networks. The monitored data and information are utilized to instruct a robotic device to clean the surface of dirty panels.

Table 2. *Cont.*

S/No.	Author(s)	Year	Aim	Methodology
37.	Dhanalakshmi K.S., et al. [25]	2021	To eliminate the tedious process of cleaning a solar panel using the manual method.	The autonomous robot, which is built on an Arduino platform, communicates with mobile devices through Bluetooth to remotely control the cleaning of solar panels.
38.	Neha S., et al. [107]	2018	To fully automate the maintenance of solar energy production.	Solar power generation is tracked, cleaned, and managed via an Internet of Things platform. The Raspberry Pi module serves as the processor, while the built-in Wi-Fi module facilitates data transmission to the cloud.
39.	Cova P., et al. [108]	2018	To create a model that takes into consideration the energy production losses caused by dust and other types of dirt.	Solar panels with proper measurements of current and voltage and a clean reference panel were set up to identify shading effects caused by different kinds of soiling.
40.	Mudang N., et al. [109]	2020	The goal of self-cleaning is to increase the effectiveness of solar electricity generation.	An LDR sensor detects obstructions on the solar panel, and a microcontroller determines whether to clean with Wiper and Spray water or continue charging the battery.
41.	Jaswanth Y., et al. [110]	2021	To create a technique for consistently and effectively cleaning solar panels.	The design of the cleaning robot comprises driving gear motors, a motor driver, and a second motor that powers the robot and is fitted with a cleaning membrane so that it may be washed with water. For damage and cleaning references, the camera records footage of the solar panels and sends it to the cloud.

4. Discussion and Future Prospects

The current status of smart system integration in solar panel monitoring and cleaning is summarized in this review. Through the proposed harmonized data structures, future assessments can be more efficiently planned and integrated by showing what data have already been used and what data can be used in the future. It can be especially beneficial when certain optimizations are implemented based on real-time data from a solar panel site. From this review, we have identified the following gaps and recommendations:

- Though the purpose of communication technologies and cloud platform implementation was justified in the past studies for monitoring real-time data for decision making, most do not relate to assessments of the analytical soundness, measurability, and platform deployment, as well as their linkages to one another. Furthermore, more theoretically based research is required to create reliable evidence for selecting communication technologies and implementing cloud platforms.

- The influencing score of the theoretical framework used and the impacts on the methodology are underrepresented in the smart systems for the solar panel. Research on theoretically based smart systems remains a bottleneck to future progress on smart systems for solar panel monitoring and cleaning.
- The majority of smart solar panel case studies are located in Asia, and large regions of the world possess no published assessments. Indian and Chinese institutions are the most prolific in this area.

The main gaps in the smart system for solar panel monitoring and cleaning are the optimal cleaning frequency and costs, which are yet to be proven with the monitored data. The modeling of energy output degradation is an important tool for increasing the bankability of solar plants since dirt does not accumulate uniformly over time, but rather is affected by variations in weather conditions from day to day.

5. Conclusions

In the systematic review, well-conducted studies have been shown to improve solar panel cleaning and monitoring through the inclusion of smart system integration. The findings of other reviews of smart systems for solar panels are consistent with the observation that smart systems for solar panel monitoring and maintenance are effective. The ability to visualize the solar panel dirt conditions can be instrumental in optimizing the cleaning time and operation. There were four areas of interventions our research identified: dirt detection, cleaning methods, wireless communication technologies for data gathering, and cloud platforms for IoT implementation. Currently, there is enough evidence, but more studies are needed to fill the identified knowledge gaps. Smart systems for solar panels have the potential to improve lifetime performance, reduce maintenance costs, reduce human intervention, as well as increase energy output. Ultimately, the optimal frequency and cost of cleaning must be determined with monitored data, but the evidence reviewed here can be helpful to practice, policy, and future research.

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