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Review

Comprehensive Review of Dust Properties and Their Influence on Photovoltaic Systems: Electrical, Optical, Thermal Models and Experimentation Techniques

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Abstract: As conventional energy sources decrease and worldwide power demand grows, the appeal of photovoltaic (PV) systems as sustainable and ecofriendly energy sources has grown. PV system installation is influenced by geographical location, orientation, and inclination angle. Despite its success, weather conditions such as dust substantially influences PV module performance. This study provides a comprehensive review of the existing literature on the impact of dust characteristics on PV systems from three distinct perspectives. Firstly, the study looks at the dust properties in different categories: optical, thermal, physical, and chemical, highlighting their significant impact on the performance of PV systems. Secondly, the research reviews various approaches and equipment used to evaluate dust's impact on PV, emphasizing the need for reliable instruments to measure its effects accurately. Finally, the study looks at modeling and predicting the influence of dust on PV systems, considering the parameters that affect electrical, optical, and thermal behavior. The review draws attention to the need for further research into dust's properties, including thermal conductivity and emissivity. This analysis highlights the need for further research to develop a scientific correlation to predict the thermal behavior of PV in dusty environments. This paper identifies areas for further research to develop more efficient and effective methods for analyzing this influence and improving PV efficiency and lifespan.

Keywords: photovoltaic (PV); dust accumulation; dust properties; experimentation devices methodologies; model predictions; future research

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1. Introduction

Photovoltaic (PV) is a technology for harnessing solar energy that uses semiconductors susceptible to the PV effect to convert the sun's rays to direct electricity [1]. Manufacturers often rate PV's output at standard test conditions (S.T.C.), where the temperature is set to 25 °C, the solar irradiance (intensity) is set to 1000 watts per square meter, and the sunlight spectrum is filtered through an atmosphere 1.5 times its normal thickness [2]. However, outdoor conditions differ from those that can be replicated in a factory. The growing popularity of PV systems leads to the importance to understand how various climatic variables—humidity, dust, temperature, wind speed, etc.—affect the effectiveness of these systems [3]. Indeed, it is important to consider the various climatic variables when designing and installing PV systems to ensure optimal performance and long-term durability.

Solar irradiance, also known as solar insolation, is the amount of sunlight that reaches the surface of the Earth [4]. Solar irradiance can vary depending on the daytime and weather conditions and can significantly affect the output of PV systems. Additionally, the inclination angle, the angle at which sunlight strikes the PV panel, can affect the amount of sunlight that is absorbed by the PV system [5]. Overall, it is essential to consider solar irradiance variability when designing and installing PV systems to ensure optimal performance and energy production. The ambient temperature affects the electrical properties of the semiconductors used in PV cells, which can decrease power output [6]. High temperatures can also cause thermal stress on the PV cells, leading to reduced performance and potential damage over time [7]. A PV cell's temperature coefficient measures how the cell's output power changes with temperature. Typically, a PV cell's output power decreases as the temperature of the cell increases. In contrast, wind speed can also influence the performance of PV systems [8]. Wind can help to increase the convective cooling of the PV system by removing the hot air and bringing in cooler air, which can help to reduce the temperature of the PV cells. Humidity can influence PV's performance as well. High humidity can cause condensation that can occur when the temperature of the PV panel is lower than the dew point temperature of the surrounding air [9]. When this happens, water vapor in the air can condense on the PV panel's surface, forming water droplets. These water droplets can scatter and absorb sunlight, reducing the amount of sunlight reaching the PV cells [10]. High humidity can also lead to corrosion of the electrical connections and potential failure of the PV system [9].

In addition, dust accumulation on PV panels can significantly impact their electrical, optical, and thermal behavior and lifespan [4,11,12]. It can decrease the amount of sunlight that arrives on the PV modules, causing a reduction in the output power. The amount reduction in power output depends on the type and amount of dust, location, and climate conditions [13]. Dust particles can scatter and absorb sunlight, reducing the amount of sunlight that strikes the PV panels [14]. It may also lead to shading effects, which can lead to hot spots on the PV cells [15]. These hot spots can increase the temperature of the PV cells, exacerbating thermal stress and leading to performance degradation and potential damage over time. Dust can also trap the heat inside the PV cells, leading to an increase in temperature [16]. In addition, dust particles can scratch the surface of the PV panel, leading to potential damage to the panel's surface and a decrease in performance.

The impact of dust on PV systems is a topic of increasing interest among researchers and academics due to the growing demand for sustainable energy production. Researchers are studying the impact of dust on PV systems, the measurement and monitoring of dust accumulation rate, and the properties of accumulated dust. They are also investigating the influence of dust on PV systems in various climates and geographical locations, including dry regions, and trying to predict the electrical and optical behavior of the PV.

Owing to the significance of investigating how dust affects PV modules, several researchers have carried out review studies [17–19]. Some of these studies were conducted as a review for considering a specific area. The objective of Ref. [20] was to conduct a literature study at the junction of particle physics and desert settings to understand PV soiling behavior and find potential mitigation techniques. The presentation included original data on environmental conditions and PV soiling in Doha, Qatar. Ref. [21] reviewed Iraq's geographical and meteorological characteristics and human activities that have increased desertification in the country, such as dust storms. An extensive review of the impact of dust deposition on PV in Iraq was provided for scholars, developers, and industrial engineers managing PV modules. Ref. [17] provided a review on the impact of dust deposition on PV surface performance and strategies to eliminate them. Moreover, various mitigation techniques to maintain performance levels and achieve Nigeria's renewable energy targets were presented. Refs. [22,23] present an overview of PV system efficiency and the impact of accumulating dust on the optics of solar radiation, while Ref. [24] reviewed image processing methods used to predict dust on solar panels and compile information to aid in the study of the subject and serve as motivation for future investigations. Ref. [25] considers the impact of collected dust on PV panel effectiveness and other environmental conditions. The study emphasized the significance of modeling dust accumulation and other environmental conditions and examined statistical and machine intelligence models used to forecast PV performance.

Although many studies have considered different aspects to review dust impacts on PV, this paper reviews and gathers information from previous studies that considered the impact of dust on PV systems in three distinct areas, as shown in Figure 1. First, the review involves analyzing existing research studies to understand the physical, chemical, and thermal properties of dust particles that accumulate on PV, and how they vary depending on their source, location, and climate conditions. Second, the research examines existing experimental studies, devices, and techniques related to investigations on dust's impact on PV. Finally, the paper reviews the scientific correlation, which has previously involved synthesizing the outcomes of the investigations and identifying any similar themes or trends. This includes determining the most effective approaches in various climates and locales, and the efficacy of modules in forecasting the influence of dust collection on the electrical, thermal, and optical performance of PV panels. This review clearly demonstrates the current state of knowledge in this field, identifies research gaps, and suggests areas for future research, including highlighting areas that require additional research. Overall, reviewing and collecting previous research on this topic benefits researchers and scholars by allowing them to grasp the present state of knowledge in the field, identify gaps in the research, and provide recommendations for future research.

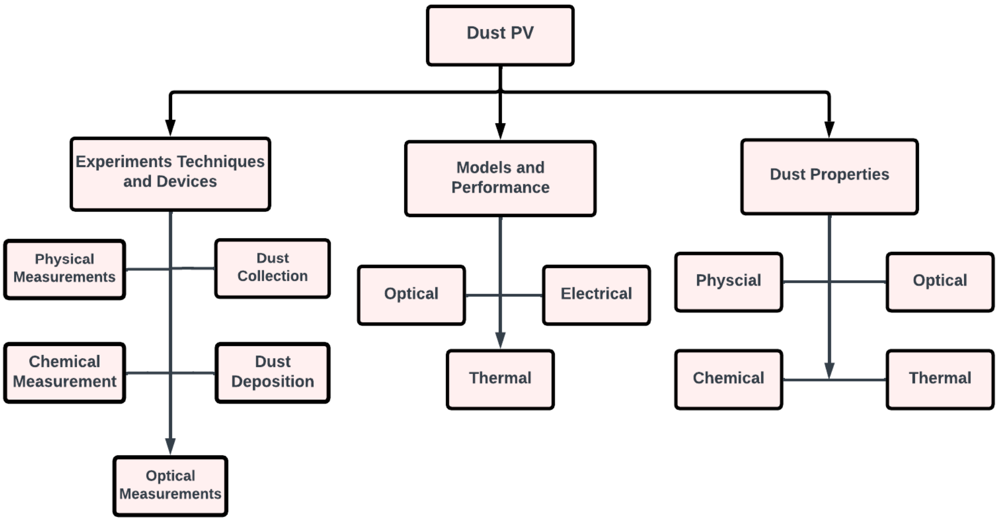

Figure 1. Illustration of the three aspects of dust's impact on PV systems.

2. Dust Properties on PV

Dust is a collection of tiny particles composed of microscopic solid inorganic and organic particles such as soil particles, ash (including pollutants from factories, vehicles, and firewood), bacteria, and so on, that has a diameter smaller than that of the air 500–1000 µm [26]. These particles vary in size, volume, chemical concentration, and shape [27]. Dust properties, such as size, shape, chemical composition, transmittance, absorption, reflection, thermal conductivity, and emissivity, can all affect the thermal and electrical behavior of PV systems [28]. It is essential to consider that dust properties can vary depending on the location and environmental conditions [28]. Therefore, understanding these properties and the specific impact of dust in each location is crucial to develop effective cleaning and maintenance strategies to mitigate the influence of dust on PV effectiveness. Dust properties can be categorized in several ways [22], such as (i) optical properties—these include transmittance, absorption, and reflection, which are regarding the capability of dust particles to interact with light; (ii) thermal properties—these include thermal conductivity, which is related to the ability of dust particles to transfer heat; and (iii) particle properties—these include the shape, size, and composition of the dust particles, which concern the chemical and physical characteristics in terms of dust particles. To develop effective study analyses or dust mitigation strategies, it is essential for researchers to comprehend these dust properties and how they affect PV performance.

2.1. Optical Properties

In the PV systems, the interaction between dust particles and light is vital since it can drastically alter the performance of these systems. The optical characteristics of dust, which include transmittance, absorption, and reflection, are what determine how this interaction plays out [29]. Dust's optical characteristics are influenced by several elements, including the particle size, shape, refractive index, and chemical content. Researchers need to understand the optical characteristics of dust and how they affect PV performance. This can include investigating the optical properties of dust under various situations. In following subsections, this paper addresses the many optical features of dust that have an impact on PV performance.

2.1.1. Dust Light Absorption

Absorption is the ability of dust particles to absorb light. Dust particles that can absorb light can reduce the light that arrives at the PV cells, lowering the PV system's efficiency [20,30]. Dust can absorb heat and sunlight, raising the PV module's temperature [16]. This can cause thermal stress on the PV cells, leading to decreased performance and potential damage over time. The amount and chemical composition of dust can significantly impact dust light absorption properties [31]. Dust composed of large particles and/or with a high absorption coefficient has a higher absorption rate than those with small particles and/or absorption coefficients [30].

Various parameters, including dust particle diameter, morphology, and elemental composition, can influence dust light absorption on PV [32]. For example, dust particles that are smaller in size are more likely to scatter light and have lower absorption rates, while larger particles are more likely to absorb and reflect light. A study by [32] used a spectrum optical absorption measurement device to measure the absorption coefficients in the wavelength's spectrum from 300 to 800 nm with an accuracy of 50 nm. For particle sizes greater than 0.5 m, the dust light absorption coefficient was shown to be associated with particle number concentration, although the correlation was weaker for smaller particles. Similarly, dust particles with irregular shapes are more likely to scatter light and have lower absorption rates than regular shapes [20]. Limestone, carbon-based soot, and red soil with oxidized iron are three common air contaminants with elevated light-absorption coefficients [30].

The chemical composition of dust particles can also affect their absorption rate, with metallic particles having a higher absorption rate than nonmetallic particles [20]. In general, dust composed of large particles and/or has a high absorption coefficient has a higher absorption rate than dust consisting of small particles and/or has a low absorption coefficient. This is why dust composed mainly of iron oxide (Fe_2O_3) has a higher absorption rate compared to dust composed mainly of silica (SiO_2) [33]. To summarize, understanding the impact of dust amount and chemical composition on the dust light absorption property is essential for investigating the impact of dust on PV performance and thermal behavior.

2.1.2. Dust Transmittance

The dust accumulation on the PV cell considerably impacts the incident solar light transmittance [34]. The transmittance of dust on PV is the ability of dust particles to allow light to pass through them. Low transmittance of dust particles can decrease the amount of light that arrives at the PV modules and reduces the efficiency of the PV system [11]. The amount and chemical composition of dust can alter how well light passes through the dust layer. The amount of dust on a surface can affect the transmittance by decreasing it as the dust layer becomes thicker [35]. This is because more dust particles scatter and absorb the light, reducing the amount of light that can pass through. The authors of [36] discovered that addition of one gram of dust per square meter reduced light transmittance by 4.1%, while [37] examined total transmission for various weights per unit area and discovered that the entire transmission reduces linearly with dust mass per unit area. In addition, the study found that the transmittance is affected by the size and shape of the dust particles, with smaller particles having a more significant impact on the transmittance. The study also found that smaller spherical and cubic particles have a more substantial effect on the transmittance than larger particles because they are more equally distributed throughout the surface of the mirror and lessen the amount of light that passes through spaces between the particles. The chemical composition of the dust can also affect the transmittance, with different elements and compounds having different optical properties.

Overall, the transmittance of dust on PV can significantly impact PV system performance, and it is essential to consider the numerous factors that impact the dust particles' transmittance rate when investigating the impact of dust on PV performance.

2.1.3. Dust Reflection

Dust reflection refers to light reflected by dust particles accumulated on PV surfaces and other optical surfaces. The amount of light that may travel through or be reflected by these surfaces can be greatly reduced by dust particles, which lowers the effectiveness and performance of the affected systems [38]. Dust reflection can be affected by numerous factors, such as the dust particles' size, shape, and composition, and the amount of dust accumulation on the surface [39]. The density of the dust deposited on the PV module significantly impacts reflection [40]. When the density of dust-deposited mass is between 0 and 65 g/m^2, reflectance rises roughly linearly with mass density, from 10.8% to 25.6%. Reflectance stays the same once the mass density exceeds 65 g/m^2.

When dust particles accumulate on a surface, they can create a diffused, scattered reflection of light, reducing the amount of light that can pass through the surface. This is known as "diffuse reflection". This can happen when dust particles are smaller than 2 mm and accumulate on the surface of the PV module, making it difficult for the light to pass through [39]. Overall, dust reflection can significantly impact the performance of systems that rely on optical surfaces, and it is vital to consider the numerous factors that affect dust reflection when investigating the effect of dust on PV effectiveness and developing dust mitigation strategies.

2.1.4. Dust Emissivity

Emissivity is the ability of dust particles to emit thermal radiation, which can impact the temperature of PV cells. Understanding how dust emissivity affects the thermal behavior of the PV systems is still extremely limited within the current state of knowledge.

The impact of dust emissivity on the thermal behavior of PV has yet to acquire much interest; on the other hand, the impact of dust emissivity on the thermal behavior of building roofs has been investigated. For example, Ref. [41] discussed the impact of dust accumulation on the thermal performance and heat-gain of building roofs in hot, dry climates, where dust accumulation on building roofs can impact the thermal behavior of the building by affecting the roof's solar absorptivity and thermal emissivity. In addition, the amount of dust on a surface can also impact the emissivity of dust. As the dust layer thickness increases, the dust particles' emissivity also increases. Ref. [42] explained how dust accumulation on a horizontal radiant barrier can affect the thermal performance and stated that insignificant amounts of dust can cause significant increases in the emissivity of radiant barriers. The test results showed that dust levels of 0.34 and 0.74 mg/cm^2 resulted in emissivity values of 0.125 and 0.185, respectively. This occurs because the increased presence of dust particles scatters and absorbs more light, changing the surface thermal properties of the underlying surface.

This review highlights the importance of understanding the effects of dust accumulation on the thermal emissivity of PV systems. Further research in this area is needed to fully address the potential impacts and improve the overall performance of PV systems in dusty climates.

3. Thermal Properties

Thermal properties of dust refer to the ability of dust particles to transfer heat. One of the most essential thermal properties is thermal conductivity, which is the ability of dust particles to transfer heat. The thermal conductivity of dust can impact the performance of PV systems by varying the temperature of the PV cells, thereby decreasing the PV system's efficiency [43]. According to an experimental investigation by Abderrezek and Fathi, the authors found that the PV temperature increased due to the accumulation of different dust types. In addition, they discovered that dust with a high thermal conductivity, such as salt, contributed to the removal of heat from the glass, whereas dust with a low thermal conductivity, such as soil and glass, led to higher surface temperatures [44]. These results demonstrate that the thermal conductivity of dust can impact the thermal performance of PV systems.

To fully understand the effect of dust on PV performance and temperature, it is crucial to consider its thermal properties, as the main composition of dust particles can increase their thermal conductivity and, consequently, affect the overall thermal behavior of the PV system. It is important to consider the numerous factors that affect the thermal conductivity rate of dust particles when investigating the impact of dust on PV temperature, as dust's thermal conductivity can influence the thermal performance of PV systems. Although these properties are considered very important and could play important role in changing the PV temperature, there is a lack of knowledge and understanding. Thus, research in this aspect needs to be conducted.

4. Physical Properties

As mentioned, the physical properties of dust include characteristics such as size, shape, and density [22]. These physical properties of dust can affect how the dust particles interact with light, heat, and other environmental factors and can have an impact on the performance of PV systems.

4.1. Dust Size

The dimensions of the dust particles that accumulate on PV systems are referred to as dust particle size. Dust particles can range in size from submicrometer to millimeter scale, so there is a wide range. Dust consists of tiny particles made up of diverse components with a variable diameter. These particles vary in size, volume, chemical composition, and form. The particle size distribution of the dust collections varies from 0.003 μm for clay particles to 190 μm for soil particles, with the majority (83%) in the range 0.3 to 60 μm [45]. The size of the dust was measured experimentally, and it revealed that the size spans from 0.1 to 1000 μm, with the bulk of collected particles (43%) having diameters ranging from 100 to 500 μm and 15% having diameters ranging from 10 to 50 μm [46]. Ref. [47] stated that the size of dust accumulated on PV panels varies between a normal day and dust storm events. On regular days, the dust's practical size is within a majority range of 0.4 and 0.5 μm, smaller than that recorded for dust storm occasions, which have a majority range of 1.1 and 1.2 μm.

Dust particle size is one of the key factors that can affect the performance of PV panels [48]. Smaller particles are more likely to accumulate on the surface of PV modules since small particles are more easily carried by wind and air currents, which may result in a greater buildup on PV surfaces [49]. However, smaller dust particles have a greater impact on reducing solar energy transmission than larger dust particles because they tend to cover more surface area on PV modules. For example, the size analysis performed by Ref. [50] on two samples of dust from two different countries revealed that the dust from Babuin, Indonesia, was dominated by larger particles than that from Perth, Australia. The researchers discovered that larger dust particles that adhered to PV glass surfaces tended to be dispersed unevenly, leaving significant gaps between them that increased the light intensity that could pass through. On the other hand, since the small particles have a higher surface area-to-volume ratio, this leads to greater solar radiation absorption and decreasing PV power performance.

Another study found that the majority of dust particles collected on PV panels had diameters ranging from 100 to 500 µm, and 15% of the dust particles had diameters ranging from 10 to 50 µm [46]. This study also indicated that smaller dust particles can impact PV performance more than larger particles. However, Ref. [48] stated that the soil particle size can affect PV module power output differently. The study investigated five different sizes of soil samples. The study found that smaller particle sizes (75 µm and smaller) had a greater impact on power output at low irradiance levels (300–500 W/m^2) but the larger particle size (150 µm) had a greater impact at higher irradiance levels (1000–1200 W/m^2).

To predict how dust affects PV system performance, it is crucial to understand the size distribution of dust particles on the panel.

4.2. Dust Shape

The shape of dust particles can vary from spherical to irregular shapes. The chemical composition of dust varies depending on its source and the environmental conditions under which it is formed. This could directly impact the dust particle shapes. For example, desert dust particles are usually irregular and angular, whereas industrial dust particles can vary in shape depending on the manufacturing process [51]. The deposition process and PV efficiency are also significantly impacted by the dust particles' weight and shape [52]. The shape of dust particles can also affect how they adhere to the surface of PV panels and impact their performance [52]. Irregular-shaped dust particles can create a rough surface on the PV panels, increasing the likelihood of adhesion and making it more difficult to remove the dust [53]. This can lead to shading and a reduction in the amount of sunlight reaching the PV panel surface, reducing the overall efficiency of the panels.

Additionally, irregular-shaped dust particles can have a greater impact on PV performance than round particles of the same size [54]. It has been found that the smooth and round particles are less likely to adhere to the surface of PV panels, while irregular-shaped particles can be more challenging to remove and may adhere more readily [26]. It is important to note that dust properties can vary depending on the location and environmental conditions. Therefore, understanding these properties and the specific impact of dust in each location is crucial to mitigate the effects of dust on PV performance since the shape of dust particles can affect how they interact with light and heat, and how they settle and accumulate on surfaces.

4.3. Dust Density

The mass of the dust particles per unit area is referred to as dust deposition density. The quantity of dust that builds up on PV panel surfaces can have a large effect on how well they work. The amount of sunlight that reaches the PV panel decreases as the dust deposition density rises, which has the effect of reducing the amount of energy the panels produce [55]. Even a small amount of dust on PV panels' surface can reduce their performance [11,56]. The performance declines as the dust accumulation intensity rises. For example, a study by [47] reported that the performance of PV modules decreased by 8.5% when the concentration of the dust accumulation was 0.5 g/m^2, and by 20% when the dust deposition density was 2 g/m^2. Additionally, high dust deposition density can create shading on the panels, which can create hot spots and reduce their overall efficiency [47]. The dust density can also create a conductive layer on the surface of the panels, which can lead to electrical leakage and potential damage to the panels [57]. Dust density can vary depending on factors such as the site's environmental conditions [55]. When analyzing the effects of dust on PV performance, it is crucial to take these elements into account. These considerations include site features, weather, and surface materials.

5. Chemical Characteristics

The chemical composition of dust particles, also known as dust composition, can significantly impact the performance of PV modules. Dust is composed of various materials, including silica, carbon, iron, aluminum, and other minerals, and the composition of dust particles that accumulate on PV panels can vary depending on the source and environmental conditions [58]. The main components of dust on PV panels include silica, calcium oxide, magnesium oxide, iron oxide, and aluminum oxide, with silica being the most prevalent component in desert regions [20]. Ref. [59] also stated that the accumulated dust on PV panels in desert regions is primarily composed of silica, while dust in coastal areas is composed mainly of salt. Additionally, Ref. [60] reports that the dust components have a significant amount of silica with clay and silt, indicating the influence of the desert and the agricultural region in the formation of the deposited dust. The primary dust pollutants in many nations were found contain silica, ash, and calcium carbonate [60]. The chemical properties of dust can affect other properties, such as optical, physical, and thermal properties, influencing how it interacts with light and heat and accumulates on PV surfaces. Understanding the chemical properties of dust is essential for predicting and mitigating its impact on PV performance and temperature.

6. Experimental Studies

PV has become one of the most promising renewable energy sources. PV modules are commonly employed to transform the Sun's energy into electricity [61]. The influence of dust on PV has been the subject of much research, and numerous experimental methodologies and equipment have been employed to examine this impact [62]. This section aims to explore the various approaches and experimental procedures used to investigate the influence of dust on PVs. This part focuses on the procedures used to collect dust samples and examine the dust characteristics on PV surfaces, together with the methods used to quantify the output of PVs and the effect of dust on PV temperature.

This study gives vital information to researchers and designers studying the effects of dust on solar systems, which will assist in expanding the renewable energy industry by helping secure the long-term viability and performance of solar systems.

6.1. Dust Collection

Gathering dust samples is an essential stage in gaining knowledge of dust on PV systems. Collecting dust samples can be accomplished through various methods, each of which has a unique set of benefits and drawbacks. As described in the following subsections, these methods can be generally organized into separate groups.

6.1.1. Collecting Accumulated Dust on PV

The accumulation of dust may be completed in a quick and uncomplicated fashion [63]. However, Ref. [64] collected the dust with a gentle brush to sweep the dust particles stuck to the PV modules' surface. Additionally, Ref. [13] studied different dust particles collected from Dhahran's solar PV surfaces using soft brushes. Afterward, the dust that was collected is placed in a container for subsequent examination. The authors of Ref. [50] collected surface dust from PV modules using a soft brush; the dust particles adhered to the PV glass surfaces were swept to the edge of the modules and then collected in a container box. Another method for dust collection from PV surfaces is electrostatic adsorption paper. The paper is dried and weighed before gathering dust to estimate its original mass. After wiping the dust off the PV module surfaces, the paper is dried and weighed again to determine the total mass of the paper and dust [65].

6.1.2. Natural Deposition on a Glass Sheet

A small glass sheet is commonly used as a dust collector in field studies to measure the dust deposition density on PV modules [66,67]. The glass sheet is placed close to the PV module, typically at the same tilt angle, and left in place for a specified period. After the specified period, the glass sheet is removed, and the dust on the surface is weighed to calculate the dust deposition density. This method is commonly used in field studies to measure the impact of dust on PV modules and is a simple and cost-effective way to measure dust deposition density. For example, a small glass sheet used by Ref. [39] with an area of 18.75 cm^2 (7.5 × 2.5 cm) was placed close to the 25-tilted PV module to measure the dust deposition density [68]. Using a small glass sheet placed near the module allows for measuring the natural dust accumulation in the environment. In addition, Ref. [69] utilizes two techniques where the dust was gathered in the form of raw dust and dust that had accumulated on exposed sheets of glass at varying degrees of tilt. Ref. [70] monitored the dust buildup on a glass sheet in natural settings, which was also investigated by exposing tilted glass sheets to the elements for 30 days and monitoring the dust accumulation and solar radiation transmittance through the sheet at regular intervals.

6.1.3. Collect Dust from Related Resources

Many different approaches have been tried and assessed by academics to collect dust from the ground. For example, Refs. [50,69] gathered the dust in the form of raw dust. However, Ref. [70] utilized dust that was produced from soft Bangkok clay that had been pulverized, dried, and sieved to produce particles with diameters ranging from 53 to 75 µm. Other scholars, such as Ref. [71], stated that the dust samples were collected from roads and sidewalks surrounding the university campus, and then crushed and sieved to acquire a composition comparable to the dust that would naturally build on the PV modules [71]. On the other hand, the process of comminution and sieving can be time-consuming and labor-intensive, and it also has the potential to introduce bias into the sample.

6.1.4. Artificial Dust

In laboratory investigations, artificial dust is frequently used to model the effects of dust collection on PV panels. Researchers are using artificial dust evaluate the effect of dust on the electrical performance of PV panels [72,73]. The artificial dust is carefully selected to mirror real-world dust features such as size, composition, and surface area. To evaluate the effectiveness of the PV model provided, the author used both artificial and natural dust in Oman [72]. Ref. [74] stated that a nontoxic commercial talcum powder was employed to simulate dust.

6.2. Dust Deposition

A dust deposition approach that is frequently used in laboratory studies to examine the effects of dust on the performance of PV modules is performed by spraying the dust on the PV surface. Researchers have been utilizing several methods to simulate the natural deposition of dust on PV surfaces or take actions to increase the precision of the findings, such as carefully regulating the size, quantity, and distribution of the dust particles on the surface.

6.2.1. Dust Deposition Chambers

Researchers use dust deposition simulation devices, such as dust chambers, to simulate dust accumulation on PV panels in a controlled laboratory environment [75]. This allows researchers to study the impact of several types and amounts of dust on PV performance, including the effect on power output, electrical transmittance, and temperature. Ref. [76] conducted their studies utilizing a dust chamber that was created to mimic dust accumulation on the surface of a solar cell. The dust was produced by a dust generator and delivered into the chamber by a blower. The dust particles were then deposited on the PV surface using a dust deposition tray. Using this dust deposition chamber, researchers could regulate the quantity and size of the dust particles deposited on the PV module and guarantee that they were dispersed uniformly throughout the surface [74].

6.2.2. Free Fall Dust Method

The free fall dust method is a typical approach used in research studies to quantify the influence of dust deposition on PV performance [77]. In this methodology, a specified height is used to drop a regulated amount of dust onto the surface of the PV panel [26]. This strategy permits an accurate and uniform application of dust to the surface of a PV module, making it a simple and cost-effective choice for researchers studying the effect of dust on PV performance. Ref. [69] deposited the dust by free fall from a height of 1 m using a cylindrical tube to limit the influence of wind currents in the laboratory.

6.2.3. Process of Manual Sieving

Dust was sieved through a fine mesh filter to ensure a uniform coating of dust covered the module. Using this technique, researchers can assure the uniformity of the dust and ensure the particles are the same size and shape before accumulating on the PV module [26]. It offers a more accurate illustration of how dust buildup affects PV performance. Ref. [68] employed a manual sieving process to quantify and evenly disperse dust on the PV module's surface. Ref. [78] described how dust was deposited on a horizontally positioned panel using a vibrating sieve. After being shaken with an acoustic vibrator to loosen the dust, the sieve's holes let the particles fall to the surface below through gravity.

6.2.4. Spraying Dusty Solution

To deposit dust on PV surfaces, a spraying approach is used that includes blending the dust with fluids to produce a homogenous slurry that can be sprayed to the surface with ease [28]. After spraying the combination onto PV surfaces, the fluids are allowed to evaporate, leaving a thin coating of dust behind. Using water to mix the dust may assist in lessening the influence of wind currents and other environmental elements that might alter the distribution of the dust particles [79]. This approach can be used to deposit varied densities of dust on the surface. The effects might be inconsistent if the dust is not equally dispersed across the surface after evaporating water.

A combination of dust (0.5 kg) and water (1 L) was sprayed on five glass sheets 30×30 cm^2 and allowed to dry [70]. The dust was applied to the PV modules using a spraying method in which dust collected from the field was mixed with water and sprayed onto the surface of the PV modules [50]. Other fluids, such as ethanol or isopropyl alcohol, might be mixed with the dust before spreading it on the glass or PV module. The fluid employed should be able to suspend dust particles and disseminate them evenly across the surface. For example, Ref. [80] stated that the dust particles were mixed with 90% alcohol, stirred with an ultrasonic oscillator for about 5 min to help them spread out, and then spread evenly on the PV glass surface. A lamp was used to speed the evaporation of alcohol. In conclusion, the spraying approach effectively deposits dust on PV surfaces, but researchers must consider the possible drawbacks and reduce their influence on the experiment's outcomes.

6.3. Chemical Measurement

Determining the chemical composition of dust that collects on PV panels is critical for understanding the influence different components have on the panels' performance [50,81]. Different chemical components and compounds can have varying impacts, such as limiting light transmission and absorption in PV panels, resulting in lower power output. Understanding the chemical composition can assist researchers in developing and optimizing cleaning procedures, protective coatings, and preventative actions to reduce the impacts of dust collection [38]. It also gives essential information for understanding local environmental conditions and potential contamination sources, which can influence long-term plans to decrease dust's impact on PV performance [17]. The next subsections describe some of the most frequently employed methods for determining the composition of dust, each with its own benefits and drawbacks.

6.3.1. X-ray Fluorescence (XRF)

Spectroscopy is a method that uses X-rays to excite the atoms in a sample, and then the energy of the fluorescence that is released is measured [63]. The advantages of XRF are its nondestructiveness and capacity to measure a large variety of components rapidly and precisely [68]. However, its sensitivity to light elements may be a limitation, and it might not be able to indicate comparable components [82]. The authors use the XRF method to analyze dust samples, and the results show that the dust is primarily composed of silicon (Si), but they stated that this technique does not detect light elements such as aluminum [82].

6.3.2. Scanning Electron Microscopy (SEM)

SEM scans a sample's surface with an electron beam to create a high-resolution picture showing the sample's composition and structure. The high resolution, the broad variety of components that may be measured, and the capacity to create intricately detailed pictures of materials are all benefits of SEM. Its sensitivity to light elements limits it, and it might be unable to distinguish comparable components. A gold layer was used in this work to coat the dust layer for investigation utilizing the Hitachi S-3400N variable-pressure SEM [71]. Because gold is a highly conductive metal that does not interfere with the electron beam used in the SEM, it is frequently employed as a coating material. Furthermore, because gold has a high atomic number, it is evident in the SEM, making examining and studying dust particles simpler. This allowed the authors to thoroughly study the shape and content of the dust particles [68].

6.3.3. Energy Dispersive X-ray Spectroscopy (EDS)

The EDS method quantifies the energy of the electrons released from a sample, revealing details about the sample's composition [83]. EDS has several benefits, including the ability to assess various components and interoperability swiftly and precisely with the SEM [84]. Its sensitivity to light elements limits it, and it might be unable to distinguish comparable components. Ref. [50] investigated the components of dust using a JCM-6000 Neo Scope Benchtop SEM equipped with EDS and X-ray diffraction (XRD) to evaluate the minerals of the dust samples. The EDS findings revealed that oxygen (O, 34%) and silicon (Si, 29.14%) were the most abundant elements in Perth dust, whereas calcium (Ca, 32.42%), oxygen (O_2, 24.59%), and iron (Fe, 23.37%) were the most abundant elements in Babuin dust. The XRD data revealed that quartzite (SiO_2) and calcium oxide (CaO) were the most common minerals discovered in Perth dust, whereas CaO was the most common mineral identified in Babuin dust. According to the SEM pictures, Perth dust had an angular form with some diagonals, whereas porous particles with ellipsoidal and spheroid shapes dominated Babuin dust.

6.3.4. X-ray Diffraction (XRD)

XRD is a nondestructive analytical method for determining a sample's crystal structure, atomic arrangement, and chemical content [83]. It is often used to investigate minerals, metals, polymers, and ceramics [63,69]. The XRD method uses a monochromatic X-ray beam to expose the sample. Because the X-rays come into contact with the atoms in the sample, they diffract in different directions. The diffracted X-rays are then detected and processed to identify the sample's crystal structure. Ref. [50] analyzed dust samples taken in Perth, Australia, and Babuin, Indonesia, using both XRD and EDS, and discovered that the results from the two methods were not the same. The principal minerals detected in Perth dust were SiO_2 and CaO, while CaO was the dominant mineral in Babuin dust. Meanwhile, the EDS data revealed that the most prevalent elements in Perth dust were O_2 and Si, whereas Ca and Fe were the most common elements in Babuin dust. So, XRD is used to identify the minerals in dust samples, whereas EDS is used to identify the elements in dust samples. Ref. [63] employed XRD analysis to pinpoint the dust's mineral buildup and pinpoint the components using the ASTM files stored in the database. The EDS may be used to determine the elements present in a sample and their relative concentrations [50].

These approaches work well together and are frequently combined to comprehend a material's properties. Nevertheless, the primary distinction is that while XRD identifies crystal structure and phase composition, XRF determines chemical composition.

Whereas EDS examines the elemental composition of a sample, SEM provides high-resolution images of a material's surface that show its microstructure, form, and elemental distribution. SEM, EDS, XRD, and XRF, respectively, use X-rays and electrons. XRD is nondestructive and requires minimal sample preparation, in contrast to SEM and EDS.

6.4. Physical Measurements

Dust attributes such as size, shape, and weight help to better understand the impact of dust on PV systems. Dust particle capacity to attach to surfaces and light transmission are affected by their size [58]. Additionally, the form of dust particles can affect their optical characteristics and their propensity to scatter light [85]. The weight of dust deposits on surfaces can also substantially affect system performance, reducing the quantity of light that arrives on the surface and diminishing the system's overall efficiency [86]. Understanding the characteristics of dust is necessary for creating efficient dust mitigation measures and enhancing the performance of dust-affected systems [86]. There are various devices and techniques used to measure the dust's physical properties and they are presented in the following subsections.

6.4.1. Shape and Weight

Various dust morphologies have different impacts on the performance deterioration of PV modules [87]. SEM is normally used to visualize the dust samples' surface morphology and particle size [50]. SEM images allow researchers to observe the physical characteristics of the dust particles, such as their shape, size, and texture.

Measuring the mass of dust deposited on the PV modules is one method of determining the buildup of dust. This may be performed with adequate precision by using a balance or scale. A Mettler PJ3000 balance, with an accuracy of 0.001 g, was used to measure the amount of dust that had collected on PV glass surfaces [88]. Ref. [69] was also able to measure dust's mass to within 0.1 milligrams. However, this approach only offers data on the total dust quantity.

Moreover, the weight of the tiny particles can be determined experimentally by weighing the glass samples before and after with a Mettler PJ3000 scale [13]. By deducting the original weight of the specimen from the final weight, the weight of the dust is computed. The weights are then divided by the total area of the glass to calculate the dust deposition density in g/m^2 [89].

More research is needed to develop an in-depth knowledge of how the shape and size of dust particles affect the performance characteristics of PV panels. Numerical simulations and modeling can be used with the comparative study to understand further the physical factors that regulate the performance decline of PV modules owing to dust collection. These simulations can also estimate how well PV modules will hold up through time in various dust conditions.

6.4.2. Size

Understanding the impact of dust on the efficiency of PV requires measuring the size of dust particles deposited on their surfaces. Dust particle size has a crucial influence in influencing the degree of shadowing and the quantity of light blocked from reaching solar cells. Scholars have used a variety of instruments to determine the precise size of dust particles. For instance, by employing the SEM images, authors could examine the dust particles' physical characteristics able to examine the physical properties of the dust particles, such as their structure, size, and roughness [68]. SEM is a method used to evaluate the surface morphology of a sample by scanning an electron beam over the sample's surface, which provides a high-resolution picture of the sample's surface [50]. A Fritsch ANALYSETTE 22 MicroTec Plus laser particle sizer was used by Ref. [71] to determine the size of the dust particles. This laser diffraction apparatus measures particle size distribution via laser beam scattering [13]. These technologies employ methods such as laser diffraction, image processing, and electron beam scanning to measure the size and form of dust particles with precision. Additionally, Ref. [69] used a microscope and image-processing tools to measure the size of the dust particles. Accurate determination of the dust particle size is necessary to comprehend the mechanisms underlying dust-induced deterioration.

6.5. Optical Measurements

Optical measurements are crucial in understanding how dust affects the performance of photovoltaic (PV) systems. To acquire insights into the mechanisms underlying the decline in PV efficiency caused by dust buildup, it is critical to analyze the optical properties of dust accumulated on PV surfaces. The presence of dust particles on the surface of PV modules modifies the system's optical characteristics, influencing essential factors, including transmittance, reflection, and absorption. As a result, understanding the optical characteristics of dust on PV surfaces is critical for creating efficient dust mitigation solutions for PV systems. This section aims to review the existing literature on optical dust measurements on PV surfaces and offers an overview of the methodologies and equipment used in this sector.

6.5.1. Spectrophotometer

A spectrophotometer is an instrument for measuring the intensity of light as a function of its wavelength. It may be used to determine a sample's transmittance or the proportion of light that travels through the sample [50]. It has been utilized to determine how much light is transmitted, absorbed, and reflected by accumulated dust particles on PV. The transmittance of the dust samples was measured utilizing a spectrophotometer, including an absorbing medium and an intensity of 4.0 cm^2 [69]. Because values below 300 nm or above 1200 nm are beyond the spectral sensitivity of most PV systems, the dust particle transmittances were evaluated across a range of wavelengths 300–1200 nm [69]. A spectrophotometer is utilized to evaluate the solar cell's spectrum transmittance to determine the dust's influence on different light wavelengths [74]. A spectrometer measures dusty PV transmittance by placing a dust-covered glass sheet in its sample chamber [90]. The spectrometer measures light transmission through the sample at various wavelengths by comparing it to light transmission through a clean glass sample. The dusty PV sample's spectral transmittance curve indicates how much incoming light is transmitted at each wavelength by the spectrometer [91].

6.5.2. Pyranometer

A pyranometer is an instrument used to measure sun irradiation on a flat surface. It is intended to determine the solar irradiance flux (W/m^2) from the hemisphere above at wavelengths ranging from 0.3 to 3 m. The solar irradiance measurement may determine how much light reaches PV cells and how dust deposition affects this. To assess the transmittance of a dusty PV module glass cover by pyranometer, the researchers utilized two test platforms that could accept a range of glass samples at varying inclination degrees. Ref. [70] utilized a pyranometer to measure the quantity of solar radiation that could pass through the clean and dusty glass. Then, they calculated the amount of light transmittance reduction caused by the dusty glass sheet. The advantages of these techniques include their accuracy and ability to provide a comprehensive understanding of the impact of dust on the transmittance of PV systems.

Overall, the advantages of these techniques include their accuracy and ability to provide a comprehensive understanding of the impact of dust on the optical properties of PV systems. A pyranometer was used to measure the overall glass transmittance; however, a spectrophotometer measured all the optical properties in different wavelengths of the spectrum transmittance.

7. Experimental Procedures

Scholars and engineers evaluate the efficiency and effectiveness of PV systems by analyzing their performance. Indoor and outdoor tests are utilized to evaluate the performance of a PV system [92]. Typically, the same equipment is utilized in indoor and outdoor studies to evaluate the PV performance, output power, electrical characteristics, and thermal behavior. However, a solar simulator is a device that creates a regulated light source to simulate the sun and is used in indoor research only [80]. This regulated environment is to assure precise and repeatable measurements. Indoor trials are appropriate for assessing a PV system's early performance and undertaking research and development [93].

In contrast, outdoor studies are performed in actual circumstances and more accurately evaluate a PV system's performance [94,95]. Field studies involve installing PV systems in various locations, such as deserts and rural or urban areas, and collecting data on dust accumulation rates and PV performance under different climate conditions and locations. Field studies provide researchers with an understanding of how PV systems perform under real-world conditions, including the impact of dust on PV effectiveness [96]. The primary benefit of outdoor trials is that they give a realistic measurement of the performance of a PV system, considering atmospheric factors including humidity, temperature, and meteorological conditions [97]. The primary drawback of outdoor studies is that they are susceptible to external influences, such as weather, which might affect the precision of data. In this section, the primary experimental instruments and research approaches applied in indoor and outdoor studies are discussed.

7.1. Dust Monitoring Systems

Dust monitoring systems are used to track the rate at which dust accumulates on PV panels through time. Dust sensors, dust samplers, and dust visualization methods may be used in these systems [47]. Field studies have been undertaken in a variety of locales across the world, including deserts, rural and urban regions, and climates. Ref. [86] employed light sensors and long-term soiling rates to detect dust for cleaning purposes. Another finding from this study was that dust accumulation was discovered by measuring the voltage and current of the PV system's output; when the system's output fell below 50% of its rated power throughout the day, dust accumulation occurred [86]. Imaging process technologies and optical imaging for PV panel dust detection were also tested [24]. Cameras, sensors, and other detecting elements can be costly, require cleaning and calibration, and may require power on top of PV panels to monitor dust [98]. A literature-based comparative analysis on PV cleaning units found that cameras and sensors are dependable and straightforward, although they need controller circuits.

However, it is essential to note that dust monitoring equipment can be affected by humidity, temperature, and wind speed, all of which can influence the rate of dust formation. To guarantee accurate and reliable results, it is essential to carefully evaluate the location and climatic conditions while selecting and employing dust monitoring equipment.

7.2. Temperature Measurements

PV temperature monitoring is critical in studying PV systems because it allows researchers to understand the system's thermal behavior and how external elements such as dust and weather impact it. These measurements aid in identifying any potential heat stress on the PV cells and its influence on overall system performance.

7.2.1. Thermal Cameras

Thermal cameras detect the surface temperature of PV panels using infrared technology [99]. They are frequently utilized because of their capacity to observe the temperature distribution throughout the surface of PV modules and detect places that may be under thermal stress [100]. Thermal imaging cameras pick up the infrared radiation given off by any object above 273 °C and then create thermal images (thermograms) with darker colors for colder parts and brighter colors for hotter areas [101]. This study examines the use of a thermal imaging camera for the detection of faults in PV modules, including the impacts of tree shade, dust, and dirt deposition, and visual examination under normal atmospheric circumstances [102].

7.2.2. Thermocouples

Thermocouples are tiny sensors that are affixed to the PV panel's front or rear surface. They are intended to offer a continuous record of temperature changes over time by measuring the temperature of the PV cells in real time. Researchers employ various approaches and placements when placing thermocouples to measure the temperature of PV modules. For instance, Ref. [16] used a nonuniform method to measure PV module temperatures where thermocouples were placed on the modules. Some modules have a single thermocouple in the center, while another set of modules has three distributed evenly along the diagonal rear surface. Ref. [103] used four K-type thermocouples mounted on two modules to measure the actual module temperature, with two thermocouples positioned on the front face and two on the back face.

While thermal cameras and thermocouples both give temperature readings for PV systems, thermal cameras can detect temperature differences throughout the whole surface of the PV panel. In contrast, thermocouples only provide measurements from the specific spots where they are mounted. Thermocouples, conversely, are less expensive and easier to install than thermal cameras, making them a viable option for some PV monitoring applications.

7.3. Electrical Measurement

Researchers use various monitoring systems and analytical tools to investigate PV system performance, electrical characteristics, and power production. These tools and methods aid in assessing PV systems' effectiveness, stability, and dependability, and offer valuable data for enhancing their operation and design. These tools are used to measure different electrical quantities, including voltage, current, power, and energy, and track the PV system's performance over time. For example, Ref. [104] utilized a voltage divider and an ACS712 current sensor to monitor the voltage and current of a PV panel. Using a Proskit MT-1210 multimeter, several electrical characteristics of the PV module production were monitored [105]. Usually, these data are recorded and monitored by the following methods: (i) power meters—the DC electrical output of the PV system, comprising the voltage and current generated by the PV modules, is measured using power meters. They give real-time information on the PV system's performance, enabling quick analysis and troubleshooting; (ii) data loggers—they record and gather information from various sensors, including power meters, temperature, and weather sensors. The performance of the PV system over time and any trends or patterns may be determined by analyzing these data.

The importance of electrical testing in determining the efficiency and durability of PV systems is undeniable. Therefore, it is crucial to employ practical monitoring tools and analytical methods. Using power meters, researchers can monitor the voltage and current produced by the PV modules and other data in real-time. To analyze the operation of the PV system over time and spot any trends or patterns, data loggers can record and collect data from numerous sensors.

7.4. Meteorological Stations

PV module design, monitoring, and operation depend on accurate weather data measurement. Weather factors, including temperature, humidity, wind speed, and solar irradiation, greatly influence how well PV modules work. Thus, the researcher of PV systems needs to understand the key variables that determine the performance of PV systems and how to measure them. Normally, scholars may utilize meteorological stations to gather the required weather data. For instance, the meteorological stations employed in Ref. [106] measured and tracked meteorological variables such as sun irradiation, temperatures, and wind velocity, while Ref. [106] employed a PC-based system under the direction of the Weather-Link application to capture meteorological data on a regular basis (every minute) for measuring air temperature, incident solar radiation, and wind speed. Following are some typical examples of the equipment and sensors used to collect meteorological information.

Accurate weather data collection is crucial for successfully designing and operating photovoltaic (PV) systems; consequently, researchers frequently rely on meteorological stations to acquire essential data. These stations, similar to those utilized in Ref. [106], utilize sensors and equipment to monitor factors such as solar irradiance, temperature, and wind speed to assist researchers in comprehending their influence on the performance of PV modules.

7.4.1. Irradiance Measurements: Pyranometers and Photometers

The quantity of solar energy incident on a surface per unit area and unit time is determined when solar irradiance is measured. Solar irradiance is measured using a variety of instruments.

Pyranometers are sensors that detect the amount of incoming solar irradiation in all directions [107]. The pyranometers are used to measure the solar irradiance at the point of acquisition and the horizontal position [108].

A photometer is a device that measures the intensity of light in a particular wavelength band [32]. It is usually used in concert with other equipment to determine the sun irradiation at a certain place. Ref. [109] investigated experimentally at North China Electric Power University's Baoding Campus under clear skies, using a photometer of the TES-1333R type to measure solar irradiance in the primary direction of sunlight to validate the accuracy of a simplified solar irradiance mathematical model calculation. These devices are used in various applications, such as meteorological stations, photovoltaic systems, and other solar energy projects.

Photometers can measure solar irradiance in various wavelength ranges, including UV, visible, and infrared. Photometers can help us understand how various dust particles affect PV panel efficiency by monitoring the spectral distribution of solar energy.

7.4.2. Measuring Ambient Temperature

Ambient temperature is one of the most critical meteorological elements influencing the performance of PV systems. High temperatures can affect the efficiency of PV cells, resulting in lower power production. Monitoring ambient temperature is critical for understanding PV module performance.

There are various techniques for determining the temperature of the surrounding environment. The most typical technique is to use a thermometer or thermocouples sensor to detect the temperature of the air surrounding the PV system. For example, a thermocouple was connected to a multimeter to obtain an accurate reading of the ambient temperature, as used in Ref. [110]. Ref. [111] utilized a K-type thermocouple attached directly to a data logger to collect the ambient temperatures. Using a temperature input module (9211; National Instrument) to measure temperatures based on thermocouple data, it was determined that K-type thermocouples (TP-01) had the maximum accuracy (2.5% R^2) [112].

7.4.3. Measuring Ambient Humidity

The amount of moisture in the air can have an impact on the operation of PV systems. To provide this information, humidity is measured using a hygrometer. The author used a humidity sensing cell, and the effect of humidity PV was examined using a humidity sensing cell [13]. Furthermore, the PV modules utilized an anemometer, temperature-collecting device, and hygrometer, which were was required to correctly detect the ambient wind speed, temperature, and humidity throughout the experiment [65].

7.4.4. Wind Speed

Wind speed measurement is critical during PV experimental tests since it can affect system efficiency and PV module cooling [113]. Wind speed influences PV system performance, and researchers must precisely monitor it to understand its impact [83]. An anemometer is typically used to monitor wind speed in PV experiments [114]. Wind tunnels, which simulate the effects of wind on photovoltaic modules, are another alternative for researching the influence of wind-blown on PV performance [115]. This wind speed measurement aids researchers in evaluating the impact of wind on PV performance and comprehending the real-world ramifications.

7.5. Accelerated Aging Tests

Accelerated aging tests are laboratory experiments designed to mimic the short-term effects of external stress on PV systems. These studies aid in understanding PV system durability and deterioration in controlled environments. Testing for accelerated aging is frequently performed using different methods, such as thermal cycling and ultraviolet (UV) exposure. The daily temperature variations PV systems encounter in the actual world are modeled by thermal cycling. At the same time, UV exposure experiments expose PV systems to intense amounts of ultraviolet radiation to study how light affects the materials in the system. For instance, in Ref. [116], during a Shanghai, China, study, 22-cell minimodules and 1-cell minimodules were subjected to outdoor aging tests using natural sunlight and environmental stress. In contrast, indoor aging was carried out in a Q-lab or Atlas Weather-Ometer® chamber with a controlled temperature of 70 °C and UV radiation at 0.55 W/m^2 @ 340 nm. An Angelatoni GTS600 test chamber was used for an accelerated aging test on modules that involved 106 heat cycles between −15 and +70 °C with a temperature change rate of 0.8 °C/min and a total length of 4.5 h per cycle [2]. Accelerated aging tests may also be used to assess how dust and other environmental conditions affect the performance and robustness of PV systems. The design and materials used in PV systems may be improved using the findings of these tests to increase their effectiveness, dependability, and longevity.

7.6. Solar Simulator

A solar simulator is a device that creates a regulated light source to simulate the sun and is used in indoor research [81]. This is a regulated environment for precise and repeatable measurements. Indoor trials are appropriate for assessing a PV system's early performance and undertaking research and development [117]. It is an essential tool for measuring the impact of environmental conditions such dust, temperature, and humidity on PV performance and gauging the efficiency of PV cells and modules. Numerous sun simulators are used in indoor experiments, such as the following examples.

- Filter-based solar simulators employ a lamp (such as xenon or halogen lamp) with a filter in front of the bulb to generate comparable light [76]. A filter is selected with a spectral distribution near that of natural sunlight, as is practical. For example, a xenon lamp has been used as a solar simulator to mimic outdoor conditions [71]. To mimic solar radiation levels, Ref. [111] used a solar simulator consisting of 90 LED lights (12 V, 50 W) connected in series and controlled by three AC–AC converters, which allowed for varying irradiation levels up to a maximum of 1000 W/m^2.
- According to international standard IEC 60904-9, a Class-AAA solar simulator is one that mimics the spectral distribution of sunshine to within 2% [68]. A solar simulator was utilized by Ref. [74] to mimic natural sunshine, and a pyranometer was employed for precise irradiance regulation. Solar simulators are normally used in combination with measuring instruments to track the power generated by solar cells to examine the efficiency and performance of solar cells under different weather situations. For

example, Ref. [69] used a solar simulator to provide illumination to the solar cell and a sensor to measure the electrical output of the solar cell. Additionally, in Ref. [50], the I–V curve of the photovoltaic panels was measured with the help of a sun simulator (SPIRE 5600SLP) where at standard test conditions (STC), the sun simulator can sweep an I–V curve in less than one second.

7.7. Monitoring System

The effectiveness of PV systems may be assessed with the use of monitoring systems. These systems measure various quantities, including environmental variables such as temperature, irradiance, and wind speed, along with current, voltage, power, and energy generation. The gathered information is utilized to assess the effectiveness and performance of the PV system and to spot any potential problems. For example, Ref. [118] used a monitoring system to monitor the PV system, which collected weather data and output PV performance using various sensors to track a lengthy study (almost 26 months) on Qatar's PV performance in harsh weather circumstances. The performance of the entire PV system was monitored by central monitoring systems, which offer a thorough picture of the system's performance.

This part of study gave an overview of the different varieties of experiments and tools that researchers use to study how dust affects PV technology. The information given can help researchers in the future choose the proper techniques and methods to determine how dust affects the performance and efficiency of PV systems. By knowing the diverse ways to perform experiments, researchers can choose the best method for their studies and obtain accurate and reliable results. However, much experimental research has yet to be performed on the thermal properties of dust, such as its thermal conductivity and emissivity. This is because they are of utmost significance for comprehending the effect that dust has on thermal behavior.

8. Modeling Dust Impacts

In recent years, PV systems have gained appeal as a renewable energy source. However, dust collection on PV panels can significantly impact their performance and energy production. Dust can reduce the quantity of light that reaches the panel, resulting in a drop in the panel's conversion efficiency. Dust can also reduce the temperature coefficient, affecting the PV panel's temperature-dependent performance. To successfully examine the influence of dust on PV performance, current models that have been established to represent the various impacts of dust must be reviewed. This section aims to examine existing models of dust's optical, thermal, and electrical effects on PV performance. This study thoroughly examines models' strengths and weaknesses, and their accuracy and dependability. The evaluation also identifies information gaps regarding the influence of dust on PV performance. This part gives useful insights into the areas where more research is needed to increase our understanding of the influence of dust on PV performance by recognizing the limits of existing models. Furthermore, the evaluation serves as a baseline for future research, enabling the construction of more accurate and dependable models. Overall, the following part of the study helps us understand the influence of dust on PV performance by assessing existing models and recommending topics for further research.

8.1. Electrical Modeling

Dust is considered a crucial factor that directly affects the deterioration of PV performance [40]. The PV module's efficiency can drop dramatically due to the dust accumulation rate, reducing the effectiveness of a PV module by changing the module's electrical properties [80]. The effect of accumulated dust on PV module efficiency has been extensively studied in numerous peer-reviewed papers, and numerous experiments have been conducted to demonstrate these effects [17]. One of the major causes of dust accumulation on the PV module is the decrease in the quantity of incident sunlight used to produce power [80]. This rate varies according to the event, such as a natural day or a sandstorm.

Owing to increased deposited dust density, the absence of cleaning conditions could significantly reduce PV generation by extending the exposure period [119]. For example, in Surabaya, Indonesia, exposure to PV modules for two weeks reduced PV productivity by 10.80% [120], while Ref. [121] reported that one month of exposure to PV modules in Baghdad, Iraq, reduced PV productivity by 31.4%. Ref. [44] demonstrated experimentally that an accumulation of 8 g/m^2 of dust in Tipaza, Algeria, resulted in a 50% reduction in PV module efficiency. Ref. [122] investigated the impact of a dust storm on PV performance; the study indicated that a single sandstorm day reduced the PV power output by more than 32%.

Finally, dust deposition on PV modules can significantly impact their output power, which must be understood and modeled for accurate projections and maintenance planning. Understanding and forecasting the influence of dust on PV performance requires modeling the dust impact on the electrical component of PV. There are numerous techniques for estimating the influence of dust on the electrical component of PV, including employing mathematical models, computer simulations, and experimental methods [123]. The accuracy and precision of these models are determined by the quality and quantity of data provided and the model's complexity.

The influence of dust deposition density on the performance of PV modules (PV) is quantitatively examined in this study, as presented in Equation (1) [124]. Furthermore, the influence of different system factors on the performance of both clean and dusty PV modules was investigated. Solar radiation intensity and ambient temperature were among the characteristics investigated. Results showing a drop in electrical efficiency had a root mean square error (RMSD) of 1.74 and a mean absolute error (MAE) of 1.30.

$$P_{PV} = \times [1 - 0.0045 \times (T_{PV} - 298.15)] \times \frac{\tau}{\tau_{clean}} \times G \times A_c \times \tau_g \times \alpha_{clean} \quad (1)$$

Total solar radiation intensity is G, A_c is the panel surface area, τ_g is the glass cover transmissivity, and PV cell absorptivity is α.

In Ref. [125], the authors use numerical methods to examine the effects of dust deposition patterns on a standalone ground-mounted solar PV installation, as presented in Equation (2). In addition, dust deposition rates on PV panels were predicted using a discrete particle model.

$$P_{PV} = k\frac{\lambda N_p \pi \rho_p d_p^3}{6 t_d S_d} T \times 100\% \quad (2)$$

where Np is the total number of dust particles released during t_d, λ is the rate at which dust is deposited, and k is the factor by which dust density affects PV efficiency. The density of dust is ρ_p, and d_p represents dust diameter. PV panel area is denoted by S_d. The time of exposure is denoted by the symbol T (day).

Ref. [126] investigated on the effect of dust buildup on the power output of a 500 kWp PV system installed at the University of Bahrain, and is described in this publication. An empirical equation (Equation (3)) was created to calculate the reduction in light transmissivity and PV power production caused by dust buildup on the PV panels.

$$Plos = 100 - 99.66e^{-0.038d} \quad (3)$$

where $Plos$ is the output power loss percentage and d is the dust density.

In Ref. [118], a wireless system was designed to collect data to capture crucial sun irradiance, relative humidity, ambient temperature, PV module temperature, dust, wind speed, and output PV power, which are only a few examples of the parameters. The findings show that over an eight-month period, panel dusting lowered PV output power by 50%. A mathematical model that predicts the output power of PV panels under various environmental conditions was created using machine learning, as presented in Equations (4) and (5).

If irradiance ≤ 534.5, then

$$Pmax = -0.0116\Delta\rho + 0.3142T_{atm} - 0.0845H + 0.0776G - 6.9486\rho + 0.2746\nu + 14.819 \quad (4)$$

otherwise, if irradiance > 534.5, then

$$Pmax = -0.0132\Delta\rho - 0.2155T_{atm} - 0.0999H - 0.0879T_{PV} + 0.0953G - 0.4429\rho + 1.1184\nu + 21.325 \quad (5)$$

where $Pmax$ is the PV output measured in watts; T_{atm} is the ambient and T_{PV} surface temperatures in degrees Celsius; H is the relative humidity in percent; G is the solar irradiance in watts per square meter; $\Delta\rho$ and ρ are dust and cumulative dust in milligrams per cubic meter; and ν is the wind speed in kilometers per hour.

A geographical investigation of the effects of dust collection and ambient temperature on PV performance was provided in Ref. [127]. Two models, multiple linear regression and artificial neural network, were developed to estimate PV system conversion efficiency based on experimental data on exposure duration to natural dust and ambient temperature. Close to 90% R^2 values suggest that both models accurately anticipate the efficiency of the conversion. The two models are used to determine the best cleaning frequency of the systems by estimating the losses (in terms of losses in system efficiency and the monetary worth of these losses), as expressed in Equation (6).

$$\hat{\eta_n} = 16.0513 - 0.024133\ Dn - 0.078743\ Tn \quad (6)$$

where $\hat{\eta_n}$ is the efficiency of day number n, Dn is the exposure day, and Tn is the daily average ambient temperature in the day.

Ref. [48] considered that the particle size composition of accumulated dust on PV modules influences as a function that impacts their power output significantly. A regression model was created to comprehend and quantify the soiling effect on the power output of a dirty PV panel. This study collected and evaluated soil samples from the Shekhawati area of India for particle size composition. The findings demonstrated that the regression model might be utilized to investigate and quantify the particle size effect on PV module soiling losses. In addition, an effective neural network model for predicting the power output of a filthy panel was established, as presented in Equation (7). The regression model's computed values agreed with the experimental data, with an R^2 value of 0.9785.

$$P = 0.44S_4 + 0.274S_5 + 0.524S_6 - 4.45S_7 + 0.061G - 18.9 \quad (7)$$

The model considered different particle size compositions of the soil (S_1–S_7) and the horizontal incidence irradiance (G) as independent variables, where the particle size of the dust was represented by S_4 = 1.76, S_5 = 83.8, S_6 = 11.44, and S_7 = 0.72 µm.

Ref. [128] studied the efficiency of PV panels using as a factor the comparison before and after sand dust deposition. A linear relationship was used to anticipate the efficiency loss based on the amount of dust gathered. Short circuit current and maximum output power both experience substantial decreases when dust particles collect on the panel's surface, up to a concentration of 1 g/m^2; however, the rate at which these values drop increases with increasing dust concentrations, as presented in Equation (8).

$$\Delta = 0.33\Delta M \quad (8)$$

where M is the increase in the number of sand dust particles (g/m^2).

Ref. [129] utilized experimental data to develop an equation that was created to calculate the output power losses of a solar panel based on the dust collection density, as presented in Equation (9). The researchers assessed the PV output power and dust deposition density under the same measurement circumstances (860 W/m^2, 40 °C).

The experimental data were fitted with an exponential and a polynomial model to provide a plot of the dust accumulation density versus output power losses. As the exponential model was proven to have a greater coefficient of determination (0.998) than the polynomial model, it was chosen as the empirical equation to compute the dust accumulation density (0.984), as stated in Equation (9).

$$D = 0.47e^{\frac{Pr}{34.93}} - 0.37 \tag{9}$$

where D is the dust deposition density (mg/cm^2) and Pr is the output power losses (%).

A theoretical model is used in Ref. [130] to forecast how dust accumulation affects PV's ability to produce energy. The current work examines experimental data on the effects of three common air pollutants—red soil, gypsum, and carbon-containing fly-ash particulate—on the energy efficiency of PV systems. The results show that the energy performance of PVs is significantly reduced, and this reduction is substantially influenced by the source and nature of the particles. A mathematical model was developed for use as an assessment technique for drawing trustworthy findings about the potential impacts of regional air pollution on the performance of PVs, as presented in Equation (10).

$$\Delta_j = \left(1 - e^{-Aj.\Delta Mj}\right) \tag{10}$$

where Δ_j is the standard deviation value corresponding to each of the three contaminants investigated. ΔM is the dust accumulation in g/m^2.

Ref. [131] described the soiling loss (LS) as an easy exponential function. The term "soiling loss" refers to the reduction in the PV system's output power brought on by dust buildup on the PV modules' surface, as presented in Equation (11).

$$Ls = KsMd \times e^{-kt} \tag{11}$$

where L_S is the soiling loss, Md is the collected dust mass, k is the cleaning rate constant, Ks is the soiling loss coefficient, and the rate at which the dust mass is cleaned from the PV module surface is the cleaning rate constant (k).

Ref. [132] used a computational fluid dynamics (CFD) simulation to model the impact of dust pollution on PV system performance where the simulated wind flow fields and dust deposition. They examined the effects of dust particle size, quantity, and gravity on PV panel dust deposition. The authors developed a simple correlation model to estimate PV efficiency decline ratios in proportion to exposure time using CFD simulation results and literature data, as expressed in Equation (12).

$$\frac{Er}{Ec} = K\frac{ƛ N_p \pi \rho_p d_p^3}{6t_d A_{PV}} T100\% \tag{12}$$

where reduced energy (Er) and clean energy (Ec) characterize PV. The number of particles that fell in each time interval is denoted by (Np/t_d). The obtained measurements are utilized to establish a fitting factor, K. A_{PV} may be used to estimate the size of the PV array. A density of p is assigned to the dust. Time, denoted by T, is measured in days.

In summary, the results of this research provide vital insights into the impact that dust collection has on the performance of PV systems and can help facilitate the development of reliable mechanisms for anticipating power loss. However, it is essential to remember that these models depend on particular dust compositions, which can shift both in terms of location and over time. Therefore, future studies should focus on investigating a wider variety of dust types and quantities to build a more comprehensive set of metrics that can forecast power loss across a variety of dust profiles.

8.2. Optical Modeling

In recent years, there has been substantial growth in the use of PV technology [133]. Yet, environmental conditions, such as accumulating dust on PV surfaces, can have a negative impact on the effectiveness and performance of PV systems. The quantity of sunlight that reaches the PV cells can be greatly reduced by the buildup of dust on the surface of PV modules, which lowers the system's electrical output [134]. To properly forecast the performance of PV systems affected by dust, it is essential to comprehend and simulate the optical characteristics of those systems.

The effect of dust deposition on the optical characteristics of PV systems has been the subject of several investigations [10,34]. Several investigations have demonstrated that dust buildup considerably decreases PV module transmittance and can significantly decrease the electrical output of PV. For example, Ref. [135] examined total transmission for various weights per unit area and discovered that the entire transmission reduces linearly with dust mass per unit area. Ref. [36] discovered that adding one gram of dust per square meter reduced light transmittance by 4.1%. Furthermore, the experimental results demonstrated that atmospheric dust accumulation reduces the relative transmittance of a PV module by 20% in just eight days.

Simulating the scattering, absorption, and reflection of light by dust particles is a crucial component of optical modeling of dust impact on PV. The drop in incoming sunlight that reaches the PV cells may be predicted using this kind of model crucial which can then be used to estimate the decrease in electrical production. This kind of simulation helps to explain how various dust particle kinds and dust buildup rates impact the performance of PV systems. The effect of dust on the optical of PV systems has been estimated using mathematical models, computer simulations, and experimental techniques [125]. Modeling their optical characteristics is crucial to anticipate dust-impacted PV systems' performance precisely. It is critical to comprehend how various dust particle types and accumulation rates impact the efficiency of PV systems.

Ref. [136] conducted studies in the Minia area of Egypt over the course of one year to determine the effect of the accumulating dust collection on PV modules with varying degrees of tilt. The study reveals that dust deposition, tilt angle, exposure time, and site environment all substantially impacted the reduction in glass transmittance. Based on the data acquired, an empirical correlation was created that may be used to determine the decrease in glass transmittance for a certain tilt angle after a specific number of days of atmospheric exposure. This correlation was created according to the experimental data that were obtained and can be expressed as Equation (13).

$$\tau = \tau_c \left[1 - 0.3437\mathrm{erf}\left(0.17\omega^{0.8473}\right)\right] \tag{13}$$

where w *is* the dust weight on PV (g/m^2), and τ_c, and τ are the clean surface transmittance and the dusty transmittance, respectively. This requires knowing the inverse of the Gauss error function erf (x).

In reference [88], a study was carried out on the effects of natural soil dust on a PV cell's transparency in dry regions, focusing on the chemical and mineralogical composition of the dust coating on the PV's transparent cover and its impact on cell performance. The study discovered that the decrease in glass transmittance caused by dust accumulation depends on variables such as the dust accumulation density, inclination angle, and position of the module concerning the dominant wind direction. The study also established a significant relationship between dust accumulation density and transmittance decrease, which can help predict the influence of dust accumulation in other places, as presented in Equation (14).

$$\Delta\tau(\%) = 0.0381\rho^4 + 0.8626\rho^3 - 6.4143\rho^2 - 15.051\rho + 16.769 \tag{14}$$

where ρ is the dust deposition density in (g/m^2) and $\Delta\tau$ (%) is the reduction in the glass transmittance.

Ref. [137] established a general model that may be applied in various geographical settings and climates to predict transmittance. In addition to analyzing the dust surface density and transmission coefficient loss over time and the variables affecting them, the study confirmed that solar panel and collector efficiency might be drastically lowered due to dust collection on their surfaces (see Equation (15)).

$$\Delta\tau(\%) = -0.001335\rho^6 + 0.04398\rho^5 - 0.5427\rho^4 + 3.05\rho^3 - 7.703\rho^2 + 11.19\rho - 2.25 \quad (15)$$

In Ref. [137], the following formula structure is used to estimate the influence of dust collection on radiation intensity (Equation (16)).

$$G = Ga \times (1 - \Delta\tau/100) \quad (16)$$

where G is the adjusted irradiance that penetrates the transparent cover and enters into the cell, and Ga denotes the amount of solar light that hits the panel's surface.

In Ref. [138] a mathematical equation is developed that describes the link between transmittance, total dust mass, average transmittance of a single layer of dust, dust particle density, dust particle radius, and solar panel area. The paper describes a detailed model of PV modules to quantify the daily loss in energy output caused by dust gathering, as presented in Equation (17).

$$\frac{\tau_2(\theta)}{\tau_1(\theta)} = e^{\left(-\frac{3\gamma}{4\rho A cos\theta}\sum_{i=1}^{n}\frac{mi}{Ri}\right)} \quad (17)$$

where mi is the total dust mass, ρ is dust particle density, Ri is dust particle radius, γ is the average transmittance of a single layer of dust, and A is the PV area.

Ref. [70] aimed to examine dust's effect on the PV panel surface's transmittance. The study discovered that dust deposition on the PV panel surface lowered its transmittance, and the amount of settled dust affected the reduction. The study assessed the loss in transmittance caused by different dust deposition densities of Bangkok clay and found a link between dust deposition density and transmittance, as presented in Equation (18). The study's findings can be utilized to forecast radiation transmittance in solar air heaters used to dry agricultural products.

$$\Delta\tau = 23.27\ln(\rho) - 23.5 \quad (18)$$

where ρ is the dust deposition density in (g/m^2) and $\Delta\tau$ (%) is the reduction in the glass transmittance.

Ref. [40] developed a mathematical model to estimate the transmittance of PV modules based on the mass density of dust deposited on the modules. The concept is founded on the Beer–Lambert equation, which asserts that a material's transmittance decreases exponentially with its thickness and absorption coefficient. The study assumed that the dust layer on the solar module is homogenous and constructed a mathematical model that connects the transmittance of the module to the dust mass density. The relationship is stated in Equation (19) as follows:

$$T = \left(1 - F^2\right)e^{-\frac{am}{p}} \quad (19)$$

where T represents the transmittance of the module, F represents the fraction of reflection light transmitted through the dust layer, a represents the absorption coefficient of the dust layer, m represents the mass density of dust deposited on the module, and p represents the thickness of the dust layer.

Overall, these investigations provide important insights into the effects of dust collection on PV system performance and may aid in the development of effective methods for predicting transmittance reduction. Nevertheless, these models are dependent on a specific type of dust, which can vary based on place or time. Future research should examine a variety of dust types and amounts to develop different parameters that can forecast any transmittance reduction for a diversity of dust types.

8.3. Thermal Modeling

Thermal simulation software and thermal modeling methods are often used to correctly anticipate the influence of different weather environment aspects on the temperature of PV panels [139,140]. Researchers may utilize these approaches to model heat transport via PV modules and anticipate temperature changes. Moreover, experimental approaches may be utilized to detect temperature changes in PV cells under varying weather circumstances, giving data that can be used to validate the model [141].

The accumulation of dust on the surface of PV modules can considerably influence their temperature and overall efficiency. This dust layer generates a highly exothermic effect within the PV module, reducing its electrical performance and perhaps causing its destruction [142]. The dust collection on PV serves as a heat trap on the PV surfaces, causing the temperature to rise. The collection of dust may create a "hot spot," which is a small area with a high-temperature concentration. Because of these hot spots on the PV module, the temperature of the module increases. Several experimental studies have experimentally investigated the relationship between dust accumulation and PV temperature. For example, a thermal camera was used by [44] to assess the thermal behavior of a dusty PV module. Dirty cells were observed to cause temperature differentials, with dusty cells increasing temperatures by up to 10 °C. Additionally, Ref. [50] examined the effect of coating material on the surface of PV modules to mitigate dust deposition on PV modules in Egypt and discovered that the untreated PV module temperature increased to 90 °C. Moreover, the coated PV module had a 10% lower cell temperature. Even worse, [143] discovered that dust accumulation on a PV module's surface could raise the dusty cell's temperature by more than 23 °C above the temperature of the other cells in the same PV module. The PV temperature may exceed this temperature limit when utilized in dusty, hot environment conditions [144], where, on the datasheets of many PV manufacturers, it is stated that the working temperature limit is less than 85 °C. Ref. [51] analyzed the effect of dust accumulation on PV modules and compared their performance to clean PV modules in Iraq. They reported that a high cell temperature for the dusty module reached 95 °C for a hot summer day with a 45 °C ambient temperature, while the clean module performed better. When the PV temperature exceeds this limit, it may cause irreversible damage. For instance, Ref. [145] stated real operating situations in the Algerian desert, the observable failures of 608 PV modules, where the front glass of the PV module was discovered to be cracked due to the high PV temperature, which is a result of the accumulated dust and high ambient temperature. There may be a variety of causes for this rise in PV temperature, all of which require further research. Several varieties of dust have been studied to determine their impact on PV temperature [44]. This study discovered that the PV temperature rose due to the accumulation of various dust types. They also found that particles with high thermal conductivity, like salt, had a role in transferring heat away from the glass. The surface temperatures of particles, such as soil and glass, with little heat conductivity, on the other hand, were more remarkable. Compared to salt dust, which kept the PV cell temperature at 50 °C, soil dust increased the temperature of the PV module to over 85 °C.

Despite the fact that numerous experimental investigations have examined the connection between dust collection and PV temperature, a correlation that can precisely predict the temperature of the PV panel has yet to be developed. These studies must offer detailed information on the factors influencing this relationship or the causes of it. The limited knowledge in this area needs more investigations of the association between dust accumulation and PV module temperature. Knowing how dust affects PV panel temperature is critical for adequately projecting energy output and assuring the lifespan of solar energy systems.

9. Conclusions

This paper provided a thorough investigation into the impact of dust on PV technology from three distinct perspectives. The first aspect of the study was to investigate the dust properties in three categories: optical, chemical, and physical. The analysis emphasized the important impact of dust, studying the characteristics of dust on PV performance. The presence of dust can impact the optical properties of a PV system, such as transmittance, reflection, and absorption. The study reported the difference in chemical properties and composition, and how this different composition could impact PV performance. Moreover, the study reported a significant lack of knowledge in the investigation of the dust's thermal characteristics and their impact on PV temperature. Further research is needed to thoroughly investigate this vital area.

The second aspect of this study focused on reviewing the numerous approaches and equipment utilized to evaluate dust's impact on PV. This paper discussed distinct strategies for collecting and spreading dust, and various methodologies for measuring the properties of dust and the effect of dust on the performance of PV systems. This paper demonstrated how critical it is to create reliable instruments that can measure dust's impact on the performance and temperature of PV systems. This will provide an opportunity for scholars to investigate dust's impact on PV systems using consistent strategies and methodologies, improving research outcomes.

The final aspect of the study was to examine modeling and prediction of dust's influence on PV systems. Different approaches to predicting PV output power and optical reduction due to the accumulating dust on PV surfaces were analyzed. These models have considered different dust parameters to predict the electrical or optical of PV modules. However, previous research has placed less attention on anticipating dust's influence on the thermal behavior of PV, despite the evidence that the accumulation of dust can dramatically raise the temperature of PV, which in turn reduces the efficiency of PV systems and shortens their lifespan. The importance of developing models that can precisely predict the impact that dust has on the thermal behavior of PV systems was emphasized throughout in this paper.

In conclusion, this paper emphasizes the significance of knowing the impact of dust on PV performance. The analysis indicated that dust qualities significantly impact PV performance and that more research is needed to examine the thermal properties of dust properly. The evaluation also emphasized the significance of creating practical tools and models for measuring and forecasting the impact of dust on PV performance. Addressing knowledge gaps through additional study will be crucial for developing more efficient and effective methods of reducing the influence of dust on PV systems and improving their efficiency and lifespan.

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References

1. Almukhtar, H.M.; Al-Tameemi, Z.H.; Al-Anbary, K.M.; Abbas, M.K.; Hsu, H.Y.; Al-Mamoori, D.H. Feasibility study of achieving reliable electricity supply using hybrid power system for rural primary schools in Iraq: A case study with Umm Qasr primary school. *Int. J. Electr. Comput. Eng.* **2019**, *9*, 2822–2830. [CrossRef]
2. Fahim, S.R.; Hasanien, H.M.; Turky, R.A.; Aleem, S.H.E.A.; Ćalasan, M. A Comprehensive Review of Photovoltaic Modules Models and Algorithms Used in Parameter Extraction. *Energies* **2022**, *15*, 8941. [CrossRef]
3. Kabeel, A.E.; Abdelgaied, M.; Sathyamurthy, R.; Kabeel, A. A comprehensive review of technologies used to improve the performance of PV systems in a view of cooling mediums, reflectors design, spectrum splitting, and economic analysis. *Environ. Sci. Pollut. Res. Int.* **2021**, *28*, 7955–7980. [CrossRef]
4. Awadh, S.M. Impact of North African Sand and Dust Storms on the Middle East Using Iraq as an Example: Causes, Sources, and Mitigation. *Atmosphere* **2023**, *14*, 180. [CrossRef]

5. Al-Dahidi, S.; Al-Nazer, S.; Ayadi, O.; Shawish, S.; Omran, N. Analysis of the effects of cell temperature on the predictability of the solar photovoltaic power production. *Int. J. Energy Econ. Policy* **2020**, *10*, 208–219. [CrossRef]
6. Jha, A.; Tripathy, P.P. Heat transfer modeling and performance evaluation of photovoltaic system in different seasonal and climatic conditions. *Renew. Energy* **2019**, *135*, 856–865. [CrossRef]
7. Goudelis, G.; Lazaridis, P.I.; Dhimish, M. A Review of Models for Photovoltaic Crack and Hotspot Prediction. *Energies* **2022**, *15*, 4303. [CrossRef]
8. Kazem, H.A.; Chaichan, M.T.; Al-Waeli, A.H.A.; Sopian, K. Effect of dust and cleaning methods on mono and polycrystalline solar photovoltaic performance: An indoor experimental study. *Sol. Energy* **2022**, *236*, 626–643. [CrossRef]
9. Quan, Z.; Lu, H.; Zhao, W.; Zheng, C.; Zhu, Z.; Qin, J.; Yue, M. A Review of Dust Deposition Mechanism and Self-Cleaning Methods for Solar Photovoltaic Modules. *Coatings* **2022**, *13*, 49. [CrossRef]
10. Smestad, G.P.; Germer, T.A.; Alrashidi, H.; Fernández, E.F.; Dey, S.; Brahma, H.; Sarmah, N.; Ghosh, A.; Sellami, N.; Hassan, I.A.I.; et al. Modelling photovoltaic soiling losses through optical characterization. *Sci. Rep.* **2020**, *10*, 1–13. [CrossRef]
11. Adıgüzel, E.; Subaşı, N.; Mumcu, T.V.; Ersoy, A. The effect of the marble dust to the efficiency of photovoltaic panels efficiency by SVM. *Energy Rep.* **2023**, *9*, 66–76. [CrossRef]
12. Sahouane, N.; Ziane, A.; Dabou, R.; Neçaibia, A.; Rouabhia, A.; Lachtar, S.; Blal, M.; Slimani, A.; Boudjamaa, T. Technical and economic study of the sand and dust accumulation impact on the energy performance of photovoltaic system in Algerian Sahara. *Renew. Energy* **2023**, *205*, 142–155. [CrossRef]
13. Said, S.A.M.; Walwil, H.M. Fundamental studies on dust fouling effects on PV module performance. *Sol. Energy* **2014**, *107*, 328–337. [CrossRef]
14. Mustafa, R.J.; Gomaa, M.R.; Al-Dhaifallah, M.; Rezk, H. Environmental impacts on the performance of solar photovoltaic systems. *Sustainability* **2020**, *12*, 608. [CrossRef]
15. Maghami, M.R.; Hizam, H.; Gomes, C.; Radzi, M.A.; Rezadad, M.I.; Hajighorbani, S. Power loss due to soiling on solar panel: A review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1307–1316. [CrossRef]
16. Guan, Y.; Zhang, H.; Xiao, B.; Zhou, Z.; Yan, X. In-situ investigation of the effect of dust deposition on the performance of polycrystalline silicon photovoltaic modules. *Renew. Energy* **2017**, *101*, 1273–1284. [CrossRef]
17. Chanchangi, Y.N.; Ghosh, A.; Sundaram, S.; Mallick, T.K. Dust and PV Performance in Nigeria: A review. *Renew. Sustain. Energy Rev.* **2020**, *121*, 109704. [CrossRef]
18. Said, S.A.M.; Hassan, G.; Walwil, H.M.; Al-Aqeeli, N. The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies. *Renew. Sustain. Energy Rev.* **2018**, *82*, 743–760. [CrossRef]
19. Vedulla, G.; Geetha, A.; Senthil, R. Review of Strategies to Mitigate Dust Deposition on Solar Photovoltaic Systems. *Energies* **2023**, *16*, 109. [CrossRef]
20. Figgis, B.; Ennaoui, A.; Ahzi, S.; Rémond, Y. Review of PV soiling particle mechanics in desert environments. *Renew. Sustain. Energy Rev.* **2017**, *76*, 872–881. [CrossRef]
21. Kazem, A.A.; Chaichan, M.T.; Kazem, H.A. Dust effect on photovoltaic utilization in Iraq: Review article. *Renew. Sustain. Energy Rev.* **2014**, *37*, 734–749. [CrossRef]
22. Jamil, W.J.; Rahman, H.A.; Shaari, S.; Salam, Z. Performance degradation of photovoltaic power system: Review on mitigation methods. *Renew. Sustain. Energy Rev.* **2017**, *67*, 876–891. [CrossRef]
23. Dust Deposition Effect on Solar Photovoltaic Modules Performance: A Review. *J. Appl. Emerg. Sci.* **2020**, *10*, 117–125. [CrossRef]
24. Dantas, G.M.; Mendes, O.L.C.; Maia, S.M.; de Alexandria, A.R. Dust detection in solar panel using image processing techniques: A review. *Res. Soc. Dev.* **2020**, *9*, e321985107. [CrossRef]
25. Abuzaid, H.; Awad, M.; Shamayleh, A. Impact of dust accumulation on photovoltaic panels: A review paper. *Int. J. Sustain. Eng.* **2022**, *15*, 266–287. [CrossRef]
26. Chanchangi, Y.N.; Ghosh, A.; Sundaram, S.; Mallick, T.K. An analytical indoor experimental study on the effect of soiling on PV, focusing on dust properties and PV surface material. *Sol. Energy* **2020**, *203*, 46–68. [CrossRef]
27. Shenouda, R.; Abd-Elhady, M.S.; Kandil, H.A. A review of dust accumulation on PV panels in the MENA and the Far East regions. *J. Eng. Appl. Sci.* **2022**, *69*, 1–29. [CrossRef]
28. Wu, Y.; Du, J.; Liu, G.; Ma, D.; Jia, F.; Klemeš, J.J.; Wang, J. A review of self-cleaning technology to reduce dust and ice accumulation in photovoltaic power generation using superhydrophobic coating. *Renew. Energy* **2022**, *185*, 1034–1061. [CrossRef]
29. Hasan, K.; Yousuf, S.B.; Tushar, M.S.H.K.; Das, B.K.; Das, P.; Islam, M.S. Effects of different environmental and operational factors on the PV performance: A comprehensive review. *Energy Sci. Eng.* **2022**, *10*, 656–675. [CrossRef]
30. Sayyah, A.; Horenstein, M.N.; Mazumder, M.K. Energy yield loss caused by dust deposition on photovoltaic panels. *Sol. Energy* **2014**, *107*, 576–604. [CrossRef]
31. Alnasser, T.M.A.; Mahdy, A.M.J.; Abass, K.I.; Chaichan, M.T.; Kazem, H.A. Impact of dust ingredient on photovoltaic performance: An experimental study. *Sol. Energy* **2020**, *195*, 651–659. [CrossRef]
32. Müller, T.; Schladitz, A.; Massling, A.; Kaaden, N.; Kandler, K.; Wiedensohler, A. Spectral absorption coefficients and imaginary parts of refractive indices of Saharan dust during SAMUM-1. *Tellus B Chem. Phys. Meteorol.* **2009**, *61*, 79–95. [CrossRef]
33. Linke, C.; Möhler, O.; Veres, A.; Mohácsi, Á.; Bozóki, Z.; Szabó, G.; Schnaiter, M. Optical properties and mineralogical composition of different Saharan mineral dust samples: A laboratory study. *Atmos. Meas. Tech.* **2006**, *6*, 3315–3323. Available online: www.atmos-chem-phys.net/6/3315/2006/ (accessed on 9 January 2022).

34. Fernández-Solas, Á.; Micheli, L.; Almonacid, F.; Fernández, E.F. Optical degradation impact on the spectral performance of photovoltaic technology. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110782. [CrossRef]
35. Lin, W.; Ma, Z.; Li, K.; Tyagi, V.; Pandey, A.K. A dynamic simulation platform for fault modelling and characterisation of building integrated photovoltaics. *Renew. Energy* **2021**, *179*, 963–981. [CrossRef]
36. Boyle, L.; Flinchpaugh, H.; Hannigan, M.P. Natural soiling of photovoltaic cover plates and the impact on transmission. *Renew. Energy* **2015**, *77*, 166–173. [CrossRef]
37. Wu, Z.; Yan, S.; Ming, T.; Zhao, X.; Zhang, N. Analysis and modeling of dust accumulation-composed spherical and cubic particles on PV module relative transmittance. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101015. [CrossRef]
38. Sarver, T.; Al-Qaraghuli, A.; Kazmerski, L.L. A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches. *Renew. Sustain. Energy Rev.* **2013**, *22*, 698–733. [CrossRef]
39. Hachicha, A.A.; Al-Sawafta, I.; Hamadou, D. Numerical and experimental investigations of dust effect on CSP performance under United Arab Emirates weather conditions. *Renew. Energy* **2019**, *143*, 263–276. [CrossRef]
40. Liu, L.; Qian, H.; Sun, E.; Li, B.; Zhang, Z.; Miao, B.; Li, Z. Power reduction mechanism of dust-deposited photovoltaic modules: An experimental study. *J. Clean. Prod.* **2022**, *378*, 134518. [CrossRef]
41. Algarni, S.; Nutter, D. Influence of dust accumulation on building roof thermal performance and radiant heat gain in hot-dry climates. *Energy Build* **2015**, *104*, 181–190. [CrossRef]
42. Levins, W.P.; Hall, J.A. *Measured Effects of Dust on The Performance of Radiant Barriers Installed on Top of Attic Insulation*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 1990.
43. Al-Ahmed, A.; Al-Sulaiman, F.A.; Khan, F. *The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions*; Springer: Berlin/Heidelberg, Germany, 2022.
44. Abderrezek, M.; Fathi, M. Experimental study of the dust effect on photovoltaic panels' energy yield. *Sol. Energy* **2017**, *142*, 308–320. [CrossRef]
45. Kadhum, A.K.; Rasheed, M.A. Some characteristics of sand and dust storm sources in Iraq. In Proceedings of the 2nd International Conference for Engineering, Technology and Sciences of Al-Kitab, ICETS 2018, Karkuk, Iraq, 4–6 December 2018; pp. 11–15. [CrossRef]
46. Abdolzadeh, M.; Nikkhah, R. Experimental study of dust deposition settled over tilted PV modules fixed in different directions in the southeast of Iran. *Environ. Sci. Pollut. Res.* **2019**, *26*, 31478–31490. [CrossRef]
47. Saidan, M.; Albaali, A.G.; Alasis, E.; Kaldellis, J.K. Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment. *Renew. Energy* **2016**, *92*, 499–505. [CrossRef]
48. Pulipaka, S.; Mani, F.; Kumar, R. Modeling of soiled PV module with neural networks and regression using particle size composition. *Sol. Energy* **2016**, *123*, 116–126. [CrossRef]
49. Tanesab, J.; Parlevliet, D.; Whale, J.; Urmee, T. Dust Effect and its Economic Analysis on PV Modules Deployed in a Temperate Climate Zone. *Energy Procedia* **2016**, *100*, 65–68. [CrossRef]
50. Tanesab, J.; Parlevliet, D.; Whale, J.; Urmee, T. The effect of dust with different morphologies on the performance degradation of photovoltaic modules. *Sustain. Energy Technol. Assess.* **2019**, *31*, 347–354. [CrossRef]
51. Salamah, T.; Ramahi, A.; Alamara, K.; Juaidi, A.; Abdallah, R.; Abdelkareem, M.A.; Amer, E.-C.; Olabi, A.G. Effect of dust and methods of cleaning on the performance of solar PV module for different climate regions: Comprehensive review. *Sci. Total Environ.* **2022**, *827*, 154050. [CrossRef]
52. Buni, M.J.B. A Review of Solar Energy Applications in Baghdad-Iraq. 2020. Available online: www.ijtrd.com (accessed on 1 March 2022).
53. Shah, A.H.; Hassan, A.; Laghari, M.S.; Alraeesi, A. The influence of cleaning frequency of photovoltaic modules on power losses in the desert climate. *Sustainability* **2020**, *12*, 9750. [CrossRef]
54. Jiang, C.-S.; Moutinho, H.R.; To, B.; Xiao, C.; Perkins, C.; Muller, M.; Al-Jassim, M.M.; Simpson, L.J. Strong Attraction and Adhesion Forces of Dust Particles by System Voltages of Photovoltaic Modules. *IEEE J. Photovolt.* **2019**, *9*, 1121–1127. [CrossRef]
55. Zarei, T.; Abdolzadeh, M.; Yaghoubi, M. Comparing the impact of climate on dust accumulation and power generation of PV modules: A comprehensive review. *Energy Sustain. Dev.* **2022**, *66*, 238–270. [CrossRef]
56. Tang, M.; Yan, Y.; Zhang, Y.; Wang, W.; An, B. Motion control of photovoltaic module dust cleaning robotic arm based on model predictive control. *J. Ind. Manag. Optim.* **2023**, *11*, 1. [CrossRef]
57. Liu, X.; Yue, S.; Lu, L.; Li, J. Mechanism underlying the effect of physical properties on the dynamic behaviours and erosion characteristics of particles on solar photovoltaic panels. *Chem. Pap.* **2022**, *76*, 4443–4457. [CrossRef]
58. Ilse, K.K.; Figgis, B.W.; Naumann, V.; Hagendorf, C.; Bagdahn, J. Fundamentals of soiling processes on photovoltaic modules. *Renew. Sustain. Energy Rev.* **2018**, *98*, 239–254. [CrossRef]
59. Liu, X.; Yue, S.; Lu, L.; Li, J. Investigation of the Dust Scaling Behaviour on Solar Photovoltaic Panels. *J. Clean. Prod.* **2021**, *295*, 126391. [CrossRef]
60. Chaichan, M.T.; Kazem, H.A.; Al-Waeli, A.H.A.; Sopian, K. The effect of dust components and contaminants on the performance of photovoltaic for the four regions in Iraq: A practical study. *Renew. Energy Environ. Sustain.* **2020**, *5*, 3. [CrossRef]
61. Craciunescu, D.; Fara, L. Investigation of the Partial Shading Effect of Photovoltaic Panels and Optimization of Their Performance Based on High-Efficiency FLC Algorithm. *Energies* **2023**, *16*, 1169. [CrossRef]

62. Chen, Y.; Liu, Y.; Tian, Z.; Dong, Y.; Zhou, Y.; Wang, X.; Wang, D. Experimental study on the effect of dust deposition on photovoltaic panels. *Energy Procedia* **2019**, *158*, 483–489. [CrossRef]
63. Chaouki, F.; Anana, W.; Laarabi, B.; Sebbar, M.A.; El Mahi, M.; Barhdadi, A.; Fathi, M.; Mrabet, A.; Benyoussef, A.; Boardman, J. Physical and chemical analysis of outdoor dust deposited on photovoltaic panels installed in Rabat. In Proceedings of the 2016 International Renewable and Sustainable Energy Conference (IRSEC), Marrakech, Morocco, 14–17 November 2016.
64. Xiong, C.; Zhang, Y.; Yuan, Q. Characterization of Dust on the Surface of Photovoltaic Panels in Low Latitude and High Altitude Plateau Areas. *J. Phys. Conf. Ser.* **2022**, *2356*, 012007. [CrossRef]
65. Zhao, W.; Lv, Y.; Zhou, Q.; Yan, W. Investigation on particle deposition criterion and dust accumulation impact on solar PV module performance. *Energy* **2021**, *233*, 121240. [CrossRef]
66. Ali, H.M.; Zafar, M.A.; Bashir, M.A.; Nasir, M.A.; Ali, M.; Siddiqui, A.M. Effect of dust deposition on the performance of photovoltaic modules in city of taxila, Pakistan. *Therm. Sci.* **2017**, *21*, 915–923. [CrossRef]
67. Olivares, D.; Ferrada, P.; Bijman, J.; Rodríguez, S.; Trigo-González, M.; Marzo, A.; Rabanal-Arabach, J.; Alonso-Montesinos, J.; Batlles, F.J.; Fuentealba, E. Determination of the Soiling Impact on Photovoltaic Modules at the Coastal Area of the Atacama Desert. *Energies* **2020**, *13*, 3819. [CrossRef]
68. Hachicha, A.A.; Al-Sawafta, I.; Said, Z. Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions. *Renew. Energy* **2019**, *141*, 287–297. [CrossRef]
69. Qasem, H.; Betts, T.R.; Müllejans, H.; Albusairi, H.; Gottschalg, R. Dust-induced shading on photovoltaic modules. *Prog. Photovolt. Res. Appl.* **2014**, *22*, 218–226. [CrossRef]
70. Mastekbayeva, G.A.; Kumar, S. Effect of Dust on the Transmittance of Low Density Polyethylene Glazing in A Tropical Climate. 2000. Available online: www.elsevier.com/locate/solener (accessed on 18 February 2022).
71. Klugmann-Radziemska, E. Degradation of electrical performance of a crystalline photovoltaic module due to dust deposition in northern Poland. *Renew. Energy* **2015**, *78*, 418–426. [CrossRef]
72. Yousif, J.H.; Kazem, H.A.; Al-Balushi, H.; Abuhmaidan, K.; Al-Badi, R. Artificial Neural Network Modelling and Experimental Evaluation of Dust and Thermal Energy Impact on Monocrystalline and Polycrystalline Photovoltaic Modules. *Energies* **2022**, *15*, 4138. [CrossRef]
73. Kazem, H.A.; Chaichan, M.T. Experimental analysis of the effect of dust's physical properties on photovoltaic modules in Northern Oman. *Sol. Energy* **2016**, *139*, 68–80. [CrossRef]
74. Abderrezek, M.; Fathi, M. Effect of dust deposition on the performance of thin film solar cell. *Elektron. Ir Elektrotechnika* **2018**, *24*, 41–45. [CrossRef]
75. Simmons, J.J.H.; Kleban, P.; Ziff, R.M. To Cite This Article: A Molki. 2010. Available online: www.fuelcellstore.com (accessed on 22 October 2022).
76. Jiang, H.; Lu, L.; Sun, K. Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules. *Atmos Environ.* **2011**, *45*, 4299–4304. [CrossRef]
77. Beattie, N.S.; Moir, R.S.; Chacko, C.; Buffoni, G.; Roberts, S.H.; Pearsall, N.M. Understanding the effects of sand and dust accumulation on photovoltaic modules. *Renew. Energy* **2012**, *48*, 448–452. [CrossRef]
78. Mazumder, M.; Mark, H.; Jeremy, S.; Peter, G.; Robert, S.; Brooks, H.; Omar, S.; Ishihara, H.; Alex, B.; Rajesh, S. Characterization of electrodynamic screen performance for dust removal from solar panels and solar hydrogen generators. *IEEE Trans. Ind. Appl.* **2013**, *49*, 1793–1800. [CrossRef]
79. Mehmood, U.; Irshad, H.M.; Al-Sulaiman, F.A.; Bashir, S.; Yilbas, B.S. Effect of Accumulation of Environmental Dust and Subsequent Mud Formation on Textural, Chemical, and Optical Properties of Silicon Wafers for Photovoltaic Cells. *IEEE J. Photovolt.* **2018**, *8*, 1274–1280. [CrossRef]
80. Xu, Z.; Qu, H.; Li, X.; Zhao, Y.; Li, Y.; Han, Z. Theoretical model of optical transmission and reflection characteristics of dusty PV modules. *Sol. Energy Mater. Sol. Cells* **2020**, *213*. [CrossRef]
81. Fan, S.; Wang, Y.; Cao, S.; Sun, T.; Liu, P. A novel method for analyzing the effect of dust accumulation on energy efficiency loss in photovoltaic (PV) system. *Energy* **2021**, *234*, 121112. [CrossRef]
82. Diop, D.; Drame, M.S.; Diallo, M.; Malec, D.; Mary, D.; Guillot, P. Modelling of Photovoltaic Modules Optical Losses Due to Saharan Dust Deposition in Dakar, Senegal, West Africa. *Smart Grid Renew. Energy* **2020**, *11*, 89–102. [CrossRef]
83. Al Garni, H.Z. The Impact of Soiling on PV Module Performance in Saudi Arabia. *Energies* **2022**, *15*, 8033. [CrossRef]
84. Mehmood, U.; Al-Sulaiman, F.A.; Yilbas, B.S. Characterization of dust collected from PV modules in the area of Dhahran, Kingdom of Saudi Arabia, and its impact on protective transparent covers for photovoltaic applications. *Sol. Energy* **2017**, *141*, 203–209. [CrossRef]
85. Mulu, A.; Ayenew, T. Characterization of Abattoir Wastewater and Evaluation of the Effectiveness of the Wastewater Treatment Systems in Luna and Kera Abattoirs in Central Ethiopia. *Int. J. Sci. Eng. Res.* **2015**, *6*, 1026–1040. Available online: http://www.ijser.org (accessed on 1 December 2022).
86. Alfaris, F.E. A Sensorless Intelligent System to Detect Dust on PV Panels for Optimized Cleaning Units. *Energies* **2023**, *16*, 1287. [CrossRef]
87. Nayshevsky, I.; Xu, Q.F.; Barahman, G.; Lyons, A.M. Fluoropolymer coatings for solar cover glass: Anti-soiling mechanisms in the presence of dew. *Sol. Energy Mater. Sol. Cells* **2020**, *206*, 110281. [CrossRef]

88. Elminir, H.K.; Ghitas, A.E.; Hamid, R.H.; El-Hussainy, F.; Beheary, M.M.; Abdel-Moneim, K.M. Effect of dust on the transparent cover of solar collectors. *Energy Convers. Manag.* **2006**, *47*, 3192–3203. [CrossRef]
89. Li, X.; Qin, H.; Zhang, Y.; Yao, W.; Li, Y.; Liu, H. Dust effect on the optical-thermal properties of absorber plate in a transpired solar air collector. *Energy Convers. Manag.* **2018**, *169*, 13–21. [CrossRef]
90. Pan, A.; Lu, H.; Zhang, L.Z. Experimental investigation of dust deposition reduction on solar cell covering glass by different self-cleaning coatings. *Energy* **2019**, *181*, 645–653. [CrossRef]
91. Tanesab, J.; Parlevliet, D.; Whale, J.; Urmee, T.; Pryor, T. The contribution of dust to performance degradation of PV modules in a temperate climate zone. *Sol. Energy* **2015**, *120*, 147–157. [CrossRef]
92. Gong, Y.; Wang, Z.; Lai, Z.; Jiang, M. TVACPSO-assisted analysis of the effects of temperature and irradiance on the PV module performances. *Energy* **2021**, *227*, 120390. [CrossRef]
93. Kumar, A.; Alaraj, M.; Rizwan, M.; Alsaidan, I.; Jamil, M. Development of Novel Model for the Assessment of Dust Accumulation on Solar PV Modules. *IEEE J. Photovolt.* **2022**, *13*, 150–157. [CrossRef]
94. Behura, A.K.; Kumar, A.; Rajak, D.K.; Pruncu, C.I.; Lamberti, L. Towards better performances for a novel rooftop solar PV system. *Sol. Energy* **2021**, *216*, 518–529. [CrossRef]
95. Panji Asmara, B. Overview of the Photovoltaic (PV) Potential Output Power Parameters of the Effect of Dust Contamination on the Surface, Tilt Angle and Use of Reflectors. In *First Mandalika International Multi-Conference on Science and Engineering 2022, MIMSE 2022 (Mechanical and Electrical) (MIMSE-MEI-2022)*; Atlantis Press: Paris, France, 2022. [CrossRef]
96. Zhang, C.; Shen, C.; Wei, S.; Wang, Y.; Lv, G.; Sun, C. A Review on Recent Development of Cooling Technologies for Photovoltaic Modules. *J. Therm. Sci.* **2020**, *29*, 1410–1430. [CrossRef]
97. Segado, P.M.; Carretero, J.; Sidrach-de-Cardona, M. Models to predict the operating temperature of different photovoltaic modules in outdoor conditions. *Prog. Photovolt. Res. Appl.* **2015**, *23*, 1267–1282. [CrossRef]
98. Khan, R.A.; Farooqui, S.A.; Khan, M.H.; Sarfraz, M.; Luqman, M.; Khan, M.F. Dust Deposition on PV Module and Its Characteristics. In *Green Energy and Technology*; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2022; pp. 59–95. [CrossRef]
99. Sohani, A.; Sayyaadi, H. Providing an accurate method for obtaining the efficiency of a photovoltaic solar module. *Renew. Energy* **2020**, *156*, 395–406. [CrossRef]
100. Chiang, W.H.; Wu, H.S.; Wu, J.S.; Lin, S.J. A Method for Estimating On-Field Photovoltaics System Efficiency Using Thermal Imaging and Weather Instrument Data and an Unmanned Aerial Vehicle. *Energies* **2022**, *15*, 5835. [CrossRef]
101. Chaudhary, A.S.; Chaturvedi, D.K. Efficient Thermal Image Segmentation for Heat Visualization in Solar Panels and Batteries using Watershed Transform. *Int. J. Image Graph. Signal Process.* **2017**, *9*, 10–17. [CrossRef]
102. Chaudhary, A.S.; Chaturvedi, D.K. Analyzing Defects of Solar Panels under Natural Atmospheric Conditions with Thermal Image Processing. *Int. J. Image Graph. Signal Process.* **2018**, *10*, 10–21. [CrossRef]
103. Elnozahy, A.; Rahman, A.K.A.; Ali, A.H.H.; Abdel-Salam, M.; Ookawara, S. Performance of a PV module integrated with standalone building in hot arid areas as enhanced by surface cooling and cleaning. *Energy Build.* **2015**, *88*, 100–109. [CrossRef]
104. Mehmood, M.U.; Ulasyar, A.; Ali, W.; Zeb, K.; Zad, H.S.; Uddin, W.; Kim, H.-J. A New Cloud-Based IoT Solution for Soiling Ratio Measurement of PV Systems Using Artificial Neural Network. *Energies* **2023**, *16*, 996. [CrossRef]
105. Al-Ghezi, M.K.S.; Ahmed, R.T.; Chaichan, M.T. The Influence of Temperature and Irradiance on Performance of the Photovoltaic Panel in the Middle of Iraq. *Int. J. Renew. Energy Dev.* **2022**, *11*, 501–513. [CrossRef]
106. Kunelbayev, M.; Amirgaliyev, Y.; Sundetov, T. Improving the Efficiency of Environmental Temperature Control in Homes and Buildings. *Energies* **2022**, *15*, 8839. [CrossRef]
107. Al Siyabi, I.; al Mayasi, A.; al Shukaili, A.; Khanna, S. Effect of soiling on solar photovoltaic performance under desert climatic conditions. *Energies* **2021**, *14*, 659. [CrossRef]
108. Ascencio-Vásquez, J.; Bevc, J.; Reba, K.; Brecl, K.; Jankovec, M.; Topič, M. Advanced PV performance modelling based on different levels of irradiance data accuracy. *Energies* **2020**, *13*, 2166. [CrossRef]
109. Liu, W.; Liu, C.; Lin, Y.; Ma, L.; Xiong, F.; Li, J. Ultra-short term forecast of photovoltaic output power under fog and haze weather. *Energies* **2018**, *11*, 528. [CrossRef]
110. Farah, A.; Khalfalla, E.; Mohamed, O. Effect of Dust on the Efficiency of Solar PV Panel in Khartoum. In Proceedings of the 6th International Conference on Energy Harvesting, Storage, and Transfer (EHST'22), Niagara Falls, ON, Canada, 8–10 June 2022. [CrossRef]
111. Hussien, H.A.; Numan, A.H.; Abdulmunem, A.R. Improving of the photovoltaic / thermal system performance using water cooling technique. *IOP Conf. Ser. Mater. Sci. Eng.* **2015**, *78*, 1–9. [CrossRef]
112. Al-Amri, F.; Maatallah, T.S.; Al-Amri, O.F.; Ali, S.; Ali, S.; Ateeq, I.S.; Zachariah, R.; Kayed, T.S. Innovative technique for achieving uniform temperatures across solar panels using heat pipes and liquid immersion cooling in the harsh climate in the Kingdom of Saudi Arabia. *Alex. Eng. J.* **2022**, *61*, 1413–1424. [CrossRef]
113. Zjavka, L. Solar and Wind Quantity 24 h—Series Prediction Using PDE-Modular Models Gradually Developed according to Spatial Pattern Similarity. *Energies* **2023**, *16*, 1085. [CrossRef]
114. Hammami, M.; Torretti, S.; Grimaccia, F.; Grandi, G. Thermal and performance analysis of a photovoltaic module with an integrated energy storage system. *Appl. Sci.* **2017**, *7*, 107. [CrossRef]

115. Fan, S.; Wang, X.; Cao, S.; Wang, Y.; Zhang, Y.; Liu, B. A novel model to determine the relationship between dust concentration and energy conversion efficiency of photovoltaic (PV) panels. *Energy* **2022**, *252*, 123927. [CrossRef]
116. Liu, J.; Tao, W.; Liu, Z.; Liu, Y.; Wang, M.; Wu, Q. Study on snail trail formation in PV module through modeling and accelerated aging tests. *Sol. Energy Mater. Sol. Cells* **2017**, *164*, 80–86. [CrossRef]
117. Lu, H.; Zheng, C. Comparison of Dust Deposition Reduction Performance by Super-Hydrophobic and Super-Hydrophilic Coatings for Solar PV Cells. *Coatings* **2022**, *12*, 502. [CrossRef]
118. Touati, F.; Alam Chowdhury, N.; Benhmed, K.; San Pedro Gonzales, A.J.R.; Al-Hitmi, M.A.; Benammar, M.; Gastli, A.; Ben-Brahim, L. Long-term performance analysis and power prediction of PV technology in the State of Qatar. *Renew. Energy* **2017**, *113*, 952–965. [CrossRef]
119. Al-Ghussain, L.; Subaih, M.A.; Annuk, A. Evaluation of the Accuracy of Different PV Estimation Models and the Effect of Dust Cleaning: Case Study a 103 MW PV Plant in Jordan. *Sustainability* **2022**, *14*, 982. [CrossRef]
120. Ramli, M.A.M.; Prasetyono, E.; Wicaksana, R.W.; Windarko, N.A.; Sedraoui, K.; Al-Turki, Y.A. On the investigation of photovoltaic output power reduction due to dust accumulation and weather conditions. *Renew. Energy* **2016**, *99*, 836–844. [CrossRef]
121. Kasim, N.K.; Al-Wattar, A.J.; Abbas, K.K. New Technique for Treatment of the dust accumulation from PV solar panels surface. *Iraqi J. Physic* **2010**, *8*, 54–59.
122. Dida, M.; Boughali, S.; Bechki, D.; Bouguettaia, H. Output power loss of crystalline silicon photovoltaic modules due to dust accumulation in Saharan environment. *Renew. Sustain. Energy Rev.* **2020**, *124*, 109787. [CrossRef]
123. Singla, P.; Duhan, M.; Saroha, S. A comprehensive review and analysis of solar forecasting techniques. *Front. Energy* **2022**, *16*, 187–223. [CrossRef]
124. Salari, A.; Hakkaki-Fard, A. A numerical study of dust deposition effects on photovoltaic modules and photovoltaic-thermal systems. *Renew. Energy* **2019**, *135*, 437–449. [CrossRef]
125. Lu, H.; Zhao, W. CFD prediction of dust pollution and impact on an isolated ground-mounted solar photovoltaic system. *Renew. Energy* **2019**, *131*, 829–840. [CrossRef]
126. Alnaser, N.W.; Dakhel, A.A.; Al Othman, M.J.; Batarseh, I.; Lee, J.K.; Najmaii, S.; Alnaser, W.E. Nanomaterials for photocatalysis View project Nonlinear Optics of Natural Dye Extracts View project Dust Accumulation Study on the Bapco 0.5 MW p PV Project at University of Bahrain. *Int. J. Power Renew. Energy Syst.* **2015**, *2*, 53. [CrossRef]
127. Hammad, B.; Al-Abed, M.; Al-Ghandoor, A.; Al-Sardeah, A.; Al-Bashir, A. Modeling and analysis of dust and temperature effects on photovoltaic systems' performance and optimal cleaning frequency: Jordan case study. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2218–2234. [CrossRef]
128. Al-hasan, A.Y.; Ghoneim, A.A. A new correlation between photovoltaic panel's efficiency and amount of sand dust accumulated on their surface. *Int. J. Sustain. Energy* **2005**, *24*, 187–197. [CrossRef]
129. Benghanem, M.; Almohammedi, A.; Khan, M.T.; Al-Masraqi, A. Effect of dust accumulation on the performance of photovoltaic panels in desert countries: A case study for Madinah, Saudi Arabia. *Int. J. Power Electron. Drive Syst.* **2018**, *9*, 1356. [CrossRef]
130. Kaldellis, J.K.; Kapsali, M. Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements. *Energy* **2011**, *36*, 5154–5161. [CrossRef]
131. Baras, A.; Jones, R.K.; Alqahtani, A.; Alodan, M.; Abdullah, K. Measured soiling loss and its economic impact for PV plants in central Saudi Arabia. In Proceedings of the 2016 Saudi Arabia Smart Grid Conference, SASG 2016, Jeddah, Saudi Arabia, 13 February 2017. [CrossRef]
132. Lu, H.; Lu, L.; Wang, Y. Numerical investigation of dust pollution on a solar photovoltaic (PV) system mounted on an isolated building. *Appl. Energy* **2016**, *180*, 27–36. [CrossRef]
133. Kother, A.H.; Jawad, Z.W.A.L.-S.W.; Kother, S.; Taha, I.A.; Almukhtar, H.; Azizan, M.M.; Rahman, A.S.F.; Hasikin, K. Assessment of renewable energy sources to generate electricity for remote areas, South Iraq. *Int. J. Power Electron. Drive Syst.* **2022**, *13*, 2378–2385. [CrossRef]
134. Hariri, N. A novel dust mitigation technology solution of a self-cleaning method for a PV module capable of harnessing reject heat using shape memory alloy. *Case Stud. Therm. Eng.* **2022**, *32*, 101894. [CrossRef]
135. Piedra, P.G.; Llanza, L.R.; Moosmüller, H. Optical losses of photovoltaic modules due to mineral dust deposition: Experimental measurements and theoretical modeling. *Sol. Energy* **2018**, *164*, 160–173. [CrossRef]
136. Hegazy, A.A. Effect of Dust Accumulation on Solar Transmittance through Glass Covers of Plate-Type Collectors. 2001. Available online: www.elsevier.nl/locate/renene (accessed on 10 January 2023).
137. Gholami, A.; Khazaee, I.; Eslami, S.; Zandi, M.; Akrami, E. Experimental investigation of dust deposition effects on photo-voltaic output performance. *Sol. Energy* **2018**, *159*, 346–352. [CrossRef]
138. Haddad, A.G.; Dhaouadi, R. Modeling and analysis of PV soiling and its effect on the transmittance of solar radiation. In Proceedings of the 2018 Advances in Science and Engineering Technology International Conferences, ASET 2018, Dubai, Sharjah, Abu Dhabi, United Arab Emirates, 11 June 2018; pp. 1–5. [CrossRef]
139. Lu, S.; Li, T.; Yan, X.; Yang, S. Evaluation of Photovoltaic Consumption Potential of Residential Temperature-Control Load Based on ANP-Fuzzy and Research on Optimal Incentive Strategy. *Energies* **2022**, *15*, 8640. [CrossRef]
140. Coskun, C.; Toygar, U.; Sarpdag, O.; Oktay, Z. Sensitivity analysis of implicit correlations for photovoltaic module temperature: A review. *J. Clean. Prod.* **2017**, *164*, 1474–1485. [CrossRef]

141. Naghavi, M.S.; Esmaeilzadeh, A.; Singh, B.; Ang, B.C.; Yoon, T.M.; Ong, K.S. Experimental and numerical assessments of underlying natural air movement on PV modules temperature. *Sol. Energy* **2021**, *216*, 610–622. [CrossRef]
142. Matusz-Kalász, D.; Bodnár, I. Operation problems of solar panel caused by the surface contamination. *Energies* **2021**, *14*, 5461. [CrossRef]
143. Fathi, M.; Abderrezek, M.; Friedrich, M. Reducing dust effects on photovoltaic panels by hydrophobic coating. *Clean Technol Environ. Policy* **2017**, *19*, 577–585. [CrossRef]
144. Tomar, V.; Tiwari, G.N.; Bhatti, T.S.; Norton, B. Thermal modeling and experimental evaluation of five different photovoltaic modules integrated on prototype test cells with and without water flow. *Energy Convers. Manag.* **2018**, *165*, 219–235. [CrossRef]
145. Santhakumari, M.; Sagar, N. A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques. *Renew. Sustain. Energy Rev.* **2019**, *110*, 83–100. [CrossRef]