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THE INFLUENCE OF DUST ON THE EFFICIENCY OF PHOTOVOLTAIC SYSTEMS: PAST EXPERIENCES, A NOVEL POSSIBILITY, AND FUTURE DEVELOPMENTS

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Abstract

This issue has been recognized as a significant problem since the 1980s. While manual cleaning was initially considered a potential solution, it has become evident that these regions necessitate automated cleaning systems. A comprehensive review and discussion on the impact of dust on PV glass, and the effect of dust particle physical and chemical properties, strategies for dust moderation and cleaning, approaches used to model dust effect, and emerging prospects in the field are presented. By examining these aspects, this study contributes to an enhanced understanding of the challenges associated with dust accumulation on PV and provides insights into potential solutions for optimized performance and stability.

Keywords: Dust; Photovoltaic; Soiling; Modelling, Dust Cleaning.

INTRODUCTION

Photovoltaic are a way to turn sunlight into electricity. They are mainly made from silicon and employ PV to take in the sun's rays and transform them into "direct current" (DC) electricity. PV can be used to supply electricity to different applications [1][2]. Solar power systems are available in a range of sizes, from compact, portable models to large, mounted PV models. The rising popularity of these systems can be attributed to their cost-effectiveness and high efficiency [3]. Performance characteristics of PV modules refer to the measurements that are used to figure out how reliable and efficient a PV system is. Key performance metrics that should be considered include module "efficiency" η_{PV}, "temperature coefficient" T_c, "maximum power point tracking" MPPT, and "power degradation" P_{deg} [4][5]. Module efficiency is the amount of power produced by the PV compared to the amount of sunlight that hits it. The T_c is the speed at which the PV power shifts due to a change in temperature. MPPT refers to the ability of a PV to adapt its power output in response to varying environmental conditions [6]. Ultimately, the energy generated by the PV module will diminish as time passes. The amount of solar radiation and temperature can significantly influence the PV output [7][6]. When the temperature goes up, the PV modules are not as effective. This is because PV are constructed using semiconductors, which are responsive to changes in temperature. As the temperature increases, the PV cells become less efficient [8]. The two primary considerations when using PV modules in desert areas are the amount of accumulated dust and the temperature. When there is less sunlight, the PV modules will not function as well. PV

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output experiences a notable decrease during winter or cloudy days. Therefore, it is crucial to consider climate factors when installing and utilizing PV modules [9].

Particles of dust exist in the air (less than 200 micron), which originate from various sources like earth, pollen, and other organic matter (as can be seen in Figure 1) [10][11][12]. It is impossible to see dust particles with the unaided eye, yet they can be viewed under a microscope. Typically, they are composed of different elements, which can include metals, minerals, and organic material. Inhaling these particles can be detrimental to one's health, resulting in respiratory issues, allergies, and skin and eye irritation [11]. The performance of PV modules is significantly affected by the presence of dust [13]. Particles of dust on the PV module's exterior diminish the amount of sunlight that comes in contact with the module, thus resulting in a lowered output power and diminished efficiency [14]. Dust has the potential to hinder air circulation around the PV module, resulting in inadequate cooling and an increase in the temperature inside the module [15]. This can shorten the lifetime of the PV module, as “hot spots” will be created that can cause it to fail prematurely [16][17].

Adıgüzel et al. [18] conducted a laboratory study to investigate the impact of dust on PV panels. Specifically, they examined how marble dust, in terms of both weight and size, affected the efficiency of PV panels. The researchers divided marble powder into eight distinct particle sizes, ranging from 35 µm to 2 mm. Each size was individually tested using three different weights: 5 gr, 10 gr, and 15 gr. The experiments were conducted on both “monocrystalline” (m-Si) and “polycrystalline” (p-Si) panels, adhering to the “Standard Test Conditions”. They measured and evaluated electrical performance parameters such as current I_{PV}, voltage V_{PV}, and power P_{PV} loss to determine the impact of marble powders with varying weights and sizes on the PV panel. The obtained data from the experiments were then analyzed using the “support vector machines” (SVM) method. The results of the SVM analysis indicated that the Cubic SVM model yielded more accurate estimations for m-Si, while the Fine Gaussian SVM method showed better performance for p-Si.

Shenouda et al. [19] developed a novel dust mitigation approach for PVs used in street light posts. The method involved combining a wind shield, an antistatic hydrophilic coating, and a mechanical vibrator. The objective was to investigate the seasonal variations in η_{PV} using this innovative dust mitigation technique. Two experiments were conducted during winter and summer, each lasting six weeks. One PV served as a reference, while the other panel was equipped with the wind shield, mechanical vibrator, and antistatic coating. The wind shield prevented southward wind flow, the antistatic coating prevented dust adherence, and the mechanical vibrator dislodged accumulated dust particles. The findings revealed that the combination of these measures effectively maintained the panel's efficiency within a 10% maintenance limit during the winter experiment. However, in the summer experiment, the maintenance limit was exceeded in the fifth week due to the absence of favorable wind direction and rainfall. These results highlight the promising potential of the combined wind shield, mechanical vibrator, and coating as an effective dust mitigation technique for PVs in light posts, particularly in winter conditions.

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Chen et al. [20] conducted experiments to investigate effect of dust on PV. The study investigates the impact of dust accumulation on the electrical parameters of PVs, including I_{PV}, V_{PV}, and P_{PV}. The findings indicate that a dust layer with a density of 10 g/m^2 can reduce the maximum P_{PV} by around 34%. These experimental results enhance our understanding of the adverse effects of dust on PVs and underscore the significance of regular cleaning and maintenance practices to maximize the performance and η_{PV} of solar energy systems.

Solar cells can be cleaned by either manual or automated methods. In manual cleaning, a brush is used to take off dust, dirt, and other particles. For automated cleaning, pressurized air, water, or special cleaning solutions may be used [21]. To safeguard the delicate components, it is necessary to dismantle the PV module and carefully inspect and clean each individual part [22]. The nature of the collected dust and debris specify the cleaning agents such as “alcohol or isopropyl”, which can be utilized for their removal. It is crucial to avoid using acidic or caustic cleaning agents on PV modules [16].

This study strives to update the discussion on the dust issue and its effects on PV, considering both current and future conditions. A dust impact model has been proposed, though it still presents a challenge, and the most recent advancements are being introduced.

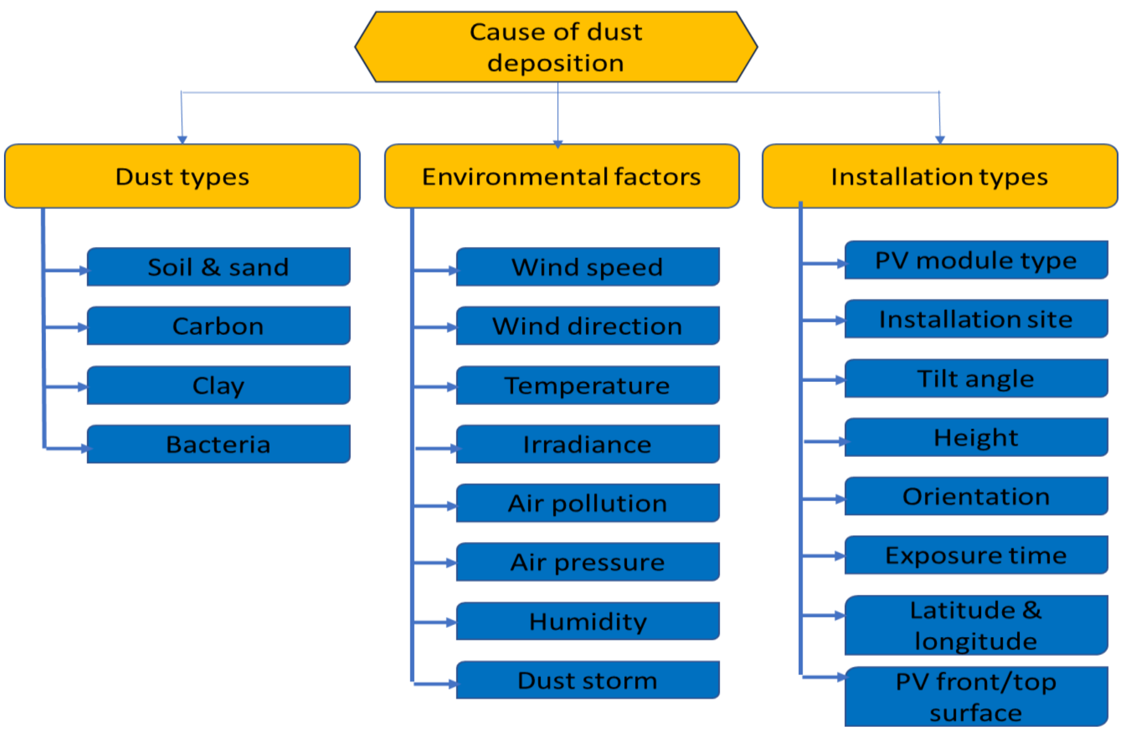

Figure 1: Various Sources from Which Dust Can Accumulate on PV

1. IMPACT OF DUST/SOILING ON TRANSPARENT MATERIALS AND GLASS

The performance of PV glass can be adversely affected by the buildup of dust. Dust particles hinder the amount of sunlight that can reach the solar cell, resulting in a decrease

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in electricity production [23]. The effectiveness of the PV is hindered by dust particles obstructing the sunlight, as illustrated in Figure 2. In addition, these particles can cause abrasions and cause harm to the glass surface, shortening its lifespan and reducing its transparency. In addition, dust behave as an insulation layer, leading to the PV glass overheating and reducing its generated energy [24].

Semaoui et al. [25] examined the impact of dust on the optical transmittance of glazing materials used in PV in a desert region. The study focuses on evaluating how dust accumulation affects the ability of light to pass through the glazing, which can significantly affect PV behaviour. The research analyzes the optical properties of the glazing under varying dust densities and assesses the reduction in transmittance. The study revealed that the accumulation of dust affect P_{PV} glazing, tilted at a 32° angle, can cause a substantial reduction in irradiance transmittance throughout the day. On average, after a period of several months, the decrease in transmittance ranged between 0% and 8%. The findings contribute to understanding the influence of dust on PV module performance and provide insights into the importance of regular cleaning and maintenance to mitigate the negative effects of dust accumulation in desert environments.

Piedra et al. [26] examined the optical losses incurred by PV due to the deposition of mineral dust. Their study utilized a combination of experimental measurements and theoretical modeling to investigate the influence of dust accumulation on the optical properties and performance of PV. Through experimental analysis, they measured the optical transmittance and reflectance of PV with different levels of dust deposition. Additionally, they developed theoretical models to simulate and predict the optical losses resulting from dust accumulation. The findings enhance our understanding of the optical impacts of dust on PV and offer valuable insights for designing and maintaining PV systems in dusty environments.

Dust particles can have various effects on transparent materials, including optical interference, reduced clarity, scratches or abrasions, and increased fragility. Optical interference occurs when dust obstructs the proper transmission of light, resulting in distorted images or reduced light transmission. The presence of dust can also cause the material to appear foggy or less clear. Additionally, dust particles can cause scratches or abrasions, making the material less transparent. Moreover, the accumulation of dust can make the material more fragile and susceptible to breakage and cracking [27].

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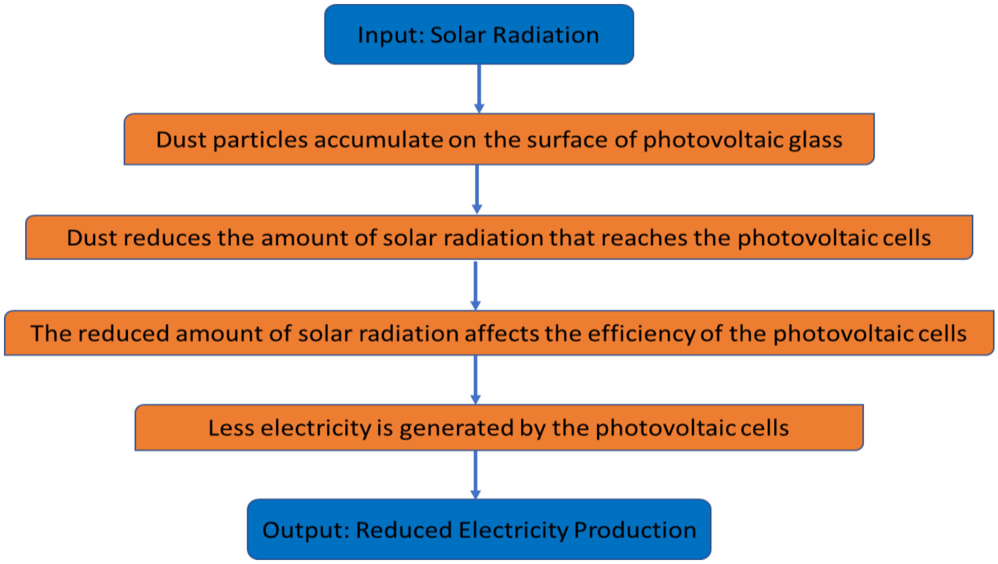

Figure 2: Impact of Dust on PV Glass

The PV performance can be influenced by various factors such as sunlight exposure duration and environmental conditions including temperature, humidity, wind, and dust. Extended exposure to sunlight enhances the energy production of the module. However, elevated cell temperatures can diminish power, and humidity levels inversely affect the module's capacity to absorb sunlight effectively. Considering wind characteristics added to dust affect accumulation properties and can also impede the module's productivity. To mitigate the effects of dust and prolonged exposure, anti-reflective coatings can be applied to the module's surface. These coatings help minimize the accumulation of dirt and dust particles [28]. It is essential to keep the PV module clean to avoid light diffusion, which will reduce the reached brightness. Additionally, dust particles in the atmosphere can settle, a process known as dust deposition [4]. Airborne dust particles settled on PV by gravity. Organic occurrences such as “wind, and air turbulence” can trigger dust deposition, as can human-made activities like industry and construction. The deposition of dust affects PV behaviour such “I-V curve”. The P_{PV}, and η_{PV} reduced with irradiance reduction due to the accumulated dust [29]. This reduction in sunlight absorption can cause electrical shorts, resulting in power interruptions. Moreover, dust accumulation can compromise the insulation and protective capabilities of the modules, ultimately reducing their lifespan and efficiency in combating environmental factors. El-Shobokshy et al. [30] provides an example of the degradation of “short circuit current” Isc, P_{PV}, and “Fill Factor” FF due to dust settling, as depicted in Figure 3. It is crucial to note that the “size”, “shape”, “type”, and “homogeneity” of dust particles can all influence the extent of performance degradation, as suggested by [31][17].

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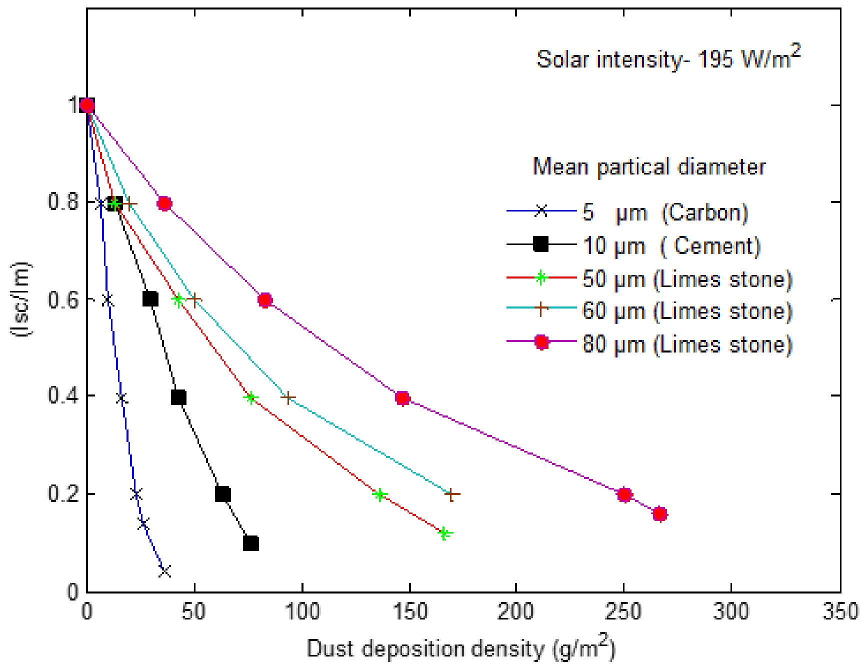
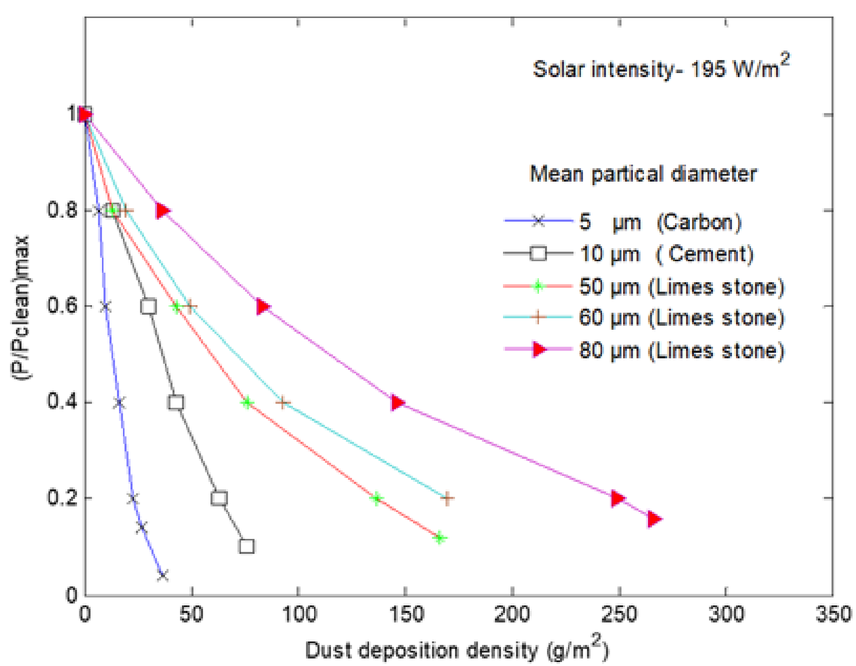


(a)



(b)

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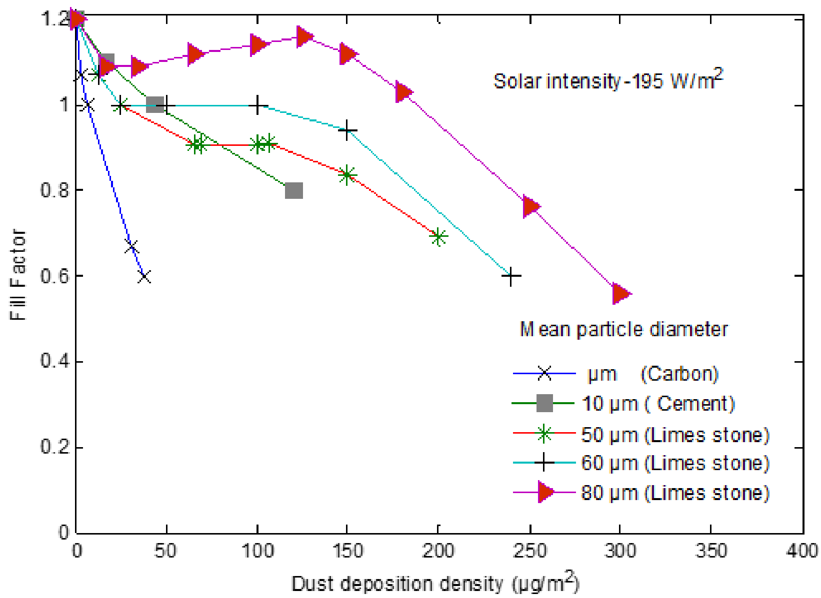

(c)

Figure 3: Illustrates The Decline in PV Module Performance Resulting from Dust Deposition, As Observed in the Variations of (a) Isc, (b) P_{PV}, and (c) FF – Data are Extracted from [30]

2. IMPACT OF DUST ON MIRRORS

Dust accumulation on mirrors or reflectors used in solar energy technology can have several negative effects on their performance as shown in Figure 4(a). The main impacts are:

- Dust particles on the mirror surface can obstruct and scatter sunlight, reducing the amount of light reflected onto the solar receiver or photovoltaic cells. This lowers the overall efficiency of the system and decreases the amount of energy generated.
- Uneven dust distribution can create shading patterns on the mirror surface. This leads to uneven heating, which can cause localized hot spots. Hot spots can damage the reflective surface and other components of the solar energy system, reducing its lifespan.
- Dust layers can introduce additional optical losses, such as absorption and scattering, which further reduce the amount of light reaching the receiver. These losses decrease the overall energy conversion efficiency of the system.
- Regular cleaning and maintenance are necessary to remove dust accumulation on mirrors or reflectors. This adds to the operational costs and maintenance efforts associated with solar energy installations. Neglected maintenance can result in prolonged periods of reduced performance or even system failure.

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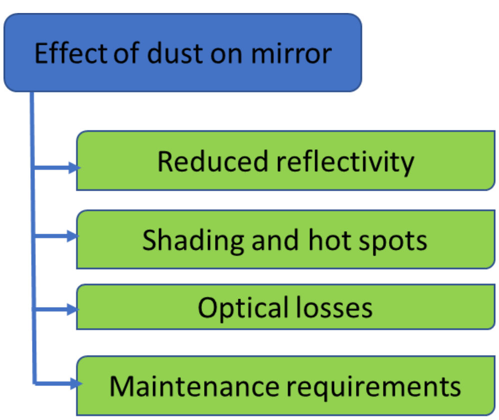
To mitigate the negative effects of dust on solar mirrors or reflectors, various measures can be taken as shown in Figure 4(b):

- Implementing regular cleaning schedules and proper cleaning techniques can help remove dust and maintain the reflector surface's cleanliness. This can involve the use of water, brushes, or specialized cleaning systems, depending on the specific technology.
- Applying hydrophobic or anti-reflective coatings to the mirror surface can help repel dust and prevent its adhesion. These coatings can reduce the need for frequent cleaning and improve the overall performance of the system.
- Some solar power plants use automated cleaning systems that employ robotic or mechanical devices to clean the mirror or reflector surfaces. These systems can be programmed to operate at regular intervals or based on specific environmental conditions, ensuring optimal performance.
- Choosing appropriate installation sites that are less prone to dust accumulation, such as areas with lower dust levels or employing effective dust mitigation strategies in high-dust regions, can minimize the impact of dust on solar mirrors or reflectors.

A proper maintenance and cleaning practices, along with the use of advanced coatings and cleaning technologies, can help mitigate the negative effects of dust on mirrors or reflectors, ensuring optimal performance and longevity of solar energy systems.

A foggy mirror occurred due to dust will diminish the effectiveness. Dust particles also obstruct light from reflecting off the mirror, leading to a decrease in clarity [32]. In addition, dirt and debris can settle on the mirror and cause the surface to become scratched, thus decreasing its reflective capacity. This can also lead to the mirror discoloring and gaining a yellowish-brown tinge [33]. Figure 4(c) depicts the procedural steps involved in analyzing the impact of dust on mirrors.



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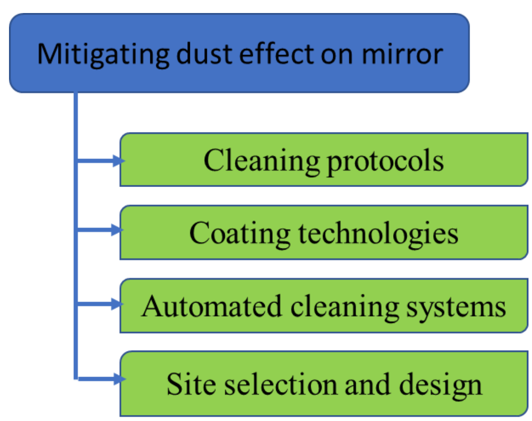

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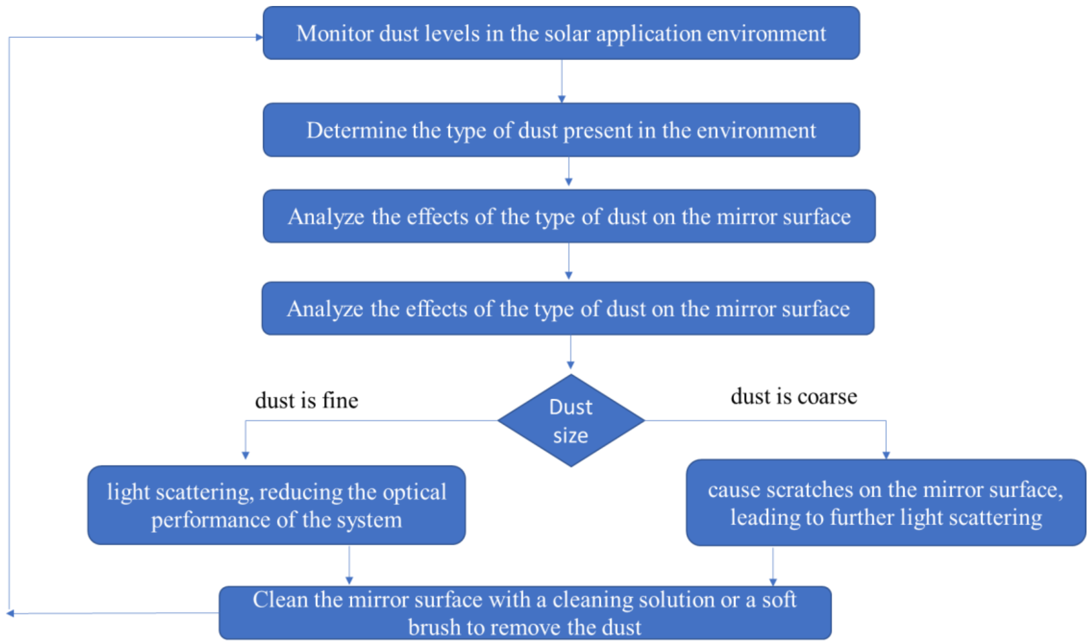

Figure 4: Impact of dust on mirror (a) effect, (b) mitigation, (c) analysis

3. CHEMISTRY AND PHYSICAL PROPERTIES OF DUST

The physical characteristics of dust particles play a crucial role in the impact they have on photovoltaic cells. Particle properties like “size”, “shape”, “electric charge”, “chemical composition” etc. can diminish both the absorption and reflection of irradiance by PV modules. The irradiance affected by particles which can “absorb”, “scatter”, and “reflect” the light and affect P_{PV}, and η_{PV} [7]. This decrease in the irradiance significantly affects cell performance and reduces overall efficiency. Increase PV temperature because of dust and due to the absorbing heat from the surroundings reduce the P_{PV}, and η_{PV} [34]. Dust particles can further elevate the “internal resistances” of the module, leading to a reduction in the electrical current generated. Additionally, dust accumulation can promote corrosion of the module's components, resulting in a shortened lifespan and decreased overall efficiency.

Reference [17] investigated how the physical qualities of dust, like size, shape, weight, and pollutant type, influence the efficiency of photovoltaic systems in Oman. Several tests were done to examine the dust characteristics, such as “microscopic examination” and “X-ray diffraction” (XRD) as seen in Figure 4.

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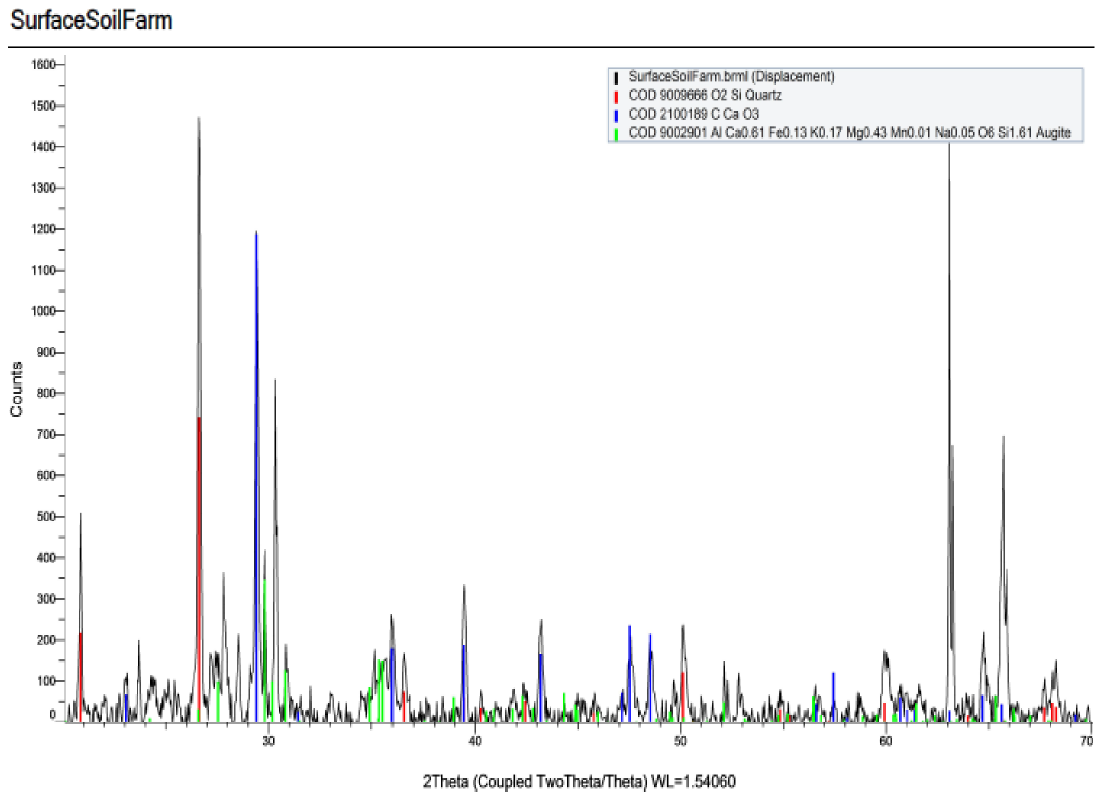
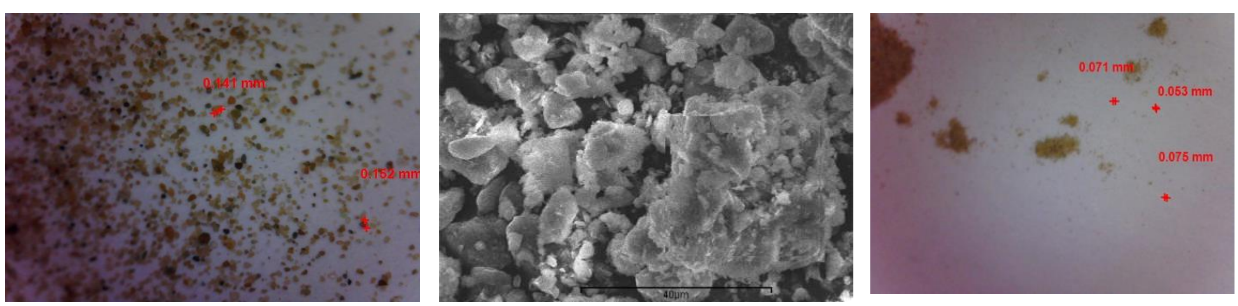


(a)



(b)

Figure 4: Portrays The Analysis Of Dust Deposition And Accumulation Through The Utilization of (a) XRD [31] and (b) microscopic imaging [17]

Particle sizes have a profound effect on the P_{PV}. If the size is particularly small, there will be less light scattered, causing more light to be absorbed by the cells, leading to an increased system performance. Conversely, the presence of large dust particles can hinder sunlight and diminish the η_{PV}. Light scattering increased due to the large particles

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size and particularly when it has “sharp edges”. Furthermore, rough and irregularly shaped dust particles can cast shadows, reduce irradiance that reaches the PVs.

4. CLEANING AND MITIGATION OF DUST

The cleaning and mitigation of dust accumulated on PVs is an important aspect of ensuring their optimal performance and longevity. Dust accumulation on PV surface can reduce the amount received irradiance, resulting in decreased energy production and efficiency. Additionally, dust particles can cause physical damage, such as scratching or etching, and interfere with the electrical connections, leading to power losses or system failures.

To address these issues, various cleaning and mitigation strategies are employed. Manual cleaning methods involve using soft brushes, sponges, or microfiber cloths along with water or mild detergent to gently remove the dust from the module surface. However, manual cleaning can be time-consuming and labor-intensive, especially for large-scale PV installations.

Automated cleaning systems offer a more efficient and convenient solution. These systems utilize mechanical brushes, wipers, or “high-pressure water jets” to remove dust from the modules. Some advanced systems incorporate robotic devices that move along the module rows, ensuring thorough and consistent cleaning. Additionally, some automated systems use sensors or monitoring technologies to detect dust accumulation and trigger the cleaning process when necessary.

In addition to cleaning, dust mitigation techniques are implemented to minimize the accumulation of dust on PV modules. These techniques include the application of “anti-reflective coatings””, hydrophobic coatings”, or “self-cleaning coatings” on the module surfaces. These coatings help reduce dust adhesion and promote the shedding of dust particles during natural weather conditions, such as rain or wind.

Furthermore, measures can be taken to minimize the impact of dust accumulation. This includes proper site selection and design considerations to reduce dust exposure, such as avoiding dusty or high-wind areas and ensuring proper module orientation. Regular inspections and maintenance are also crucial to identify and address any issues related to dust accumulation or module degradation.

Sánchez-Barroso et al. [35] explored the optimal cleaning frequency for PVs installed in the dehesa, a type of agroforestry system. The study applies Markov chain modeling to estimate the appropriate interval for panel cleaning. The authors conducted field experiments where soiling rate data, PV panel efficiency, and meteorological conditions in a dehesa site has been collected. They used this data to construct a Markov chain model that represents the dynamic process of panel soiling. By analyzing the model, they aimed to determine the optimal cleaning periodicity that minimizes the dust effect on PV. The study results indicated that the optimal cleaning frequency for PV panels in the dehesa depends on various factors, including dust accumulation rate, panel efficiency decay rate, and local weather conditions. The authors found that for the studied dehesa site, a cleaning interval of around 30 days yielded optimal results in terms of maximizing

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the electricity production of the PV panels. Insights has been provided in this study on the management and maintenance of PV systems installed in agroforestry environments, specifically the dehesa. The use of Markov chain modeling offers a systematic approach to estimate the appropriate cleaning periodicity based on site-specific conditions, contributing to the optimization of PV panel performance and energy production in such settings.

Younis and Onsa [36] provided an overview of cleaning practices and their impact on PV performance in “Middle East and North Africa region” MENA. The study aims to summarize the existing knowledge and research findings on PV cleaning operations in this specific geographical area. The authors begin by discussing the main sources of soiling in the region, which include dust, sand, and atmospheric pollutants. They highlight the challenges posed by these environmental factors and the subsequent negative effects on PV system efficiency. The paper further delves into various cleaning techniques employed in MENA, including manual cleaning, water-based cleaning, and robotic cleaning. The researchers analyze the impact of cleaning operations on PV behaviour and present a comprehensive summary of studies conducted in the region. They explore the effects of different cleaning frequencies, water quality, and cleaning methods on module efficiency, energy yield, and return on investment. Additionally, the authors discuss the influence of temperature and dust accumulation on the efficacy of cleaning operations.

The impact of electrostatic cleaning on PVs in Jordan has been studied by Al-Salaymeh et al. [37]. The study aims to assess the effectiveness of electrostatic cleaning in removing dust particles from PVs and improving their energy generation. The authors conducted field experiments in different locations across Jordan to evaluate the performance of PVs before and after electrostatic cleaning. They measured various parameters such as module temperature, irradiance, and I-V characteristics to assess the cleaning effect. The paper explored the impact of dust accumulation and temperature on the cleaning process. The authors claimed that electrostatic cleaning significantly improves the performance of PVs. Cleaning process effectively removes dust from the module and enhance the P_{PV}, and η_{PV}. The researchers observed improvements in module temperature, irradiance, and electrical characteristics after electrostatic cleaning. Furthermore, the study discusses the impact of environmental elements on the effectiveness of electrostatic cleaning. It highlights the importance of considering ambient temperature and dust accumulation levels in determining the optimal cleaning frequency and efficiency. The authors also provide insights into the potential economic benefits of implementing electrostatic cleaning techniques in Jordan's PV systems.

Hariri [38] presented a new dust mitigation technology for PV modules. The study introduces a “self-cleaning method” that utilizes shape memory alloy (SMA) to remove dust particles from the PV module surface while simultaneously harnessing the waste heat generated by the PVs. The authors focus on addressing the challenges posed by dust accumulation on PV modules, which can lead to reduced energy output and efficiency. The proposed SMA incorporates wires embedded in the PV module structure.

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These wires are activated by the waste heat produced by the PVs, allowing them to deform and effectively remove dust from PVs.

The paper discusses the experimental setup used to evaluate the execution of the self-cleaning method. Various factors like dust accumulation, cleaning efficiency, and PV electrical performance are measured and analyzed. A comparison between self-cleaning, and conventional PV “without the SMA wires” was conducted. The results demonstrated the self-cleaning method’s effectiveness in reducing dust deposition on PV. The SMA wires successfully remove dust particles, leading to improved energy generation and enhanced module performance. Additionally, the utilization of waste heat to power the self-cleaning process adds a unique feature to the system. The research highlights the potential benefits of the proposed technology solution, including increased energy production and reduced maintenance requirements for PV systems. The self-cleaning method using SMA presents a promising approach for addressing dust-related issues in PV installations and improving their long-term performance.

The effective cleaning and mitigation of dust on PVs (see Figure 5) are essential for maintaining their performance and extending their lifespan. Choosing the appropriate cleaning method, considering site-specific factors, and implementing preventive measures can help optimize the η_{PV} in the presence of dust accumulation [39].

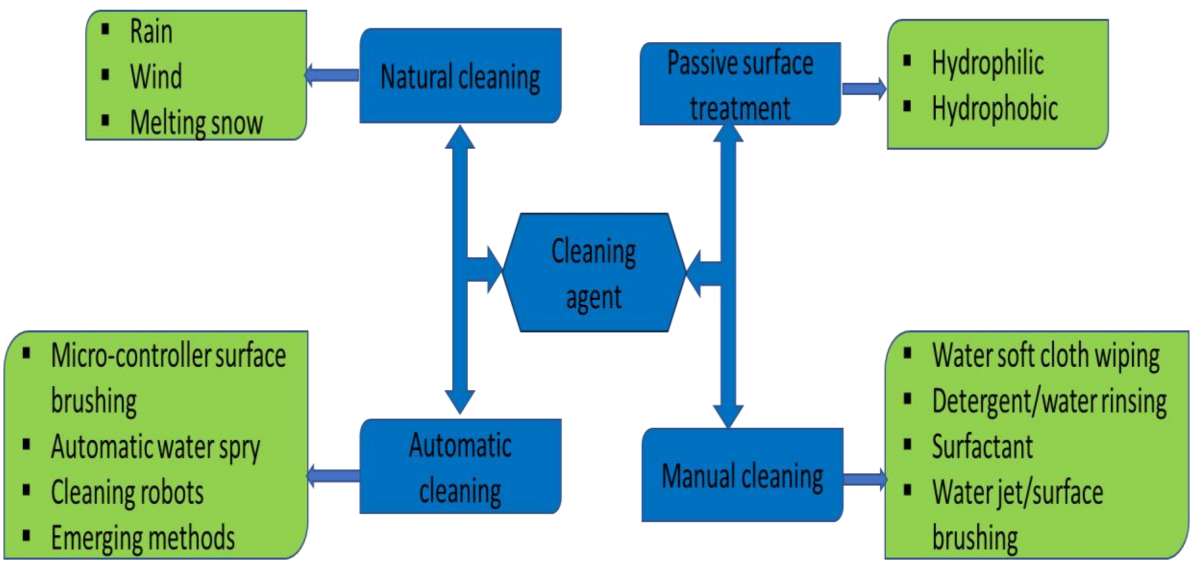

Figure 5: Dust Cleaning Methods

The process of removing dust from PV modules, as depicted in Figure 5, eliminates dust and other debris from the module's surface. The presence of dust causes increased reflection of light from the module, resulting in a reduction of the received irradiance and consequently lowering the electricity generated. Figure 6 demonstrates various automated techniques for dust cleaning, including “brushing robots” and “high-pressure water jets”. On the other hand, manual cleaning method can be accomplished by using a “brush and mild detergent” [40][12][41][42][43], can also be employed. The use of

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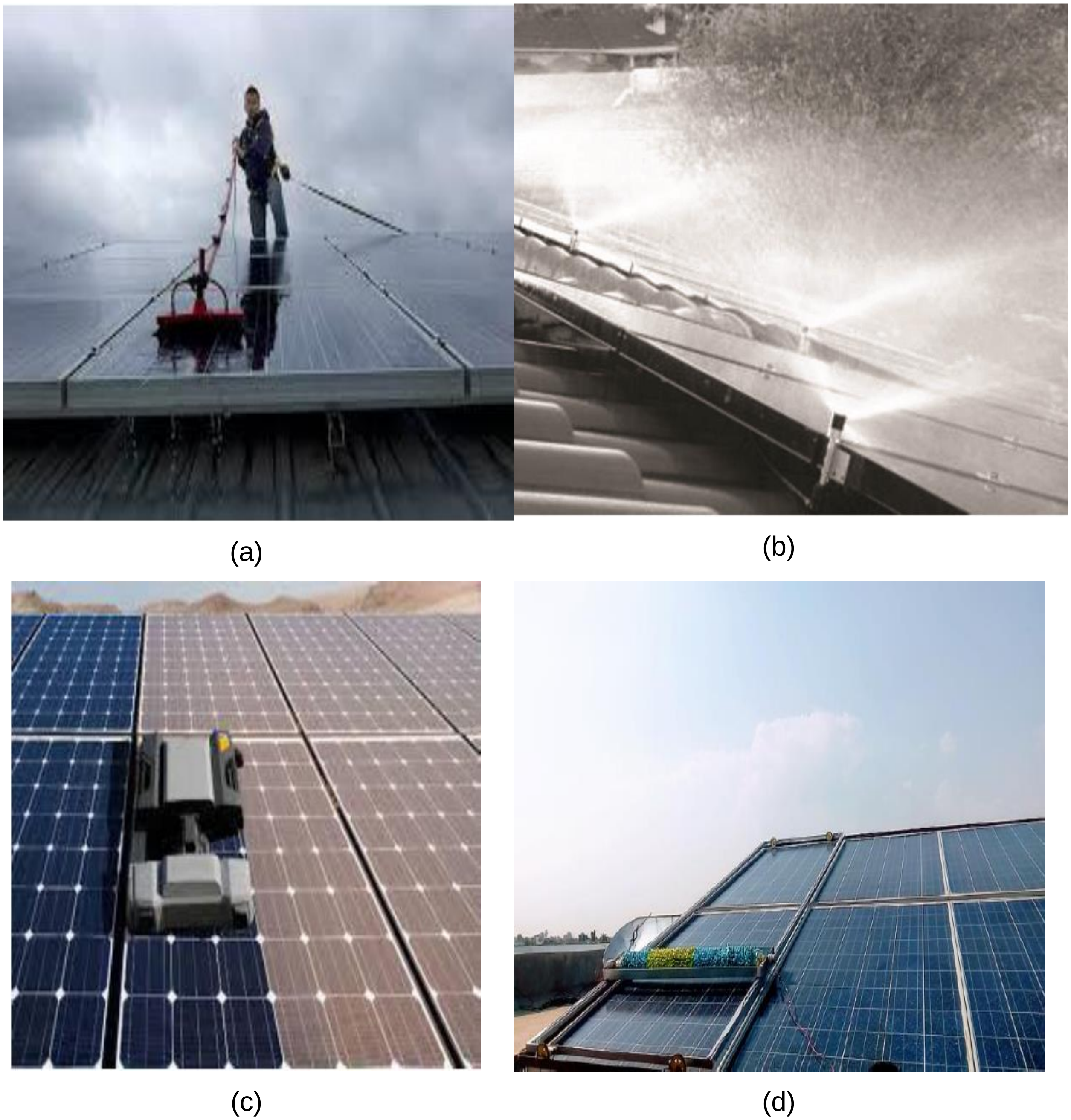
automated dust cleaning systems offers advantages such as preventing dust accumulation over time, reducing labor, and enhancing safety.



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

Figure 6: Cleaning methods (a) manual [41], (b) water [43], (c) robotic [12], (d) autocleaning [44][45]

5. DUST MODELLING

Dust/Soil modelling is a methodology utilized to examine the particle characteristics like “optical”, “chemical” and “physical” properties. This technique enables the simulation and

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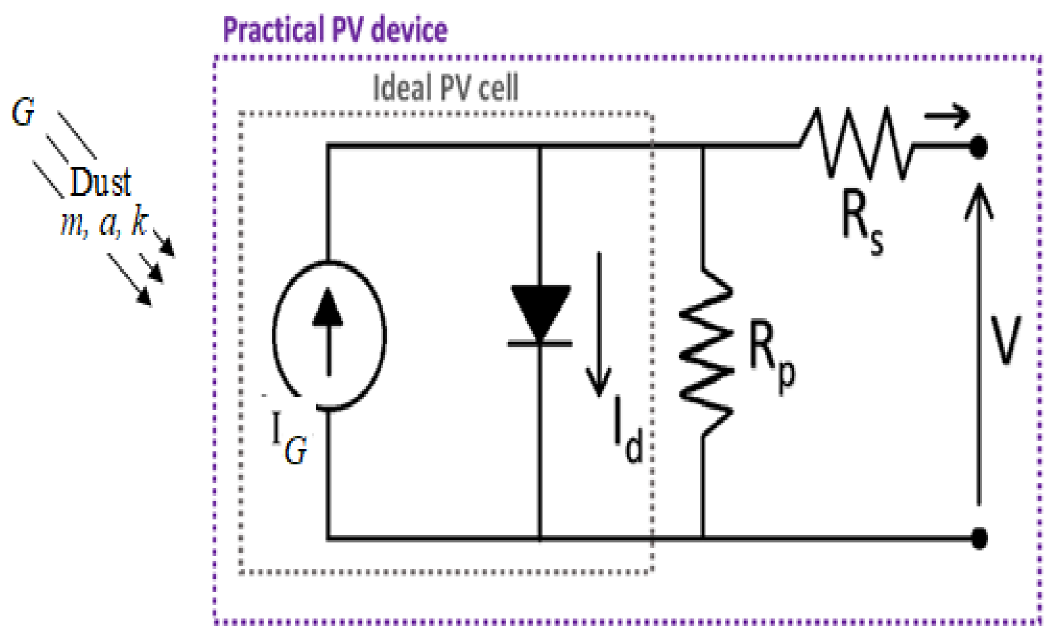
analysis of dust particles in diverse environments [46][47]. Models employ a combination of "numerical and analytical" approaches to anticipate the pattern, composition, and conduct of dust and how they affect the effectiveness of photovoltaics. Dust modelling is utilized in many different areas, like climate modelling, astrophysics, astronomy, and planetary science [48]. Investigating the characteristics of dust can help scientists better understand the development and form of PV systems. Numerous scientists have simulated the influence of dust on PV and measured particular performance metrics, like energy output [49], η_{PV} [50], P_{PV} [51], FF [52][53], transmittance ratio [54], etc. Researchers can gain an understanding of the development of dust by modeling its characteristics. Nonetheless, many proposed models in the literature are primarily limited to case studies and rely on simplistic assumptions, resulting in limited accuracy. Therefore, there is an urgent requirement for a comprehensive model that can effectively capture the impact of dust on PV. Only a small amount of research has been conducted on developing an overarching model. One such model, proposed by [55], introduces enhancements to the existing solar cell "one-diode model". Figure 7(a) shows the proposed model.



(a)

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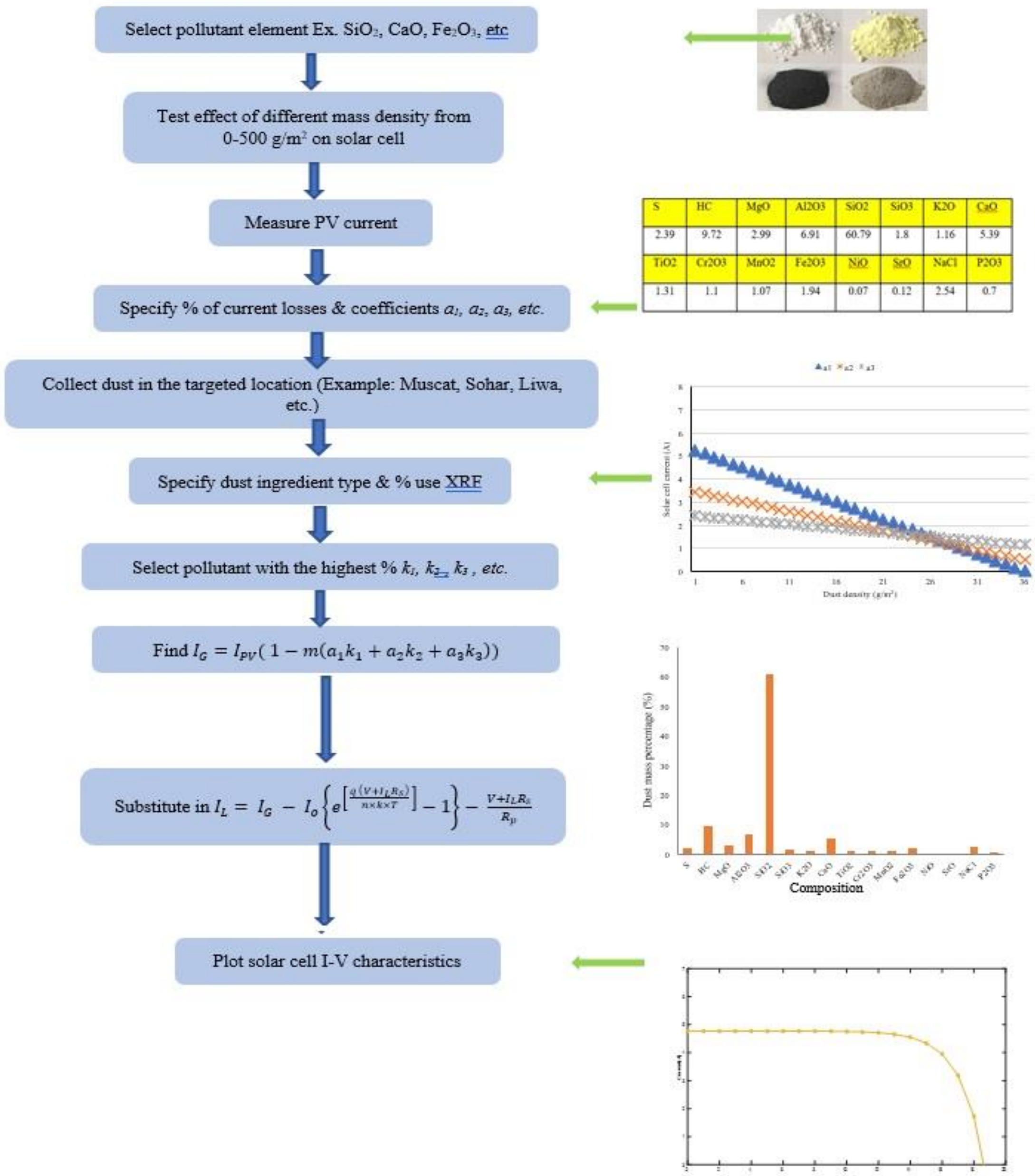

(b)

Figure 7: depicts the following: (a) The incorporation of dust impact in the one-diode model, (b) a flowchart outlining the proposed model

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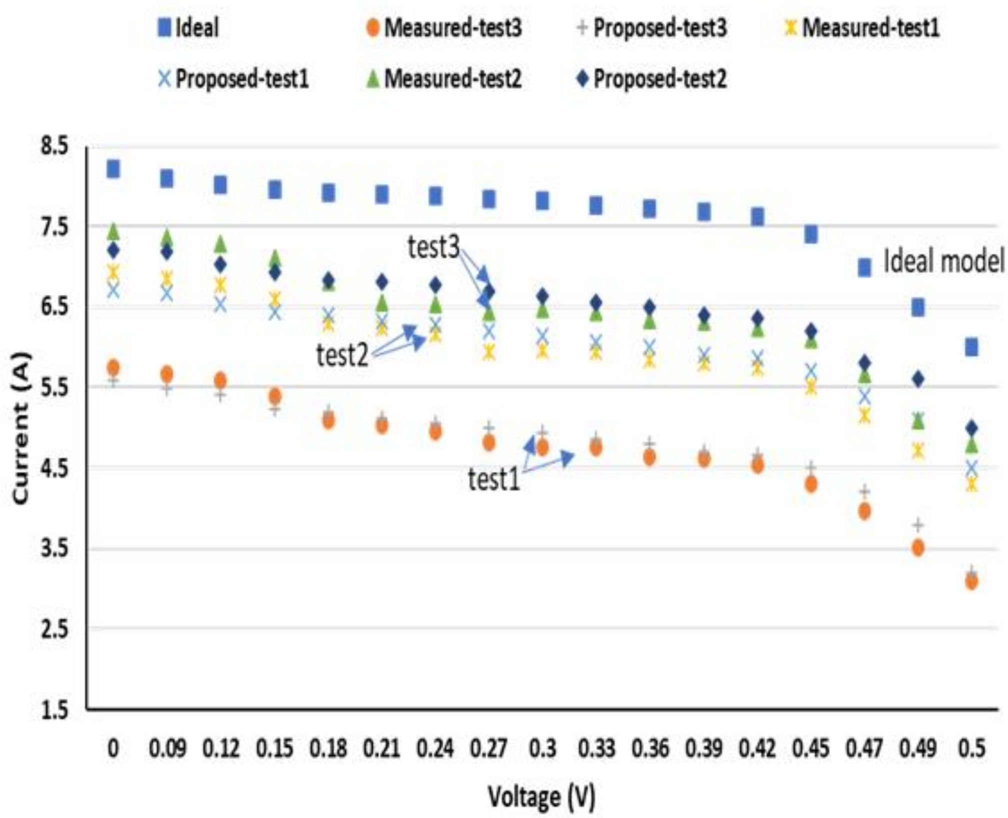

(c)

Figure 8: I-V Characteristics Corresponding to Different Tests [55]

The model proposed in equations (1) and (2) is depicted.

$$I_L = I_G - I_o\left\{e^{\left[\frac{q\,(V+I_L R_S)}{n\times k\times T}\right]} - 1\right\} - \frac{V+I_L R_S}{R_p} \quad (1)$$

$$I_G = I_{PV}(\,1 - m(a_1k_1 + a_2k_2 + a_3k_3 + \cdots + a_nk_n)) \quad (2)$$

Where I_G is the "PV photo-generated current considering dust impact (in A)", *m* is the "dust accumulated mass density ($m = \Delta m/Ac$ in kg/m^2)", *a* (a_1, a_2, *and* a_3) is the "dust element coefficients (in m^2.kg^{-1})", and *k* (k_1, k_2 *and* k_3) is the "dust elements parameter (unitless)", and *n* is the "number of parameters".

In Figure 7(b), the k is resolved by employing XRD analysis to identify the composition and proportions of dust components at the specific site. For instance, if the XRD analysis reveals multiple components and the predominant elements are SiO2, CaO, and Fe2O3, their respective proportions, denoted as k1, k2, and k3, are determined to be 41%, 23%, and 19%. These coefficients represent the impact of the assigned dust elements on the losses in I_{PV}. The model is applicable when dust particles are uniformly or semi-uniformly distributed on PV. In Figure 8, the proposed model is validated by comparing the I-V characteristics obtained from laboratory measurements and ideal model.

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6. NEW PROSPECTS AND BEYOND

The increasing popularity of PVs in desert regions can be attributed to their cost-effectiveness and the availability of inexpensive land for installation. Their simple installation process and minimal infrastructure requirements make them particularly attractive for remote areas and individuals seeking self-sufficiency in electricity generation. Furthermore, advancements in technology have led to a decrease in the cost of PVs, enhancing their affordability and accessibility. Consequently, the trend of PV installation in arid regions is expected to continue as more people recognize the advantages of sustainable energy continues to evolve. However, it is important to address the challenges posed by high temperatures and dust accumulation, which can potentially harm these systems in desert environments. This study focuses on addressing these issues in order to provide a promising outlook for the future of photovoltaic in such areas. The following points highlight some key aspects that contribute to a new perspective and advancements in this field.

- There is still a research gap in developing a comprehensive dust model that can be universally applied across PV systems. This model should consider various elements like dust “composition”, particle “size”, “shape”, “weight”, and “homogeneity” to accurately assess its impact on PVs.
- Standardization of tests is essential to evaluate the effects of dust on PVs consistently. Parameters like sampling time for “dust accumulation”, “cleaning frequency”, “dust uniformity”, “measurement duration”, and “sampling intervals” need to be standardized to ensure reliable and comparable results across different studies.
- Proposed models should go beyond considering only the mass of dust particles. They should incorporate additional parameters like particle “size”, “shape”, “composition”, “weight”, “distribution uniformity”, and “system orientation”. By considering these parameters, the models can provide a more thorough understanding of the dust impact on PV behaviour.
- Environmental factors such as “ambient temperature”, “relative humidity”, and “wind speed” play a significant role in dust behavior and its interaction with PV modules. Therefore, these factors should be considered when modeling the effects of dust. By incorporating environmental parameters, a more accurate assessment of dust's impact can be achieved.
- It is crucial to incorporate the dust model into software used for PV system design. This integration will enable designers and engineers to evaluate the performance and efficiency of PVs in dust-prone environments. Moreover, the applicability of the model can extend beyond Earth, with potential use in extraterrestrial environments like Mars and other space missions.

By addressing these critical points, researchers can bridge the existing research gap, establish standardized testing protocols, develop comprehensive models, consider

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environmental factors, and provide practical tools for PV system design and optimization in various terrestrial and extraterrestrial settings.

7. CONCLUSIONS

Dust acting a sizable role in affecting the electrical performance of photovoltaics. It diminishes the amount of available utilized irradiance, thereby reducing the module's efficiency. Moreover, dust accumulation can lead to corrosion and electrical shorts, resulting in premature malfunction. Additionally, it hinders the cooling capabilities of the module, causing elevated operating temperatures and further performance deterioration. Minimizing dust levels on PV modules is crucial for maintaining optimal performance. This study has reexamined the impacts of dust and highlighted new research avenues that warrant deeper exploration.

- Dust particles possess the potential to cause etching, discoloration, and scratches on glass surfaces. When dust particles embed themselves in the glass, it renders the surface more susceptible to “etching and scratching”. Furthermore, dust can retain moisture and lead to the formation of water spots and mud, resulting in scattering of light and discoloration of the glass. Exploring the challenges of modeling dust, while considering these factors, presents an important area of research.
- Dust particles exhibit various sizes and shapes, posing difficulties in their study. These particles can diminish the performance of PV by absorbing a portion of irradiance and limiting the amount of light reaching the PVs. Consequently, this reduces the electricity generation capacity of the cells. To gain a better understanding of these effects, further research and standardization are required to investigate the “size and shape” of particles.
- The procedure of generalizing the modeling of dust's effect on PVs entails simulating the physical and chemical characteristics of dust elements and investigating how they interrelate with the environment and other objects. This modeling approach helps us recognize the behavior of airborne dust and its various physical and chemical properties. Furthermore, the development of generalized models can assist in determining the optimal size of PV systems, leading to improvements in technical performance and economic viability.

DECLARATION OF INTEREST STATEMENT

“We the authors declare no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript”.

CONFLICT OF INTERESTS

“The authors declare that there is no conflict of interests regarding the publication of this brief note”.

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