



**The Role of Accumulated Dust Chemical Composition on Photovoltaic Thermal  
Performance: Advanced Modeling and Experimental Analysis**

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## **Preface**

This thesis was developed at the School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, New Zealand, to satisfy the requirements for obtaining a Doctor of Philosophy (PhD) degree. The research was conducted from October 2020 to April 2024 under the guidance of Prof. Tek Tjing Lie and Dr. Wisam Al-Shohani. This thesis aimed to explore how dust characteristics affect the thermal performance of photovoltaic (PV) modules in dusty weather conditions.

This exploration encompasses a mix of experimental inquiries and the formulation of theoretical models to anticipate PV temperature across diverse dust scenarios. Furthermore, it underscores the importance of incorporating dust properties into the evaluation of PV module performance. This endeavor entailed both empirical research and the utilization of global data pertaining to how dust influences the optical properties of PV systems for characterizing these properties.

The insights garnered from this thesis have been encapsulated into manuscripts. Each chapter of the thesis begins with a clear delineation of the connection between the manuscript's content and the overarching theme of the thesis. Furthermore, every chapter is dedicated to elucidating the research presented within these manuscripts.

## **Abstract**

One of the significant challenges affecting photovoltaic (PV) performance is the influence of environmental conditions. Cloud cover, rain, and high temperatures can reduce PV efficiency. Among these, dust impacts PV performance and leads to secondary effects, such as increased PV temperature.

This PhD thesis delves deeply into the impact of dust accumulation on photovoltaic (PV) modules, focusing on their thermal and optical performances. Firstly, the study identifies gaps in existing research and highlights the lack of consideration of how dust accumulation can impact PV temperature and the mathematical and specific correlation between dust accumulated weight and type on PV temperature. Additionally, the literature review reveals that a generalized module calculation is required to determine dust optical properties, which can help researchers and scholars identify the impact of dust on PV optical properties.

This study introduces a comprehensive approach that integrates a wide range of dust characteristics into the thermal and optical analysis of PV modules. This research unfolds through several phases, each delving into distinct yet interconnected aspects of how dust affects PV efficiency.

Regarding thermal effects, the investigation exposes the limitations of existing methodologies inadequately accounting for dust parameters. This revelation propels the research forward, employing advanced experimental setups and innovative mathematical models. These models, distinguished by their inclusion of absorption, emittance, and meteorological data, surpass traditional approaches in forecasting PV temperatures across varied dust conditions. The meticulous empirical validation against real-world scenarios underscores these novel formulations' heightened accuracy and practicality. Tested under real weather conditions, these models demonstrate a notable improvement in predicting PV module temperatures, achieving the lowest mean absolute error (MAE) of 1.4 compared to traditional methods, marking a significant advancement in the field.

In the subsequent phase, the research underscored the optical considerations that consider essential parameters to determine the PV temperature. The study has employed intelligent methodologies such as Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR) to develop a novel model. Those models incorporate dust weight and the principal elements in the chemical composition of dust particles. This segment of the study, drawing from over 300 experimental observations and leveraging more than 600 global datasets, has yielded notable predictive precision which can predict the dusty PV

surface the most important dust optical properties, which are emissivity, absorption, and transmittance where those parameters can play a crucial role to predict the PV performance and temperature. Additionally, the predictive novel has been compared with other modules that have been developed using different techniques to produce the transmittance of dusty PV using The Mean Squared Errors (MSEs). This developed module achieved the lowest MSE, where 1.8 is achieved for the ANN models and 8.44 for the MLR models, setting new benchmarks for predictive accuracy within dust's influence on PV modules.

The culmination of experimental insights and enhanced predictive accuracy constitutes the foundation of this thesis, providing a comprehensive perspective on the impact of dust on PV modules. This study addresses several critical research gaps, including the lack of specific models that integrate both the thermal and optical effects of dust accumulation, the absence of clear correlations between dust properties and PV temperature, and the need for generalized methods to quantify dust's optical properties (such as transmittance, absorption, and emissivity). These contributions, supported by empirical validation and advanced predictive modelling, significantly advance understanding and mitigating dust's effects on PV systems. The research's original contributions are validated through comparative analysis with existing literature, showcasing its superior predictive capabilities. This thesis significantly contributes to the field of PV technology by addressing crucial knowledge gaps and introducing improved methodological frameworks. It underscores the significance of a thorough comprehension of dust's profound influence on PV modules, advocating for a multidisciplinary approach to bolster the position of solar energy in the global energy market, particularly in regions grappling with dust-related challenges.

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### **Attestation of Authorship**

I hereby declare that this submission is my own work and that the work presented in this thesis is solely based on my own research. The content of this PhD work is original, except where the work is referenced. I also declare that this work has not been submitted in whole or in part for the purpose of degree or qualification at any degree-awarding institute. I declare that this thesis is my own work and contains nothing as an outcome of work done in internal and/or external collaboration.

.....

Hussam Almukhtar

April 2024

## Co-Authored Works

Chapter title	Author	Contribution(%)
Chapter 2: Comprehensive Review of Dust Properties and Their Influence on Photovoltaic Systems: Electrical, Optical, Thermal Models and Experimentation Techniques	Hussam Almkhtar	70
	T. T. Lie	10
	Wisam A. M. Al-Shohani	10
	Timothy Anderson	5
	Zaid Al-Tameemi	5
Chapter 3: Comprehensive analysis of dust impact on photovoltaic module temperature: Experimental insights and mathematical modeling	Hussam Almkhtar	75
	T. T. Lie	15
	Wisam A. M. Al-Shohani	10
Chapter 4: Dust Impact on Photovoltaic Modules: Global Data, Predictive Models, Emphasis on Chemical Composition	Hussam Almkhtar	75
	T. T. Lie	15
	Wisam A. M. Al-Shohani	10

We, the undersigned, hereby agree to the percentages of participation to the chapters identified above:

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## **Publications During the PhD Programme**

Almukhtar, H., Lie, T. T., Al-Shohani, W. A., Anderson, T., & Al-Tameemi, Z. (2023). Comprehensive review of dust properties and their influence on photovoltaic systems: Electrical, optical, thermal models and experimentation techniques. *Energies*, 16(8), 3401. **(Published)**

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# Chapter 1: Introduction

## 1. Background

The escalating urgency of the climate crisis, compounded by the finite nature of fossil fuels, has precipitated a profound global shift towards sustainable and renewable energy sources. Embracing renewable energy options such as solar power instead of relying solely on fossil fuels presents a significant opportunity to mitigate climate change. Photovoltaic (PV) systems, which harness sunlight to generate electricity, stand out as pivotal players in this transition. The advancement of PV technology holds immense promise in curbing pollution and reducing reliance on traditional energy sources, thereby combating global warming. This technology's versatility allows for its deployment wherever needed. Several factors underscore the critical importance of PV systems in achieving sustainable energy goals. Notably, they capitalize on ubiquitous sunlight, ensuring a perpetually available energy source [1]. Furthermore, recent years have witnessed remarkable strides in PV technology, resulting in substantial cost reductions for PV modules. This cost decline has positioned PV systems to compete more effectively with conventional electricity generation methods [2]. The transition towards renewable energy sources, notably solar power, is increasingly evident, reflecting a burgeoning global interest. Projections indicate a substantial rise in solar photovoltaic installations, potentially positioning it as the second-largest electricity source worldwide by 2050 [3], as depicted in Figure 1.

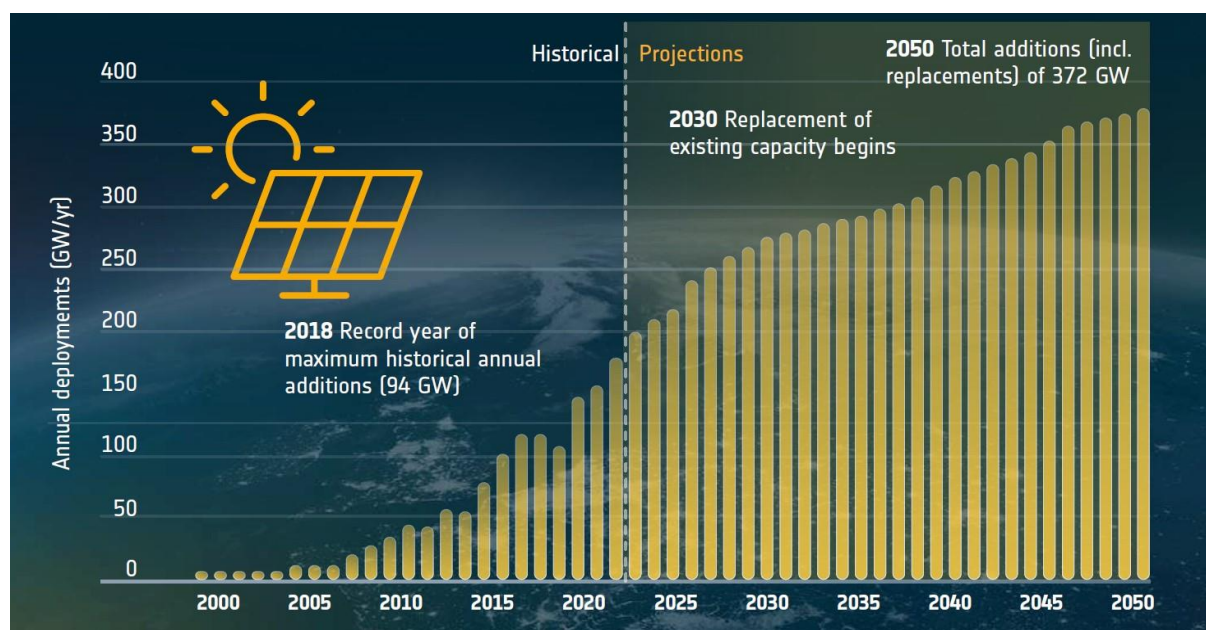


Figure 1 Current and Future Perspective of Utilizing PV Modules [3]

Furthermore, PV systems can be installed in various sizes, ranging from small setups on household rooftops to expansive solar farms. Yet, to fully leverage the potential of PV technology, enhancing its efficiency is paramount. Efficiency in this context denotes the percentage of incident solar energy that PV modules can convert into electricity. Although PV systems hold significant promise as sustainable energy sources, their performance varies across different environments. Environmental factors directly impact crucial efficiency metrics and the long-term resilience of PV installations, underscoring the importance of a comprehensive understanding for strategic solar deployment and optimization.

## **2. The Impact of Environmental Factors on PV Performance**

While PV modules have garnered significant attention in the pursuit of sustainable power generation [4], their efficacy hinges greatly on how efficiently they can harness solar energy, a process influenced by various environmental factors as illustrated in Figure 2 [5]. Understanding the intricate interplay of these factors with PV performance is crucial for optimizing energy production and ensuring the long-term reliability of solar technologies [6].

The primary driver of PV performance is solar irradiance, which quantifies the intensity of sunlight reaching the Earth's surface [4]. Fluctuations in solar irradiance, whether due to daily cycles, seasonal variations, or weather conditions, directly impact the amount of energy captured by PV modules [7]. Cloud cover, atmospheric pollution, and geographical location are among the factors contributing to these fluctuations. Hence, meticulous site selection and system design are imperative to maximize energy yield [8].

While sunlight is indispensable for PV operation, excessive heat can dampen its performance. It is well-established that PV modules experience diminished efficiency as temperatures rise [9]. Therefore, mitigating thermal effects is essential for sustaining optimal performance, particularly in regions characterized by high ambient temperatures [10].

Partial shading poses a significant challenge to PV systems, resulting in power mismatches at the cell level [11]. This phenomenon can cause a PV system to operate at reduced capacity and may even lead to the formation of local hot spots that could cause permanent damage to the PV module [12]. Moreover, the tilt angle and orientation of PV modules play a pivotal role in maximizing energy capture across different locations, seasons, and throughout the day [13]. Adjusting the tilt angle of the PV module according to geographical location and solar

trajectory can markedly enhance annual energy generation compared to horizontal PV installation [14].

Elevated humidity levels, particularly prevalent in coastal regions, can accelerate the degradation of PV materials [15]. This may result in the formation of rust on metal frames and electrical components, adversely affecting the long-term reliability of PV systems [16].

PV installation is susceptible to various risks, including severe weather phenomena. Hail, dust storms, and lightning strikes pose significant threats to PV modules [17]. During the system design phase, it is imperative to consider potential adverse weather conditions in the area and incorporate protective measures to mitigate potential hazards [18].

Furthermore, the build-up of dust, dirt, bird droppings, pollen, and other particulates on PV module surfaces diminishes sunlight transmittance, thereby affecting overall system efficiency [19]. This accumulation of soiling represents a multifaceted threat that influences the optical, electrical, and thermal behavior of PV modules. The subsequent section will delve into these impacts in detail.

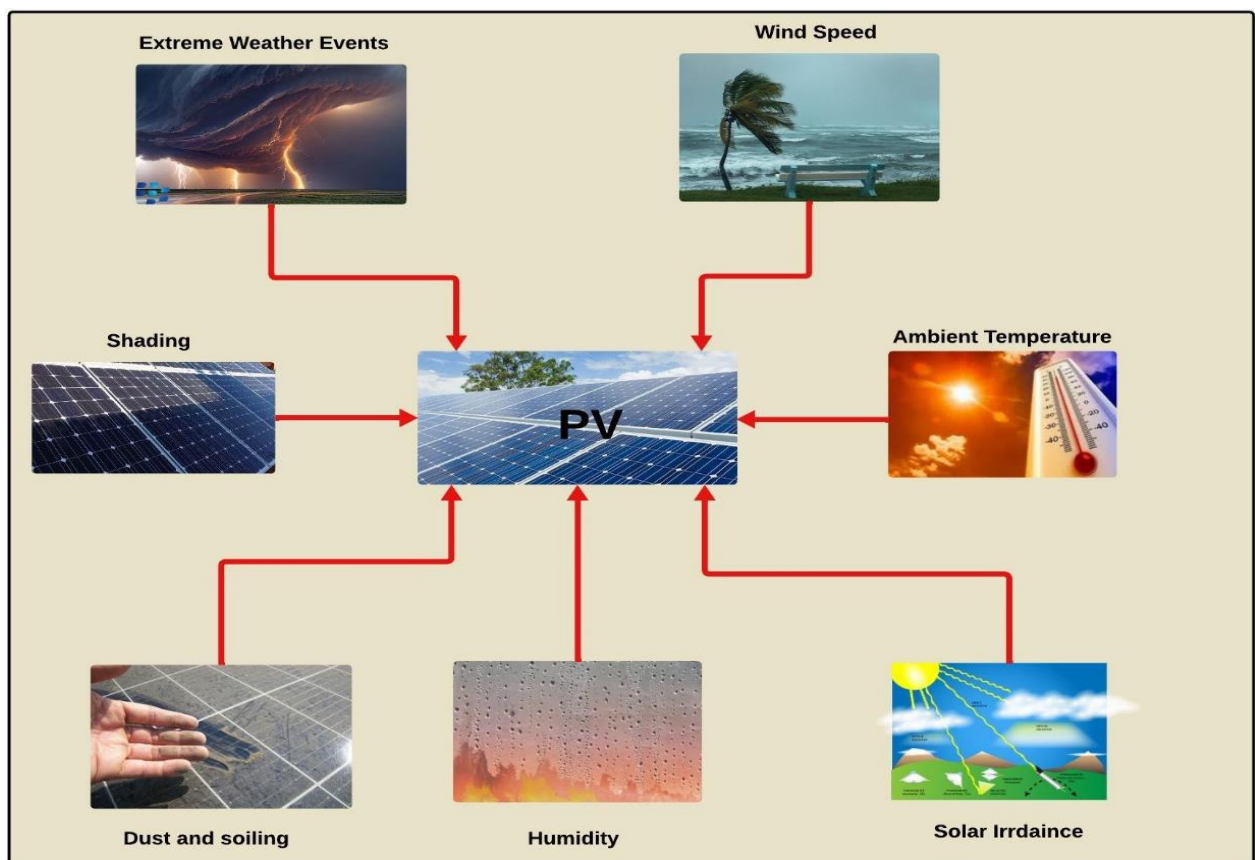


Figure 2 Environmental Factors Influencing the Efficiency of PV Module Performance

### 3. The impact of dust on PV

The performance of PV modules relies on the conversion of incident sunlight into electricity. However, the accumulation of dust on the PV surface results in the formation of a thin layer. This layer of dust affects the transmittance of incoming irradiance, output power, and the thermal characteristics of the PV modules [20]. The subsequent subsections will review the current literature regarding the influence of dust properties on the performance and lifespan of PV modules.

#### 3.1 The impact of dust on the electrical characteristics

Dust is a critical factor directly impacting the degradation of PV performance [21]. The efficiency of PV modules can experience significant drops due to the accumulation of dust, leading to physical damage and alterations in the module's electrical properties [22], [23]. The effect of accumulated dust on PV module efficiency has been extensively researched in numerous peer-reviewed papers, with various experiments conducted to illustrate these effects [24], [25].

The build-up of dust on PV modules diminishes the amount of incident sunlight utilized for electricity generation, with the rate of reduction varying depending on factors such as natural conditions or sandstorms. In instances where cleaning does not occur, prolonged exposure to increased dust density can substantially impair PV productivity. For instance, in Surabaya, Indonesia, two weeks of exposure to solar panels resulted in a 10.80% reduction in PV productivity [26]. Similarly, in Baghdad, Iraq, one month of exposure led to a 31.4% reduction [27], with an accumulation of  $0.64 \text{ g/m}^3$  of dust reduced PV efficiency to 15.87% [28]. Experimental findings in Tipaza, Algeria, demonstrated that an accumulation of  $8 \text{ g/m}^2$  of dust led to a 50% reduction in panel efficiency [29]. In Zarqa, Jordan, exposure to PV modules resulted in a daily power output reduction of 0.768% [30].

Furthermore, investigations into the impact of dust storms on PV performance have revealed substantial reductions in output, with a single sandstorm day leading to over a 32% decrease in power output from the PV power plant. This reduction can be attributed to the amount of dust accumulated on the PV modules [31]. The quantity of power lost is directly proportional to the amount of dust deposited on the panel surface, as demonstrated experimentally by Dida et al. (2020), where the accumulation of 2.7 and  $4.4 \text{ g/m}^2$  of dust resulted in reductions in PV production by 5.71% and 8.41%, respectively [31]. Furthermore, investigations by Ullah et al.

(2020), have revealed a linear relationship between dust accumulation and power loss, indicating a decrease in PV energy from 0.2 to 23% as dust levels increase from 10 to 185 mg [32]. In summary, dust deposition on PV modules can significantly diminish the output of the modules. The impact of dust on the optical characteristics.

The accumulation of dust on the surface of PV modules directly affects the amount of sunlight reaching the solar cells, thereby influencing the optical properties of the PV surface [33]. Research by [33] investigated total transmission for various dust weights per unit area and found that overall transmission decreases linearly with dust mass per unit area. Additionally, [34] observed that the addition of one gram of dust per square meter reduced sunlight transmittance by 4.1%.

Furthermore, studies have examined the impact of dust settling on sunlight transmittance. Research by [35] revealed that dust settlement not only reduces the transmittance of the top glass surface of PV modules but also significantly affects incident sunlight transmittance. Experimental results from [36] showed that atmospheric dust accumulation can reduce the relative transmittance of a PV module by 20% in just during eight days. Moreover, [36] investigated the influence of dust accumulation on the surface transmission of PV modules, demonstrating that dust deposition on the front module surface can reduce the transmission by up to 25% over 70 days.

Hasan and Sayigh [37] explored the effect of dust on glass transmittance by subjecting samples to outdoor conditions in Kuwait for 38 days. Their findings revealed a 6% reduction in transmittance when the samples were tilted horizontally. This reduction in transmittance can be attributed to the catastrophic soiling mechanism, where dust particles agglomerate and compress on surfaces, forming a solid link following drying [38]. This cementation process exacerbates dust accumulation, leading to a significant reduction in the performance of PV modules by scattering and absorbing solar energy.

### 3.2 The Impact of Accumulated Dust on PV Temperature

The accumulation of dust on PV modules poses serious consequences beyond merely reducing power output. One critical effect is a significant increase in module operating temperature, which can lead to severe performance degradation and shorten the module's lifespan. Manufacturers typically specify maximum operating temperatures, typically around 85 °C, in

their datasheets to prevent damage [39]. However, in dusty and hot climates, these limits can be surpassed, as noted by Kazem et al. in 2014 [40].

An illustrative example can be found in the harsh Algerian desert, where dust-related overheating has been associated with front glass cracking in approximately 680 commercial PV modules as shown in Figure 3 [41].

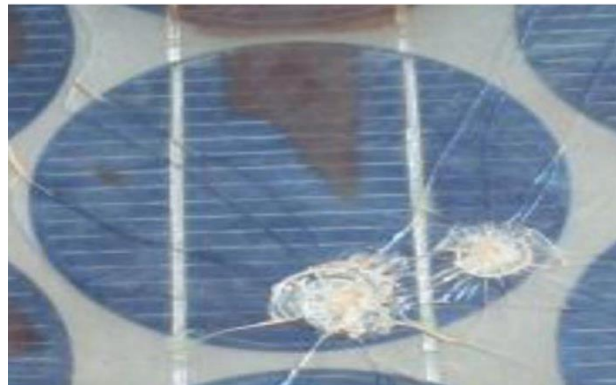


Figure 3 Significant faults discovered in the PV module in a dusty hot environment [41]

Dust functions as a thermal insulator, trapping solar energy and elevating PV module temperatures. Numerous studies consistently demonstrate that modules covered with dust operate at higher temperatures, resulting in reduced output compared to clean ones [40]. In extreme cases, temperature increases of over 23 °C have been recorded [29], leading to hotspots where localized areas reach dangerously high temperatures, further compromising cell performance [42].

Elevated PV module temperatures precipitate a series of detrimental effects: decreased power output, heightened risk of irreversible damage, and accelerated long-term degradation [41]. Research suggests that different types of dust influence temperatures in varying ways, with soil dust causing higher temperatures compared to salt dust [29].

#### **4. Research Gaps and Questions**

Through comprehensive investigation and review of existing literature on the thermal and optical effects of dust on PV modules, this study has uncovered several notable research gaps. These findings can be categorized into two distinct parts of research:

Part 1 - Thermal Effects Analysis:

- Comprehensive dust impact analysis: Existing studies have primarily focused on the effects of dust on transmittance, often neglecting critical factors such as absorption and emittance that significantly influence the thermal behavior and efficiency of PV modules.
- Advanced experimental techniques: More advanced experimental methods are needed to study the effects of dust on sunlight absorption and heat dissipation in PV modules.
- Integration of dust characteristics in thermal models: Many current models do not adequately incorporate the full range of dust characteristics, meteorological data, and PV parameters, which are needed for accurate temperature estimation of PV modules.
- Model validation and comparative analysis: A significant gap exists in the rigorous validation of new thermal models against real-world data, especially under varied dust conditions.

#### Part 2 - Optical and Chemical Analysis:

- Region-specific limitations: Existing studies predominantly focus on dust types specific to certain regions, limiting the generalizability of the findings across different weather conditions.
- Dust characterization: Most current models to estimate the optical properties consider only the weight of the dust, overlooking crucial factors such as its chemical composition, which can significantly influence the optical properties.
- Optical properties analysis: The literature primarily addresses the impact of dust on transmittance, while other critical optical properties like absorbance and emissivity are often neglected. A comprehensive understanding of these properties is essential for evaluating the thermal behavior and efficiency of PV modules.
- Analytical techniques: Simple analytical methods like curve fitting are frequently used to estimate changes in optical properties due to dust, which may not accurately represent the complex interplay between dust's chemical and optical characteristics.
- Mathematical modeling: Typically, models are confined to specific ranges of dust weight, which could lead to inaccuracies in scenarios with broader dust accumulation. There is a highlighted need for more inclusive mathematical models considering a more comprehensive range of dust characteristics beyond just weight.

The following research questions guide the investigation:

1. How can we enhance the accuracy of PV temperature and efficiency estimations by integrating often overlooked factors such as absorption, emittance, and chemical composition of dust?
2. What advanced experimental and mathematical modeling techniques can be developed to understand and predict the comprehensive impact of dust on the thermal and optical properties of PV modules?
3. In what ways can the new models be validated against real-weather scenarios to ensure accuracy and practical applicability under various dust conditions?
4. How can the incorporation of diverse datasets covering a broad range of dust characteristics improve the generalizability and accuracy of PV system predictions, particularly in addressing region-specific limitations?
5. What advanced modeling techniques can be used to create new models that accurately predict changes in optical properties due to dust accumulation?

This comprehensive study endeavors to bridge the identified gaps, offering an integrated understanding of how dust accumulation influences the thermal behavior and optical properties of PV modules. Through addressing these areas, the research aims to provide holistic insights and practical tools for predicting the effects of dust accumulation on PV modules.

## **5. Methodological Approach Overview**

This dissertation embarks on a thorough investigation into the influence of dust accumulation on the thermal and optical performance of PV modules, employing a combination of experimental analysis and mathematical modeling. Each chapter of this study delves into distinct aspects of dust's impact on PV modules, employing specific methodological approaches to achieve the study's objectives and address its central questions.

The introductory chapter commences with a comprehensive literature review, critically assessing existing studies to pinpoint gaps in the current understanding of dust's effects on PV modules. This chapter guides the methodological decisions made in subsequent analyses by underscoring the necessity for a more nuanced understanding of dust's thermal and optical impacts on PV performance.

Chapter 3 conducts a comprehensive analysis of the impact of dust on PV module temperature, introducing a detailed methodological approach aimed at establishing mathematical

correlations between dust properties and PV module thermal performance. The methodology encompasses:

- Theoretical framework development: Construction of mathematical models that capture the intricate relationship between dust accumulation and PV module temperature, encompassing both simplified and complex multi-layer structures.
- Empirical validation: Execution of outdoor experiments to validate these mathematical correlations, involving systematic dust collection and analysis under real-world conditions.
- Data synthesis and analysis: Integration of experimental findings with model predictions to assess the accuracy and applicability of the proposed models.

Following an examination of the significance of dust properties for estimating PV temperature, Chapter 4 delves into global data and predictive modeling, with specific emphasis on the chemical composition of dust. This chapter shifts focus to the optical properties of dusty PV modules, employing the following methodological approach:

- Data collation and analysis: Compilation of a comprehensive dataset from global sources, emphasizing the chemical composition of dust and its varied impacts on PV modules across different regions.
- Advanced predictive modeling: Utilization of Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR) to develop robust models capable of predicting changes in the optical properties of PV modules due to dust accumulation.
- Experimental validation and comparative analysis: Validation of these models through experimental data and comparison of the findings against existing literature to ascertain their accuracy and broader applicability.

The methodology in this chapter aims to deepen the understanding of how dust's chemical composition affects the optical performance of PV modules and refine predictive models for better management of dust effects.

This dissertation employs a structured methodological approach to investigate the impact of dust on PV systems. Subsequent chapters will offer more detailed explanations and justifications for the chosen approaches.

## **6. Dissertation Structure Overview**

This Ph.D. thesis follows Auckland University of Technology (AUT)'s Format Two, also referred to as the "Manuscript Format". As per this format, except for the initial and final chapters, the core chapters are presented as manuscripts intended for publication. Consequently, there may be inherent repetitions in these chapters due to the structure. Each manuscript chapter commences with an introduction section, aimed at providing context and ensuring connectivity within the thesis framework.

### **Chapter 1: General Introduction**

This opening chapter introduces the thesis, emphasizing the significance of PV systems and the detrimental impact of dust accumulation. It establishes the study's objectives, questions, and scope, setting the stage for in-depth research in subsequent chapters.

### **Chapter 2: Comprehensive Review of Dust Properties and Their Influence on Photovoltaic Systems**

This Chapter reviews the literature on dust's optical, thermal, physical, and chemical aspects. It highlights the need for advanced research to investigate the impact of dust on PV thermal efficiency in dusty conditions.

### **Chapter 3: Comprehensive Analysis of Dust Impact on Photovoltaic Module Temperature**

This Chapter addresses the knowledge gap regarding dust's effect on PV module temperature. The Chapter offers insights into accurate PV temperature estimation in dusty environments through experiments and a novel mathematical model considering key dust characteristics.

### **Chapter 4: Dust Impact on Photovoltaic Modules: Global Data, Predictive Models, and Chemical Composition Emphasis**

This Chapter focuses on the chemical impact of dust on PV modules. This study uses experimental data, global data, and advanced modeling to improve understanding of dust effects on PV optical properties, showcasing the international applicability of these findings.

### **Chapter 5: Conclusion and Future Research Directions**

This concluding chapter provides a summary of the thesis, encapsulating key findings and reflecting on the research objectives. It offers conclusive remarks and outlines potential avenues for future research to address the challenges posed by environmental dust on PV modules.

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## **Chapter 2: Manuscript 1 - Literature Review**

This manuscript delves into the impact of dust accumulation on PV systems, offering a comprehensive review of various dust properties and their influence on PV system performance. It examines electrical, optical, and thermal models, elucidating how dust affects these fundamental aspects of PV performance. Additionally, it explores established experimental techniques utilized to quantify the impact of dust deposition on PV panels. The aim of this manuscript is to synthesize current knowledge on dust-PV interactions, shedding light on the ramifications of dust accumulation on PV systems and providing insights for researchers striving to optimize PV efficiency in dusty environments. Furthermore, the manuscript concludes by identifying areas within this field that warrant further investigation. It underscores the necessity for comprehensive research into dust's thermal properties, such as conductivity and emissivity, to enhance predictive thermal modeling of PV systems operating in dusty conditions.

# ***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

## 1. Introduction

Photovoltaic 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 [17,18,19]. 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.

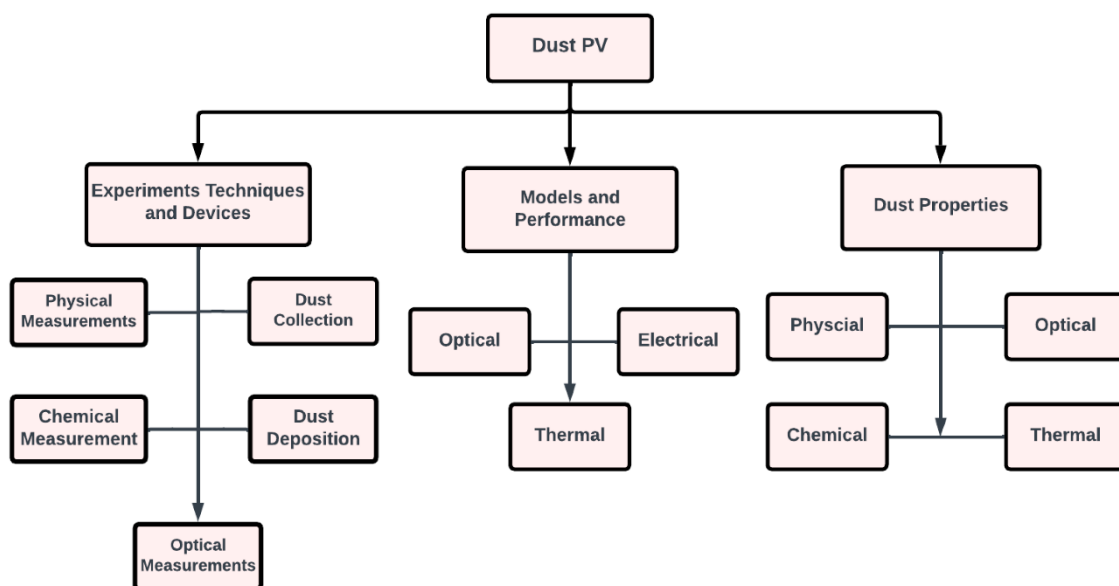


Figure 1. Illustration of the three aspects of dust’s impact on PV systems.

## 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  $\mu\text{m}$  [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  $\mu\text{m}$ , 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 ( $\text{Fe}_2\text{O}_3$ ) has a higher absorption rate compared to dust composed mainly of silica ( $\text{SiO}_2$ ) [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<sup>2</sup>, 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<sup>2</sup>.

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<sup>2</sup> 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  $\mu\text{m}$  for clay particles to 190  $\mu\text{m}$  for soil particles, with the majority (83%) in the range 0.3 to 60  $\mu\text{m}$  [45]. The size of the dust was measured experimentally, and it revealed that the size spans from 0.1 to 1000  $\mu\text{m}$ , with the bulk of collected particles (43%) having diameters ranging from 100 to 500  $\mu\text{m}$  and 15% having diameters ranging from 10 to 50  $\mu\text{m}$  [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  $\mu\text{m}$ , smaller than that recorded for dust storm occasions, which have a majority range of 1.1 and 1.2  $\mu\text{m}$ .

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  $\mu\text{m}$ , and 15% of the dust particles had diameters ranging from 10 to 50  $\mu\text{m}$  [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  $\mu\text{m}$  and smaller) had a greater impact on power output at low irradiance levels (300–500  $\text{W}/\text{m}^2$ ) but the larger particle size (150  $\mu\text{m}$ ) had a greater impact at higher irradiance levels (1000–1200  $\text{W}/\text{m}^2$ ).

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<sup>2</sup>, and by 20% when the dust deposition density was 2 g/m<sup>2</sup>. 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<sup>2</sup> (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 to 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  $30 \times 30$  cm<sup>2</sup> 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<sub>2</sub>, 24.59%), and iron (Fe, 23.37%) were the most abundant elements in Babuin dust. The XRD data revealed that quartzite (SiO<sub>2</sub>) 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<sub>2</sub> 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<sub>2</sub> 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<sup>2</sup> [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 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<sup>2</sup> [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<sup>2</sup>) 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 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% R2) [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 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<sup>2</sup> @ 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<sup>2</sup>.

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<sup>2</sup> 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 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.

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

Total solar radiation intensity is  $G$ ,  $A_c$  is the panel surface area,  $\tau_g$  is the glass cover transmissivity, and PV cell absorptivity is  $\alpha$ , PV efficiency is  $\eta$ , the transmittance of a clean surface is  $\tau_{clean}$

In Ref. [126], 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  $N_p$  is the total number of dust particles released during  $t_d$ ,  $\lambda$  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  $\rho_p$ , 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. [127] 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.

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

where  $P_{los}$  is the output power loss percentage and  $d$  is the dust density.

In Ref. [119], 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  $\leq 534.5$ , then

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

otherwise, if irradiance  $> 534.5$ , then

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

where  $P_{max}$  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  $\rho$  are dust and cumulative dust in milligrams per cubic meter; and  $v$  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. [128]. 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  $S_7 = 0.72 \mu\text{m}$ . Please note that the coefficients for  $S_1$ ,  $S_2$ ,  $S_3$  are zero.

Ref. [129] 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  $1 \text{ g/m}^2$ ; however, the rate at which these values drop increases with increasing dust concentrations, as presented in Equation (8).

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

where  $M$  is the increase in the number of sand dust particles ( $\text{g/m}^2$ )

Ref. [130] 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 ( $860 \text{ W/m}^2$ ,  $40 \text{ }^\circ\text{C}$ ).

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).

$$D = 0.47e^{\frac{Pr}{34.93}} - 0.37 \quad (9)$$

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

A theoretical model is used in Ref. [131] 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).

$$\Delta\eta_j = \eta(1 - e^{-A_j \Delta M_j}) \quad (10)$$

where  $\Delta\eta_j$  is the standard deviation value corresponding to each of the three contaminants investigated.  $\Delta M$  is the dust accumulation in  $\text{g}/\text{m}^2$ .

Ref. [132] 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).

$$L_s = K_s M_d \times e^{-kt} \quad (11)$$

where  $L_s$  is the soiling loss,  $M_d$  is the collected dust mass,  $k$  is the cleaning rate constant,  $K_s$  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. [133] 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).

$$\frac{Er}{Ec} = K \frac{\lambda N_p \pi \rho_p d_p^3}{6 t_d A_{PV}} T 100\% \quad (12)$$

where reduced energy ( $Er$ ) and clean energy ( $Ec$ ) characterize PV. The number of particles that fell in each time interval is denoted by  $(N_p/t_d)$ . 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 [134]. 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 [135]. 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 [10,136]. Several investigations have demonstrated that dust buildup considerably decreases PV module transmittance and can significantly decrease the electrical output of PV. For example, Ref. [137] 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 [126]. 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. [138] 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).

$$\tau = \tau_c [1 - 0.3437 \operatorname{erf}(0.17\omega^{0.8473})] \quad (13)$$

where  $w$  is the dust weight on PV ( $\text{g}/\text{m}^2$ ), and  $\tau_c$ , and  $\tau$  are the clean surface transmittance and the dusty transmittance, respectively. This requires knowing the inverse of the Gauss error function  $\operatorname{erf}(x)$ .

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).

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

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

Ref. [139] 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. [139], 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,  $\rho$  is dust particle density,  $Ri$  is dust particle radius,  $\gamma$  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  $\rho$  is the dust deposition density in ( $\text{g}/\text{m}^2$ ) 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:

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

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.

#### Author Contributions

Conceptualization, methodology, writing—original draft preparation, H.A.; writing—review and editing, supervision, investigation, and visualization, T.T.L., W.A.M.A.-S., T.A. and Z.A.-T. All authors have read and agreed to the published version of the manuscript.

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## **Chapter 3: Manuscript 2 – The Impact of Dust on PV Temperature**

This manuscript delves into the impact of dust on the temperature and efficiency of PV modules. Dust accumulation presents a significant challenge to solar energy systems, and this manuscript introduces a novel, advanced mathematical model aimed at precisely predicting PV module temperature under dusty conditions. The model incorporates unique dust properties such as emissivity, absorbance, and transmittance to enhance existing prediction tools. Its formulation prioritizes the accuracy of temperature predictions, crucial for optimizing solar energy systems. The authors showcase the model's superiority over existing methods. Importantly, this study provides valuable insights into how dust influences solar panel performance and offers guidance for maximizing energy output in real-world scenarios.

# **Comprehensive analysis of dust impact on photovoltaic module temperature: Experimental insights and mathematical modelling**

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**Abstract:**

Dust accumulation substantially impacts the efficiency and thermal behavior of photovoltaic (PV) modules. Addressing a current knowledge gap, this article presents a comprehensive assessment of the impact of dust on PV module temperature. This endeavor includes a combination of systematic experiments with a novel developed mathematical model that uniquely incorporates key dust parameters such as emissivity, absorbance, and transmittance. The model enhances accuracy in estimating PV module temperature compared to existing mathematical models, which often overlook heat absorption due to dust and specific dust characteristics. These parameters are measured using specialized devices to ensure realistic values. Outdoor experiments are conducted to validate the model's predictions under real weather conditions, further highlighting the importance of accurate PV temperature estimation in dusty environments. Additionally, a comparative analysis is performed with existing mathematical models for PV temperature prediction, demonstrating the superior performance of the proposed model, which achieves the lowest average prediction error (mean absolute error of 1.4). These findings provide valuable insights into the estimation of PV temperature in dusty conditions, bridging the gap between theoretical modeling and practical application and underscoring the novelty and innovation introduced in this research.

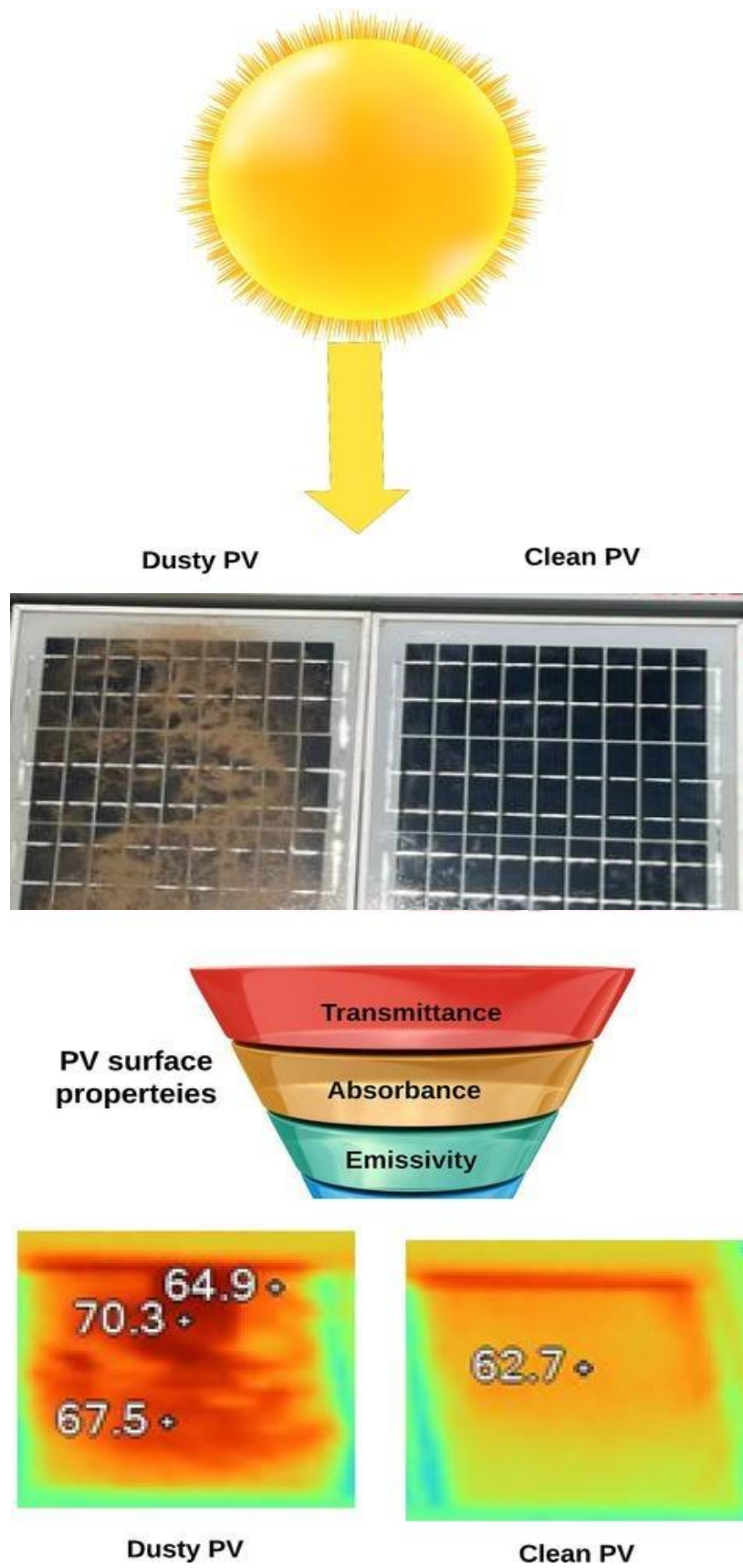


Figure Graphical abstract.

## Nomenclature

<b>Symbol</b>	<b>Description</b>
$T_{PV}$	Temperature of the PV module ( $^{\circ}\text{C}$ )
$T_a$	Ambient temperature surrounding the PV module ( $^{\circ}\text{C}$ )
$G$	Solar irradiance received by the module ( $\text{W}/\text{m}^2$ )
$v$	Wind speed impacting the module ( $\text{m}/\text{s}$ )
$\omega$	Humidity level (%)
$\alpha$	Absorptivity coefficient of the PV module (Dimensionless)
$\eta$	Efficiency of the PV module (%)
$\tau$	Transmittance of the module (Dimensionless)
$U_l$	Overall heat loss coefficient of the module ( $\text{W}/\text{m}^2\text{C}$ )
$U_v$	Coefficient related to wind speed ( $\text{W}/\text{m}^2\text{C}$ )
$\gamma$	Coefficient indicating the thermal impact on the electrical PV coefficient (Dimensionless)
$\beta$	Coefficient for PV cell temperature dependency ( $^{\circ}\text{C}^{-1}$ )
$\sigma$	Stefan-Boltzmann constant ( $\text{W}/\text{m}^2\text{K}^4$ )
$h_c$	Convective heat transfer coefficient ( $\text{W}/\text{m}^2\text{C}$ )
$h_r$	Radiative heat transfer coefficient ( $\text{W}/\text{m}^2\text{C}$ )
$Q_{in}$	Energy input to the PV module (W)
$Q_{out}$	Energy output from the PV layer (via convection and radiation) (W)
$\alpha_d$	Absorptivity of the dusty layer (Dimensionless)
$\tau_c$	Transmittance of the clean surface (Dimensionless)
$\epsilon_{PV}$	Emissivity of the PV module (Dimensionless)
$T_{sky}$	Sky temperature ( $^{\circ}\text{C}$ )
$T_g$	Temperature of the glass layer of the PV module ( $^{\circ}\text{C}$ )
$L_g$	Thickness of the glass layer (m)
$k_g$	Thermal conductivity of the glass layer ( $\text{W}/\text{m}^{\circ}\text{C}$ )
$T_{E1}$	Temperature of the EVA1 layer ( $^{\circ}\text{C}$ )
$k_E$	Thermal conductivity of the EVA1 layer ( $\text{W}/\text{m}^{\circ}\text{C}$ )
$T_c$	Temperature of the PV cell ( $^{\circ}\text{C}$ )
$k_b$	Thermal conductivity of the back surface (Tedlar) ( $\text{W}/\text{m}^{\circ}\text{C}$ )
$L_b$	Thickness of the back surface (Tedlar) (m)
$Q_{conv}$	Convective heat loss (W)
$Q_{rad}$	Radiative heat loss (W)
$\epsilon_b$	Emissivity of the back layer of the PV module (Dimensionless)

## 1. Introduction

Climate change and increasing energy demand have heightened the global importance of seeking sustainable energy solutions [1]. Among the array of renewable energy alternatives, PV technology has emerged as a transformative force capable of converting solar energy into electricity [2]. With the advent of cleaner energy and reduced environmental impact, this technology has fostered the possibility of a more sustainable future [3], [4]. However, PV technology's performance and efficiency are closely linked to weather patterns, material properties, and environmental factors [5].

For instance, one of the most significant threats to PV technology's performance is the deposition of dust on PV module systems [6]. Dust affects energy absorption, heat dissipation, and thermal equilibrium on module surfaces, thereby influencing the operational dynamics of PV systems [7], [8]. Dust accumulation is more frequent in arid and semi-arid regions like the Middle East and North Africa, which boast high solar energy potential [9]. The accumulation of dust particles on PV module surfaces diminishes the intensity of incident sunlight reaching the solar cells, resulting in reduced power output [10]. This phenomenon has been extensively studied, with numerous research papers reporting significant declines in PV system performance due to dust accumulation with a reduction of up to 50 % depending on dust levels [7], [11]. Furthermore, dust presents a notable challenge to the efficiency of solar technologies like Concentrated Solar Power (CSP) systems. The accumulation of dust on the CSP systems can scatter and absorb sunlight, reducing the amount of solar radiation reaching the target. This can lead to decreased thermal efficiency and reduced electricity generation [12], [13].

Furthermore, dust accumulation can create uneven temperatures and hot spots, leading to overall higher temperatures in PV modules and decreased efficiency [7]. Understanding the effects of dust accumulation and its interaction with temperature changes is vital for enhancing PV system efficiency and reliability [14]. Consequently, accurate temperature predictions are pivotal for comprehending and enhancing solar energy system performance [15]. Dust buildup is an essential key factor affecting PV module efficiency [16]. The extent of this impact varies based on the specific geographic location and local environmental conditions [17]. This following section offers a concise overview of the current state of research in estimating PV temperature, emphasizing the evolution of approaches and identifying the existing challenges.

Accurate temperature prediction for PV modules is crucial for enhancing the performance and efficiency of PV systems. Numerous studies have developed methods and models for

estimating PV temperature, taking various environmental factors into consideration. This section provides an overview of the existing literature, emphasizing key approaches and challenges.

Early research studies in PV temperature estimation primarily focused on establishing simple empirical relationships between PV module temperature, solar irradiation, and ambient temperature [18]. While these empirical correlations laid the foundation for understanding PV module temperature behaviour, they often lacked precision. As research advanced, more sophisticated models were developed, incorporating additional variables that influence PV temperature. These models tackled the complexities by considering various environmental factors including ambient air temperature, solar irradiation, and wind speed [19].

Furthermore, studies have highlighted the impact of optical properties and dust accumulation on PV temperature. Some researchers have emphasised the necessity of accounting for the reduction of light caused by dust in temperature prediction models, given its significant effect on light scattering. This led to the inclusion of dust-related factors in temperature estimation equations, such as transmittance [20]. Additionally, efforts to enhance PV temperature predictions included analytical models that incorporated weather conditions and principles of heat transfer, such as natural convection and radiation, as demonstrated by Tomar et al. [21]. This approach bridged the gap between theoretical analysis and experimental validation, providing deeper insights into PV temperature behaviour [21].

Mathematical models have expanded to encompass electrical, thermal, and optical elements, offering a comprehensive perspective by accounting for the intricate relationships among various parameters. Gupta et al. [10] developed a comprehensive model that predicts PV temperature by integrating electrical, thermal, and optical elements, recognising the complex nature of temperature behaviour in PV modules.

In summary, research has evolved from early studies focused on ambient factors to advanced approaches that consider heat transmission processes, optical properties, and the effects of dust accumulation. These advancements reflect ongoing efforts to improve PV temperature estimation, thereby enhancing the accuracy and reliability of predicting PV module behaviour under diverse climatic conditions. Table 1 provides equations and correlations derived from published research, facilitating the calculation of PV temperatures while accounting for various environmental variables, optical module properties, and heat transport equations.

Table 1. Equations and correlations for estimating photovoltaic temperature from published research.

Ref.	Year	Parameters	Equation	Eq. No
[18]	1985	$T_a$	$T_{PV} = 0.0282G + T_a$	(1)
[22]	2005	$T_a, G$	$T_{PV} = 30 + 0.0175(G - 300) + 1.14(T_a - 25)$	(2)
[23]	2004	$T_a, G$	$T_{PV} = T_a + (3 \times G/1000)$	(3)
[24]	1986	$T_a, G, v$	$T_{PV} = T_a + 0.022G(1 + 0.009T_a)(1 - 0.063v)$	(4)
[19]	1997	$T_a, G, v$	$T_{PV} = 3.81 + 0.0282G + 1.31T_a - 1.65v$	(5)
[25]	2014	$T_a, G, v$	$T_{PV} = 0.943 \times T_a + 0.0195 \times G - 1.528 \times v + 0.3529$	(6)
[26]	1984	$T_a, G, v$	$T_{PV} = 3.12 + 0.025G + 0.899T_a - 1.3v$	(7)
[27]	2003	$T_a, G, v$	$T_{PV} = 4.3 + 0.0028G + 0.943T_a - 1.528v$	(8)
[28]	2007	$T_a, G, v$	$T_{PV} = 0.943 \times T_a + 0.028 \times G - 1.528 \times v + 4.3$	(9)
[29]	2016	$T_a, G, v$	$T_{PV} = 1.4 \times T_{atm} + 0.1(G - 500)^{-v^{0.8}}$	(10)
[30]	2008	$T_a, G, v$	$T_{PV} = T_a + (G/(27.307 + 3.0381v))$	(11)
[23]	2004	$T_a, G, v$	$T_{PV} = G \cdot \{e^{-3.47-0.075v}\} + T_a + 3 \times G/1000$	(12)
[31]	2008	$T_a, G, v$	$T_{PV} = 2.08 + 0.0182G + 1.038T_a - 1.13v$	(13)
[32]	2008	$T_a, G, v, \omega$	$T_{PV} = T_a + G \times 0.32 \times \frac{w}{8.91} + 2 \times v$	(14)
[14]	2013	$T_a, G, v, \omega$	$T_{PV} = 30.60 + 0.409T_a + 0.014G - 0.15w - 0.377v$	(15)
[33]	2014	$T_a, G, v, \omega$	$T_{PV} = T_a + Bh \left[ \frac{G}{800} (NOCT - 20) \right] + Ch(w_h - w_1)$	(16)
[34]	2020	$T_a, G, v, \omega$	$T_{PV} = \frac{1}{3} \times [3.941T_a + 281.7 \times (G/1000)^{0.01088} + 269.1w^{0.005602} - 0.1761v + 275.9] - 273.15$	(17)
[20]	2014	$T_a, G, \alpha, \eta$	$T_{PV} = T_a + G \alpha [1 - \eta]/29$	(18)
[35]	2013	$T_a, G, v, \tau, \alpha, \eta$	$T_{PV} = T_a + ((\alpha \cdot G (1 - \eta)) / ((12.85 + 1.06v) \times 2))$	(19)
[21]	2018	$T_a, G, v, \tau, \alpha, \eta, U_l$	$T_{PV} = T_a + G \frac{\tau \cdot \alpha}{U_l} [1 - \eta]$ $U_l = hr + hc, h_c = 2.8 + 3 \times v,$ $h_r = \epsilon_{PV} \sigma (T_{PV} + T_{sky})(T_{PV}^2 + T_{sky}^2)$	(20)
[36]	2006	$T_a, G, v, \tau, \alpha, \eta, U_l$	$T_{PV} = \frac{U_{PV} T_a + G \times (\alpha_c \tau - \eta_0 - \beta \eta_{ref} T_{ref})}{U_{PV} - G \beta \eta_{ref}}$ $U_{PV} = 26.6 + 2.3v$	(21)
[15]	2018	$T_a, G, v, \tau, \alpha, \eta, U_l$	$T_{PV} = \frac{U_v T_a + G \times (\alpha_c \tau - \eta_{stc} (1 - \beta T_{ref})) (1 + \gamma \ln(\frac{G}{G_0}))}{U_v + \beta \eta_{ref} ((1 + \gamma \ln(\frac{G}{G_0})) G)}$ $U_v = 26.6 + 2.3v, (\tau \alpha) = 0.81$	(22)
King et al. cited in [15]	2018	$T_a, G, v, \tau, \alpha, \eta, U_l$	$[(\tau \alpha) - \eta] G = U_v (T_{PV} - T_a)$ $U_v = 26.6 + 2.3v,$	(23)

TPV represents the temperature of the PV module.  $T_a$  is the ambient temperature surrounding the PV module.  $G$  denotes the solar irradiance received by the module.  $v$  is the wind speed impacting the module.  $\omega$  symbolizes humidity.  $A$  is the absorptivity coefficient of the module.  $\eta$  symbolizes the efficiency of the PV module.  $\tau$  represent the transmissance.  $U_l$  is the overall heat loss coefficient of the module.  $U_v$  denotes a coefficient related to wind speed.  $\gamma$  and  $\beta$  are a coefficient indicating thermal impact on the electrical PV coefficient.  $\sigma$  representing the

Stefan-Boltzmann constant. Finally,  $h_c$  and  $h_r$  are the convective and radiative heat transfer coefficients, respectively.

Achieving optimal performance in solar energy systems necessitates a comprehensive understanding of the diverse methods and equations employed in the calculation of PV module temperatures. While previous research has explored the effects of dust on transmittance, it frequently neglects other crucial dust-related factors, including absorption and emittance. These parameters are of utmost importance as they directly impact the thermal behaviour of PV. This research is geared towards enhancing the precision of PV temperature estimations, consequently bolstering the effectiveness of PV technology, by addressing these often-overlooked factors. Comprehending the intricate effects of dust accumulation is essential to estimate PV module temperature.

Therefore, this study employs detailed experiments and advanced mathematical models to investigate the impact of dust on PV module temperature.

- Detailed investigations have been made into the influence of dust characteristics on light absorption, transmission, and heat dissipation. Using UV–vis Spectroscopy, transmittance and absorbance of the dust layer are measured. Concurrently, the emissivity of dust-coated PV surfaces is determined using the advanced INGLS TIR100-2 measuring device.
- Building on these empirical findings, the study introduces a novel mathematical model that integrates dust characteristics, meteorological variables, and PV parameters. This comprehensive framework provides precise temperature estimations, addressing gaps in existing studies which often overlook the role of dust characteristics on internal heat transfer processes within PV modules.
- The approach extends from theoretical foundations to practical applications, validating the developed model by comparing its predictions against actual temperature variations observed in dusty PV systems.
- In a comparative evaluation, the model demonstrates superior performance over existing mathematical models, especially in dust weather condition, highlighting its potential for broader applicability and enhanced accuracy.

## 2. Methodology

This paper introduces an approach to establish a mathematical correlation between dust properties and the thermal performance of PV modules. The methodology comprises two interrelated components: a theoretical framework involving mathematical correlations and an empirical approach that validates these correlations. The study is conducted in an arid environment, encompassing the location, experimental setup, and procedure for dust collection during regional storms. Analytical techniques are employed to characterize the chemical composition of the collected dust, along with measurements of its emissivity and optical properties. Outdoor experiments involving various PV modules are conducted to validate the developed mathematical correlations. Subsequent sections will offer a comprehensive overview of these key facets of the methodology.

### a. Development of mathematical correlations

This study endeavours to construct a robust mathematical model that comprehensively addresses the intricate correlation between dust accumulation and PV module temperature. The research employs two interconnected strategies to explore the relationship between dust accumulation and PV module temperature. The first strategy prioritises by treating the PV module as a single-layer structure. Conversely, the second strategy involves a more comprehensive analysis that considers the PV module's five-layer composition. This advanced approach incorporates heat transfer mechanisms within each layer to ensure the model accurately mirrors real-world conditions. The model is meticulously tuned to encompass both the complex thermal behaviours of the PV module and the distinctive characteristics of its multiple layers.

#### 1. Simplified dusty PV module energy balance equation

Initially, the study concentrates on treating the PV module as a single layer to simplify the comprehension of the energy balance equation and to provide a more straightforward representation. This approach facilitates a more concise demonstration of the energy balance equation for a dusty PV glass surface. Figure 1 illustrates that solar energy is converted into electrical power, with a significant portion remaining as heat. Typically, this heat is released into the atmosphere through convection and radiation from both sides of the PV module.

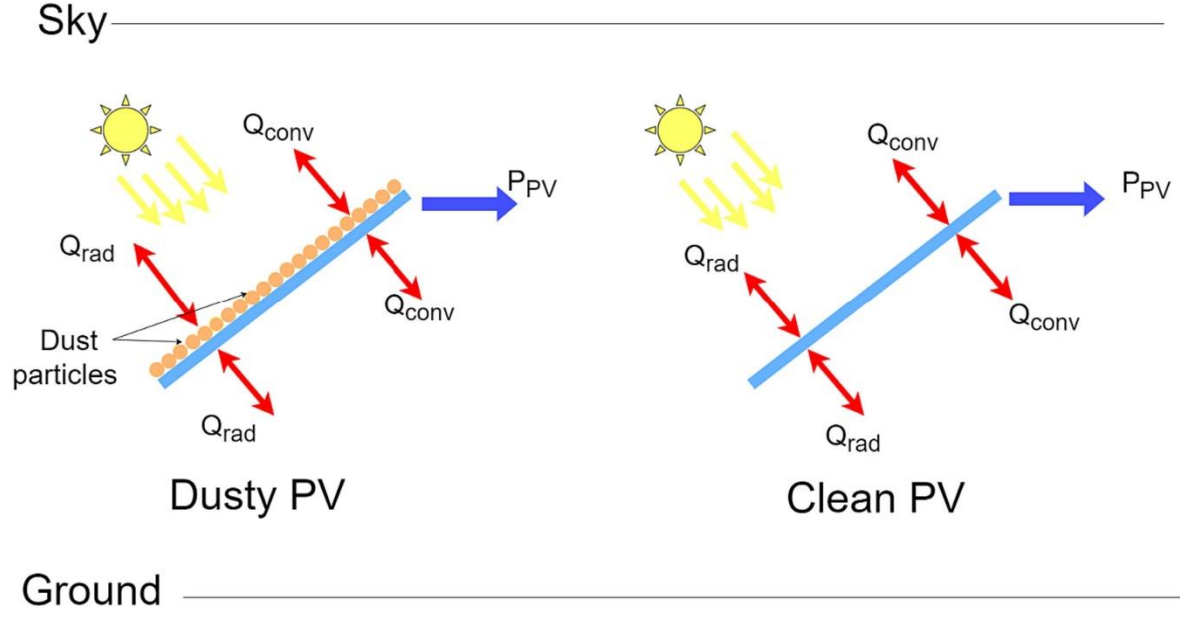


Figure 1 Comparative visualization of energy flow input and output analysis in clean and dust PV modules.

The energy balance equations are formulated under specific assumptions governing heat transfer. These assumptions encompass one-dimensional heat transfer within a single PV layer and steady-state conditions. These simplifications are made to streamline mathematical calculations while retaining the core understanding of the PV module's thermal behaviour. As evident in Figure 1, the energy balance equation for the dusty PV surface can be represented by Eq. (24) as follows:

$$Q_{in} = Q_{out}$$

$$Q_{abs}(dust + PV\ cell) = Q_{gen} + (Q_{conv} + Q_{rad})$$

$$\alpha_d G + \tau \alpha_c G (1 - \eta_{PV}) = 2h(T_{PV} - T_a) + 2h_r(T_{PV} - T_{sky})$$

$$T_{PV} = \frac{[\alpha_d G + \tau \alpha_c G (1 - \eta_{PV}) + 2h_r T_{sky} + 2h_c T_a]}{2(h + h_r)} \quad (24)$$

where,  $Q_{in}$  represents the energy input to the PV module, which includes the heat absorbed by the dusty layer and PV cell ( $Q_{abs} = \alpha_d G + \tau \alpha_c G$ ).  $Q_{out}$  represents the energy output from the PV layer, including heat loss to the atmosphere through convection ( $Q_{conv} = Q_{convection}$ ) and radiation ( $Q_{rad} = Q_{radiation}$ ).  $G$  represents solar radiation,  $h$  and  $h_r$  (convection and radiation heat transfer coefficients) can be calculated as described in Eqs. (25) and (26) [43]. Additionally, the properties of the PV module include absorption coefficient ( $\alpha_c$ ), emissivity ( $\epsilon_{PV}$ ), and

temperature of PV module ( $T_{PV}$ ).  $T_a$  represents ambient temperature, and  $T_{sky}$  represents sky temperature, which can be calculated by Eq. (27) as follows [44]:

$$h_r = \epsilon_{PV}\sigma(T_{PV}^2 + T_{sky}^2)(T_{PV} + T_{sky}) \quad (25)$$

$$h = 11.9 + 2.2v \quad (26)$$

$$T_{sky}=0.0552T_a^{1.5} \quad (27)$$

This simplified energy balance equation captures the fundamental heat transfer processes between the dusty PV glass surface and its surroundings. The equation takes into consideration the absorbed solar radiation, heat conduction, convection, and radiation, offering a concise representation of the thermal interactions responsible for the temperature increase of the PV module due to dust accumulation. Further elaboration on the intricate thermal behaviour of dust will be comprehensively discussed in the subsequent section, providing a detailed insight into its effects on the PV temperature.

The temperature equation for the clean PV module remains identical to that of the dusty scenario, except it omits the initial temperature affected by dust absorption, denoted as  $\alpha_d G$ .

## 2. Five-Layer Structure PV Module Energy Balance Equation

This subsection focuses on the thermal model, which takes into account the distinct layers, including the PV module. These layers comprise the glass, EVA1, PV cell, EVA2, and Tedlar, as depicted in Figure 2A. Each layer is treated as a separate node in the model, and energy balance equations are established for each node, as shown in Figure 2B. These equations encompass each layer's energy input and output and incorporate various environmental factors to replicate real weather conditions.

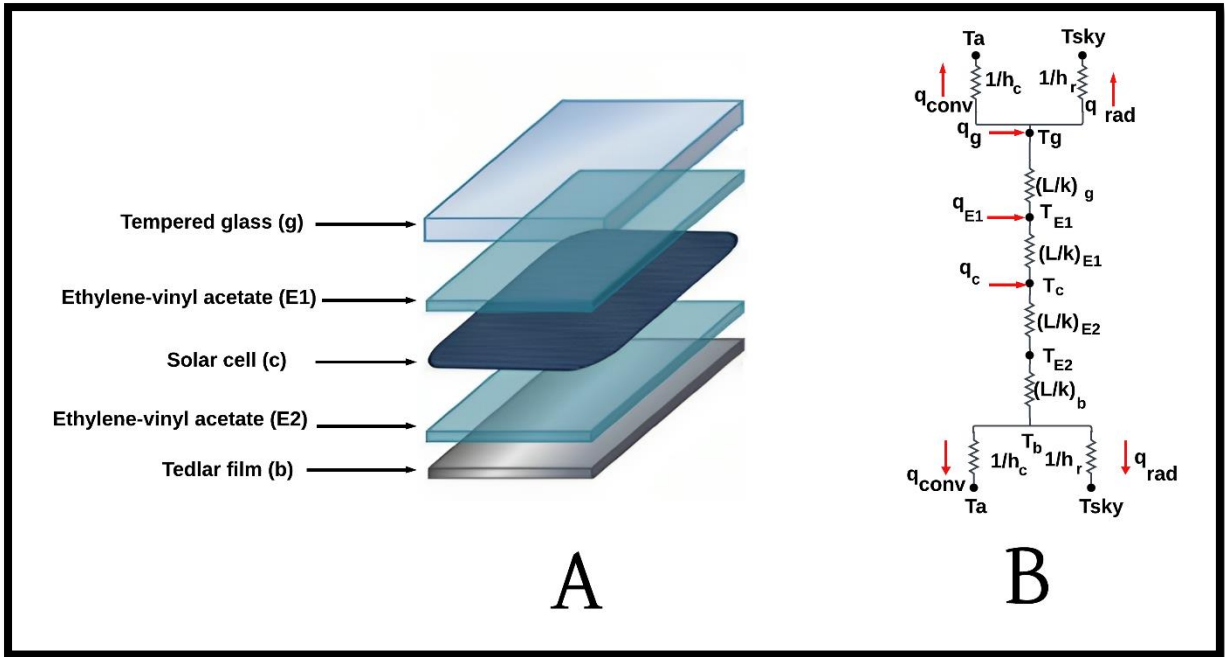


Figure 2. A. Typical solar module components materials and B. Thermal equivalent circuit

The energy balance equations are formulated under specific assumptions concerning the heat transfer process. These assumptions encompass one-dimensional heat transfer within each layer, steady-state conditions with constant temperature within each layer, and negligible temperature variations across the layers. These simplifications are introduced to streamline the mathematical calculations while still capturing the fundamental thermal behaviour of the PV module.

The analysis comprises two stages: Firstly, the thermal model is applied to analyse the clean PV module, representing dust-free conditions. This initial analysis unveils the PV module's temperature distribution and performance characteristics under ideal conditions. Secondly, the model is expanded to account for dust accumulation on the PV surfaces. By incorporating the effects of dust particles, the thermal model quantifies the resulting temperature and performance changes. The derived energy balance equations facilitate a comparison with the baseline, shedding light on the impact of dust accumulation on the module's behaviour.

### Clean PV

The energy balance equation for the PV glass surface can be represented by Eq. (28) as follows:

$$Q_{in} = Q_{out}$$

$$Q_{abs} + Q_{cond} = (Q_{conv} + Q_{rad})$$

$$\alpha_g G + \frac{k_g}{L_g} (T_{E1} - T_g) = h(T_g - T_a) + \epsilon_g \sigma (T_g^4 - T_{sky}^4) \quad (28)$$

$Q_{in}$  represents the energy input to the glass layer, which includes the heat absorbed by the glass ( $Q_{abs} = \alpha_g G$ ) and the heat conducted from the second layer EVA ( $Q_{con} = Q_{conduction}$ ).  $Q_{out}$  represents the energy output from the glass layer, including heat loss to the atmosphere through convection ( $Q_{conv} = Q_{convection}$ ) and radiation ( $Q_{rad} = Q_{radiation}$ ).  $T_{E1}$  represents the temperature of the EVA1 layer. Additionally, the properties of the glass layer include absorption coefficient ( $\alpha_g$ ), thickness ( $L_g$ ), thermal conductivity ( $k_g$ ), emissivity ( $\epsilon_g$ ), and temperature of the PV glass layer ( $T_g$ ).

In the second layer EVA1, the energy balance equations can be expressed by Eq. (29) as follows:

Energy balance equation for EVA1 layer:

$$Q_{in} = Q_{out}$$

$$Q_{abs} + Q_{con_{c \rightarrow EVA1}} = Q_{con_{EVA1 \rightarrow g}}$$

$$\alpha_E G + \frac{k_E}{L_E} (T_c - T_{E1}) = \frac{k_g}{L_g} (T_{E1} - T_g) \quad (29)$$

where  $Q_{in}$  represents the energy input to the EVA1 layer, which includes the absorbed heat from by EVA1 ( $\alpha_E G$ ) and the heat conducted from the PV cell layer  $Q_{con_{c \rightarrow EVA1}}$ . Meanwhile,  $Q_{out}$  represents the energy output from the EVA1 layer, the heat conducted to the PV glass layer.  $Q_{con_{EVA1 \rightarrow g}}$ . Additionally, the properties of the EVA1 layer include absorption coefficient ( $\alpha_E$ ), thickness ( $L_E$ ), thermal conductivity ( $k_E$ ), and temperature of the PV cell ( $T_c$ ).

For the PV cell layer, the energy balance equation can be expressed by Eq. (30) as follows:

$$Q_{in} = Q_{out}$$

$$Q_{abs} = Q_{gen} + Q_{con_{c \rightarrow E1}} + Q_{con_{c \rightarrow E2}}$$

$$\tau \alpha_c G = \tau \alpha_c G \eta_{PV} + \frac{k_E}{L_E} (T_c - T_{E1}) + \frac{k_E}{L_E} (T_c - T_{E2})$$

$$\tau \alpha_c G (1 - \eta_{PV}) = \frac{k_E}{L_E} (T_c - T_{E1}) + \frac{k_E}{L_E} (T_c - T_{E2}) \quad (30)$$

$Q_{in}$  represents the solar energy striking the PV cell layer, which is the absorbed heat from solar radiation ( $\tau\alpha_c G$ ) multiplied by the transmittance factor that accounts for the absorption or reflection of sunlight by the surface of preceding layers.  $Q_{out}$  represents the generated electrical power and the heat conducted to the EVA1 and EVA2 layers. Additionally, the properties of the PV cell include transmittance absorption coefficient ( $\tau\alpha_c$ ), PV efficiency at working conditions ( $\eta_{PV}$ ), which depends on the PV cell temperature as expressed in Eq. (31) [39].

$$\eta_{PV} = \eta_{ref} (1 - \beta(T_c - T_{a(ref)})) \quad (31)$$

where,  $\eta_{ref}$  is the PV efficiency at STC ( $1000 \text{ Wm}^{-2}$ ,  $25 \text{ }^\circ\text{C}$ ),  $\beta$  is the PV cell temperature coefficient [ $^\circ\text{C}^{-1}$ ], and  $T_c$  is the PV cell temperature [ $^\circ\text{C}$ ].

For the fourth layer EVA2, the energy balance equations can be expressed by Eq. (32) as follows:

Energy balance equation for EVA2 layer:

$$Q_{in} = Q_{out}$$

$$Q_{con_{c \rightarrow EVA2}} = Q_{con_{EVA1 \rightarrow bakc}}$$

$$\frac{k_E}{L_E}(T_c - T_{E2}) = \frac{k_b}{L_b}(T_{E2} - T_b) \quad (32)$$

where,  $Q_{in}$  represents the energy input to the EVA2 layer, which is the heat conducted from the PV cell layer  $Q_{con_{c \rightarrow EVA2}}$ . Meanwhile,  $Q_{out}$  represents the energy output from the EVA2 layer, which is the heat conducted to the PV back layer (Tedlar)  $Q_{con_{EVA2 \rightarrow b}}$ .  $T_b$  is the back surface temperature of the PV module, and  $k_b$  and  $L_b$  denote the thermal conductivity and thickness, respectively, of the back surface of the PV module.

For the Tedlar layer (back surface of PV), the energy balance equation can be expressed by Eq. (33) as follows:

$$Q_{in} = Q_{out}$$

$$Q_{con_{E \rightarrow b}} = Q_{conv} + Q_{rad}$$

$$\frac{k_b}{L_d}(T_{E2} - T_b) = hA(T_b - T_a) + \epsilon_b \sigma A(T_b^4 - T_{sky}^4) \quad (33)$$

where,  $Q_{in}$  represents the energy input to the Tedler layer, which is the heat conducted from the EVA2 layer  $Q_{con_{E2 \rightarrow b}}$ .  $Q_{out}$  represents the energy output from the Back surface, which includes the heat loss to the atmosphere through convection ( $Q_{conv} = Q_{convection}$ ) and radiation ( $Q_{rad} = Q_{radiation}$ ).  $\epsilon_b$  is the emissivity of the back layer of the PV module.

### Dusty PV

The PV glass surface layer is primarily affected when dust accumulates on a PV module. The presence of dust on the module surface results in heat transfer through three main mechanisms [40]:

- Conduction: Heat is transferred between the PV module and dust particles and among the dust particles themselves.
- Convection: Heat is exchanged through convective heat transfer between the dust particles and the surrounding environment, as well as between the PV module and the surrounding environment.
- Radiation: Heat is radiated from the dust particles to other particles and from the particles to the sky. Additionally, heat is radiated from the PV module surface to the sky and the dust. Figure 3 illustrates the different pathways of heat transfer.

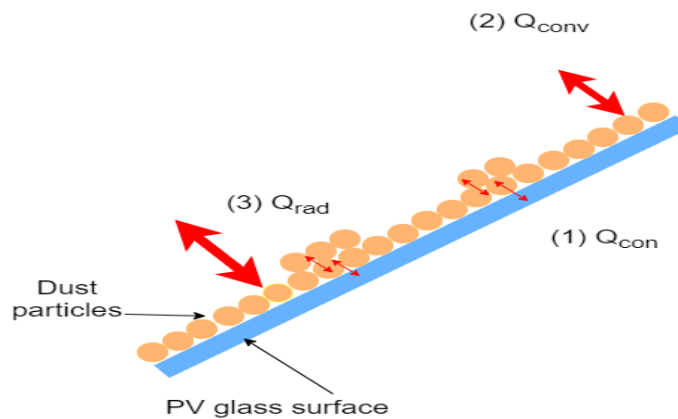


Figure 3 Heat transport mechanisms in the dusty front side surface of the module - conduction (1), convection (2), and radiation (3).

However, due to the thermal equilibrium among dust particles and PV glass surface, the combined conduction and radiation heat transfer among dust particles can be neglected. Furthermore, because the dust particles are significantly smaller than the surface area of the PV module, radiant heat transfer does not occur, as the view factors between the particles and

the PV surface are near zero bb. Therefore, this study will assume the primary impact is on the absorption of the glass surface. Consequently, the main distinction between dusty and clean PV modules lies in the glass layer, where the equation will be given in Eq. (34) as follows:

$$Q_{in} = Q_{out}$$

$$Q_{abs}(g + d) + Q_{cond} = (Q_{con} + Q_{rad})$$

$$(\alpha_g + \alpha_d)G + \frac{k_g}{L_g}(T_{E1} - T_g) = h(T_g - T_a) + \epsilon_{dg}\sigma(T_g^4 - T_{sky}^4) \quad (34)$$

$Q_{in}$  represents the energy input to the glass layer, including the heat absorbed by the glass and dust layer and the heat conducted from the second layer.  $Q_{out}$  represents the energy output from the glass layer, which includes heat loss via convection and radiation. Additionally, the properties of the dust layer include  $\alpha_d$  (absorption coefficient) and  $\epsilon_{dg}$  (emissivity).

Considering these factors, this study assumes that the combined impact of dust accumulation primarily affects the absorption on the glass surface, which is the primary reason for the increase in the PV surface temperature. As the dust settles on the PV module surface, it reduces the transmittance of solar radiation through the glass, resulting in higher absorption of solar energy by the dusty module. This increased absorption leads to an elevation in the PV surface temperature, impacting the overall performance and efficiency of the PV module.

Therefore, the flowchart in Figure 4 illustrates the equations used to calculate the impact of dust on PV temperature, along with the primary devices required to measure the dust parameters. These devices have been employed to replicate real-world conditions and ensure accurate calculations. The flowchart outlines the step-by-step process of accounting for dust effects on PV temperature, considering the altered transmittance and absorption on the glass surface due to dust accumulation. By utilising the measured dust parameters and applying the derived equations, valuable insights are gained into the PV module's actual temperature rise and performance changes under dusty conditions.

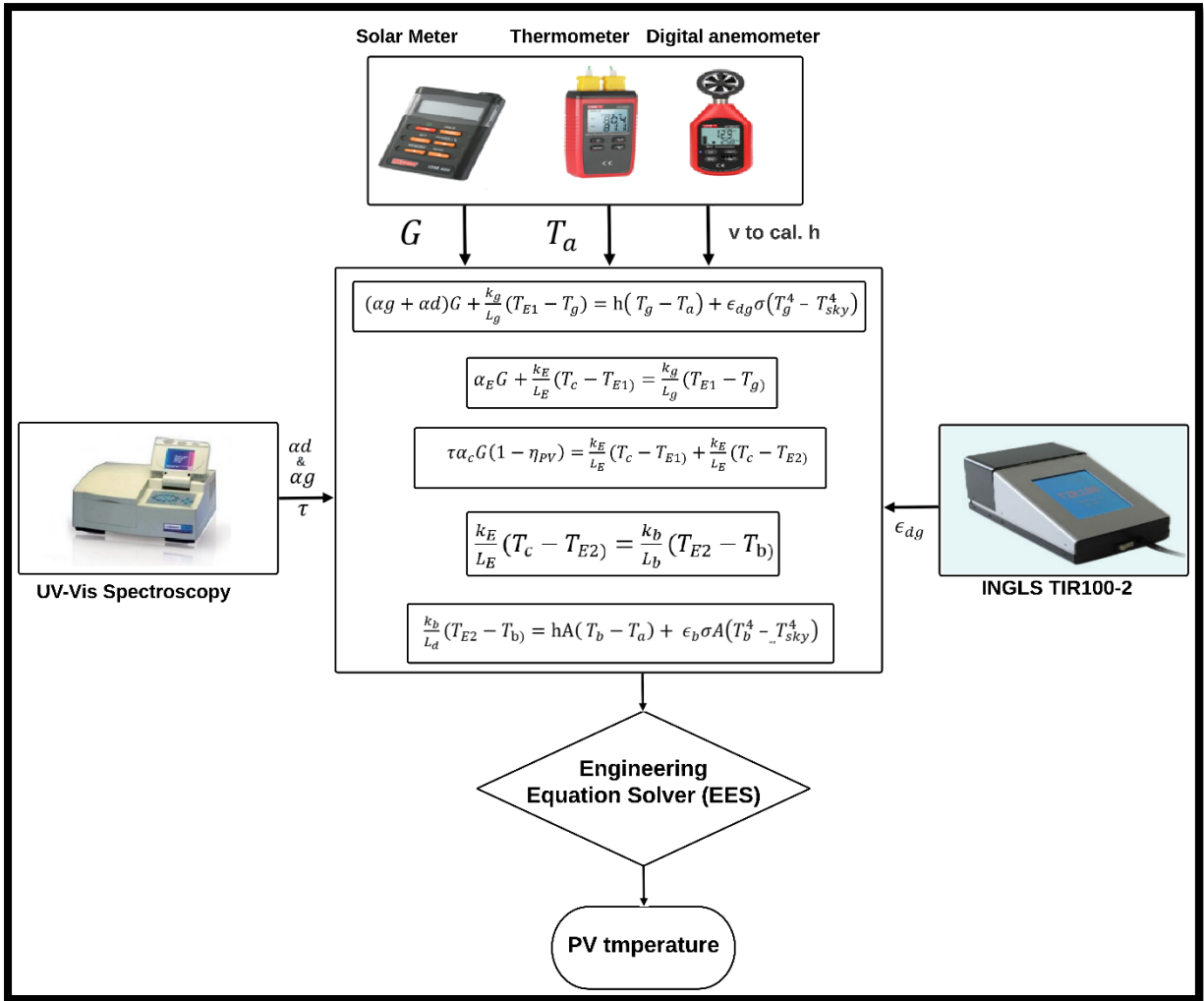


Figure 4 Flowchart for estimating the impact of dust on PV temperature.

The calculation equations will integrate additional pertinent values and parameters from Table 2, which includes parameter values obtained from published work. These parameters encompass thermal conductivity ( $k$ ), thickness ( $L$ ), transmittance, and absorption coefficients for clean PV materials, all of which are crucial for precise assessments. However, to accurately estimate the behaviour of the dusty PV module, further investigation will be necessary to ascertain the parameters specific to dusty conditions. This meticulous approach guarantees a more accurate and realistic estimation of the impact of dust on the PV module's behaviour, facilitating a comprehensive analysis and dependable results.

Table 2. Properties of different layers in PV modules [41], [42].

No	Layer	Properties			
		<i>Length L (mm)</i>	<i>Thermal conductivity k (Wm<sup>-1</sup>K<sup>-1</sup>)</i>	Emissivity	Absorptivity
1	Glass	3	0.9	0.88	0.2
2	EVA1,2	0.5	0.35		0.02
3	PV cell	0.3	148		0.85
5	PV back	0.1	0.2	0.87	0.5

b. Study location and experimental setup.

Dust phenomena fall under the category of dry climatic events originating from the thermal heating of the air near the Earth's surface [43]. These phenomena are especially prevalent in arid and semi-arid locations, such as the Middle East and North Africa [44]. Given the ideal conditions in these areas for studying the effects of dust on PV modules, this research is concentrated on data collection in Iraq. Iraq is characterized by high ambient temperatures, intense solar radiation, and frequent dust storms resulting in substantial dust accumulation. This unique combination of factors makes Iraq an apt location for investigating the impact of dust on PV module temperature.

For this study, dust samples were collected from two distinct regional dust storms in Iraq. By obtaining dust samples from these regional dust storms, the research aims to analyse the collected dust's characteristics and composition and investigate their influence on the temperature and performance of PV modules. This data collection approach enables a comprehensive examination of the variations in dust properties and their potential impact on PV systems in Iraq.

1. Dust Collection Procedure

The experimental setup involved strategically placing a large 4 × 4 meter plastic sheet outdoors to capture dust during regional dust storms. When a dust storm occurred, the wind transported dust particles that settled and accumulated on the sheet. This method facilitated the collection of dust samples from multiple dust storms, enabling a comparative analysis of their

characteristics and effects. The sheet remained in position throughout the dust storm to capture a representative sample of the deposited dust. Once the dust storm subsided, the plastic sheet with the accumulated dust was carefully gathered to preserve the sample's integrity.

The collected dust samples were stored in a controlled environment to prevent any alteration of their properties. Subsequently, the collected dust samples underwent various analyses, including physical and chemical characterisation, to determine properties such as particle size, shape, chemical composition, emissivity, transmittance, and absorption. These analyses provided a comprehensive understanding of the dust samples' characteristics and their potential effects on the performance of PV modules. By employing this collection method and conducting a thorough analysis, the study aimed to gain insights into the variations in dust composition and characteristics, enhancing the understanding of the impact of dust on PV module temperature and performance.

### 2.2.2 Dust Characterization

The fundamental properties of the collected dust samples were investigated to gain a comprehensive understanding of their characteristics.

#### 2.2.2.1 Chemical parameters of dust

X-ray fluorescence (XRF) analysis was utilised to examine the chemical composition of the gathered dust samples. This analytical technique entailed subjecting the dust particles to X-rays, inducing them to emit distinctive fluorescent X-rays. Subsequently, the emitted X-rays were measured and scrutinised to ascertain the elemental composition of the dust samples. The XRF analysis yielded valuable insights into the presence and concentration of various elements within the dust.

#### 2.2.2.2 The emissivity of the dusty PV surface

The emissivity of the dusty PV surface was determined using the thermal emissivity measuring device (INGLAS TIR100-2), as depicted in Figure 5. Prior to conducting the measurements, the instrument underwent preheating over an hour to ensure temperature stability. Calibration of the instrument was achieved using two reference surfaces with known emissivity values: white and black surfaces. Subsequently, the collected dust samples were uniformly distributed on the PV surface, and emissivity measurements were recorded. This procedure was repeated

for varying amounts of dust and samples from different dust storms, enabling the capture of a broad spectrum of emissivity values.

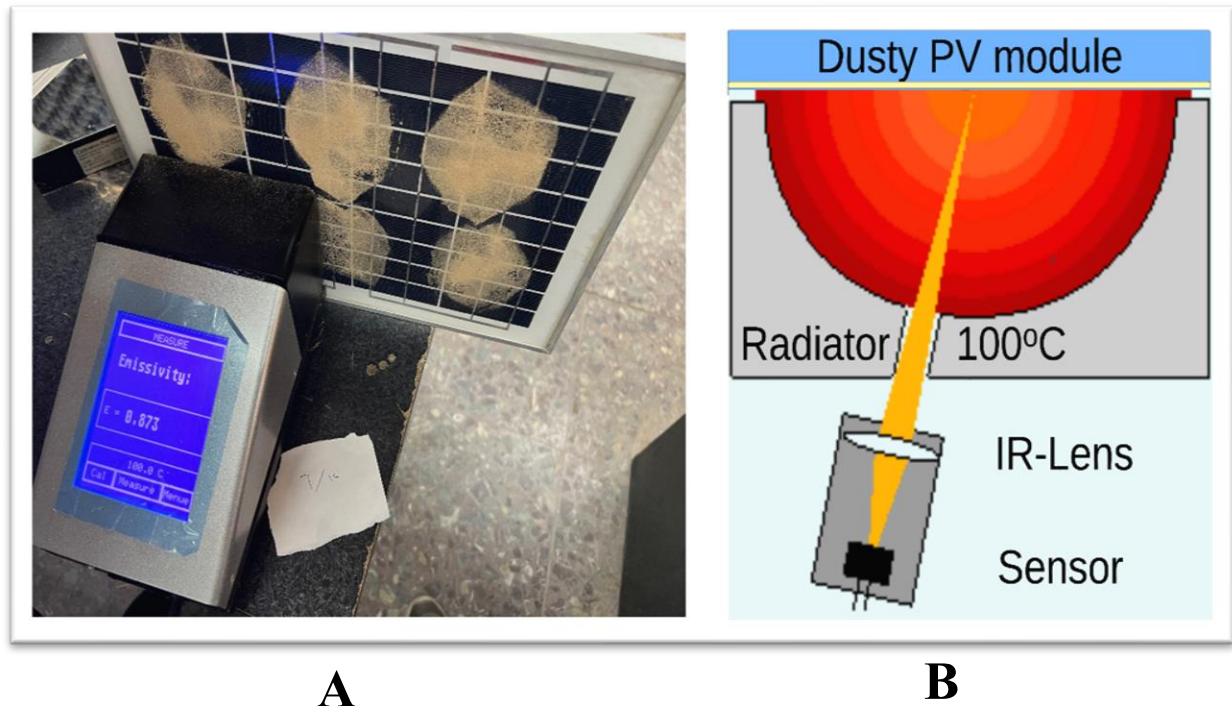


Figure 5 demonstrates dusty PV emissivity measurement. B: emissivity measurement principle for the tir100-2. A: photographic representation of the device.

### 2.2.2.3 Optical Properties of the Dusty PV Surface

Small glass sheets ( $25.4 \times 76.2$  mm) were coated with the collected dust particles to examine the transmittance and absorption characteristics of the dust, as illustrated in Figure 6. These dust-coated glass sheets underwent analysis using UV-Vis Spectroscopy Instrumentation following established standards. The UV-Vis Spectroscopy analysis offered insights into the transmittance and absorption properties of the dust samples, facilitating a deeper comprehension of their optical influence on PV systems.

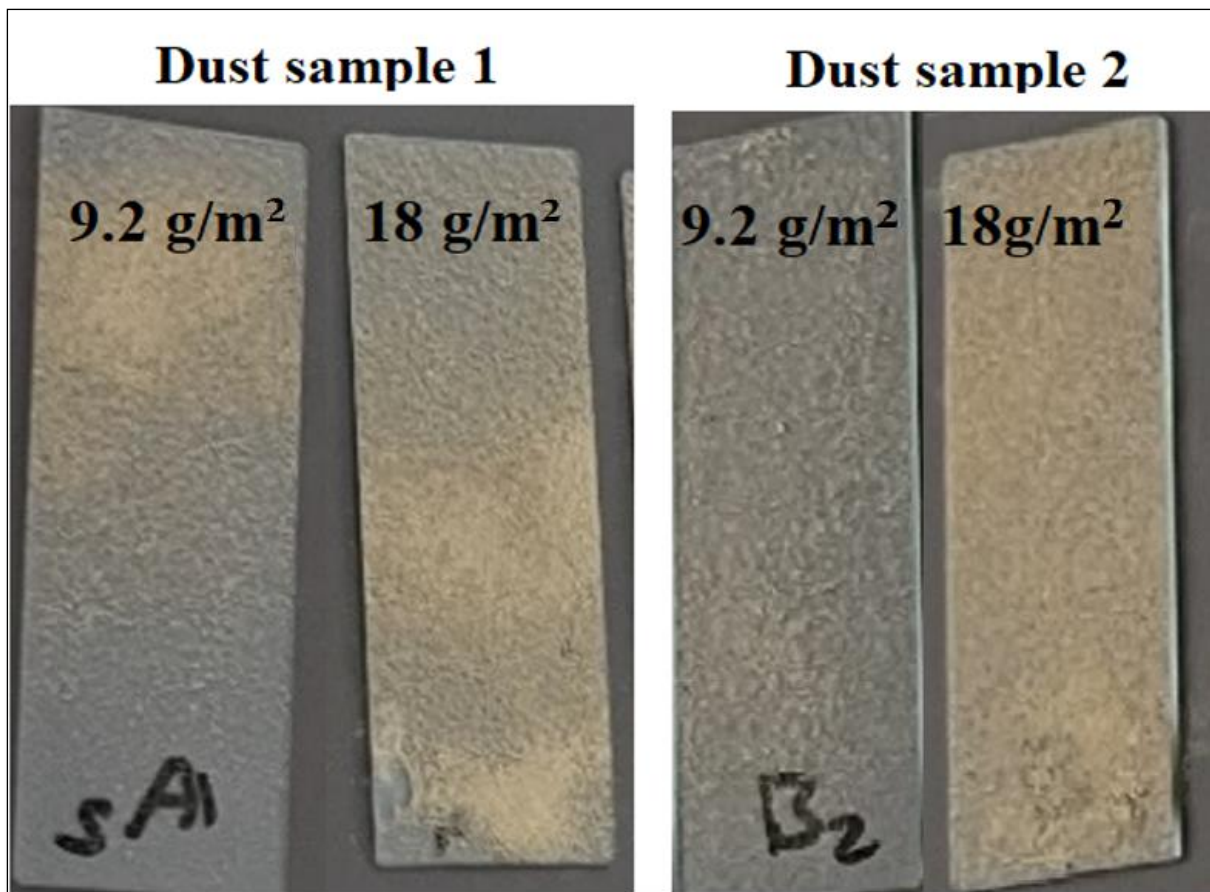


Figure 6 Glass sheets coated with the collected dust for sample 1 and 2

All experiments, including XRF analysis, emissivity measurements, and transmittance and absorption analysis, were conducted by established standard methods in a specialized laboratory.

### 2.3 Outdoor Experimental Setup

The outdoor experiments were conducted in Baghdad, Iraq, under outdoor conditions to replicate real weather conditions.

An outdoor experiment involved the utilisation of three identical PV modules with specific technical specifications, as detailed in Table 3. Each module served a specific purpose:

- Reference Panel: A clean PV module was utilised as the control group to establish baseline performance.
- PV Module 2: The PV module is exposed to a specific type and quantity of dust to simulate real-world environmental conditions.

- PV Module 3: Exposed to a different type of dust with the same quantity to provide data concerning the influence of diverse dust compositions.

All three PV modules were affixed to a custom-built frame, ensuring that they were aligned in the same orientation and tilt angle for consistent measurements. The orientation was adjusted to guarantee direct sunlight exposure, and the tilt angle was regularly modified to maintain optimal solar energy absorption.

Table 3 The PV module's technical specifications.

Maximum power at STC ( $P_{max}$ )	10 (W)	Cell type	Monocrystalline
The voltage at the maximum power point ( $V_{mp}$ )	17.6 (V)	N. cell	36
Current at the maximum power point ( $I_{mp}$ )	0.57 (A)	Dimensions	320 × 350 (mm)
Open circuit voltage ( $V_{oc}$ )	21.6 (V)	Weight	1 kg
Short circuit current ( $I_{sc}$ )	0.62 (A)	Power temperature coefficient	-0.36%/°C <sup>2</sup>
NOCT	45 °C	Power measurement tolerance	-0.03

During the outdoor experiments, the following parameters were consistently measured and recorded:

- Temperature Data: Ambient temperature was monitored using thermal couples to record the environmental temperature, while thermal cameras were employed to measure the temperature of each PV module at regular intervals.
- Solar Radiation: Solar irradiance incident on the PV modules was documented using pyranometers.
- Other Environmental Factors: Additional environmental factors, such as wind speed, were measured using a wind speed meter.
- The Solar Module Analyzer was utilised to assess the performance and output of each PV module, providing valuable data on efficiency and power generation under varying dust conditions.

Figure 7 illustrates the outdoor experiment setup, depicting the positioning of three identical PV modules, the custom-built frame, and the array of measurement tools employed for data collection during the study, the PC's role in the setup is to collect and read data from the

measurement instruments. The instruments and devices utilised for data collection in the outdoor experiment are detailed in Table 4, which provides information about the equipment's make, model, accuracy, and measuring ranges, including pyranometers, thermal cameras, wind speed meters, and the solar module analyzer.

Table 4 Instrument device and specification used in the outdoor experiment

Experimental equipment	Manufacturer and model	Measurement error
Pyranometers	RS PRO Solar Power Meter ISM400	$\pm 10 \text{ W/m}^2$
Thermometer	Uni-T UT320D	$\pm (0.5\% + 1)$
Solar module analyzer	PROVA 200	$\pm 1\%$
Digital anemometer	UNI-T UT363	$\pm 0.1 \text{ m/s}$
Thermal camera	Fluke Ti10	$\pm 2^\circ\text{C}$

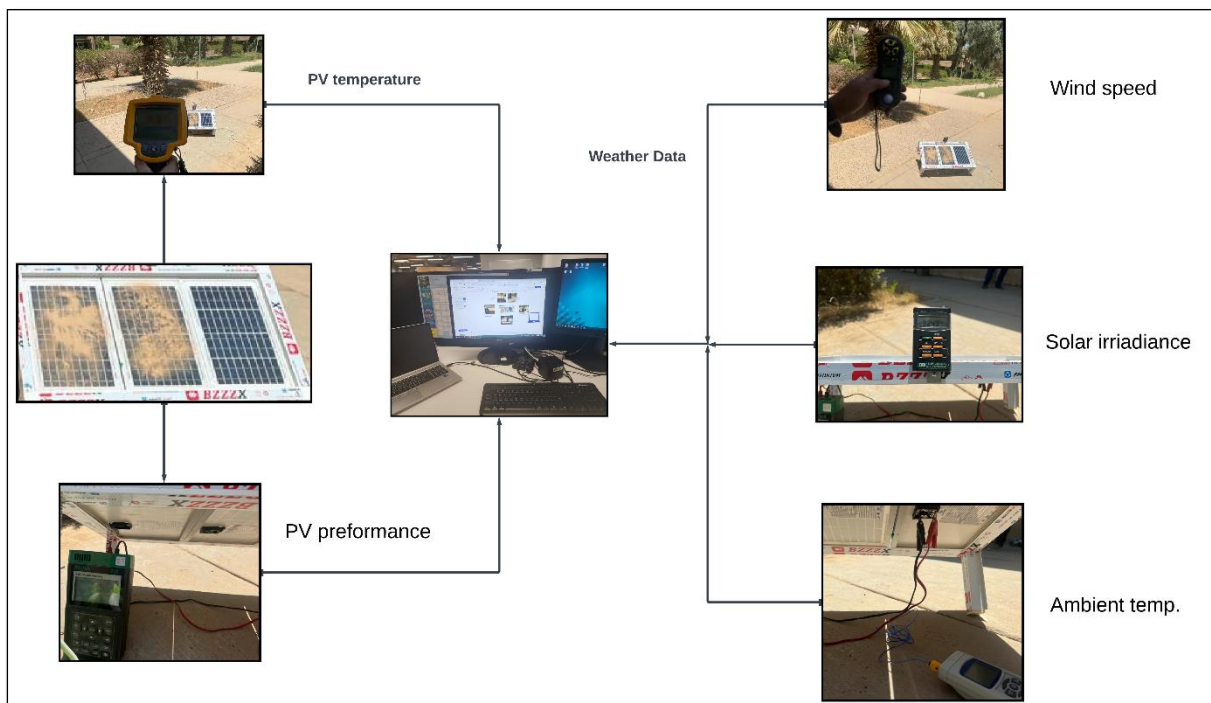


Figure 7 illustrates the arrangement of the outdoor experiment with the three identical PV modules.

To gain a comprehensive understanding of the effects of dust accumulation on PV modules, two sets of experiments were conducted to investigate the impact of both the quantity and composition of dust on PV temperature and performance. To align the study with real-world conditions, dust samples were collected from two regional dust storm events that occurred in Middle Eastern countries on May 13 and May 23, 2022. These samples, identified as "Dust Sample 1" and "Dust Sample 2," directly represent actual environmental conditions. Two different dust amounts were considered: 9.2 and 18 g/m<sup>2</sup>. The experimental data has been organized in Table 5 for ease of reference and to maintain clarity.

Table 5: Experimental test samples

<b>Test set</b>	<b>Dust sample</b>	<b>Dust weight (g/m<sup>2</sup>)</b>
<b>Test set 1</b>	Dust sample 1	18
	Dust sample 2	18
<b>Test set 2</b>	Dust sample 1	9.2
	Dust sample 2	9.2

The outdoor experiments were conducted during the summer season and on a hot day, precisely from 11:30 a.m. to 1:30 p.m. This timeframe was chosen to precisely assess the impacts of varying dust levels and compositions on the temperature and performance of the PV modules. It also enabled the observation of variations in environmental conditions and seasonal changes that might affect the PV modules' performance. The experiments were repeated multiple times to ensure the reliability and validity of the results. Each replication was conducted under similar conditions, ensuring consistency in the setup and data collection procedures.

### **3. Result and discussion**

The study's results and discussion section have been divided into three main categories. Firstly, the dust properties are presented. This section includes the results obtained from laboratory tests conducted by specialists to measure dust properties, such as transmittance, absorptance, emissivity, and the chemical composition of the dust.

Secondly, the outcomes of the theoretical model have been compared with the outdoor results to determine the accuracy of the proposed mathematical model.

Finally, the outdoor results have been presented and analysed. This section encompasses the experiments' results obtained from three PV modules installed outdoors under realistic weather conditions, including PV module temperature performance.

In each of these categories, a detailed analysis and discussion of the results are provided to offer a comprehensive understanding of the impact of dust on PV performance.

### 3.1 Characteristics and Chemical Composition of the Dust Sample

The dust samples used in this study were collected during Iraq's regional dust storms on the 13th and 23rd of May, 2022. The investigation aimed to understand the chemical and optical properties of dust and their influence on PV temperature.

#### ***3.1.1 Chemical Analysis:***

To elucidate the chemical composition of the dust samples, the XRD method was employed. The results from this analysis are visualized in Figure 8, which depicts the XRF scan showing the proportion of various elements in each dust type. A comprehensive breakdown of the chemical composition is provided in Table 6. In Figure 8, the x-axis represents the energy levels in keV (kilo electron volts), while the y-axis indicates the detected signal intensity in kbps (kilo counts per second). Notably, the reading on the x-axis approaches zero after the 45 keV mark due to the diminishing presence of certain elements beyond this energy level. The results highlight the presence of significant components, including Si, Al, Fe, Ca, Mg, S, and K, among others. The proportions of these elements are detailed below. These findings played

a pivotal role in comprehending material properties and their influence on PV performance, with slight observation between the two samples.

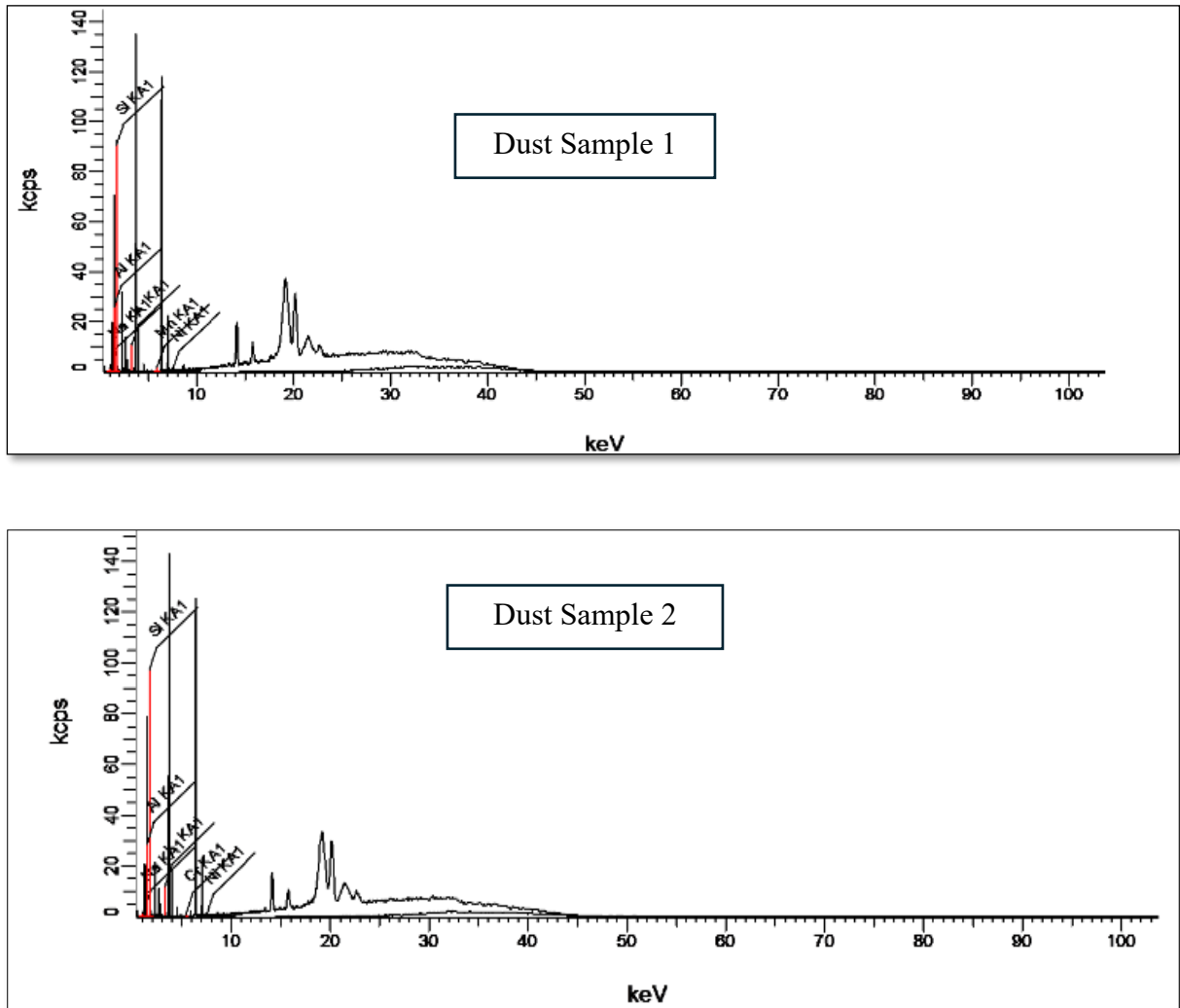


Figure 8 The XRF Scan shows the proportion of various elements and materials in each dust type.

Table 6 The proportion of various elements and materials present in each dust type

Element	Dust Sample 1 (13-May)	Dust Sample 2 (23-May)
Si (%)	30.31	31.35
Al (%)	9.27	9.80
Fe (%)	9.49	9.70
Ca (%)	34.78	34.80
Mg (%)	5.01	5.01
S (%)	5.47	3.50
K (%)	2.69	2.82

### 3.2 The optical characteristics

The optical characteristics of the dust samples held significant importance in this study, given their crucial role in understanding developing an accurate model for assessing the impact of dust on PV temperature. Precise measurements and analyses were conducted to investigate the dust samples' transmittance, absorption, and emissivity properties. This rigorous approach was taken to ensure the reliability and validity of the developed model, emphasizing the importance of employing accurate data rather than estimated values.

Figures 9 and 10 illustrate the transmittance and absorbance results obtained from the UV-Vis Spectroscopy for two different types and two different weights of dust (dust sample 1 (dust 1) and dust sample 2 (dust 2)). These graphs depict variations in transmittance and absorption attributable to dust type and weight. The data analysis allows for a deeper understanding of how different dust compositions and densities affect light transmission and absorption through the samples. These measured values serve as crucial inputs for the proposed model, enabling the accuracy of the assessment of the dust's effects on PV modules.

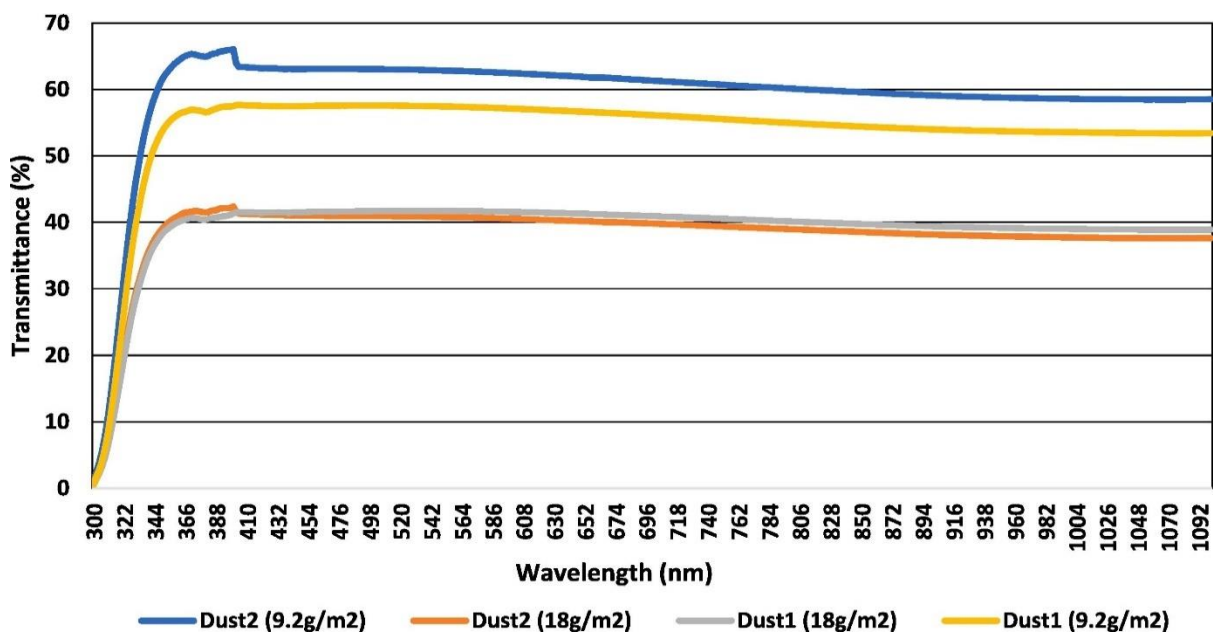


Figure 9 Transmittance trends of different dust types and amounts

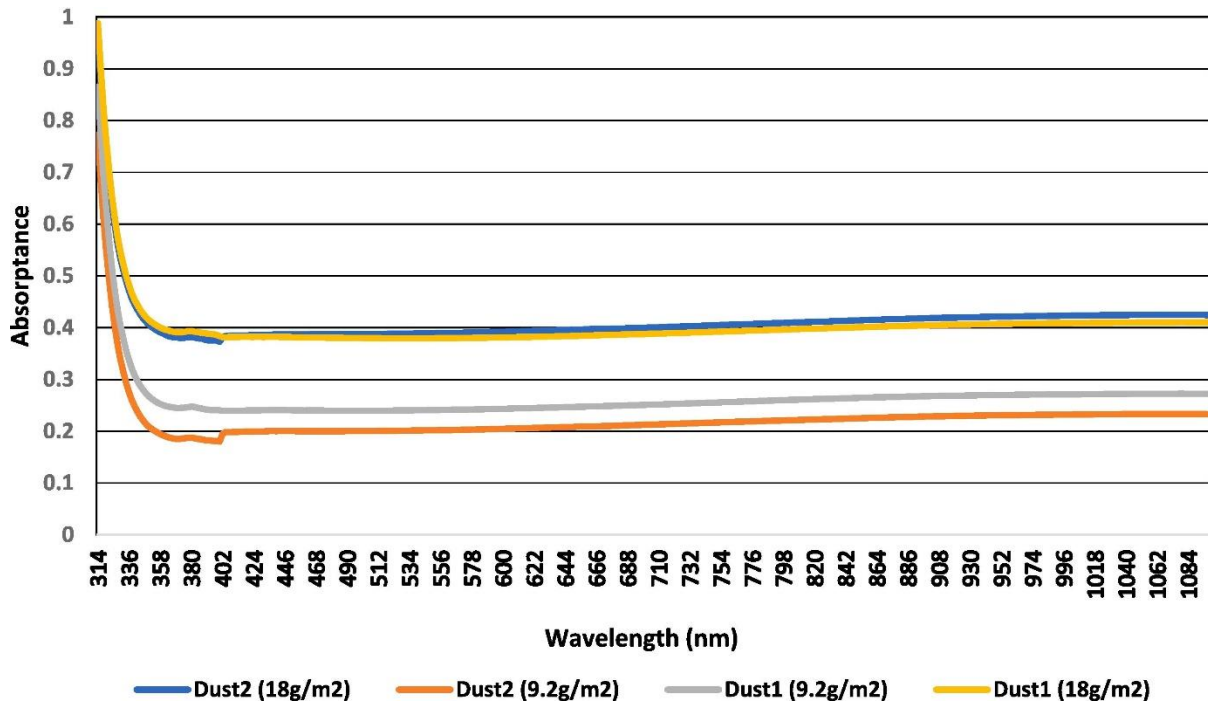


Figure 10 Absorption trends of different dust types and amounts.

### 3.2.1 The emissivity of PV module

Emissivity, another critical optical property, was examined in the laboratory experiments using the INGLAS TIR100-2 Thermal emissivity measuring instrument, as described in the methodology Section above. Emissivity plays a significant role in determining the radiative heat transfer characteristics of PV surfaces covered with dust. The measured emissivity data for different dust types and densities are presented in Table 7.

The optical results, summarized in Table 7, offer valuable insights into the potential impact of different dust types on various applications and systems. This table highlights the optical properties of the dust, essential for refining the calculations of the developed equations and accurately assessing the effects of dust on PV temperature.

Table 7 Dust sample optical properties: changes in optical properties with varying dust densities and chemical compositions

Dust type	Transmittance		Absorbance		Emissivity	
	9.2 g/m <sup>2</sup>	18 g/m <sup>2</sup>	9.2 g/m <sup>2</sup>	18 g/m <sup>2</sup>	9.2 g/m <sup>2</sup>	18 g/m <sup>2</sup>
<b>Dust 1</b>	56 %)	41%	0.25	0.39	0.871	0.886
<b>Dust 2</b>	62%	40%	0.21	0.4	0.889	0.902

A comprehensive understanding dust's complex chemical and optical properties is essential for refining the calculations of the developed equations and accurately assessing the effects of dust on PV temperature.

The observed trends in the optical properties provide insights into the behaviour of dust-covered surfaces and their influence on PV performance. As the amount of dust increased, the transmittance decreased, highlighting the obstructive nature of higher dust densities. Conversely, absorption and emissivity values increased with higher dust density, indicating greater light interaction and heat radiation. These fluctuations in optical properties underscore the significance of using accurate data to estimate the impact of dust on PV temperature.

When comparing different dust types, slight variations in the optical property values were observed, attributed to the distinct compositions and sizes of dust particles in each sample. Variations in chemical composition can alter the optical properties, affecting scattering and absorption characteristics, while differences in particle size can further influence the optical behavior of the dust samples. Understanding these variations is crucial for accurately modeling the impact of specific dust types on PV modules. These intricacies in dust properties lead us to the next phase of our study, focusing on real-world implications.

### **3.2.2 Outdoor Results**

Building upon the insights gained from the analysis of dust properties, the primary objective of the outdoor experiments was to validate the developed mathematical calculations for estimating PV temperature under dusty conditions. Three PV modules were used: one was kept clean, while the other two were exposed to different dust compositions, weighing 0.9g and 1.8g, respectively.

Figure 11 illustrates thermal imaging conducted using the thermal camera, as detailed in the methodology section. This visualization provides a comprehensive understanding of the temperature distribution across the PV modules. The thermal images vividly demonstrate a correlation between the dust accumulation on the PV modules and elevated PV cell temperatures. As shown in Figure 11, distinct temperature points are indicated with accompanying temperature readings. This temperature fluctuation is crucial for comprehending how the PV modules respond to varying dust levels and how this interaction impacts their thermal behaviour.

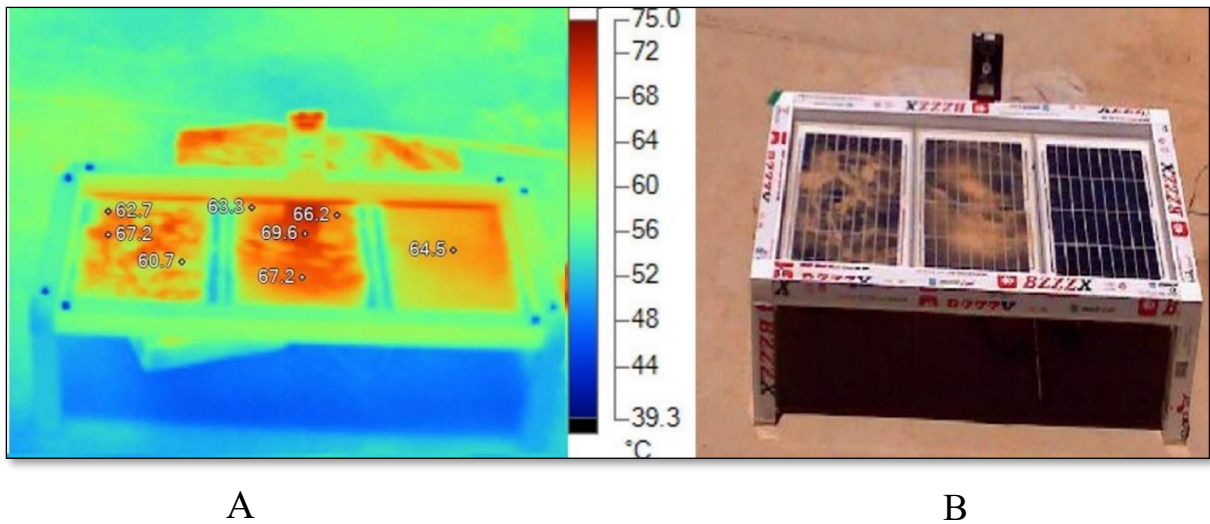


Figure 11 Thermal Imaging Comparison (A) Thermal imaging captured using a thermal camera, highlighting temperature ( $^{\circ}\text{C}$ ) variations. (B) Visible image.

The PV analyser (PROVO 2000) evaluated the electrical performance of the PV modules. Figure 12 presents the I-V characteristics of the clean and dusty PV modules. The clean PV module exhibited the expected V-I curve (Figure 12A). In contrast, the dusty PV modules exhibited deviations (Figure 12B) attributed to the impact of dust on the module's optical properties, which influenced its efficiency and electrical output.

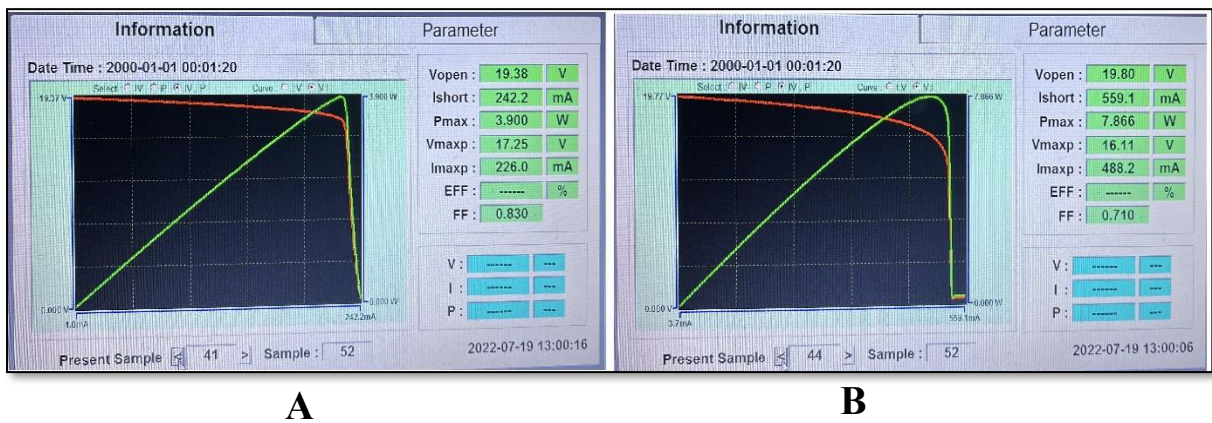


Figure 12: V-I (Voltage-Current) Characteristics of PV Modules: (A) V-I of a Dusty PV Module, and (B) V-I of a Clean PV Module.

The analysis revealed a significant impact on PV current due to the reduced incident light intensity reaching the PV cell. However, the effect on PV voltage was relatively minor, as dust accumulation mainly influenced the optical properties of the light-absorbing layer. Overall, the dusty PV modules experienced considerably lower electrical power output.

In addition to temperature data, the outdoor experiments collected other crucial atmospheric environment parameters using the mentioned devices. These parameters, including solar irradiance ( $G$ ), wind speed ( $V$ ), and ambient temperature ( $T_a$ ), are vital for developing accurate calculations and validating the developed models. Table 8 presents a comprehensive set of these parameters alongside the electrical and temperature measurements of the clean and dusty PV panels. Combining these atmospheric parameters with the temperature data enables a more thorough analysis of the impact of dust on PV performance under varying environmental conditions.

Table 8 Outdoor data results for weather conditions, PV temperature, and output power for the clean and dusty PVs.

		Weather data			Clean PV		Dusty sample 1		Dusty sample 2	
	Time	Solar irradiance $G$ ( $\text{w/m}^2$ )	Wind speed $v$ ( $\text{m/s}^2$ )	Ambient temperature $T_a$ ( $^{\circ}\text{C}$ )	$T_{\text{PV}}$ ( $^{\circ}\text{C}$ )	Power (W)	$T_{\text{PV}}$ ( $^{\circ}\text{C}$ )	Power (W)	$T_{\text{PV}}$ ( $^{\circ}\text{C}$ )	Power (W)
<b>Test 1</b> <b>18 g/m<sup>2</sup></b>	10:20	910	0.5	44.0	67.50	7.46	68.2	3.78	66.8	3.21
	10:40	930	1.2	44.8	63.80	7.80	66.8	3.86	66.2	3.24
	10:50	930	1.0	45.0	63.00	7.95	66.8	3.90	65.3	3.28
<b>Test 2</b> <b>9 g/m<sup>2</sup></b>	11:30	950	0.5	45.7	64.5	7.49	69.6	4.43	67.2	4.92
	11:50	938	0.5	47.5	66.00	7.61	70.3	4.23	68.8	4.89

These findings underscore the effects of dust on PV systems and emphasise how different dust compositions and weights directly influence PV cell temperature and electrical output power. The data from the outdoor experiments offer conclusive evidence of the substantial impact of dust on PV temperature and performance, prompting a deeper dive into the theoretical framework that governs these interactions. The rise in PV cell temperature and the variations in electrical characteristics due to dust accumulation highlight the importance of precise estimations of PV temperature and other atmospheric parameters.

### 3.3 Simulation results

In light of the empirical evidence obtained from the outdoor experiments, the study employed an iterative solution process facilitated by the Engineering Equation Solver (EES) software to effectively address the complex thermal dynamics of a multi-layered PV module under changing weather conditions. The entire process can be summarised in a flowchart that outlines the sequential steps to achieve the desired results, as depicted in Figure 13.

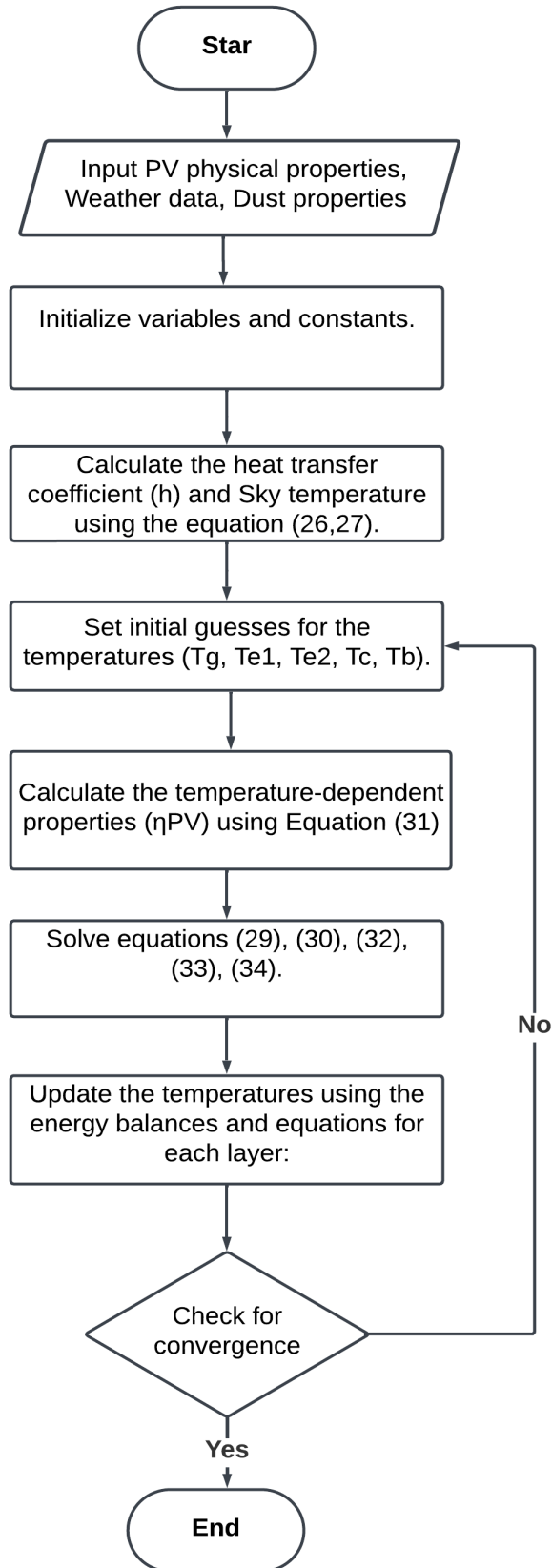


Figure 13 Solution process for analysing multi-layered photovoltaic module thermal dynamics using EES software.

The flowchart emphasises the iterative solution process enabled by the EES software for solving a complex equation system. It specifically addresses the intricate thermal dynamics of a multi-layered PV module under varying weather conditions. The process commences with the initialisation of variables and the establishment of initial temperature estimates. Through iterative cycles, EES computes temperature-dependent properties and heat transfer coefficients among the layers. Net heat transfer rates are then analysed, and variables are updated using energy balances and layer-specific equations. A convergence check, which measures the disparities between current and previous values, guides the process. Revised estimates are employed if convergence is not achieved, sustaining the iterative loop until the defined convergence criterion is met. Upon satisfaction of this criterion, the loop concludes, yielding a set of reliably estimated PV layer temperatures that constitute the solution. EES orchestrates this complex process by integrating weather data, properties of the PV material, and experimental details to achieve a dependable and effective solution for the equations. These solutions then needed empirical validation to confirm their accuracy and reliability.

### 3.4 Validation of Mathematical Model

Following the derivation of the theoretical solutions, the validation process entailed comparing the predictions of the mathematical model with the outcomes obtained from the outdoor experiments conducted under real-world weather conditions. The temperatures listed in Table 9 correspond to measurements taken for PV modules in various scenarios. To further assess the accuracy of the developed equation, the Mean Absolute Error (MAE) method was employed - a dependable metric for evaluating predictive precision. Eq. (35) computes the MAE, facilitating a comparison between the developed equation and experimental results.

$$MAE = \frac{1}{n} \sum_{i=1}^n |T_{predicted} - T_{observed}| \quad (35)$$

Table 9: The compression results of the experimental, new simplified, and five-layer developed models, and the MEA.

	<b>T<sub>PV</sub> (°C) (Experimental data)</b>	<b>T<sub>PV</sub> (°C) (Simplified model)</b>	<b>T<sub>PV</sub> (°C) (Five layers model)</b>
<b>Clean PV</b>	67.5	59.0	63.68
	63.8	59.1	63.48
	63.0	59.6	64.08
<b>Dusty 1 (18 g/m<sup>2</sup>)</b>	68.2	58.6	65.20
	66.8	58.8	65.00
	66.8	59.3	65.60
<b>Dusty1 (9.2 g/m<sup>2</sup>)</b>	69.6	60.6	67.10
	70.3	62.4	68.60
<b>Dusty 2 (18 g/m<sup>2</sup>)</b>	66.8	58.6	65.30
	66.2	58.8	65.00
	65.3	59.3	65.60
<b>Dusty 2 (9.2 g/m<sup>2</sup>)</b>	67.2	60.6	67.00
	68.8	62.4	68.50
<b>MAE</b>		7.17	1.46

Table 9 presents a comparison between the model's predictions with the corresponding experimental results. The assessment of the model predictions and the outdoor experimental data demonstrated a close agreement, with MAE of 7.2 and 1.46, respectively. This validation confirms the model's efficacy in capturing the impact of dust on PV temperature. The theoretical calculations closely aligned with the experimental results, affirming the reliability and consistency of the developed equations. To further emphasise the reliability of the developed model, it was pivotal to compare it against existing equations in the literature.

### 3.5 Comparison with Established Equations

Having validated the accuracy and effectiveness of our developed correlation equation, it was subjected to further scrutiny through a comprehensive comparative analysis with established equations for estimating PV temperature in dusty environments. This evaluation assessed the equation's performance by contrasting it with previously established mathematical models. To ensure a thorough assessment, the developed equation was compared with Eqs. (18) to (23) from the existing literature. This subset of equations was selected for their incorporation of optical properties and consideration of the reduction in light transmission resulting from dust accumulation. The comparison involved both actual PV temperature data collected from the author's outdoor experiments and the calculated values using the developed equations and the eight selected equations (Eqs. (18) to (23)) designated for comparison, as presented in Table

10. This comprehensive evaluation underscores the importance of accounting for dust parameters to achieve accurate prediction of PV temperature.

Table 10 PV temperature in degrees Celsius ( $^{\circ}\text{C}$ ) from experiments, developed and published equations.

	Experiment	Simplified model	Five layers model	Eq.18	Eq.19	Eq.20	Eq.21	Eq.22	Eq.23
<b>Clean PV</b>	67.5	59.0	63.68	67.7	69.7	68.4	68.2	67.7	65.3
	63.8	59.1	63.48	69.0	69.7	66.2	65.6	65.3	65.4
	63.0	59.6	64.08	69.2	70.3	67.3	66.9	66.5	65.9
<b>Dusty 1 18 g/m<sup>2</sup></b>	68.2	58.6	65.20	54.3	55.1	48.8	46.3	46.4	44.0
	66.8	58.8	65.00	55.3	55.6	49.0	44.5	44.6	44.8
	66.8	59.3	65.60	55.5	56.0	49.4	45.4	45.5	45.0
<b>Dusty 1 9.2 g/m<sup>2</sup></b>	69.6	60.6	67.10	52.6	53.2	50.1	47.5	47.5	45.0
	70.3	62.4	68.60	54.3	54.9	51.9	49.4	49.4	46.8
<b>Dusty 2 18 g/m<sup>2</sup></b>	66.8	58.6	65.30	54.5	55.4	48.8	46.3	46.4	44.0
	66.2	58.8	65.00	55.6	55.9	49.0	44.5	44.7	44.8
	65.3	59.3	65.60	55.8	56.2	49.4	45.5	45.6	45.0
<b>Dusty 2 9.2 g/m<sup>2</sup></b>	67.2	60.6	67.00	51.5	52.0	49.8	47.1	47.2	44.7
	68.8	62.4	68.50	53.2	53.7	51.5	49.0	49.1	46.5

The performance of Eqs. (18) to (23) in predicting dusty PV temperature in dusty conditions is visualised in Figure 14. This clustered chart displays the MAE values, making it easy to compare their performance across different experiments. Notably, Eqs. (18) to (23) exhibit strong predictive capabilities, but it's worth noting that the developed equation consistently outperforms all others. The results of the comparative evaluation clearly underscore the superior accuracy of the developed equation. While Eqs. (21) and (22) achieve good predictions for clean surfaces, their accuracy diminishes for dusty surfaces. In contrast, the new simplified and five-layer equations for PV surfaces demonstrate enhanced accuracy, with MAEs of 7.1 and 1.4, respectively.

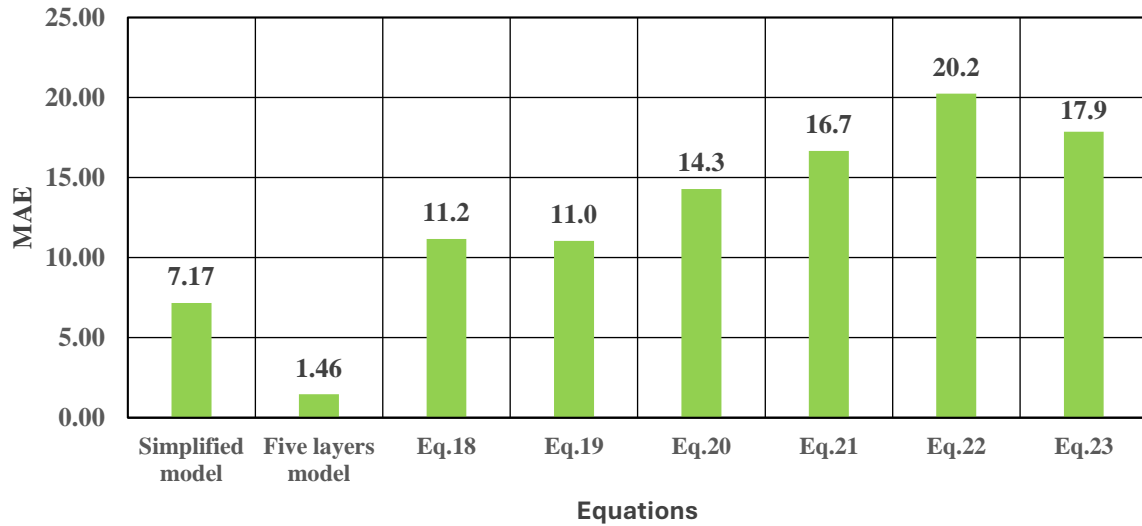


Figure 14 Mean absolute error values for developed equations and equations 18-23 in predicting dusty PV temperature.

The accuracy of the developed equation makes it an excellent tool for estimating PV temperature while accounting for the sensitive interaction between optical and thermal properties on dusty PV surfaces. The study's findings emphasise the importance of including dust parameters for precise temperature estimations.

#### 4. Conclusion

In conclusion, this study provides a comprehensive exploration of the intricate relationship between dust accumulation and PV module systems. Through systematic experimental analysis and advanced mathematical modeling, the research reveals the significant impact of dust on PV temperature and efficiency. Employing experimental techniques, critical optical properties such as transmittance, absorbance, and emissivity are quantitatively examined, shedding light on their crucial role in influencing heat transfer within the PV modules.

The outdoor experiments emphasise elevated PV cell temperatures and diminished electrical output power in dusty PV systems, highlighting the urgent need for accurate PV temperature estimation in dusty environments. The developed mathematical models, both the simplified one and the one consisting of five derived equations solved by the EES program, can accurately predict PV temperatures across different surfaces with MAEs of 7.1 and 1.4 respectively. Validation against experimental data verifies its precision in capturing the nuanced influences of dust on PV temperature.

Furthermore, this study extends to a comparative evaluation of established equations, encompassing optical properties and dust-related effects. The developed mathematical model emerges as a superior predictor of PV temperature in dusty conditions, exhibiting the lowest MAE. This research contributes to a deeper understanding of the intricate interplay between dust accumulation and PV module performance. It paves the way for future innovations in the field by providing a robust framework for analyzing the impacts of dust on PV modules. By integrating dust parameters and optical properties, the findings hold profound practical implications for accurately estimating PV temperature, enhancing efficiency, and ensuring reliability in dusty environments.

In light of the findings, the study asserts the significance of delving deeper into the multifaceted impacts of dust accumulation, and it encourages the exploration of adaptive strategies and advanced materials to mitigate the adverse effects of dust on PV modules.

Prospects:

1. Future research should focus on the intertwined effects of dust accumulation and high-temperature environments on the long-term degradation of PV modules.
2. Understanding these combined effects can guide the development of superior materials and designs that ensure PV modules retain their efficiency over extended periods, even in harsh conditions.
3. Investigations into how dust and temperature extremes impact PV module lifespans can inform more effective maintenance practices, leading to improved durability and performance.
4. Research into the combined impacts of dust accumulation and extreme temperatures can yield insights into potential weakness and pave the way for innovative module designs.
5. Continued exploration of advanced materials that resist the adverse effects of dust accumulation will be pivotal in enhancing the efficiency and longevity of PV modules in dusty environments.

This underscores the pressing need for collaborative efforts and interdisciplinary research to advance the field of solar energy and address the challenges posed by environmental conditions.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## **Chapter 4: Manuscript 3 – Dust Impact on PV Modules: Global Data, Models, and Chemical Composition**

This manuscript explores the effects of dust accumulation on the efficiency of PV modules, underscoring the importance of dust's chemical composition and accumulation weight. Drawing from an analysis of over 300 experimental readings gathered from diverse regions, the study integrates global datasets and employs advanced predictive methodologies, including Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR), within a MATLAB framework. The manuscript illustrates how the incorporation of key dust components (Si, Fe, Ca, and Al) into predictive models significantly enhances their accuracy across various environmental conditions. A comparative analysis with existing studies reveals that our models achieve Mean Squared Errors (MSEs) of 1.8% for ANN and 8.44% for MLR, surpassing previous benchmarks. These findings underscore the importance of understanding the chemical and physical characteristics of dust in maintaining PV module efficiency, particularly in regions prone to dust accumulation. This research presents a comprehensive approach to modeling the impact of dust on PV modules, offering valuable insights for optimizing solar energy utilization on a global scale.

# Dust Impact on Photovoltaic Modules: Global Data, Predictive Models, Emphasis on Chemical Composition

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## Abstract:

This study explores the influence of dust on optical properties such as transmittance, absorptance, and emissivity of photovoltaic (PV) modules using over 300 experimental readings from various dust types. These readings were collected during regional storms and ground sources, data encompass different weight levels. Incorporating 690 global datasets and leveraging Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR) in MATLAB, the study integrates key dust chemical components (Si, Fe, Ca, Al) and weight to predict the PV optical properties. This approach enhances models' predictive accuracy across diverse environmental settings, which in turn enables more accurate forecasting of PV power output and thermal behavior under varying dust conditions, as these optical properties govern the module equations. Additionally, comparative analysis with existing literature shows superior accuracy, achieving Mean Squared Errors (MSEs) of 1.8 and 8.44, surpassing previous benchmarks. Results underscore the global efficacy of our methodologies in revealing dust's impact on PV module thermal behaviour and efficiency.

## 1. Introduction:

The development of PV technology, which involves converting sunlight into electricity, marks a significant shift in energy generation [1]. Although PV modules are typically tested under current environmental conditions at the manufacturing stages, their deployment in the real world presents unique challenges, particularly under the dust accumulation situation. The dust accumulation on the PV surface impacts the electrical, optical, and thermal characteristics of PV modules by obstructing the sunlight, which leads to a decrease in electrical output [2]. This impact varies based on different factors such as dust composition, quantity, PV module orientation, and environmental conditions.

It is crucial to understand how dust influences the optical properties of PV modules in terms of PV glass transmittance, absorbance and reflected light as well as emitting heat from its surface.

The dust will absorb more light and, in turn, reduce efficiency and increase module temperature [3]. Additionally, the light transmittance and reflection due to dust accumulation play pivotal roles in PV performance which can lead to changing the output power. Moreover, dust emissivity, often overlooked, can influence thermal behavior in PV systems. The chemical composition and quantity of accumulated dust on PV modules could play an important factor in influencing the optical properties of PV.

Understanding the interaction between dust contamination and the PV modules is considered very essential for enhancing the efficiency of PV systems to optimize the use of solar energy. This understanding becomes increasingly vital as the global community shifts towards renewable energy sources. Therefore, Numerous studies have investigated the impact of dust deposition on PV system optical properties. For example, Piedra et al. [4] demonstrated that there is a linear correlation between the light transmission through PV modules with increasing dust accumulation. Another study revealed that adding just one gram of dust per square meter could result in a 4.1% reduction in light transmittance [5].

Most research in this area has primarily focused on dust's effect on transmittance, which directly impacts the electrical performance of PV modules. Gholami [6] conducted experiments on the reduction in transmittance coefficient due to dust accumulation on PV surfaces and formulated a specific equation that correlates between dust surface density and transmittance.

Diop et al. [7] investigated optical losses in PV modules due to Saharan dust deposition in Senegal. They have provided detailed insights into how dust thickness and deposits change the transmittance and reflectance percentages. This insight is crucial as it highlights the need for regular cleaning of solar panels in similar dusty environments to maintain energy efficiency. Elminir et al. [8] established an equation relating dust deposition density to the reduction in transmittance of PV modules in Egypt, highlighting regional variances in dust impacts.

Studies in Saudi Arabia by Said and Walwil [9] focused on dust fouling effects on PV module performance, detailing the chemical composition of dust and its correlation with reduced transmittance. The predominance of Calcium, Silicon, and Iron in the dust composition was emphasized. In China, Liu et al. [10] explored the power reduction mechanism of dust-deposited photovoltaic modules, revealing a significant decrease in transmittance with increasing dust density, indicating a threshold beyond which the impact on PV module performance stabilizes. This research quantified the power reduction mechanism in dust-

deposited photovoltaic modules, correlating dust thickness and spectral composition with the percentage decrease in energy generation.

Wu et al. [11] introduced a mathematical model assessing the influence of dust particle shape on relative transmittance in photovoltaic systems. Validated through simulations and experiments, the model highlights that cubic dust particles induce a more significant reduction in transmittance compared to spherical particles. However, aspects like absorptance and emissivity, crucial for thermal behaviour, have received comparatively less attention in the literature. A wide range of experimental studies have investigated the impact of dust on light transmittance, and many of them have developed different mathematical modules to predict this impact on transmittance, as shown in Table 1.

Table 1. Comparative Models to Estimate Dust Impact on PV Panel Transmittance.

Study	Model Equation
[6]	$\Delta\tau (\%) = -0.001335\rho^6 + 0.04398\rho^5 + 0.5427\rho^4 + 3.05\rho^3 - 7.703\rho^2 + 11.19\rho - 2.25$
[8]	$\Delta\tau (\%) = 0.0381\rho^4 + 0.8626\rho^3 - 6.4143\rho^2 - 15.051\rho + 16.769$
[9]	$\Delta\tau(\%) = 0.004\rho + 0.0269$
[10]	$T = (1 - F^2) e^{(-am/p)}$
[12]	$T(\%) = 66.66\exp(-0.038 \times \rho)$
[13]	$\tau = \tau_c[1 - 0.3437\text{erf}(0.17\rho^{0.8473})]$
[14]	$\Delta\tau = 23.27 \ln(\rho) - 23.5$
[5]	$\Delta\tau = 4.1\rho$
[15]	$\Delta\tau = -43.156 \exp(-0.125\rho) + 43.152$
	$\Delta\tau = -0.208\rho^2 + 5.074\rho + 0.12$
Conceição et al. cited in [16]	$\Delta\tau = 1 - 0.02545\rho$
[17]	$\Delta\tau = 4.39 \rho + 0.507$

Where  $\rho$  represents the dust density and is measured in grams per square meter.

to further optimize the performance of PV modules in dusty environments, it is essential to consider a broader range of environmental parameters that affect their characteristics. In particular, dust accumulation requires detailed modeling to fully understand its impact. For this reason, machine learning models like Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR) offer powerful tools for predicting and optimizing PV module performance

under varying conditions [18]. Comparing these methods' effectiveness could significantly enhance the accuracy of PV performance predictions in real-world scenarios [19].

Although previous studies on the impact of dust on PV systems have made significant contributions, there are several key limitations that this research aims to address:

- **Region-specific restrictions:** all the previous studies focus more on certain dust types that are partially dependent on some regions. Therefore, the results may not generalize in different environmental conditions.
- **Consider only the dust weight:** The current models have been considered mainly the one character of dust, which is the dust weight, and have neglected very important elements, which is the chemical composition of dust.
- **Limited the optical properties:** In fact, while the literature mainly investigated and developed different modules on the effect of dust on transmittance, all other important optical properties like absorbance and emissivity have been relatively neglected. Understanding these properties is essential for recognizing the thermal behaviour and hence the efficiency of the PV module.
- **Prevailing research predominantly explores the impact of dust on transmittance,** overlooking equally crucial optical properties like absorbance and emissivity. Understanding these properties is essential for comprehending the thermal behaviour and efficiency of PV modules.
- **Simple analytical techniques:** simple techniques such as curve fitting procedures may not well describe the complex relations between dust characteristics and the performance of optical PV systems.
- **Limited mathematical models:** The most commonly used models are limited within specific dust weight ranges which may result in inaccuracies whenever used in wider dust accumulation scenarios.

These gaps demonstrated the necessity for a more detailed and complicated analytical approach to accurately predict the impact of dust on PV optical properties. Therefore, the main aims and objectives of this study are:

- **Broader applicability:** This study would involve a wide range of dust types from different global locations; therefore, it is enhancing generalizability within multiple environmental dusty conditions.

- Considering chemical composition for optimal understanding: It extends the analysis to include the dust weight as well as the dust chemical composition (e.g., Si, Fe, Ca, and Al) into predictive models to thoroughly evaluate its impact on optical properties.
- In-depth optical evaluation: the study detailed analysis of not only the transmittance, but also absorbance, and emissivity for understanding the impact of dust on the optical characteristics of the PV systems.
- Advanced modeling techniques: it has been employing more complex modeling techniques such as ANN and MLR in MATLAB to develop new models that would be capable of predicting any changes in the optical properties caused by dust accumulation.
- Incorporating diverse datasets: the study utilizes a diverse multinational dataset which is covering a wide range of dust weights and chemical compositions to ensure the accuracy and applicability of mathematical models in various dust accumulation scenarios.

The study contributes to a significant improvement in predicting the PV optical properties when addressing these identified gaps, where it offers a more holistic perspective on how dust accumulation affects the optical properties of PV modules and provides practical tools for predicting the optical impact of dust accumulation on PV surfaces.

## **2. Methodology**

This section demonstrates the methodology, highlighting in-depth dataset collection procedures. It illustrates how the experimental data from this study have been combined with previous experimental data from global research findings to create a detailed and extensive dataset. Additionally, the study demonstrates the utilization of complex analytical methods, specifically Artificial Neural Networks and Multiple Linear Regression in MATLAB. These methods provide a strong predictive base for evaluating the various optical characteristics of PV modules, considering varying dust deposition weights and types.

### **2.1 Collation of Dust Study Data and Sources**

This research has followed the established testing protocols used by Almkhtar et al. [20] to guarantee uniformity in the data collection methods. Dust samples were carefully collected using a similar detailed method in previous studies. This involved using a large plastic sheet to gather samples during three regional dust storms. Additionally, ground-based samples from the

same regions have been collected. In this approach, uniformity of data was ensured, maintaining direct comparison with the results of previous studies.

The experimental procedure included many analyses: X-ray fluorescence (XRF) and the INGLAS TIR100-2 device were used to determine the dust's chemical composition and emissivity. At the same time, UV-Vis spectroscopy assessed transmittance and absorptance on PV module surfaces. The optical properties were examined across different dust weights and compositions to represent real accumulation scenarios, aligning with the methodology outlined in Almukhtar et al. [20] These efforts aimed to extensively evaluate how dust affects the optical properties of PV modules and ensure consistency with prior methodologies for a thorough analysis.

Additionally, there was significant integration of data from external studies. This involved a thorough review and analysis of existing literature, adhering to specific inclusion criteria to guarantee its relevance and comparability with our experimental data. Emphasis was placed on studies investigating the chemical composition of dust, as this aspect was crucial for understanding its impact on PV modules. Prioritization was given to research providing both chemical composition and dust weight data, facilitating an in-depth analysis correlating the dust's chemical makeup with its weight. The selected studies exhibited a wide range of dust weights, from 0.7 to 42 g/m<sup>2</sup>, ensuring a broad spectrum for analysis. Geographical diversity was maintained in study selection, analysing experimental work from various countries to gain a global perspective on dust characteristics under different climatic conditions. Over 700 samples from these selected studies were analysed, forming a reliable dataset that expanded the scope and depth of our extensive analysis. Table 2 presents the data sources and arrangement utilized for this study from previous research.

Table 2. demonstrates the number of data that will be collected from the investigation experimental for this study.

Study	Country	Data reading Size	Chemical Composition
[6]	Iran	560	Si:50.26%, Fe:7.23%, Ca:27.31%, Al:7.92% and other components.
[7]	Senegal	5	Si:50.1%, Fe:16.8%, Ca:10.6%, Al 0.5% and other components.
[8]	Egypt	48	Si: 49.25%, Ca: 35.55%, Al: 4.43%, Fe: 4.24% and other components.

[9]	Saudi Arabia	28	Ca: 47.0%, Si: 20.5%, Fe: 16.0%, Al: 4.0% and other components.
[10]	China	45	Ca: 10.4%, Si: 50%, Fe: 3.8%, Al: 26% and other components.
[20]	Iraq	4	Si (%) 30.31, 31.35 Al (%) 9.27, 9.80 Fe (%) 9.49, 9.70 Ca (%)34.78, 34.80 and other components.

Table 3 presents experimental readings for various optical properties categorized by different types of dust. Initially, samples from three distinct storms (types A, B, and C) underwent analysis for their transmittance and absorbance properties, involving six readings per type. Following this, a comparative analysis was conducted between dust collected during storms and ground-collected dust (A and G), comprising 33 readings each for transmittance, absorbance, and emissivity measurements. Lastly, a comparative study among the three storm types (A, B, and C) focused on emissivity properties, with 6 readings for each type.

Table 3. Experimental Readings of Optical Properties for Different Dust Categories - Storms A, B, C, and Ground-Collected Dust

Experimental Investigation	Dust Types	Number of Readings	Properties Analyzed
Dust from three distinct storms	A, B, C	18 (6 per type) *	Transmittance
Dust from three distinct storms	A, B, C	18 (6 per type) *	Absorbance
Comparative analysis: dust storm vs. ground collected	A and G (Dust storm and ground)	66 (33 each)	Transmittance
Comparative analysis: dust storm vs. ground collected	A and G (Dust storm and ground)	66 (33 each)	Absorbance
Comparative analysis: dust storm vs. ground collected	A&G (Dust Storm and Ground)	66 (33 each) *	Emissivity
Comparative study: Three dust storm types	A, B, C	54 (18 per type)	Emissivity
<b>Total</b>		<b>306</b>	

\*Specifically, for dust types A and B, only two sets of readings for transmittance, absorbance, and emissivity data were previously published in our work from [20].

## 2.2 Analytical Methods

The study leveraged MATLAB's computational capabilities for two complicated analytical methods: ANN and MLR. These methods played a crucial role in predicting the optical properties of dust-coated PV modules, accounting for both chemical composition and dust weight.

### 2.2.1 Artificial Neural Networks

ANNs served as the primary tool for predicting the optical properties of PV modules. These networks, inspired by the human brain, excel at identifying complex patterns within data. Leveraging MATLAB's neural network toolbox, the ANN process involved key steps:

- **Data Input:** The network was fed an extensive dataset comprising chemical composition and dust weights from various samples.
- **Network Structure:** This included multiple layers featuring an input layer, two hidden layers for computation (20 and 15 neurons, respectively), and an output layer for predictions, as illustrated in Figure 1. Due to a process of trial and error, these choices were made to capture complex features and patterns from the input data while balancing model complexity and the risk of overfitting.

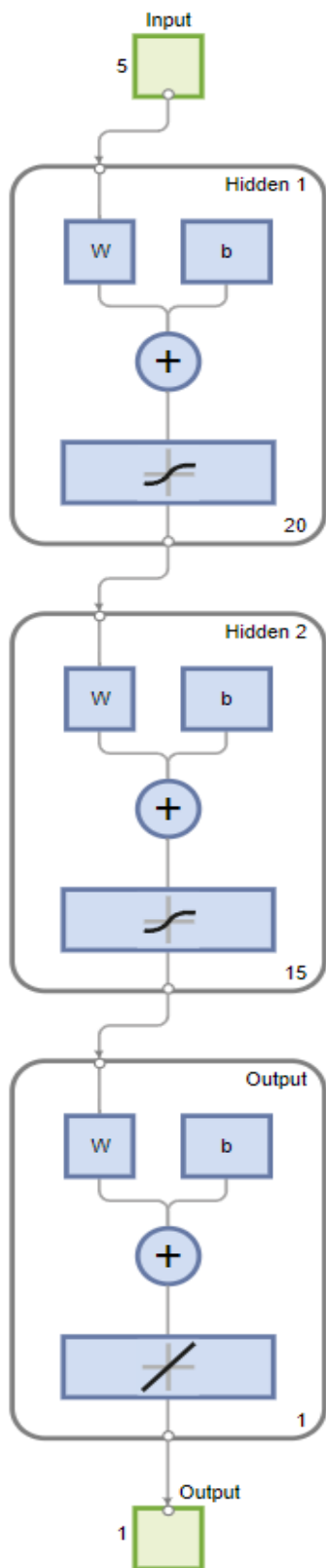


Figure 4. Structure of ANN with Two Hidden Layers (20 and 15 Neurons) Developed in MATLAB

Furthermore, the training and testing phases involved splitting the data into training (70%), validation (15%), and testing (15%) sets. This split ensures a well-rounded evaluation, helps prevent overfitting, and is commonly used by scholars. The network underwent training using Bayesian Regularization backpropagation (*trainbr* function) for 500 epochs, with a *max\_fail* criterion of 10. The ANN training process stops when either the maximum of 500 epochs is reached or if validation performance does not improve for 10 consecutive checks, which helps prevent overfitting. The ANN proved particularly effective in handling non-linear relationships within the complex dataset. Table 4 presents the key hyperparameters of the ANN.

Table 4. Hyperparameters of the Artificial Neural Network (ANN)

<b>Hyperparameter</b>	<b>Value</b>
Input Data	Chemical composition and dust weights from various samples
Network Structure	Input layer, two hidden layers, and output layer
Number of Neurons in Hidden Layers	20 neurons in the first hidden layer, 15 neurons in the second hidden layer
Output Layer	Single output for prediction
Data Split	70% training, 15% validation, 15% testing
Training Algorithm	Bayesian Regularization backpropagation ( <i>trainbr</i> )
Epochs	500 maximum
Max Fail Criterion	10 consecutive checks without improvement in validation performance
Stopping Criteria	Either 500 epochs reached or <i>max_fail</i> criterion triggered
Prevention of Overfitting	Validation performance monitoring and <i>max_fail</i> criterion
Tool Used	MATLAB Neural Network Toolbox

### 2.2.2 Multiple Linear Regression

MLR served as a complementary analytical method to ANN. This statistical technique models the relationship between a dependent variable and multiple independent variables. The MLR process in MATLAB involved:

- **Variable Identification:** This study considers the independent variables, which are the chemical composition and dust weights, and their relation to the dependent variables, which are the optical properties.
- **Model Development:** A linear equation has been constructed to identify the optimal combination of independent variables for predicting the dependent variable using the film function.

- Coefficient Analysis: the study determines coefficients for each variable to understand their impact on the optical properties. This provides an understanding of the importance of chemical composition and dust weight in predicting the optical characteristics.

The integration of ANN and MLR in this study provides a detailed approach to the impact of dust on the optical properties of PV modules. The ANN is adept at handling complex data patterns, and MLR offers insights into linear relationships. Utilizing both ANN and MLR to predict the dust impact contributes to enhancing the precision of predictions. The flowcharts in Figure 2 detail each step of these analytical methods and offer a visual guide for enhanced clarity and comprehension.

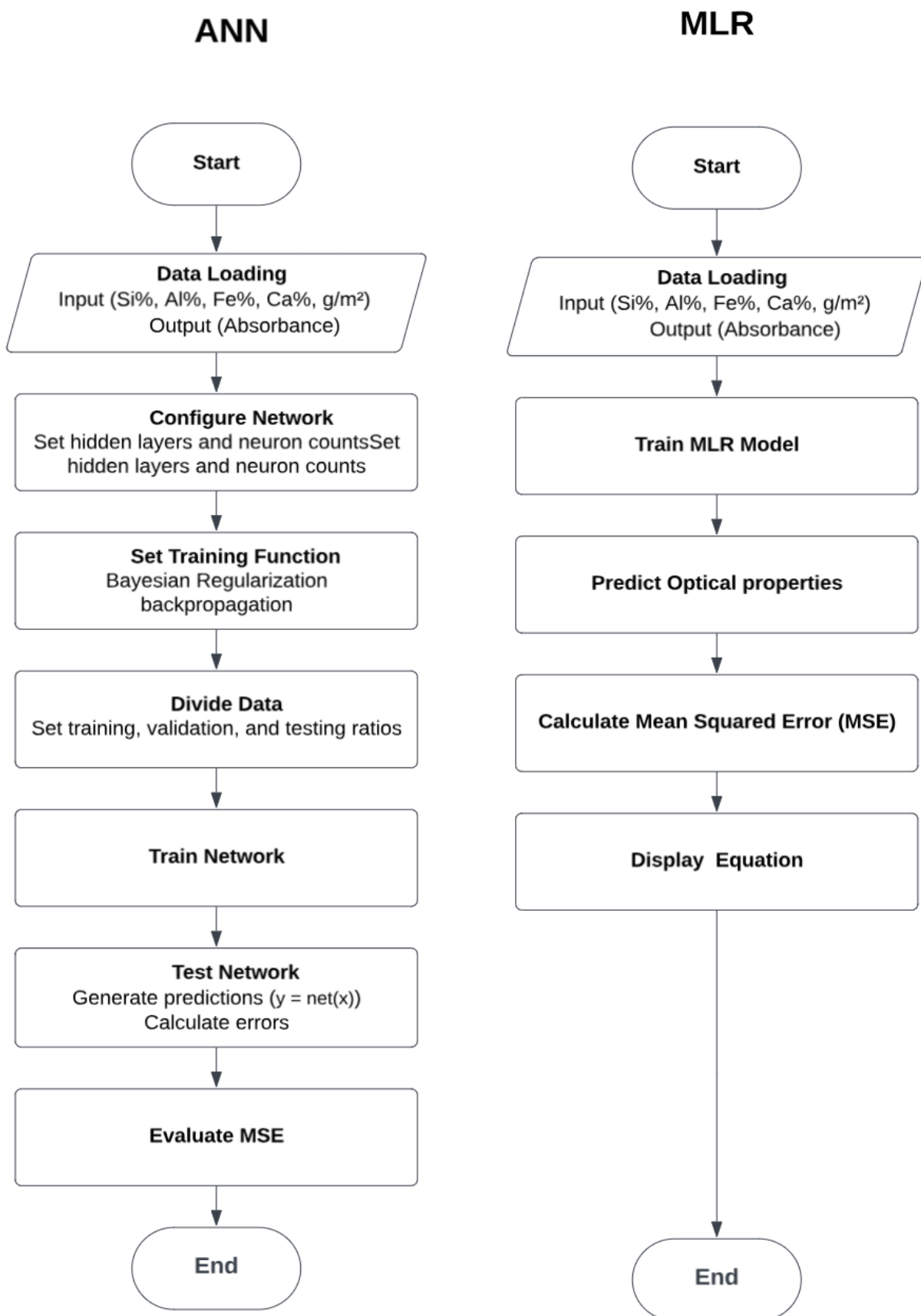


Figure 5. Demonstrates the analytical methods step-by-step flowcharts for clarity and comprehension.

### 2.3 Mean Squared Error (MSE) Calculation

The Mean Squared Error (MSE) is a commonly used metric to evaluate the performance of predictive models, particularly in regression analysis [21]. MSE quantifies the average squared difference between the observed actual outcomes and the outcomes predicted by the model. It is defined by the following equation:

$$MSE = \left(\frac{1}{n}\right) \Sigma (\text{experimental valu} - \text{predicted values obtained from the model})^2$$

Where: n is the number of observations. The MSE is a non-negative value, where a lower MSE indicates a better fit of the model to the data, implying higher accuracy in the model's predictions. A value of zero would indicate a perfect fit, where the predicted values are exactly equal to the observed values.

## 3. Results and Discussion

This section presents an analysis of the research findings. It combines the details of the impact of dust on PV modules. This includes considering various factors, which are the chemical composition and weight of dust and its diverse influence on optical properties. Additionally, the section discusses the practical implementation that comes with these findings.

### 3.1 Chemical Composition of Dust Samples

All examined dust samples have been analyzed to determine their chemical composition. Table 5 details the chemical composition of four dust types A, B, C and G. Types A and B have been previously published in a separate paper [20].

Table 5. The proportion of various elements and materials present in each dust type.

Element	Dust storm A	Dust storm B	Dust storm C	Ground-Dust G
Si (%)	30.31	31.35	29.16	46.03
Al (%)	9.27	9.8	8.50	1.20
Fe (%)	9.49	9.7	8.40	15.20
Ca (%)	34.78	34.8	36.11	20.29
Mg (%)	5.01	5.01	4.80	2.00
Na (%)	5.47	3.5	0.684	2.49
K (%)	2.69	2.82	2.819	0.75
S (%)	5.47	3.51	7.347	0.70
Ti (%)	0.969	1.137	0.985	0.34

These results contribute to understanding the material components and how they possibly influence PV optical characteristics. Table 5 provides a detailed quantitative analysis of the elemental composition in dust samples from different dust types. Key components, including Silicon (Si), Aluminium (Al), Iron (Fe), Calcium (Ca), Magnesium (Mg), Sulphur (S), and Potassium (K), are highlighted. The data reveals significant differences, especially between the dust storms and ground-collected dust in these elements, with notable levels of Si, Al, Fe, and Ca, which affect the dust's physical and optical properties. For example, high Silicon concentrations, especially in soil dust, indicate its possible influence on altering light absorption and scattering patterns. Understanding these differences in chemical composition is crucial for demonstrating how dust affects PV module performance, possibly affecting factors like transmittance, absorbance, emissivity, and general efficiency.

It's important to note that although the research focuses on elements found in high concentrations, the cumulative effect of all components, including those in small amounts, can still contribute to the overall behavior of dust and its impact on PV modules. However, to simplify the study in predicting optical properties using MATLAB, prioritizing the analysis of the critical elements offers a focused and relevant understanding of the impact of dust accumulation.

### **3.2 Influence of Dust Characteristics on PV Optical Performance**

This section demonstrates the results from experimental tests on how different dust types and weights influence the optical performance of PV systems. The key findings related to the effects of dust on transmittance, absorbance, and emissivity are crucial factors impacting both PV efficiency and thermal behavior.

#### **3.2.1 Experimental Results for the Optical Properties of PV Systems**

This subsection provides a thorough analysis of the optical behaviors exhibited by PV systems under the influence of different types and weights of dust. The study distinctly emphasizes the impact of dust accumulation on absorption, transmittance, and emissivity within the dusty glass layer of PV modules. Visual representations of these relationships are illustrated in scatter charts (Figures 3-5).

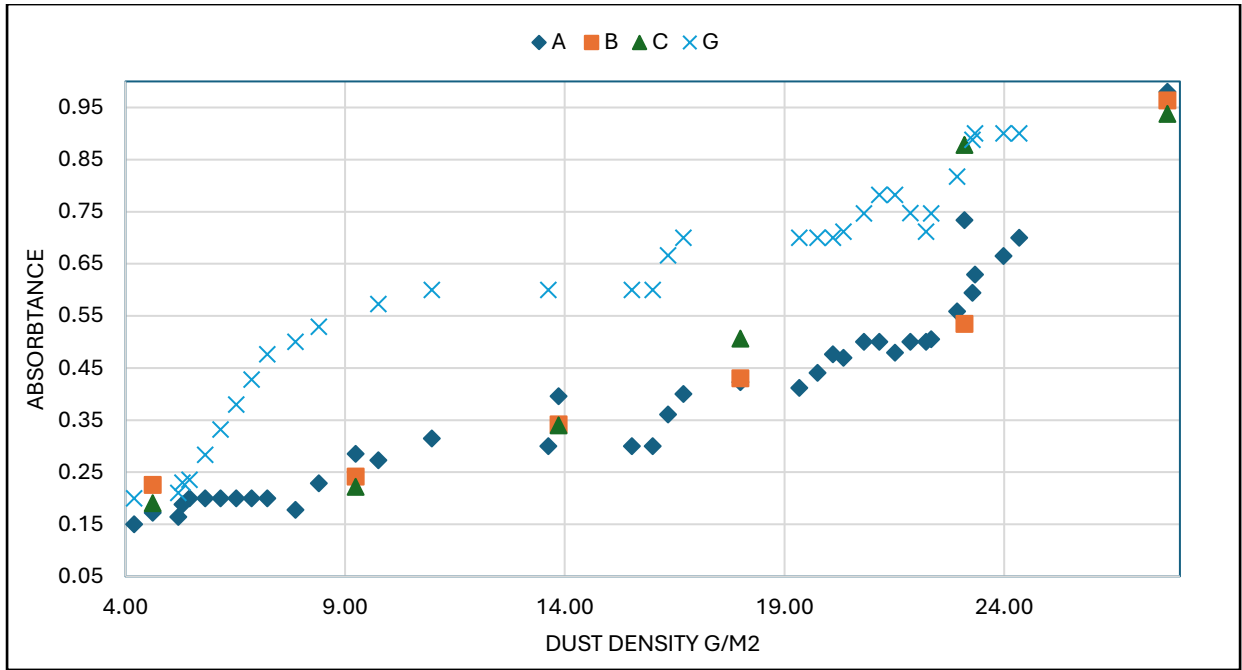


Figure 3. Absorbance Comparison Between Storm-Collected (A, B, C) and Ground-Collected (G) Dust. \*For dust type A and B at the weight (9.2 and 18) g/m<sup>2</sup> from Ref. [20].

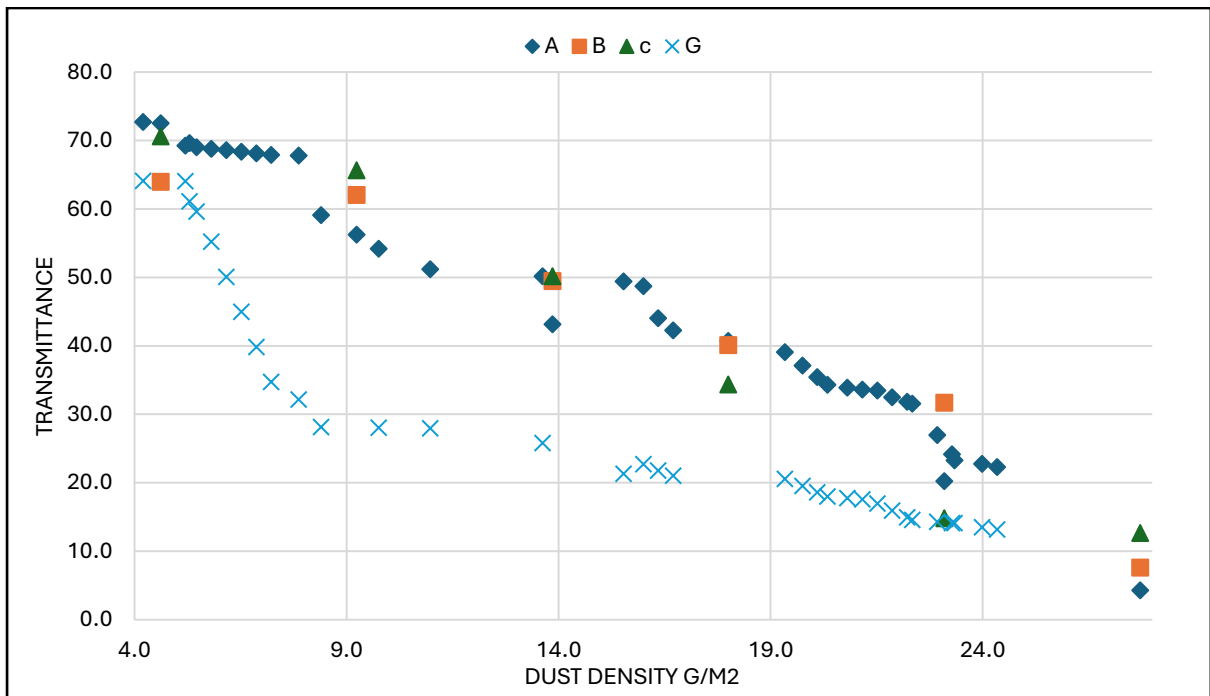


Figure 4. Transmittance Comparison Between Storm-Collected (A, B, C) and Ground-Collected (G) Dust. \*For dust type A and B at weight (9.2, 18) g/m<sup>2</sup> from Ref. [20].

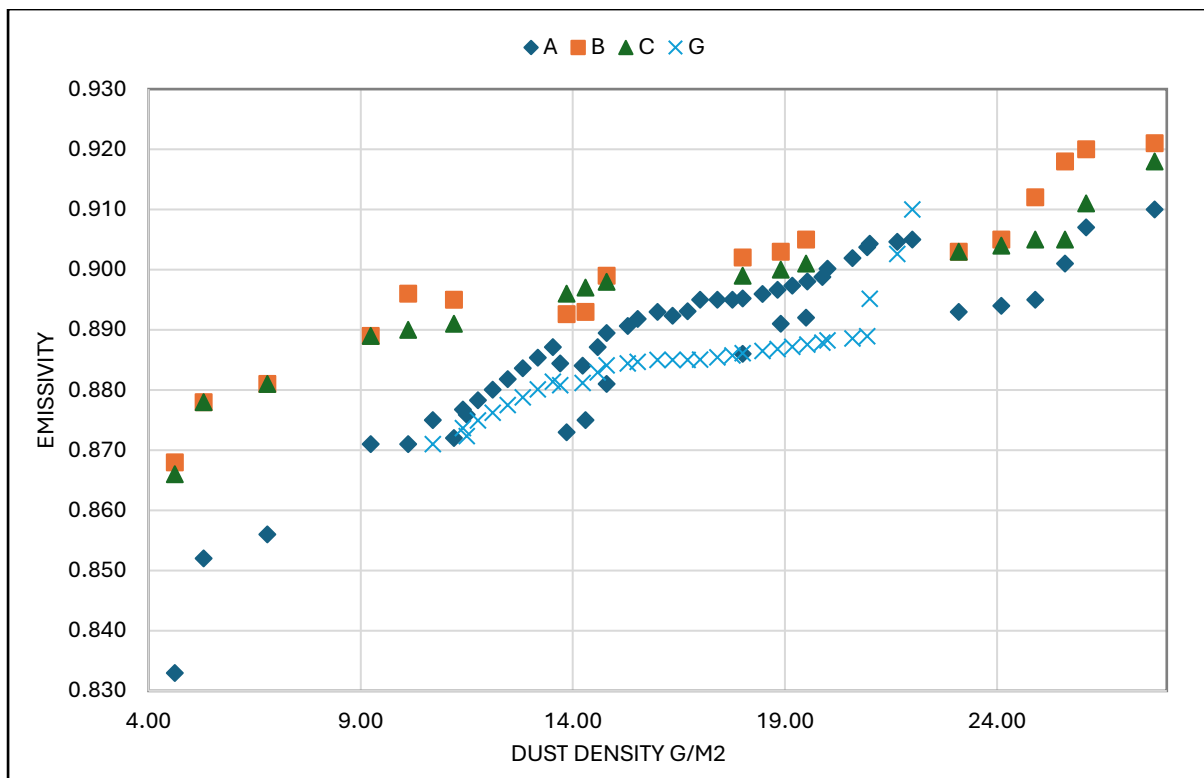


Figure 5. Emissivity Comparison Between Storm-Collected (A, B, C) and Ground-Collected (G) Dust.

\*For dust type A and B at weight (9.2, 18) g/m<sup>2</sup> from Ref [20].

A notable finding reveals an inverse relationship between dust weight and transmittance. For example, Type A dust's transmittance decreases from 72.5% at 4.6 g/m<sup>2</sup> to 20.25% at 23.1 g/m<sup>2</sup> (Figure 3), indicating obstructed light passage. In contrast, both absorbance and emissivity increase with dust weight, suggesting enhanced light entrapment and increased radiation emission. Notably, Type G dust is more effective at blocking light than Types A, B, and C, leading to a substantial increase in absorbance values as its weight accumulates. However, Types A, B, and C also exhibit increased absorbance with heavier dust layers, with a plateau effect of around 27.71 g/m<sup>2</sup>, suggesting a maximum threshold for light absorption. Anomalies in Type G dust, such as the absorbance value at 23.28 g/m<sup>2</sup>, indicate possible variations in dust composition or aggregation.

The study further distinguishes optical properties between dust collected during storms and ground samples. For instance, storm-collected Type A dust at 11.5 g/m<sup>2</sup> shows a transmittance of 69.24% and absorbance of 0.164, contrasting with ground-collected Type G dust, which exhibits a transmittance of 64.07% and higher absorbance. The differences in optical properties between the dust collected from storms and the ground are due to their different physical and chemical properties. This research has found non-linear patterns and anomalies in

transmittance, absorbance, and emissivity at specific dust concentrations. This highlighted how complex the interaction between dust and PV modules can be, and it points out the need for an in-depth analysis. Additionally, the study demonstrates the impact of dust on the optical characteristics of PV systems. Even a small amount of dust can lead to a significant impact on transmittance, absorbance, and emissivity. This influences the thermal behavior and efficiency of PV systems.

### 3.2.2 MATLAB Results

In this section, the study reveals the outcomes of applying ANN and MLR to estimate the impact of dust on the optical properties of PV modules.

#### 3.2.2.1 Predicting Optical Characteristics of PV with ANN

The ANN has considered five inputs to predict different optical features. These include the most common chemical elements found in dust, which are silicon (Si%), Aluminium (Al%), Iron (Fe%), Calcium (Ca%), and the total dust weight per square meter (g/m<sup>2</sup>). Each optical property was analyzed using distinct datasets: 88 experimental samples for absorbance, 120 for emissivity, and over 700 samples from various nations for transmittance. The data were divided into training, validation, and testing subsets with ratios of 70%, 15%, and 15%. The training across all studies involved 500 epochs with a maximum failure criterion set at 10. The performance of the ANN for each optical property is summarized in Table 6.

Table 6. Summary of ANN Performance for Each Optical Property

Optical Property	Sample Size	Training R	Validation R	Testing R	Overall R	Best Validation Performance
Absorbance	88	0.990	0.986	0.981	0.988	0.057
Emissivity	120	0.967	0.954	0.878	0.957	0.053
Transmittance	>700	0.998	0.999	0.997	0.998	0.00192

#### 3.2.2.2 Discussion and Comparative Analysis

The analysis exposes differing degrees of accuracy across the three optical properties:

- Absorbance: Demonstrated high accuracy, affirming the model's proficiency in comprehending the influence of dust composition and weight on absorbance.
- Emissivity: Displayed slightly lower R values but still presented substantial accuracy, indicating the model's effectiveness in predicting material emissivity.
- Transmittance: Attained the highest accuracy among the three, with exceptional R values, particularly in the validation phase.

The superior performance in transmittance analysis can be attributed to several factors:

- Larger Sample Size: The transmittance study utilized over 700 samples, significantly larger than the datasets for absorbance and emissivity. This extensive sample size likely contributed to the model's ability to generalize better and capture a broader range of scenarios.
- Dataset Diversity: The transmittance dataset includes data from different countries. This data provides a varied range of environmental conditions and dust compositions, which enhances the model's learning and predictive capabilities.

The outcomes highlight the flexibility and dependability of the ANN in examining different optical properties in various dusty scenarios. Although the prediction of the three properties demonstrated strong predictive abilities, the transmittance analysis was particularly notable. This emphasizes the capability of ANN models to manage large and varied datasets.

### 3.2.2.3 Predictive Optical Characteristics of PV with MLR

The MLR models were developed and executed in MATLAB. These MLR models offer straightforward, linear correlations to understand the impact of various dust levels on these optical properties. The models incorporate five inputs, including the highest concentration of chemical components of dust (Si%, Al%, Fe%, Ca%) and the dust weight per square meter ( $\text{g/m}^2$ ).

Each MLR model is trained using the same dataset used with ANN, and the film function in MATLAB establishes a linear model between the input and the respective optical properties. It has evaluated the model performance using the Mean Squared Error (MSE). The performance details and equations of each MLR model are summarized in Table 7.

Table 7. MLR Model Performance Using MSE

Optical Property	Sample Size	MSE	R-squared
Absorbance	88	0.0084	0.858
Emissivity	120	2.6E-05	0.862
Transmittance	>700	8.4	0.912

Model Equation

$$\text{Absorbance} = -0.117 \times \text{Si}\% - 0.047 \times \text{Al}\% + 0.321 \times \text{Fe}\% + 0.021 \times \text{Ca}\% + 0.045 \times \rho \quad \text{eq. (1)}$$

$$\text{Emissivity} = 0.0205 \times \text{Si}\% + 0.0029 \times \text{Al}\% - 0.0218 \times \text{Fe}\% + 0.0117 \times \text{Ca}\% + 0.0020\rho \quad \text{eq. (2)}$$

$$\text{Transmittance} = 40.708 + 10.605 \times \text{Si}\% + 3.909 \times \text{Al}\% - 53.529 \times \text{Fe}\% + 102.728 \times \text{Ca}\% + 15.936 \times \rho \quad \text{eq. (3)}$$

Where Si%, Al%, Fe%, and Ca% represent the percentage concentrations of Silicon, Aluminum, Iron, and Calcium in the dust sample, while  $\rho$  represents the dust weight per square meter, representing the amount of dust accumulation on the surface of the PV module,

### 3.2.2.4 Discussion and Comparative Analysis

#### ***Absorbance:***

The low MSE of 0.0084 in the model, about absorbance, indicates its high accuracy in predicting absorbance changes. This accuracy is crucial for analyzing the thermal behavior of PV systems. Furthermore, the model boasts an R-squared value of 0.858. This means it successfully explains 85.8% of the variation in emissivity, underlining its effectiveness in the context of the variables utilized. Notably, the negative coefficients for Silicon (Si%) and Aluminium (Al%) suggest that an increase in these elements leads to lower absorbance. This could be due to their reflective properties. In contrast, the positive coefficient for Iron (Fe%) indicates that higher Iron concentrations enhance absorbance, likely because of Iron's darker color and greater capacity for heat absorption. Additionally, the positive coefficient for dust weight ( $\text{g/m}^2$ ) is consistent with the expectation that more dust leads to increased absorbance.

#### ***Emissivity:***

The emissivity model performed with an especially low Mean Squared Error (MSE) of 0.000026, representing its high precision in predicting changes in emissivity within PV

systems. It has an R-squared value of 0.862, capturing 86.2% of emissivity variance, indicating a high fit level. The model equation shows positive coefficients for Si% and Calcium (Ca%), suggesting that increasing these elements correlates with higher emissivity. Silicon may enhance emissive properties due to being a major component of sand. A negative coefficient for Fe% implies that Iron reduces emissivity, possibly by retaining heat. A low positive coefficient for dust weight indicates that heavier dust accumulation marginally increases emissivity.

### ***Transmittance:***

The transmittance model, with a higher MSE of 8.4, indicates more variability in predictions, possibly due to a larger dataset size (>700 observations) and diversity in experimental conditions from various publications. It has the highest R-squared value of 0.912, explaining 91.2% of the variance in transmittance, and an adjusted R-squared of 0.911, confirming robustness despite numerous predictors. Unlike absorbance and emissivity, transmittance data comes from multiple sources, introducing variations. The model equation reveals a large negative coefficient for Fe%, indicating a substantial decrease in transmittance with increasing Iron content, due to its opacity and light-absorbing characteristics. In contrast, a high positive coefficient for Ca% suggests Calcium significantly increases transmittance, likely due to its light-scattering properties. Positive coefficients for Si% and Al% imply a moderate increase in transmittance with their concentration. The coefficient for dust weight indicates that heavier dust layers reduce transmittance, aligning with the understanding that thicker dust layers block more light.

### **3.3 Overall Implications**

The variations in MSE across different optical properties underscore the distinct challenges in modeling each optical property, emphasizing the significance of selecting appropriate predictors for accurate modeling. While all models demonstrate good predictive capabilities, as indicated by their R-squared values, the variations highlight that some properties, such as transmittance, are more complex to predict. Understanding these interactions is crucial for developing more accurate predictive models, which can significantly enhance the prediction of PV module temperature and overall performance. Accurate modeling is essential not only for optimizing the design of PV systems in dusty environments but also for informing maintenance practices. By predicting when and how dust accumulation impacts performance and temperature, these models can guide the timing and necessity of cleaning interventions to avoid

overheating that could damage or threaten the PV technology. This approach ensures that PV systems operate at peak efficiency with minimal downtime, ultimately improving the longevity and cost-effectiveness of solar installations in areas prone to dust accumulation.

### 3.3.1 Comparative Analysis of ANN and MLR Models for Predicting Optical Properties of PV Modules.

This section offers a comparative analysis of ANN and MLR models in predicting the influence of dust on the absorbance, emissivity, and transmittance of photovoltaic modules. The performance of each model is evaluated using metrics like R-squared ( $R^2$ ), Adjusted  $R^2$ , and Mean Squared Error (MSE), as detailed in Table 8.

Table 8. Comparative Performance of ANN and MLR Models for Optical Properties

Optical Property	Model Type	$R^2$ (%)	Adjusted $R^2$ (%)	MSE
Absorbance	ANN	98.751	98.741	0.004007
	MLR	85.8	85.1	0.008398
Emissivity	ANN	95.697	95.69	4.02E-05
	MLR	86.2	85.7	0.000026
Transmittance	ANN	99.778	99.777	1.8
	MLR	91.2	91.1	8.4

Figures 6, 7, and 8 compare the experimental results and the prediction values made by MLR and ANN models for transmittance, absorbance, and emissivity. This visual representation helps in understanding how closely each model is from the experimental data.

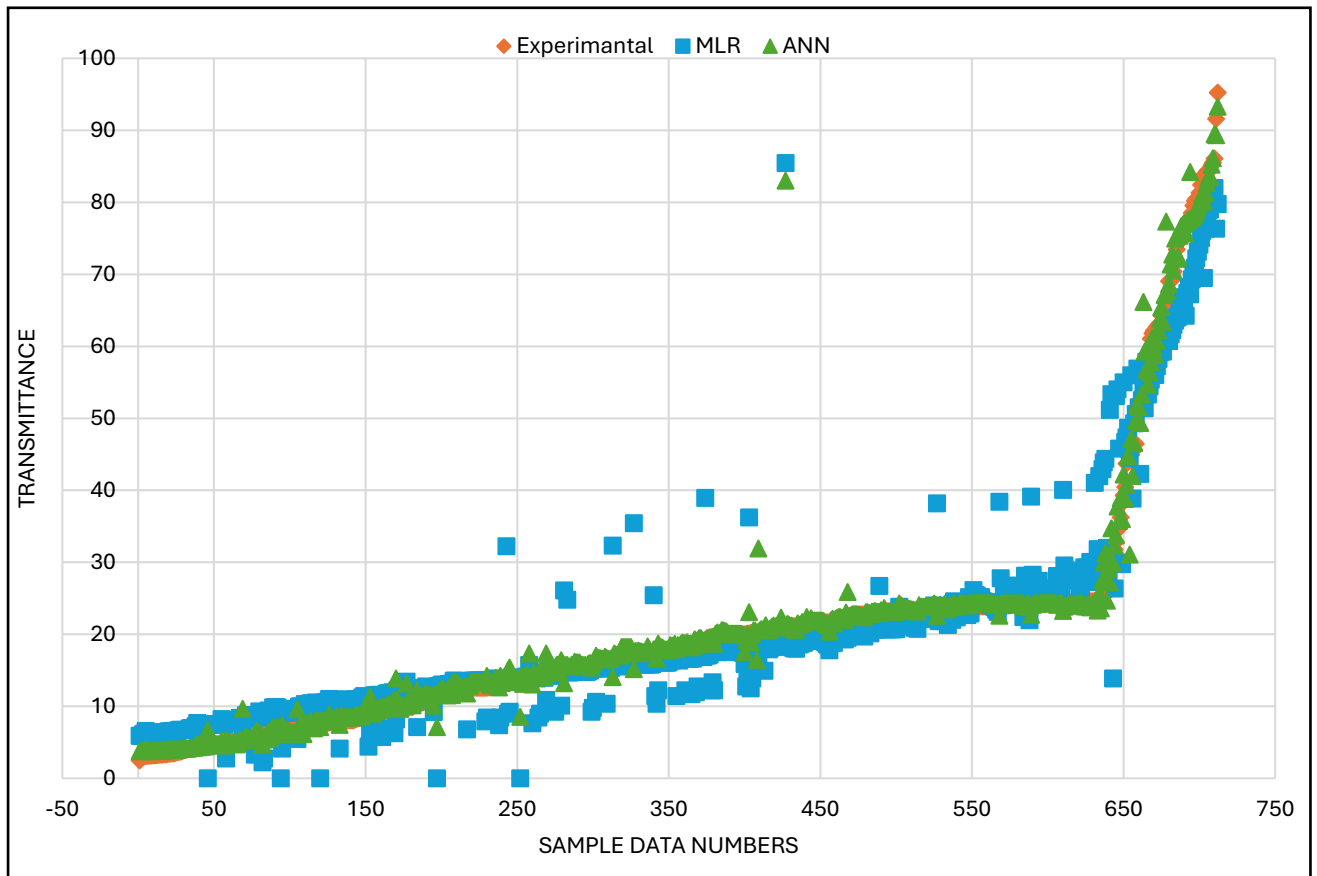


Figure 6. Transmittance Comparison: Evaluating Experimental Values Against MLR and ANN Forecasts

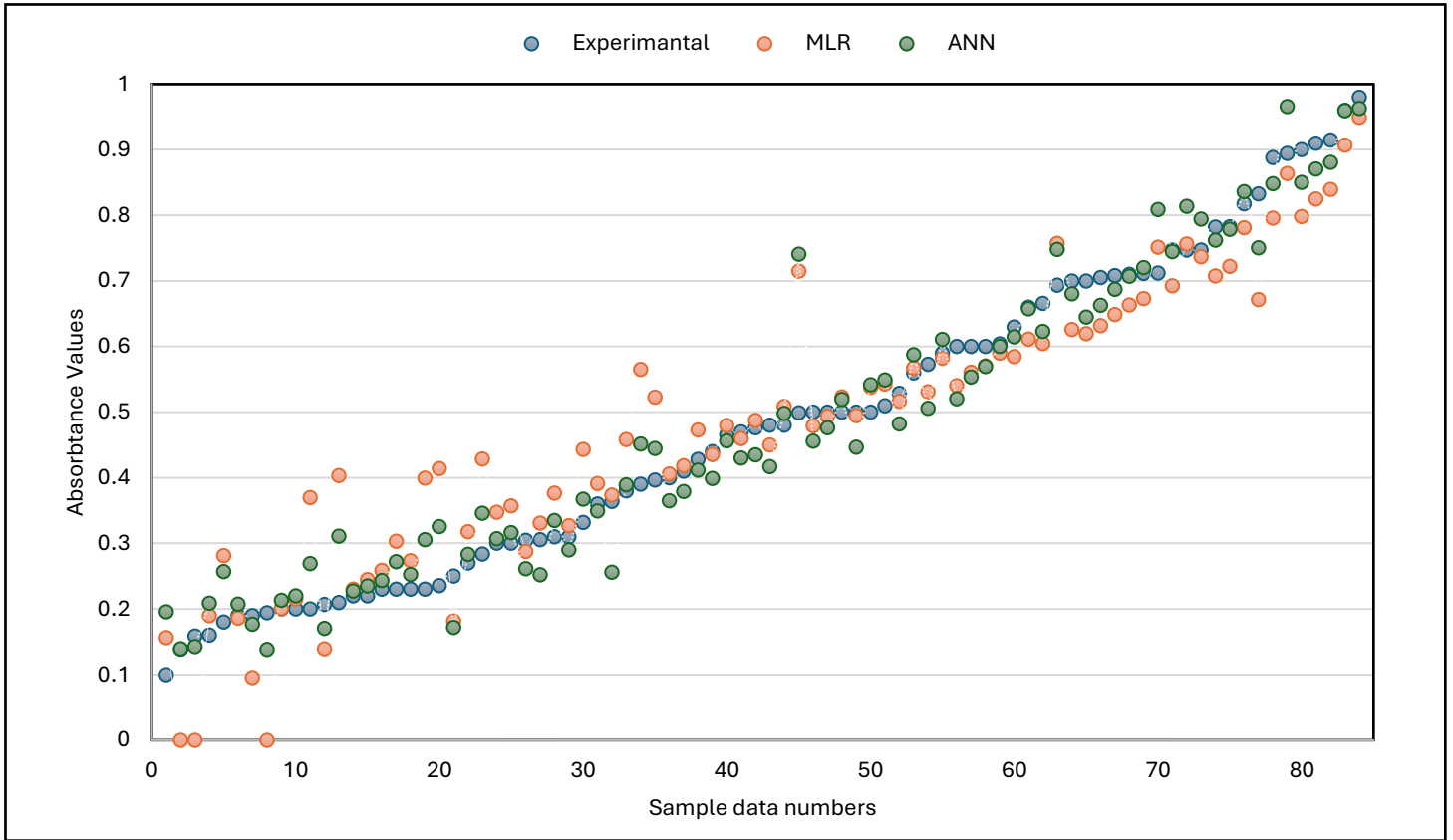


Figure 7. Absorbance Analysis: Experimental vs. Predicted (MLR & ANN)

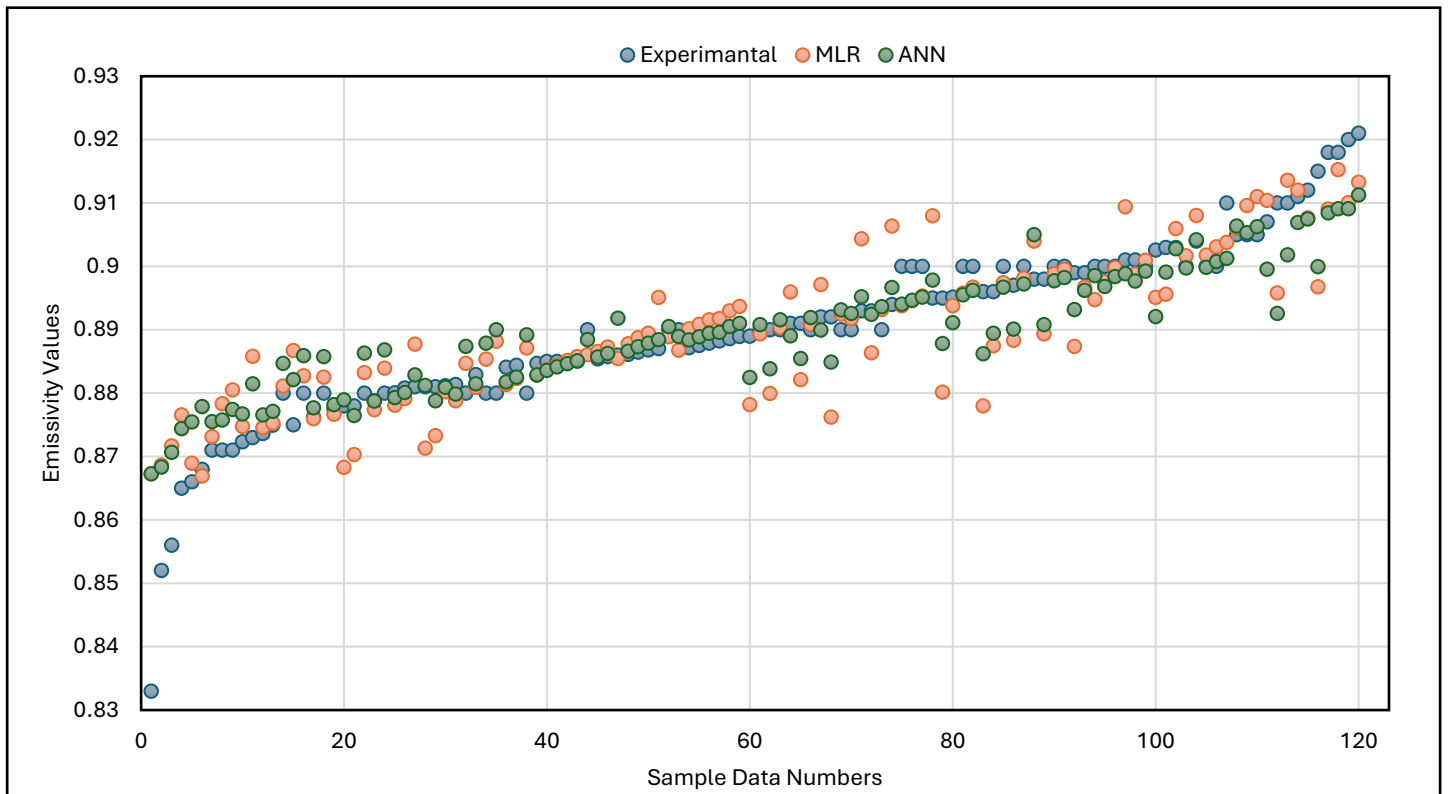


Figure 8. Emissivity Trends: Comparing Actual Data with MLR and ANN Predictions

The overall performance of ANN models demonstrates higher  $R^2$  and Adjusted  $R^2$  values across all optical properties, indicating a stronger fit to the data than MLR models. This superiority indicates that ANN is more efficient in capturing the complex, non-linear interactions between dust characteristics and optical properties. Additionally, lower MSE values in ANN models further demonstrate better predictive accuracy, particularly in capturing the variability within the data, as noted in the absorbance and emissivity models. Although the ANN models have shown superior performance, they are more complex and less interpretable than MLR models. The linear equations of MLR provide ease of understanding, making it beneficial for assessments or explanations between the input and output parameters.

### 3.4 Comparative Analysis of Transmittance Reduction Predictions

The study extensively compares the predictive capabilities of various models in estimating transmittance reduction due to dust accumulation on PV glass. It has compared the prediction values from this study and those from the published modules in Table 2 with experimental values listed in Table 3 and the experiment data from this study. Since there are many prediction values from the previous modules, the dataset underwent filtering to exclude values outside the 0-100% range, resulting in varying numbers of exclusions across different models. MSE values were then calculated for each model using the filtered dataset. The details of exclusions and MSE values are summarized in Table 9, and a scatter chart in Figures 9 and 10 visually compares these model predictions against actual data.

Table 9. Comparative Analysis of Excluded Values and Mean Squared Error (MSE) Across Various Models

Model Reference	Number of Values Excluded	MSE
MLR (Multiple Linear Regression)	0	8.4
ANN (Artificial Neural Networks)	0	1.8
[6]	80	7.792
[8]	73	12.965
[14]	153	31.974
[5]	5	34.001
[9]	0	387.115
[12]	0	669.309
[15] A	0	109.90
[15] B	5	192.39
[17]	9	120.76
Conceição et al. cited in [16]	1	663.75

This analysis is crucial for evaluating the reliability and precision of different predictive models in the context of PV system performance. Accurate predictions of transmittance reduction are essential for optimizing PV system maintenance, particularly in dusty environments.

The ANN model demonstrates the lowest MSE (1.8), indicating high accuracy and predictive performance. While the MLR model's MSE is higher than ANN's, it still shows commendable predictive capability. The calculated MSE for other equations indicates varying levels of accuracy, which are far away from the ANN and MLR.

This analysis provides a clear picture of each model's predictive accuracy. With its high accuracy and robustness, the ANN model is an excellent choice for complex scenarios in PV system analysis. The MLR model, though less precise, offers valuable predictions and is beneficial where interpretability is crucial. The variability in MSE, among other equations, underscores the need for careful model selection based on specific requirements and data characteristics in PV research and maintenance applications.

The experimental data, consistently depicted in blue, serves as a benchmark against which the predictions of other models are evaluated. Each chart contrasts the experimental data with one of the models, highlighting the deviation of model predictions from actual data. This analysis reinforces the findings discussed earlier, underscoring the superiority of the ANN model in terms of accuracy, as evidenced by its closer alignment with the experimental data. Likewise, the visual data supports the robust performance of the MLR model and highlights the variability in accuracy among the other models. Limitation

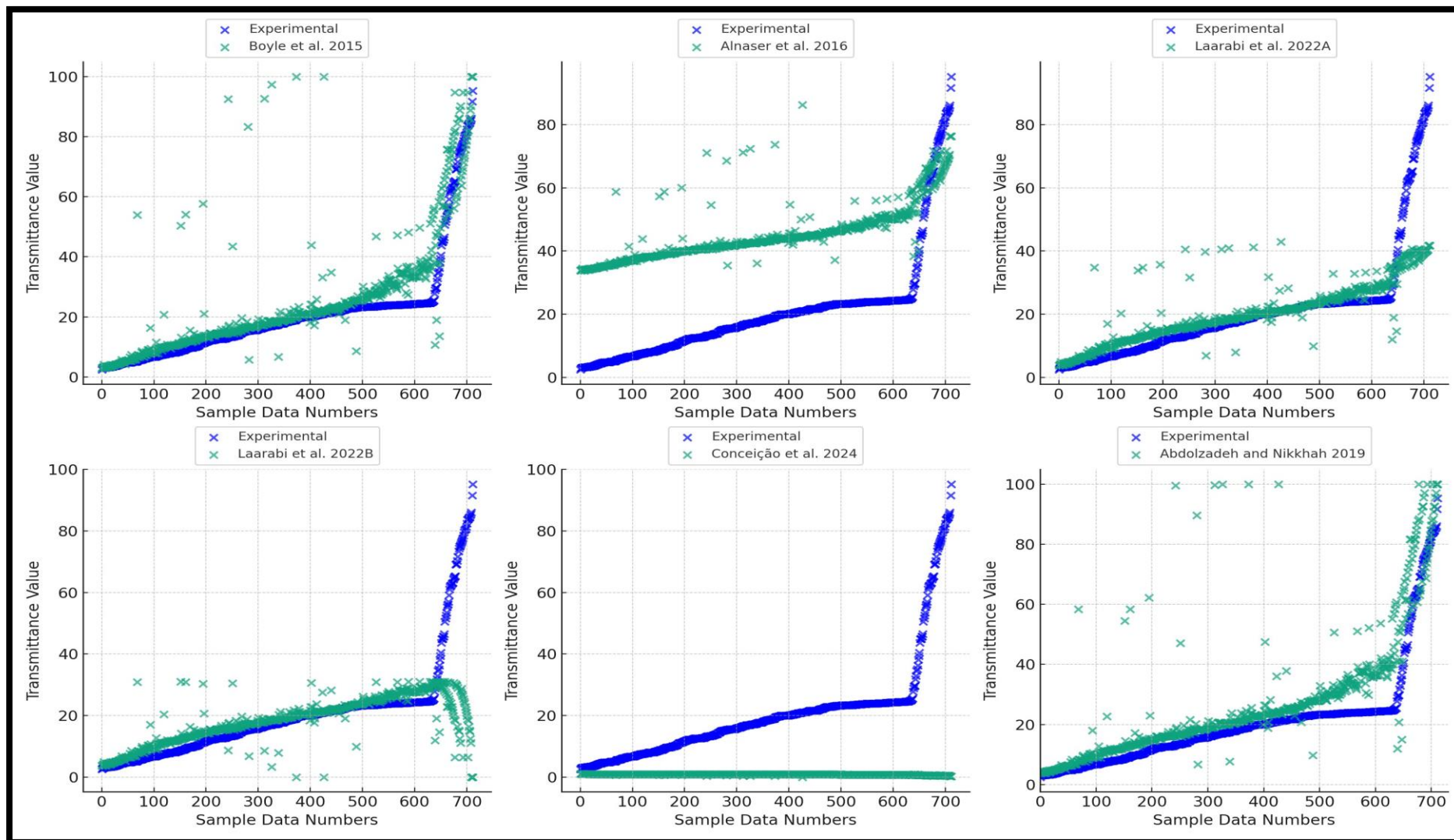


Figure 9 Scatter chart visualizing model predictions vs. experimental data\* across diverse analytical methods \* *The experimental data from different references as demonstrated in Table 2 as well as our experiments.*

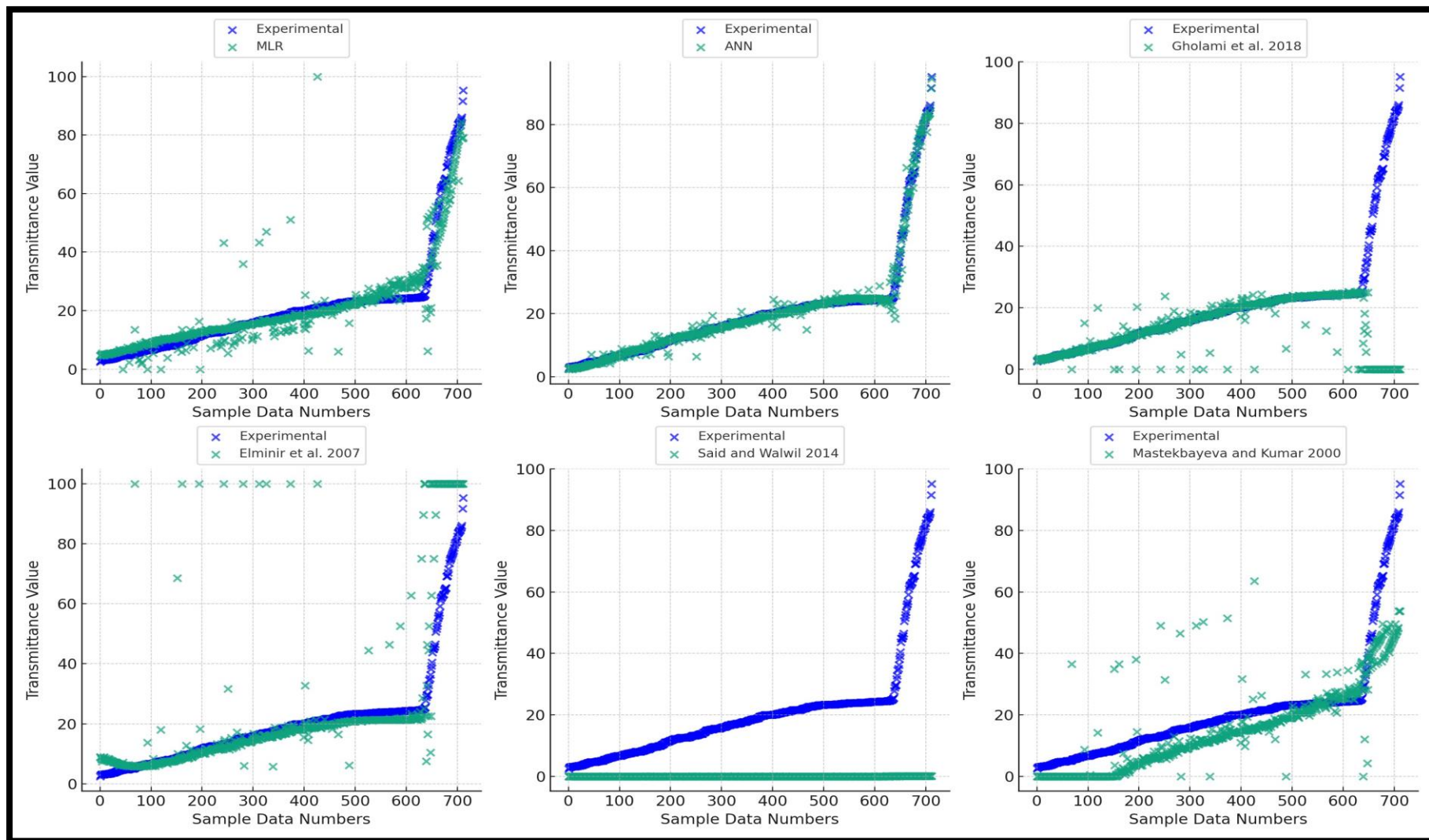


Figure 10. scatter chart visualizing model predictions vs. experimental data\* across diverse analytical methods. \* The experimental data from different references, as demonstrated in Table 2, as well as our experiments.

#### **4. Conclusions**

The study signifies a significant step forward in comprehending the effects of dust accumulation on the optical properties of PV glass. Through the integration of experimental investigations and more accurate predictive modeling utilizing ANN and MLR, the research sheds new light on how dust influences PV technology. Notably, the ANN model achieved a remarkably lower MSE of 1.8, while the MLR model achieved an MSE of 8.44, indicating high predictive accuracy. These findings, highlighting their superiority in predicting the impact of dust on PV optical properties, especially when compared with existing data, underscore the effectiveness of these methodologies in forecasting the consequences of dust accumulation on PV systems. The findings underscore the significance of precisely predicting the impact of dust on the optical properties of PV modules, which is crucial for anticipating thermal effects and ensuring the efficiency of PV installations.

For future research directions, expanding experimental sample sizes to include emissivity and absorbance data from diverse nations would contribute to a more extensive understanding of the impact of dust across various geographical conditions. Additionally, the research could delve into the diverse composition of dust, considering various component materials. It could further explore physical aspects, particularly focusing on the shape and size of particles. Understanding these interactions is paramount for developing more accurate predictive models and effective cleaning methodologies. Additionally, current models need more detailed consideration of dust particle size and shape, significantly affecting prediction accuracy. Addressing these factors may contribute to improving model precision.

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# Chapter 5: Conclusions and Future Work

## 1. Introduction

This study provides a thorough exploration of the ramifications of dust accumulation on PV modules. Each chapter delves into distinct facets of this phenomenon, collectively offering a holistic comprehension of its effects on the thermal and optical performance of PV modules. Beginning with an extensive literature review aimed at pinpointing gaps in existing knowledge, this study proceeds to elucidate the intricate interplay between dust characteristics and PV module temperature through a combination of experimental investigations and analytical modeling.

The initial phase of the study entails a comprehensive review of the properties of accumulated dust particles and their impact on PV modules. It underscores the pivotal connection between dust characteristics and PV performance, elucidating how dust particles, through their optical, thermal, physical, and chemical properties, can impede sunlight transmission, absorb heat, and induce corrosion. Such impediments significantly diminish PV efficiency and may lead to enduring damage. While current measurement techniques offer insights, there exists a pressing need for more precise tools to comprehensively understand dust's influence on PV systems. Notably, a meticulous analysis of dust's thermal properties, such as heat absorbance and emissivity, is identified as imperative for elucidating its effect on the thermal equilibrium of PV modules. Additionally, the study advocates for the development of robust scientific models that precisely correlate specific dust properties with variations in PV system performance and module thermal behavior, thereby facilitating the advancement of techniques for analyzing dust impacts.

Building upon this foundational review, the subsequent segment of the study concentrates on the thermal consequences of dust accumulation on PV modules. Novel module equations are developed to estimate the impact of dust on PV temperature, elucidating how varying dust compositions may affect temperature dynamics and emphasizing the pivotal role of dust's optical properties in governing PV temperature. This segment integrates mathematical and experimental frameworks to explore hypotheses regarding the influence of dust on PV temperature, thereby emphasizing the importance of investigating how dust's chemical composition critically influences optical properties such as transmittance, absorption, and emissivity.

The final part of the dissertation expands upon the preceding analyses, specifically examining how the chemical composition and weight of dust influence the optical properties of PV modules. By developing robust prediction techniques based on a comprehensive dataset, this segment aims to understand the intricate interactions between different types and quantities of dust on the optical impact of PV modules. By focusing on the optical effects of dust accumulation, this section complements earlier analyses, providing a comprehensive overview of how dust can alter PV temperature.

## **2. Conclusions and Contributions**

This thesis provides an in-depth analysis of the impacts of dust accumulation on PV modules. Chapter 2 conducts a comprehensive literature review, elucidating the nexus between dust properties and PV performance. It underscores the significance of comprehending dust's optical, thermal, physical, and chemical characteristics, while emphasizing the necessity for more precise methodologies to assess its influence on PV systems. This review discerns a gap in detailed examinations of dust's thermal properties and underscores the requirement for models that establish links between these properties and alterations in PV system behavior.

Expanding upon this gap, Chapter 3 delves into the repercussions of dust on PV temperature. It introduces innovative module equations to estimate the thermal consequences of dust, revealing the impact of dust composition on PV temperature and the substantial influence of dust's optical properties on regulating PV temperature. The chapter subsequently presents a mathematical and experimental framework for scrutinizing dust's effect on PV temperature. Compared to existing models, this novel model demonstrates significantly enhanced accuracy in forecasting PV temperatures under dusty conditions, achieving a mean absolute error (MAE) as low as 1.4.

Chapter 4 delves into the consequence of accumulated dust composition and weight on the optical properties of PV modules, including transmittance, absorbance, and emissivity. Utilizing robust prediction techniques incorporating a comprehensive dataset of over 300 experimental readings as well as more than 650 global data, it elucidates the intricate interplay between various types and quantities of dust, offering a comprehensive understanding of how dust alters PV optical and thermal properties. The Artificial Neural Network (ANN) model exhibits exceptional accuracy with a mean squared error (MSE)

of only 1.8%, while the Multiple Linear Regression (MLR) model attains an MSE of 8.44%.

In summary, this research advances our ability to predict and mitigate the impacts of dust on PV modules. Key contributions include:

- Identifying the significance of dust's thermal and optical properties: This study underscores how dust properties influence PV module temperature, a factor often underestimated in existing models.
- Developing a more accurate model: The new model integrates dust characteristics like emissivity, absorbance, and transmittance, leading to superior prediction accuracy for PV temperatures in dusty environments, with MAEs as low as 1.4.
- Highlighting the role of dust composition: The work demonstrates how different chemical compositions of dust significantly alter PV optical properties and therefore temperature.
- Introducing advanced predictive techniques: Using ANN and MLR enables the creation of comprehensive models for predicting the diverse effects of dust accumulation on PV modules, exhibiting notable accuracy with MSEs as low as 1.8%.
- Providing practical insights: This study provides practical insights by measuring the emissivity of the PV module surface, facilitating accurate measurements of PV radiation. Furthermore, it offers guidance for designing experiments aimed at measuring PV module heat radiation and conducting effective outdoor dust experiments.

### **3. Future Research Recommendations**

This comprehensive study provides invaluable insights into the intricate impacts of dust accumulation on photovoltaic systems, laying a solid groundwork for further exploration into optimized cleaning, design, and predictive modeling. To advance dust mitigation strategies and maximize PV module efficiency, the following areas require in-depth investigation:

#### **a. Expanding the Dust Dataset:**

- Diverse dust types and origins: Conduct experiments with a wider range of dust samples sourced from various global locations to capture the full spectrum of regional variations in chemical composition and physical properties. This expanded dataset will facilitate the

refinement of existing models, ultimately enhancing their adaptability and predictive accuracy on a global scale.

- Advanced characterization techniques: Explore state-of-the-art methods to analyze dust's thermal properties (especially thermal conductivity and specific heat capacity), particle size distribution, morphology, hygroscopicity, and adhesion properties. A nuanced understanding of these characteristics will shed further light on the complex interplay between dust and PV module performance.

b. Advanced Modeling Approaches:

- Machine learning and hybrid models: Experiment with various machine learning techniques (such as support vector machines, random forests, and deep learning) to uncover hidden patterns and potential non-linear relationships between dust properties, environmental factors, and PV performance degradation. Consider developing hybrid models that combine the strengths of analytical and machine learning approaches for optimal precision and interpretability.

- Uncertainty quantification: Integrate uncertainty analysis and sensitivity studies to assess how variations in input data (such as dust composition and meteorological conditions) affect model predictions. This will facilitate the reliable assessment of model robustness and identify areas for enhancement.

c. Long-Term Dust Dynamics and Degradation Mechanisms:

- Real-world exposure studies: Establish long-term test setups in diverse environments to monitor the evolution of dust accumulation patterns, weathering effects, and their impact on PV module deterioration over extended periods. This will inform the development of more durable materials and tailored cleaning schedules for different environments.

- Combined environmental factors: Investigate how dust interacts with other environmental factors like elevated temperatures, humidity, UV radiation, and wind erosion. Adopting a multi-factorial approach will unveil potential synergistic effects influencing long-term PV system performance.

d. Technological and Policy Innovations:

- Intelligent cleaning and monitoring systems: Develop smart cleaning systems that leverage real-time monitoring of dust levels and performance loss predictions. These

systems will enable optimized cleaning schedules, thereby reducing maintenance costs and maximizing PV output.

- Self-cleaning coatings and surface modifications: Research anti-reflective and superhydrophobic surface treatments for PV modules to minimize dust adhesion and facilitate self-cleaning processes through natural rainfall.
- Performance benchmarks and standards: Collaborate with standards organizations to establish international benchmarks for measuring the impact of dust on PV systems. Standardization will facilitate performance comparisons across different technologies and environments, fostering innovation in dust mitigation solutions.

By addressing these future research directions, we can pave the way for the development of highly efficient and resilient PV systems capable of thriving even in the most challenging environments. Through continuous innovation and a multidisciplinary approach, we can unlock the full potential of solar energy and expedite the global transition towards a sustainable future.