

**DEVELOPMENT OF ELECTRODYNAMIC DUST  
REPELLENT SURFACES FOR PHOTOVOLTAIC  
SOLAR CELLS**

BY

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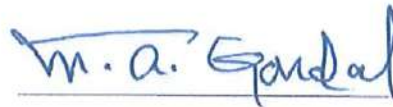


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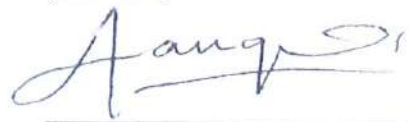
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I dedicated to my ever-loving family, wife, daughter, and teachers

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## **LIST OF ABBREVIATIONS**

PV: Photovoltaic

EDS: Electrodynamic Dust Shield

RH: Relative Humidity

PCB: Printed Circuit Board

PMMA: Poly (methyl methacrylate)

PET: polyethylene terephthalate

CE: Conductive Electrodes

AC: Alternating Current

Cu: Copper

Ag: Silver

AgNw: Silver nanowire

Cr: Chrome

FTO: Fluorine Tin Oxide

ITO: Indium Tin Oxide

AZO: Aluminum-doped Zinc Oxide

ZnO:F: Florine doped Zinc Oxide

PU: Polyurethane

OCA: Optical Clear Adhesive

ETFE: Ethylene Tetrafluoroethylene

HVG: High Voltage Generator

XRD: X-Ray Diffraction

XPS: X-Ray Photoelectron Spectroscopy

SEM: Scanning Electron Microscope

EDX: Energy-Dispersive X-ray Spectroscopy

LIBS: Laser-Induced Breakdown Spectroscopy

COMSOL: Computer Solution

FF: Fill Factor

$I_{sc}$ : Short Circuit Current

$V_{oc}$ : Open Circuit Voltage

## ABSTRACT

Full Name : [SAEED ABDULLA SAEED BAQRAF]

Thesis Title : [Development of Electrodynamic Dust Repellent Surfaces for Photovoltaic Solar Cells]

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Currently, Large-scale solar PV systems installations are taking place in the desert environment and space to harness abundant solar energy effectively. Dust accumulation on the surface of photovoltaic panels is the most severe problem, as dust deposition significantly reduces photovoltaic energy generation efficiency. Thus, removing dust from the photovoltaic panels has become very important to increase the rate of energy efficiency of the photovoltaic panels. The dust particles could be reduced using traditional dust cleaning techniques. But, in the harsh and hostile desert environment, these approaches require a lot of water, complicated mechanical instruments, enormous logistics, and personnel. An electrodynamic dust shielding system has been developed at our laboratory to remove dust particles from the surface of the photovoltaic panels. The electrodynamic system has been successfully tested for dust mitigation. The unique features of our approach are that it is cost-effective, easy to install, and no human resources are required as it is an unmanned system. This work presents the design and fabrication of a locally made multi-phase electrodynamic dust repulsion system. The dust removal efficiency of the EDS system was optimized for the electrode geometry and the electrical parameters like alternating current source voltage and frequency. The dust removal efficiency as high as  $(90-92) \pm 1$  % was observed for an optimum combination of geometrical and electrical

parameters of the electrodynamic dust shielding system. The operation and the optimization of the electrodynamic dust shielding system were elucidated by analyzing various electrostatic and mechanical forces and the generation of traveling and standing waves involved in this process. The electrodynamic dust shielding system was applied to the solar cell under natural sunlight to study the system's efficacy in improving the solar cell's photovoltaic performance in a dusty environment. As the dust characteristics play an essential role in the dust removal efficiency, the morphological, elemental characterizations, and dust particle size analysis of the dust from the natural sandstorm were also characterized.

## ملخص الرسالة

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حاليًا ، تجري تركيبات أنظمة الطاقة الشمسية الكهروضوئية على نطاق واسع في البيئة الصحراوية والفضائية لتسخير الطاقة الشمسية الوفيرة في ذلك النطاق بشكل فعال. يعد تراكم الغبار على سطح الألواح الكهروضوئية هو المشكلة الأكثر صرامة والأكثر ضررًا للألواح الكهروضوئية ، حيث يقلل ترسب الغبار من كفاءة توليد الطاقة الكهروضوئية بشكل كبير. وبالتالي ، فإن إزالة الغبار من الألواح الكهروضوئية أصبح أمرًا مهمًا للغاية لزيادة معدل كفاءة الطاقة بواسطة الألواح الكهروضوئية. يمكن تقليل جزيئات الغبار باستخدام تقنيات تنظيف الغبار التقليدية. ولكن في البيئة الصحراوية القاسية والمعادية ، تتطلب هذه الأساليب الكثير من المياه ، والأدوات الميكانيكية المعقدة ، والخدمات اللوجستية الهائلة ، والموظفين وهذا يؤدي إلى تكاليف باهظة جدا. ولكن ، تم تطوير نظام للحماية من الغبار في مختبرنا ويسمى بالدرع الكهروديناميكي لإزالة جزيئات الغبار من سطح الألواح الكهروضوئية. يعتمد مبدأ عمل النظام الكهروديناميكي على تطبيق المبدأ الكهروستاتيكي باستخدام الموجات الكهروستاتيكية والقوى الكهروستاتيكية لرفع وطررد جزيئات الغبار من الغطاء الخارجي للألواح الكهروضوئية والحد من تجمع جزيئات الغبار على أسطحها وقد تم اختبار النظام الكهروديناميكي بنجاح لتخفيف الغبار. تتمثل الميزات الفريدة لنظامنا في أنه فعال من حيث قلة التكلفة وسهل التركيب ولا يحتاج إلى قوة بشرية لأنه نظام أتمتة. في هذا العمل ، نقدم تصميم وتصنيع نظام طرد الغبار الكهروديناميكي محلي الصنع متعدد المراحل. تم تحسين كفاءة إزالة الغبار لنظام الكهروديناميكي لهندسة القطب والمعلومات الكهربائية مثل جهد وتردد مصدر التيار المتناوب. تمت ملاحظة كفاءة إزالة الغبار التي تصل إلى (٩٠-٩٢)± للحصول على مزيج مثالي من المعلومات الهندسية والكهربائية لنظام الحماية من الغبار الكهروديناميكي. تم توضيح تشغيل وتحسين نظام الحماية من الغبار الكهروديناميكي من خلال تحليل مختلف القوى الكهروستاتيكية والميكانيكية وتوليد موجات السفر والوقوف المتضمنة في هذه العملية. تم تطبيق نظام الحماية الكهروديناميكي على

الخلية الشمسية تحت ضوء الشمس الطبيعي لدراسة فعالية النظام في تحسين الأداء الكهروضوئي للخلية الشمسية في البيئة المترتبة. نظرًا لأن خصائص الغبار تلعب دورًا أساسيًا في كفاءة إزالة الغبار ، فقد تم أيضًا دراسة الخصائص المورفولوجية والعنصرية وتحليل حجم جزيئات الغبار للغبار من العاصفة الرملية الطبيعية.

# **CHAPTER 1**

## **INTRODUCTION**

Solar energy gained great significance as it represents an environmentally friendly, clean, and sustainable energy source. In the last decades, the growing awareness of environmental repercussions caused by fossil fuels and ever-increasing global energy demand has sparked off the use of alternative green energy sources, and now every passing year records a gratifying increase in the annual share of energy production through renewable energy sources in general and solar energy in particular [1], [2], [3]. Solar energy developments have been a hot topic, and photovoltaic solar cells are essential to this field [1], [2]. Solar light transmission in solar cells is a vital factor in the efficiency of photovoltaic devices [4]. The photovoltaic solar cells depend on the amount of harvesting light that falls from the sun; thus, the more suitable place to build the solar panel is an area with high solar radiation. Highly intense solar radiation in the desert environment makes the desert terrains the best fertile grounds for solar harvesting. Hence, the ten largest solar energy panels in the world have been commissioned in deserts, such as the Arabian Peninsula (Saudi Arabia), in which there is abundant sunshine throughout the year [4], [5], [6].

However, severe technological and natural limitations are posed in effectively harnessing the abundant solar radiation in the desert. The solar panels get too hot at extreme desert temperature, and this not only reduces the characteristic photovoltaic conversion efficiency and cause thermal instability but also speeds up the degradation and electrochemical corrosion of solar panels [7],

[8]. The temperature-induced instability and degradation can be managed by improving the quality of the solar material, providing a heat-resistant coating, or even converting the extra heat energy into electricity, as in thermo-photovoltaic cells. Another more difficult challenge in photovoltaic (PV) technology is how to combat the inevitable dust and sand accumulation on the solar panels, which is typical of any vast sandy desert environment [9]. The gathered dust on the solar panel can significantly reduce the transmittance of the active spectral region of the solar radiation onto the photosensitive material, resulting in the gradual diminishing of power output and the transmittance of incident radiation, i.e., it prevents the solar light from reaching the panel, thus affecting the efficiency of PV systems [4], [10], [11]. Moreover, the effect of dust on the deterioration of photovoltaic performance depends on the chemical compositions, size distributions, thickness, and the electrostatic nature of the accumulated dust [9], [11], [12]. Many conventional and non-conventional methods of prevention and remediation of dust accumulation have been intensely researched and applied, and each of these prevailing methods poses several practical and economic constraints, such as large man powers and a tremendous amount of water, which are very costly for cleaning the solar panels [8], [10], [11], [13]. Manual cleaning with water and cleaning agents may sound practical and straightforward. However, the scarcity of the local availability of water, transportation of water to inhospitable desert terrain, lack of rainfall, and the requirement of a large workforce are some of the limitations of manual cleaning [4]. Mechanical methods of dust removal like water jet cleaning, air blowing, and ultrasonic vibrations have been tried, but the high frequency and amplitude of vibrations can damage the physical and crystal structure of the panels and disengage the electrical connections [8], [13], [14]. There have been many reports on the elimination of dust accumulation by water-repellent (hydrophobic) and dust-repellent material coated on the solar panel in order to render

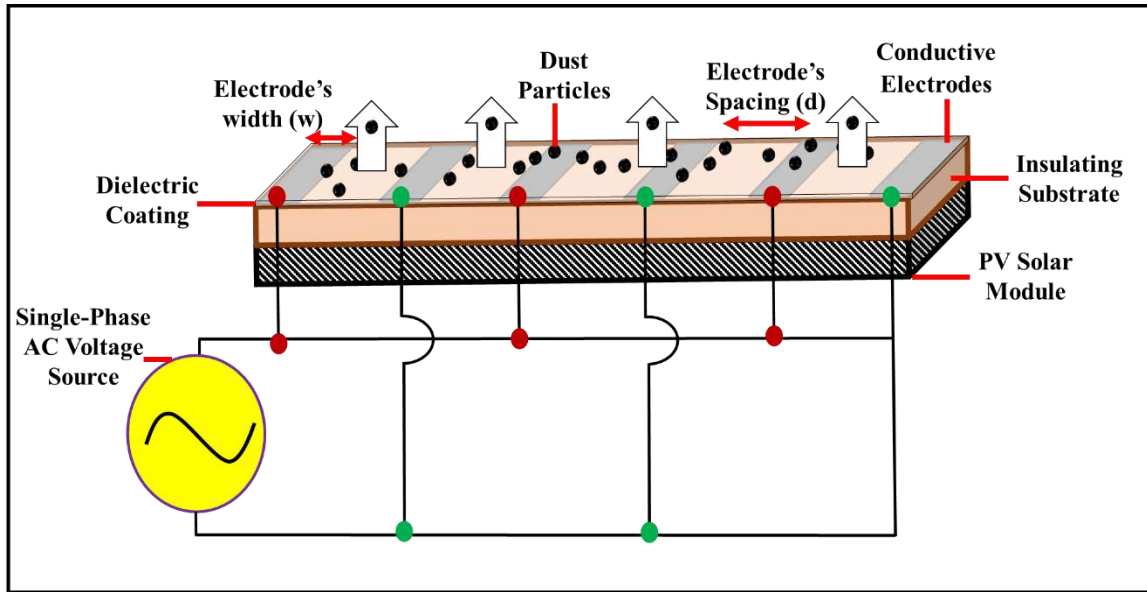
low adhesion of dust, which can easily roll off in the typical wind condition [8], [12]. Gravity-driven dust elimination is possible by tilting the solar panels to minimize dust accumulation. However, the result is still insignificant, considering the huge amount of dust and violent sandstorms in the desert environment [14], [15].

In order to maintain consistent power generation from PV solar panels, new technology has recently been developed for cleaning solar panels without water use [4], [14]. The electrodynamic dust shield system is a successful method for mitigating the accumulation of dust on solar panels, and the same method can be extended to thermal radiators and optical systems [16], [17], [18]. Many variants of electrostatic and electrodynamic dust shields (EDS) have been developed and designed for the dust mitigation of solar panels in the intense dusty environment, including for installations in space missions [18], [19], [20]. Either a standalone thin structure that covers the front surface of a solar module or a component that is integrated into a solar module can make up the EDS system. A solar module can also have both systems [21], [22]. The installation of an EDS system over the top transparent surfaces of photovoltaic solar panels has an efficient function in cleaning the solar panels from dust accumulation in the semi-arid area [3]. The EDS integration with PV solar panels installed in the desert regions could increase the produced energy via daily cleaning of solar plants. This integration leads to a decrease in the utilization of water. It reduces the overall cost of using mechanical methods to clean PV panels from dust particles deposited on solar cells board [3], [7].

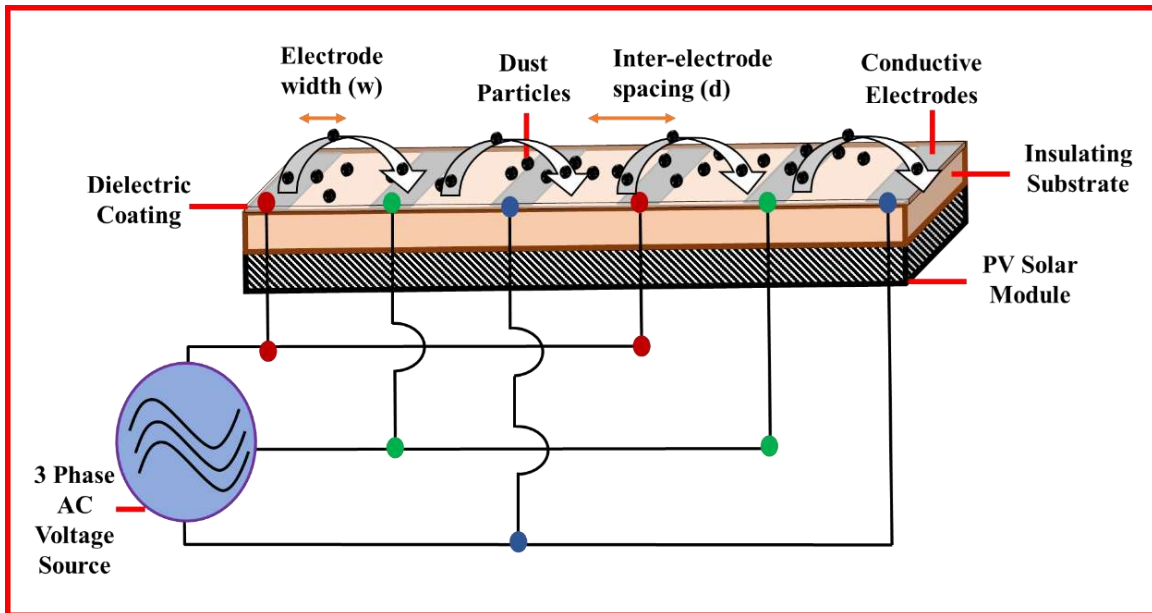
The typical EDS system comprises a set of interdigitated electrodes located on the surface of the PV panel, below a functional dielectric coating, and electrically connected either to a single-phase or three-phase alternating (AC) voltage source in order to establish a non-uniform electric field in between the neighboring electrodes, and to initiate a standing or traveling wave on the

PV surface under dust shielding as shown in figure 1&2 [18], [19], [21], [22]. In the case of a single-phase AC voltage source, the oscillating electric field travels back and forth due to the polarity change and creates a standing wave between the electrodes. This imparts a force on the charged particle in the field region. In this process, even the neutral dust particles get charged by induction charging on the surface of the dielectric material, or tribo-charging due to inter-particle collision. These newly charged dust particles are also subjected to the above force [23], [24], [25]. In the case of a three-phase AC voltage source, due to a 180-degree phase difference between the waves connected to the adjacent electrodes, the change of potential in rhythmic steps creates a traveling wave. Eventually, the dust particles are either driven along or opposite to the direction of propagation of the traveling wave [7], [25], [26].

In EDS, various mechanical and electrostatic forces interact both positively and unfavorably to produce the final net vertical and horizontal components of acceleration that cause the dust particles to lift and spread from the PV system's active surface [22], [27], [28], [29]. Hence, the electrical characteristics of the AC voltage source (phase, voltage, and frequency), the geometry of the electrodes (width, thickness, and spacing), the dielectric properties of the material, the size distribution, the charge states of the dust particles, the dielectric properties of the dust particle, and the environmental conditions all affect the effectiveness of the dust removal mechanisms [30]. The electrical power demand for the EDS is relatively low (a few watts), regardless of its size, as the power needed to remove the dust particle on the EDS is of the order of mW ( $\mu\text{A.kV}$ ) [25], [31]. In conclusion, the electrodynamic dust shield is a great solution and one of the most practical ways to eliminate dust buildup on solar panels and transparent surfaces. [32].



**Figure 1.1.** A diagram of the locally-made single-phase EDS system.



**Figure 1.2.** A diagram of the locally-made three-phase EDS system.

## 1.1. Statement of Problem

The photovoltaic solar panels depend on the amount of harvesting light that falls from the sun. The potential intensity of falling light is different from one location to another. The Arab Gulf States in the Middle East have more solar power than other places in the world. These countries

have a remarkable ability to build large solar panels, but they face a mighty challenge in achieving solar energy stations. The primary obstacle to the development of solar systems in the Arab Gulf States and around the world is dust. Dust particles deposited on the solar panels and the space mission's equipment, like camera ports, optical mirrors, robotic arms, and robots, cause serious damage [22]. The deposition of dust particles on solar panels impacts solar cell performance. Dust depositions on PV modules reduce output power and incident radiation transmittance, i.e., they block solar light from reaching the panel, lowering PV system efficiency [14]. To avoid this reduction in efficiency, solar panels need frequent cleaning. In This work, we will focus on overcoming this problem via a highly influencing cleaning process to remove dust particles without manual intervention to clean the solar panels.

## **1.2. Research Objectives**

The primary intention of this research is to design and develop an Electrodynamic Dust Shield (EDS) system of this setup locally for anti-dust solutions for different surfaces. The specific objectives are the following:

1. To fabricate conductive electrodes using a conductive material.
2. To apply the fabricated electrodes as electrodynamic dust-repellent surfaces and measure dust removal efficiency.
3. To examine the impact of the spatial distribution of the conductive electrodes on dust removal efficiency.
4. To find the applied voltage's optimal values and frequency for efficient dust removal in Saudi Arabia.
5. To characterize the structure, morphology, and chemical composition of dust in Saudi Arabia using different analytical techniques.

6. To investigate the effect of dust size on the performance of the EDS device.
7. To apply the EDS system on real solar cells.

### 1.3. Thesis Organization

The chapters of this Thesis are divided into seven chapters and organized as follows



**Chapter 1** consists of introducing photovoltaic solar panels, technological and natural limitations that severely affect the panels with an emphasis on the dust problem, and cleaning methods that remove dust particles from the surfaces of panels with special concentrate on the electrodynamic dust shield system.



**Chapter 2** deals with the literature review of the definition and creation of dust on solar surfaces, the impact of dust on photovoltaic solar panels, and solutions for removing dust particles from solar panels. This chapter also discusses the literature review of the electrodynamic dust shield system; it deals with the EDS system's components, function, and charging. This chapter mentions the influence of the EDS system on the PV panel's performance and compares the EDS system with other solutions for removing dust.



**Chapter 3** deals with the forces that influence the removing dust process; it discusses the electrical and mechanical forces inside and outside the dust particle with more details about the electric field.



**Chapter 4** deals with the experimental and theoretical work performed to achieve the milestone of this thesis work. It includes the EDS setup, Methodology, dust samples, simulation programs, and characterization techniques employed throughout the thesis work



**Chapter 5** deals with the results and discussions; it describes the mechanism of the EDS system and explains the main findings throughout the thesis work. The application

of the EDS system on the real solar cell and the dominant parameters that influence the EDS performance are also explained in this chapter.



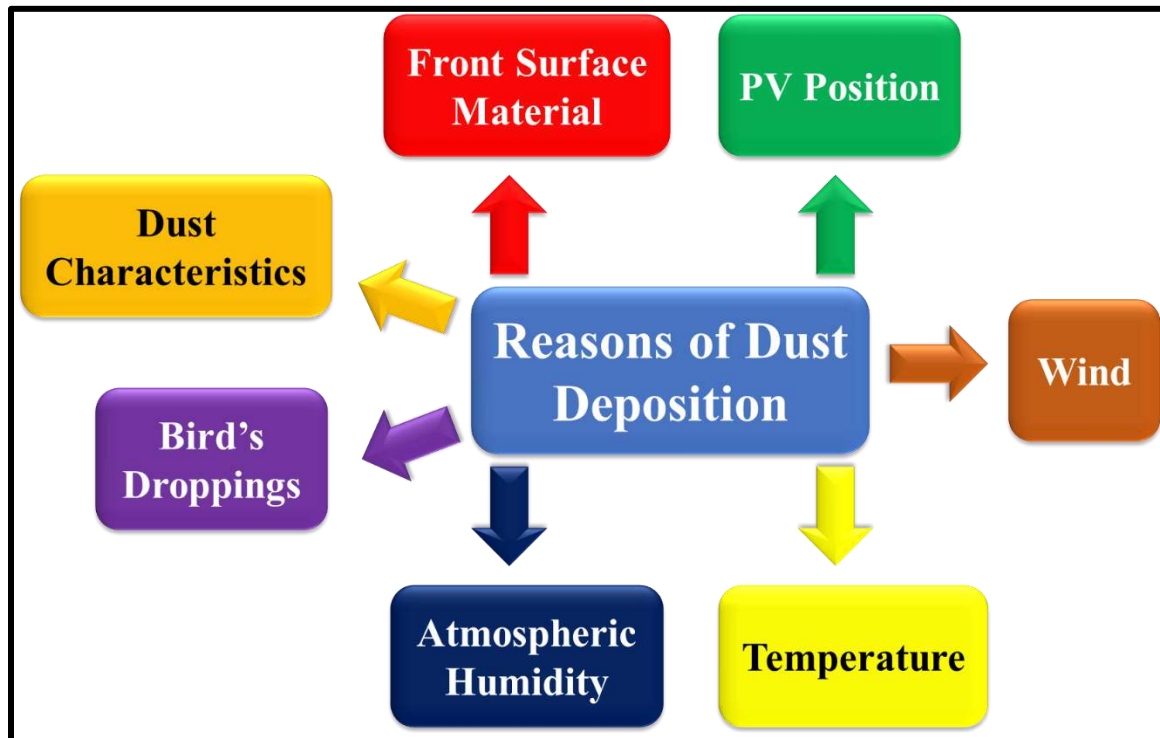
**Chapter 6** concludes all the overall thesis work with future suggestions.

## **CHAPTER 2**

### **LITERATURE REVIEW**

Reduced energy output from dust collection on flat-panel photovoltaic (PV) solar panels is a major issue in their functioning. As a result of absorption and scattering losses of the incident light, energy yield is drastically reduced when the dust is deposited. One of the most important things that can be done to combat global warming is to increase electricity production from renewable sources. The sunbelt and Middle Eastern countries, such as the Arab Gulf States, have a greater potential for solar energy than many other parts of the world. Solar energy systems encounter a significant obstacle in nations with highly hot, dry climates due to the rapid accumulation of dust particles on their surfaces [33]. Dust deposition rates and particle characteristics vary greatly from location to location. Several variables, such as wind speed and direction, temperature, moisture, dust properties, humidity, and installation variables like tilt angle, orientation, height, the front surface of the PV module, and location of the PV module's installation site, contribute to the dust deposition phenomenon on the PV surfaces, as shown in figure 2.1[11], [34]. Figure 2.1 summarizes the various factors that caused the dust deposition on the PV modules. Dust particles have a significant impact on PV performance [35]. It drastically reduces the PV panels' performance; as a result, the cost of electricity produced rises, and solar energy systems are no longer competitive with readily available fossil fuel supplies like natural gas [33].

Here, we provide an in-depth analysis of how dust accumulation on photovoltaic solar panels reduces energy production. The most important reports on dust phenomena are summarized in this overview, including the definition of dust and the conditions that cause dust deposition on solar surfaces. The review documented the effects of dust deposition on the output performance of solar plants and the energy yield losses on operational plants across the globe. Natural, manual, automatic, and coating approaches and newly emerging cleaning methods are discussed as ways to combat the dust phenomenon.



**Figure 2.1.** A diagram of conditions that cause dust deposition on solar surfaces.

## 2.1. Dust phenomenon

The term "dust" is used to describe any particles that are smaller than 500  $\mu\text{m}$  in size. This is roughly the diameter of an optical communication fiber or ten times that of a human hair [10], [13]. Dust refers to small, dry, solid particles suspended by natural forces in the air

and spread by air. These dust particles in the air are associated with a number of causes, including soil particles displaced by natural forces, such as wind (aeolian dust) [34], [36], [37], [38], [39], [40], [41], [42], [43], volcanic eruption, vehicle movement, pollution, and through the use of synthetic or chemical methods (crushing, grinding, milling, drilling, demolition, etc.) [8]. These microparticles can float in the air for extended periods [44] and move long distances before finally coming to rest on the ground under the influence of gravity [45]. The settling of dust particles on the PV surface increased by different factors, explained in the next section.

## **2.2. Factors influence the rate of dust deposition on the PV module**

A variety of factors contributed to dust accumulation on the PV surface. We discussed some of these parameters in this chapter, such as the front surface material of the PV module and the location of its installation site, wind, temperature, ambient humidity, dust characteristics, and bird droppings.

### **2.2.1. Material of front surface of PV module**

The surface property of a PV module significantly impacts the dust deposition rate [13]. The dust deposition rate varies on PV modules from surface to surface. The front surface of the PV module's apparent texture and coating significantly impact the dust deposition process and PV characteristics [46]. One of the earliest research on this topic was conducted by Garg et al. [47]. They investigated how the dust collection rate affected the amount of light that could pass through different substances (glass and plastic plates). They noticed that the electrostatic properties of plastic cover plates cause them to accumulate more dust than glass plates. They revealed that the light transmittance on PV cells decreased less on the glass plate. The rate of dust deposition on the front surface of PV

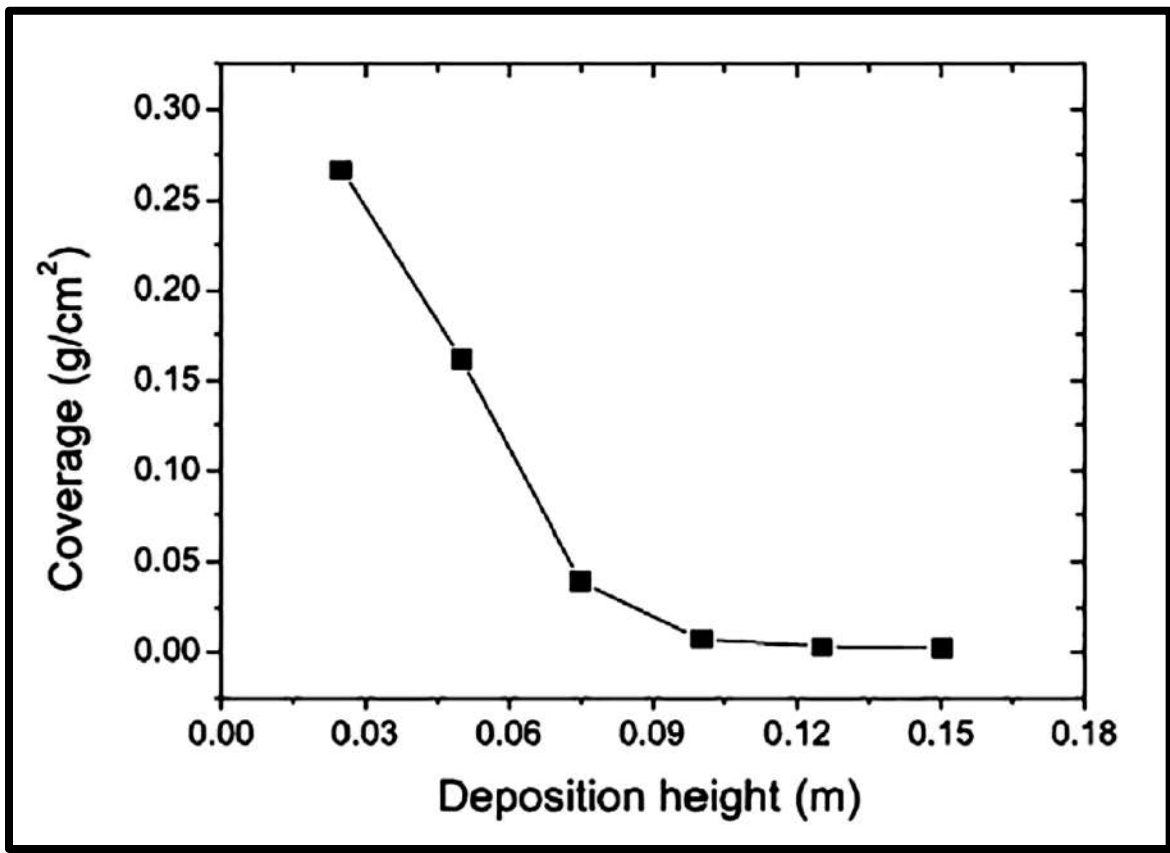
cells with glass, acrylic, and polyvinyl chloride (PVC) surfaces was investigated by Nahar et al. [48]. They noticed that the amount of dust deposition on acrylic and PVC surfaces was higher than on glass surfaces. In other words, glass surfaces will have higher PV cell transmittance than PVC and acrylic surfaces since there is less dust buildup on glass than on acrylic. According to Kalogirou et al. [49], a protective coating made of glass that sits on top of a PV module's surface is less susceptible to dust buildup than a layer made of Tedlar. To investigate the impact of dust deposition on optical transmission losses, Hee et al. [50] deposited  $\text{TiO}_2$  on two sample glass slides at two distinct thicknesses of 40 nm and 60 nm. They first calculated the transmission of a glass slide with no coating and slides with coatings of 40 and 60 nm  $\text{TiO}_2$  as 90.86 percent, 90.15 percent, and 89.15 percent, respectively. After ten days of exposure, they saw that the optical transmission of the three samples declined at rates of 0.261%, 0.231%, and 0.1671% daily. They claimed that the  $\text{TiO}_2$  coating's self-cleaning property, which aids rain in more effectively removing deposited dust particles from glass slides, is responsible for the coated glass slides' better transmission loss rate. In other words, an increase in  $\text{TiO}_2$  coating results in a decrease in the dust deposition rate, which lowers the rate of glass surface transmission loss. In conclusion, the rate at which dust particles settle on a PV surface is significantly affected by the substance that makes up the PV module's front surface.

## **2.2.2. Photovoltaic solar cells position**

### **2.2.2.1. Height position of the PV module**

According to Cano et al., the dust concentration in the air drops rapidly with the height of the dust source under typical conditions. The lower the dust concentration, the higher the level of the dust source. When the PV module is put in a high position, dust deposition on

its surface is reduced. Wind speed increases with altitude; hence, the higher the height of the PV module installation location, the larger the effect of the wind on the PV module and the more cleaning of the PV module [51]. Beattie et al. [52] experimented with a simulated laboratory setting. They mimicked dust accumulation on the PV module. As shown in figure 2.2, this group demonstrated that the dust deposition rate on the photovoltaic unit decreased as the height of the PV module increased. Figure 2.2 depicts the relationship between the rate of dust accumulation on the PV and the height of the source from which the dust is deposited.



**Figure 2.2.** Dust density varies with the height of the dust source [52].

#### **2.2.2.2. An inclination angle of the PV module**

The rate at which dust particles build on PV surfaces and the amount of solar energy that falls on PV panel surfaces are both impacted by the tilt angle and orientation of the PV module [53], [54], [55], [56], [57].

Dust particles prefer to settle on the PV solar panels installed at a fixed angle rather than tilted surfaces. When PV cells with a flat inclination (horizontal position), the panel's entire surface faces upward, and gravity pull causes a higher rate of dust accumulation. However, for a 90-degree tilt angle of PV (vertical position), due to the gravitational attraction, the dust particles will roll from the upper sections of the inclined module to the lower parts, reducing the rate of dust deposition [58]. The effect of gravitational force on dust particle settlement on PV modules rises as the tilt angle increases. In other words, due to gravitational attraction, dust formation reduces as the inclination angle increases from horizontal to vertical. In such instances, more dust deposition will occur due to particle impaction aided by electrostatic adhesion forces if the particles are charged. Most dust particles in arid areas acquire a substantial electrical charge during wind erosion from the soil. The wind also removes the dust that has accumulated. The dust removal rate at a high tilt angle at a relatively high wind speed will be more effective. The conclusion is that tilting the surface of PV modules can prevent dust deposition due to gravity.[59], [60], [61], [62], [63], [64], [65].

The experiment was carried out by Nahar et al. [48] to assess the influence of dust collection on the transmittance of different glazing materials, such as glass acrylic and PVC sheet with varied tilt angles. They saw an increase in transmittance as the tilt angle

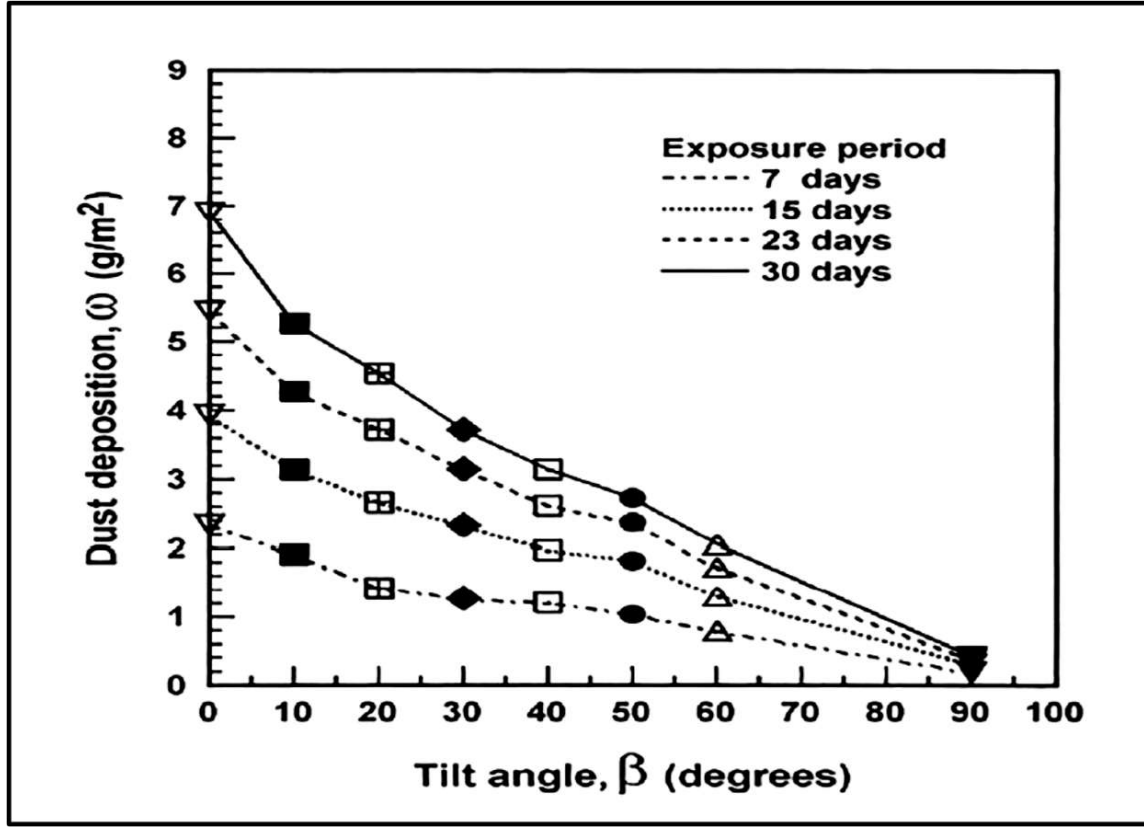
increased because dust deposition decreased as the tilt angle increased from the horizontal axis.

According to Hegazy et al. [54], surface dust elements with a mean diameter of three micrometers or more gathered more quickly on low-inclined PV modules, but surface dust density with smaller particles (less than one micrometer) was higher on the high-inclined PV module. As seen in figure 2.3, the relationship between dust particles and the PV surface is the main cause of this kind of accumulation. Fig 2.3 demonstrates how the dust density varies with tilt angle and exposure time and how the dust deposition rate reduces with increasing tilt angle. Choosing the ideal tilt angle that would minimize dust accumulation while maximizing the amount of solar radiation captured is crucial. Based on the output data collected by the PV system, Navid et al. [66] suggested a method to determine the best orientation and placement of the PV system. Their model offers a precise estimation for azimuth, tilt, and PV panel position. The outcome indicates that latitude, longitude, azimuth, and tilt can be approximated to be  $4.08^\circ$ ,  $0.2^\circ$ ,  $5.85^\circ$ , and  $2.75^\circ$ , respectively, for a typical PV system.

The ideal tilt angles of solar panels installed in Saudi Arabia were experimentally evaluated by Tarek et al. [67]; in the simulation phase, MATLAB software was utilized to optimize the proper orientation. They discovered that to capture 99.5% of the incoming solar radiation in the testing area, tilt angles needed to be modified six times annually.

Xu et al. [68] reported that  $(\text{latitude} \pm 15^\circ)$  might be considered the ideal tilt angle in relation to the local latitude. The authors provided a more precise formula, which is  $(\text{latitude} \pm 8^\circ)$ , but others recommended that  $\text{latitude} \pm 2.8$  in accordance with particular coastline radiation

statistics. However, due to geographic factors and limits, the precision of the suggested formulas is not always guaranteed.



**Figure 2.3.** The effect of tilt angle on dust deposition on PV surfaces at various exposure times [54].

### 2.2.3. Wind

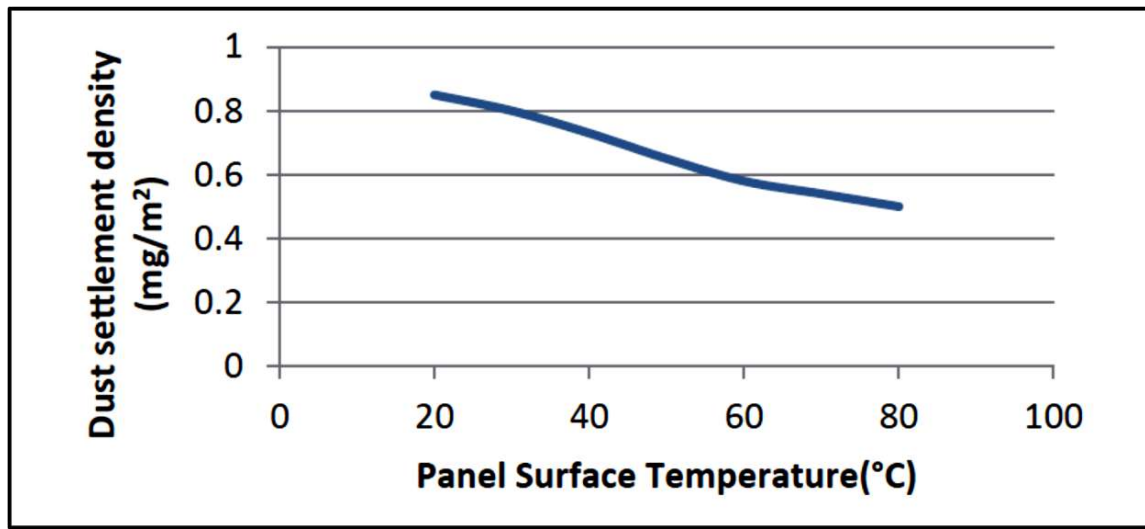
The accumulation and removal of dust from the surface of the solar PV module are significantly influenced by wind. It acts like a dust-transporting agent. Depending on the region, the wind's impact on the rate of dust settlement can vary. The amount of airborne dust transported by the wind from various sites influences dust deposition rates. It is influenced by the wind's direction and speed [13]. Elminir et al. [55] claimed that the wind's direction and the surface's orientation affect dust deposition. When comparing the dust settlement rates of high- and low-velocity winds, the latter is preferable because of the

lower concentration of airborne dust carried by the former [34], [45], [63]. Clarke et al. [9] stated that in Libya's desert, the dust deposition rate is largely proportional to the average monthly wind speed. He observed that the minimum velocity was about 6.5 m/s required to raise dust particles from the soil. After two weeks of exposure to the elements, Hegazy et al. [54] found that the rate of dust deposition on a module at a specific tilt angle decreased due to the wind blowing. S. Bingulac et al. [37], F. C. Christo [42], [43], Goossens et al. [63], [64],[69], El-Shobokshy et al. [70] studied the relationship between wind (speed & direction) and the concentration of dust particles on the surface of PV modules. They carried out a number of simulated tests to determine the impact of wind (speed & direction) and dust deposition rate on PV module performance. They observed that increased dust deposition is a direct cause of the decreased PV performance. They discovered that the free-stream wind velocity and the sedimentation on the PV module are inversely related. In other words, the PV module received more deposits due to the higher wind speeds. They also discussed the connection between the position of the PV panels and wind direction. They found that the lowest dust was deposited on PV panel surfaces when tilted at a significant angle. The PV module accumulated the most dust particles when the PV panels were positioned at a small tilt angle. PV modules in deserts and other areas with significant soiling conditions should be deployed at a high inclination angle in areas with low wind velocities and airborne dust concentrations, as suggested by Goossens et al. [69].

#### **2.2.4. Temperature**

Both ambient temperature and changes in the temperature of the PV module's front surface impact the process of dust buildup on the module. Mekhilef et al. [34], and Gostein et al. [71], mentioned that the moisture surrounding the PV module installation site decreases at

high ambient temperatures, such as those found in semi-arid and desert regions. This results in a drying of the local climate, making it easier for dust particles to be picked up by the wind and deposited on the PV module's surface. In contrast, the PV module's surface will become more sticky and stickier in the low-temperature region near the sea, where there may be a large concentration of vapor that will condense to form water drops, attracting more airborne dust particles. Jiang et al. [72] found that dust deposition density is highest when module surface temperature equals air temperature. Dust settlement densities also decrease as PV module surface temperature rises. Figure 2.4 shows that the module with the highest surface temperature has the lowest dust density.

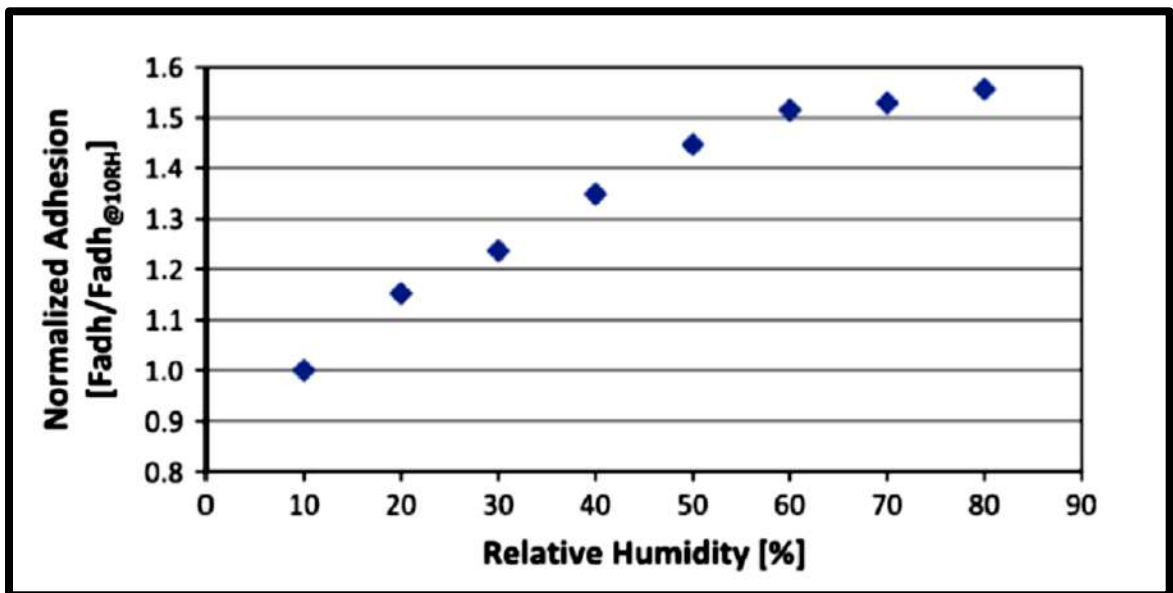


**Figure 2.4.** Surface temperature affects dust density [72].

### 2.2.5. Atmospheric humidity

Dust accumulation and photovoltaic (PV) cell performance are both influenced by humidity and relative humidity. To put it another way, humidity is the amount of water vapor in the air. In contrast, relative humidity is the ratio of that amount to the maximum amount present in the air at the same temperature. So, when the RH rises, does the water vapor concentration in the air. Due to the cold temperature, water vapor will condense to

create droplets of water on the surface. This makes the surface stickier [71] and attracts more airborne dust, reducing the efficiency of the PV [73], [74]. High RH also reduces solar irradiation due to increased water vapor absorption [34], [75]. Several researches looked at how solar panel functionality was affected by the correlation between humidity and the rate of dust deposition on PV surfaces. According to Said et al. [76], relative humidity causes adhesive and supporting dust layers to form on the PV module's surface. The area where dust elements meet the top surface of the PV module significantly impacts the bonding abilities of dust elements on level surfaces. Due to the capillary forces created between the dust components and the glass surfaces, high relative humidity (RH) encourages the adhering of dust and the creation of sticky dust layers on PV surfaces. They established, as shown in figure 2.5, that dust particle adherence on the PV surface increases as the relative humidity does. As the humidity level rises, more water condenses in the space between the dust element and the surface, forming a capillary connection that enhances the bonding force between the bead and the surface (see Figure 2.5).

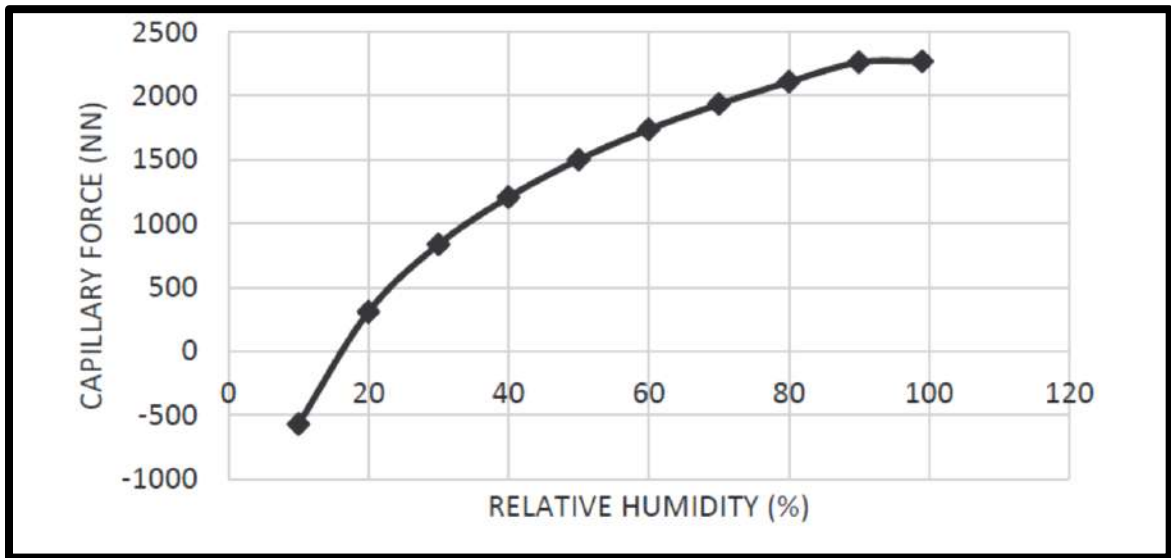


**Figure 2.5.** Relationship between the adhesion force and relative humidity level [76]

Mekhilef et al. [34] discovered that the atmosphere's humidity significantly impacts the force of adhesion between dust particles and the PV module's surface. They noted that countries near oceans have high levels of humidity, which causes dust particles on the top surface of the PV module to become more sticky. Additionally, it has been found that an increase in adhesion of roughly 80% occurs when relative humidity goes from 40% to 80%. The efficiency of solar panels increased as the relative humidity dropped because fewer dust particles stuck to the surface; however, as the absolute humidity rose, more dust accumulated on solar surfaces, and the performance of solar panels fell. In Sudan's tropical Savannah region (latitude: 13.6° N), Gwandu et al. [75] looked into the impact of RH on visible solar irradiance. They looked into how wind and relative humidity affected the efficiency of monocrystalline silicon PV modules. They noticed that the RH was low during the hours of 8:00 and 11:00 in the morning when the wind speed was at its highest. They discovered that when the wind was blowing quickly, the RH in the area of the PV modules decreased, and the temperature of the cells dropped, enhancing the efficiency of the cells. In contrast, the RH was high between 14:30 and 7:00 pm when the wind speed dropped. The relative humidity fell as the wind picked up, and the solar panels' efficiency rose because fewer dust particles stuck to the surface [77], [78].

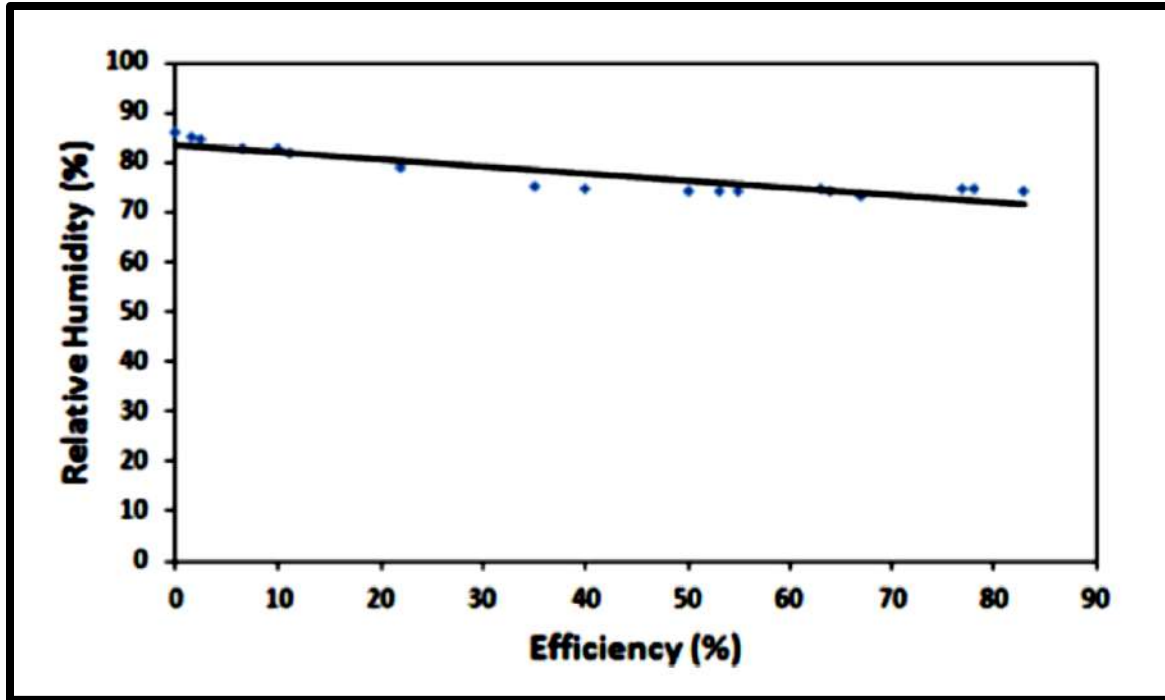
Isaifan et al. [79] conducted an experimental investigation to understand better the mechanism of adhesion force between dust elements and PV surfaces. Gravitational forces, capillary forces, electrostatic forces, and van der Waal forces were all evaluated. They discovered that under high relative humidity, capillary force dominates the bonding process between dust elements and PV module surfaces, accounting for 98 percent of total forces.

In contrast, van der Waal force controls under dry conditions. The relationship between relative humidity and capillary force is depicted in Fig. 2.6.



**Figure 2.6.** The relationship between relative humidity and capillary force [79].

Ettah et al. [80] examined the influence of relative humidity on the output of PV modules. As shown in figure 2.7, they found that an improvement in the efficiency of the PV cells was connected to a drop in the humidity level surrounding the PV modules. Figure 2.7 depicts the decrease in efficiency as humidity increases. It has been shown that with a 20% rise in relative humidity, the power dropped by around 3.16 W due to increased dust deposition on the PV surface [81].

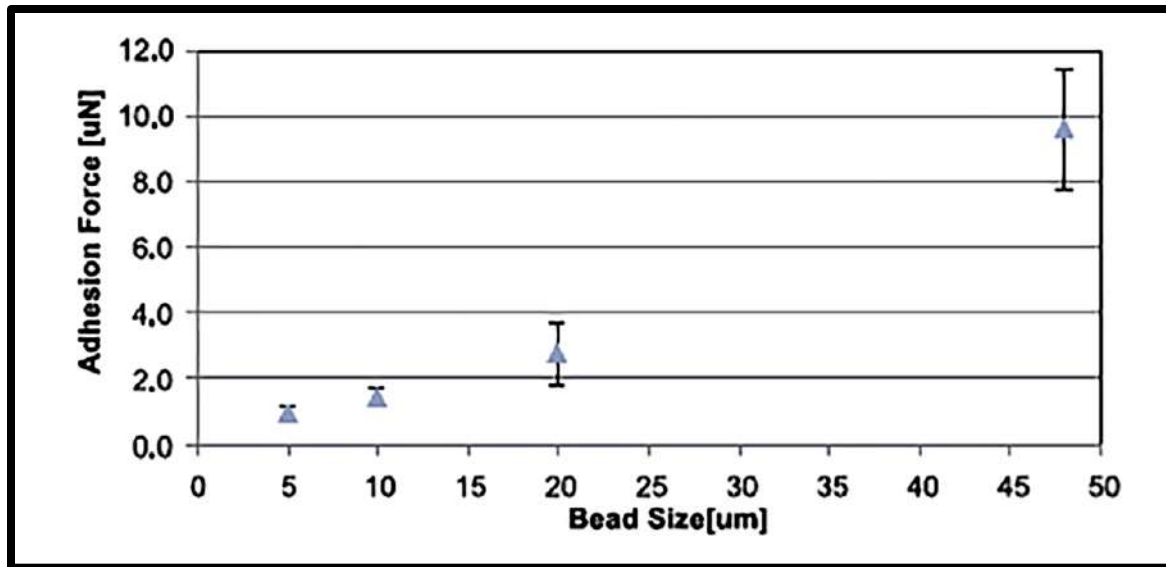


**Figure 2.7.** The influence that relative humidity has on the effectiveness of photovoltaic modules [80].

#### 2.2.6. Dust characteristics

Dust deposition and accumulation rates on PV modules in deserts and semi-arid regions vary greatly due to unevenly distributed dust storms, such as in the Middle East and North Africa [82]. In different parts of the world, dust particles may have different sizes, shapes, densities, compositions, charges, and morphologies. These characteristics affect the rate of dust deposition on the PV modules, which in turn depends on the region's geography, climate, and urbanization [28]. El- Shobokshy et al. [83] investigated the relationship between the rate of dust deposition and the PV efficiency and the physical and chemical characteristics of dust particles. They employed three different types of limestone particles with median diameters of 5, 10, 50, 60, and 80  $\mu\text{m}$ , respectively, as well as carbon, cement, and cement. They discovered that on PV surfaces, finer dust particles, those with a diameter

of less than 5  $\mu\text{m}$  tend to settle more than coarser ones, those with a diameter of more than 5  $\mu\text{m}$ . They noticed that smaller dust particles deposited slower than larger ones but that the lower rate of finer dust particles had a greater impact than larger dust particles. This is because smaller, more concentrated particles deposited on the cover glass surface have a bigger surface area than their larger counterparts. Additionally, they discovered that the finer dust particles with high wind speed might be removed more difficult than the coarser dust particles, which decreases the rate of dust deposition on PV solar panels. According to Kohli et al. [84], the wind attrition of dust particles from the surface causes them to become charged. These dust particles arrive close to the surface, already energized by previously energized dust particles. According to the dust particles' polarity and the surface charge distribution, the coulomb force takes effect, which can be either attracting or repulsive. While the particle with the same polarity is re-suspended in the air, the attractive force will further enhance the density of the dust deposition. Using research on the adhesion force between solid particles, Corn [85] showed that this force dramatically increased with particle size. Adhesion force was shown to increase significantly with particle size in a study by Brown et al. [86]. An anti-soiling hydrophilic coating was put to the glass cover, lowering the surface's dust soiling to an acceptable level. They discovered that the adhesion between particles and rough surfaces depends on the contact region between them. Figure 2.8 shows that the adhesion force increases with the bead size, suggesting that this is because more of the bead's surface area is in contact with the surface.[76].



**Figure 2.8.** The influence that the size of dust particles has on the bonding (adhesive) force [76].

Dust date can also affect dust deposition. Goossens et al. [87] found that daytime dust is higher than nighttime. In the same study, nighttime aeolian dust was coarser than daytime dust. Meteorological data accumulated over the years made it possible to anticipate the timing and location of dust events. According to research by Dayan et al. [88], the months of December through May, with the peak occurring in March, are considered the "high dust season" in Beer Sheba, Israel, in the Negev desert. Three of Abu Dhabi, UAE's annual sandstorms typically occur in March, according to research by El-Nashar [89]. According to Hegazy et al. [54], dust storms are common in the Minia area of Egypt during April and May. According to studies by Gwandu et al. [75] and Sanusi [90], the months of December through March in Ogbomoso, Nigeria, see the highest levels of dust collection on PV surfaces.

### **2.2.7. Bird's droppings**

The bird droppings phenomenon contributes to the PV Module's surface dust. Dust deposition is the most important component in deserts, and bird poop speeds up the deposition process. This organic material reduces the amount of light reaching the cell and increases the pace at which dust settles on PV panels by providing adhesive areas for dust particles. As the number of birds in an area increases, so does the amount of dust that settles on the ground, reducing the efficiency of photovoltaic modules. The areas impacted by bird excrement remain in the shade until cleaned, resulting in hot zones on the PV surfaces. Bird poop can also corrode the metal supports of PV panels [57]. Hammond et al. [91] and Al-Amari et al. [92] examined the impact of bird droppings on the solar panel. They discovered that the impact of bird droppings outweighed the impact of dust accumulation. The impacted portion of the solar cell is permanently damaged in addition to temporary flaws. It is common practice to employ techniques including bird control netting, bird spikes, loud bird scares, low-current electric barriers, and nontoxic bird control solutions. Some techniques may eventually stop working because birds easily adjust to these made-up risks [93].

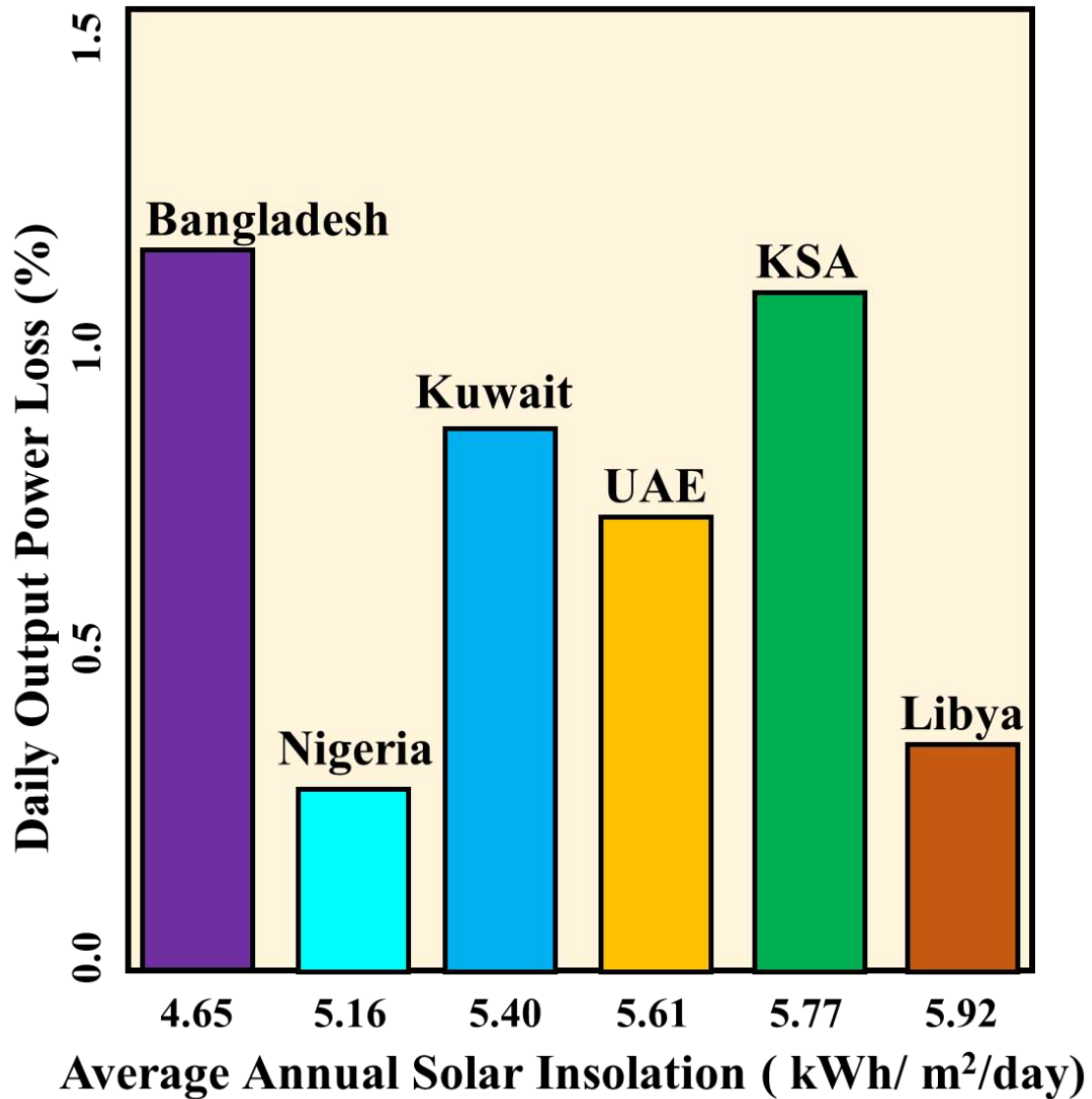
## **2.3. Dust impacts on PV solar panels**

Both changeable and unchangeable elements determine PV module efficiency. As a result, dust is an unchangeable component that falls under the category of location-dependent environmental factors [94]. Dust particle deposition rate causes significant variation in the performance of PV modules, thus causing great revenue losses in solar power installations [33]. The output power, transmittance, temperature, and efficiency of PV modules are all significantly impacted by dust particles. First and foremost, dust can scatter sunlight if it is

suspended in the atmosphere and has a size greater than the wavelength of the solar irradiation beam. This reduces the quantity of solar radiation that reaches the module's surface and lowers the PV module's output power. When paired with the impact of air pollution, this effect worsens [44], [95]. Dust and air pollutants (i.e., poisonous gases and suspended particles) in the atmosphere have been shown to reduce the output power of PV modules by more than 60% [96]. Second, the optical characteristics of the PV module can alter depending on how quickly dust is deposited on its surface. The output power of a PV module is decreased when a dense layer of dust particles forms on its surface, which encourages light reflection and absorption and lowers the PV module's surface transmissivity [15]. Thirdly, the micro surface structures of PV panels can be created when dust particles and humidity interact. The PV module's performance is decreased by this adherent layer of dust particles because it raises the surface temperature and causes some surface shadowing. Basic cleaning methods struggle to remove this layer of moisture and dust, especially if water use is prohibited dust on the performance of the solar panels[11]. Different studies studied the effects of rate deposition of dust particles on the PV performance. We summarize some of these papers in the following.

### **2.3.1. Reduction on the output power of solar panel**

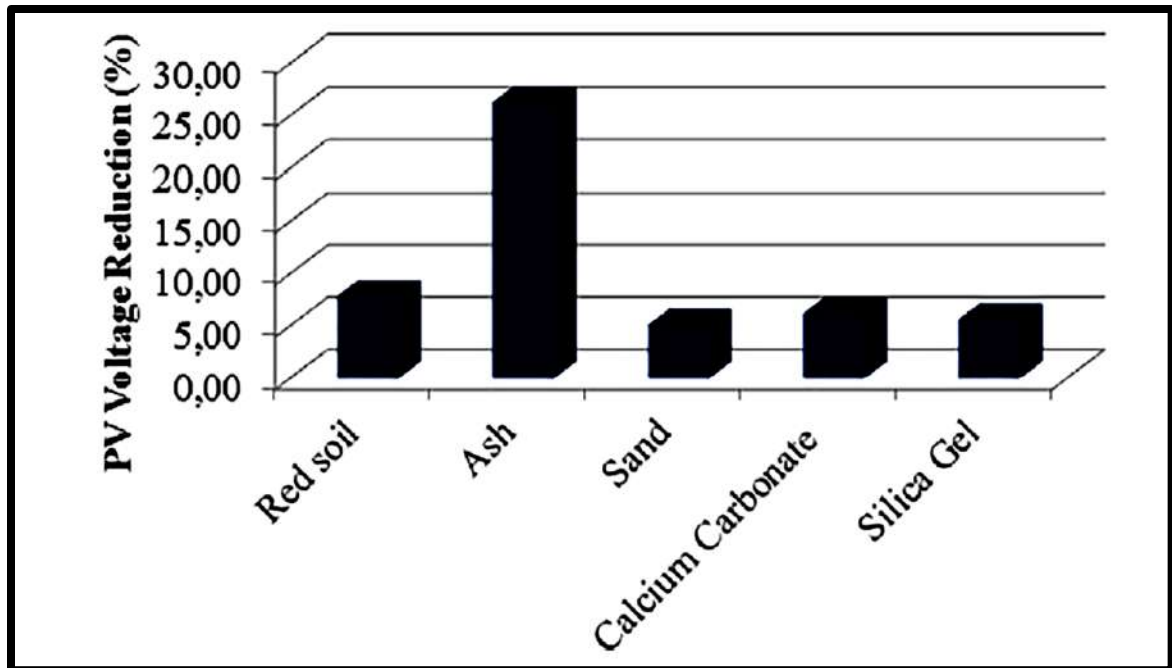
According to Figure 2.9, countries in the Middle East and North Africa (hot and humid environment) reported daily power output losses that averaged more than 20 percent due to the region's high dust levels and lack of rainfall. Power losses of solar panels in Bangladesh, Nigeria, Kuwait, United Arab Emirates (UAE), Kingdom of Saudi Arabia (KSA), and Libya, as seen in Figure 2.9, due to dust deposition on solar surfaces. [14], [15].



**Figure 2.9.** Dust deposition on solar surfaces causes daily power losses in the Middle East and North Africa [14].

In Dhahran, Saudi Arabia, Said et al. [36], [59], [76], [97] showed a 50% decrease in PV power output after six months of outside exposure. This indicates that if a PV panel isn't cleaned for a week in this area, where rainfall is quite infrequent, it will lose around 2% of its power production. In Doha, Qatar, Guo et al. [44] reported a daily loss in PV power generation of between 0.4 and 0.8 percent. This indicates that if a PV panel in this

environment is not clean for a month, it can lose between 12 and 24 percent of its power output. In Iraq, Al-Soleimani et al. [96] investigated the influence of dust accumulation on the output power of PV panels. They discovered that over a year, more than 60% of the PV module's output power might be reduced. Lorenzo et al. [98] looked at the effects of nonuniform dust accumulation rates on PV arrays. They discovered that dusty modules operate at much lower voltages than clean modules in the same row. The cause for this is the formation of hot spots on the PV panels as a result of dust deposition. The higher rate of dust buildup causes more hot spots, resulting in larger output power losses on PV solar cells. Sulaiman et al. [99] investigated how dust deposition affected the PV module's output power. They utilized talcum powder and mud-like dust particles. They discovered that the PV module's output power has decreased by 18 and 16.2 percent, respectively. They conclude that the PV module's efficiency can be reduced by 50% due to dirt buildup on the front sheet. The average daily drop in output power of PV modules during a 365-day period is roughly 4.4 percent, according to Zorrilla-Casanova et al. [100]. They blamed PV module's dust buildup for this drop. They stated, when there has been light rain for a while, more dust accumulates on the PV surface, reducing the output power of the module by up to 20%. The effects of ash, sand, silica, red soil, and calcium carbonate dust components on the PV module were investigated by Kazem et al. [101]. The results, which are depicted in Figure 2.10, show that ash has the greatest impact on the PV module voltage because its particles are so minute. When ash formed on the PV module's front surface, there was a 25 percent maximum loss in PV voltage, as was observed.

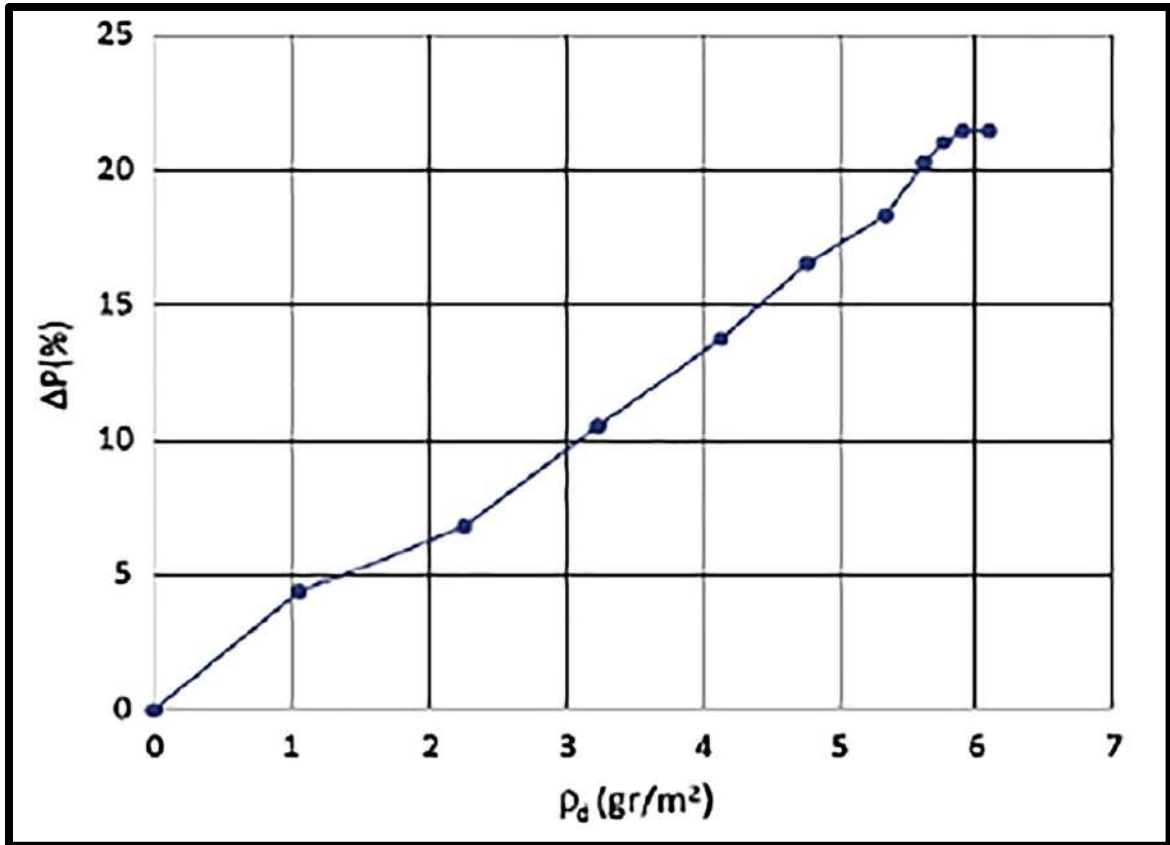


**Figure 2.10.** PV output voltage drop due to dust particles [101].

Rajput et al.'s [102] experimental investigation of the effect of dust accumulation on the Photovoltaic module surface provided a concept of electrical performance. They get to the conclusion that the electrical properties of the solar panel are dependent on the rate of dust deposition. In order to ascertain the effects of dust deposition, Rao et al. [103] conducted studies both indoors and outside. Due to the  $1.4 \text{ g/m}^2$  dust density, the power loss in the outdoor test was between 5 and 6 percent, whereas the power loss in the indoor test was between 45 and 55 percent of the maximum probable influence yield. Any increase in the dust deposition rate on the PV panel's surface causes an increase in the module's efficiency loss. The effects of dust on various PV panels were investigated by Ketjoy et al. [104]. Researchers looked into how dust accumulation affected PV modules made from various silicon varieties. They found that a dust accumulation of 260 mg reduced yield output power by 3.50 percent for amorphous silicon, 7.28 percent for monocrystalline silicon, 2.96 percent for multi-crystalline silicon, and 425 mg reduced 5.79 percent for amorphous

silicon, 2.83 percent for monocrystalline silicon, and 6.03 percent for multi-crystalline silicon PV modules. Chaichan et al. [105] modeled the impact of air pollution and dust on the PV module. The data demonstrates that the PV module's efficiency was reduced due to a mix of dust and air contaminations. The routine cleaning of a solar cell reduces its yield energy by about 8% while exposing the module to dust for two months reduces it to around 12%. The effects of dust on solar panels were studied by Saidan et al. [106]. When they measured the output power of the PV module, they found that it had decreased due to dust accumulation. Without cleaning, the average efficiency drops by 6.24 percent after one day, 11.8 percent after one week, and 18.74 percent after one month after installation. The experiment was conducted by Gholami et al. [107] to assess the effect of dust deposition on PV module production. The outcomes are displayed in Figure 2.11. Based on the data presented in Figure 2.11, the output from the solar module dropped by 21.47 percent after 70 days of no rain due to 6.1 (g/m<sup>2</sup>) of dust accumulated on the PV module. The experiment was conducted by Abderrezek et al. [108] to examine the influence of dust deposition on PV modules' electrical, optical, and thermal properties. They found that when dust particles are evenly dispersed, the solar radiation is scattered away from the PV module, while when the dust is randomly dispersed, shadows are seen, contributing to the hotspot phenomenon. When the dirt components landed on the very bottom edge of the PV module, they caused a reduction in output power of between 10 and 16 percent. According to Monto et al. [62], there are two forms of dust-related shading: soft shading, which refers to concentrated air dust, and hard shading, which relates to dust that accumulates on the PV module. Soft shading occurs when the amount of dust in the atmosphere is high, or some dust particles have been collected on the PV module. Soft shading reduces the PV module's output

current while maintaining a constant voltage. When a large amount of dust accumulates and prevents light from accessing the PV module, hardening shading develops. The number of PV module-shaded cells determines the effect of severe shading. There will be some yield energy with reduced PV module yield voltage if some cells are shaded while others receive solar light.



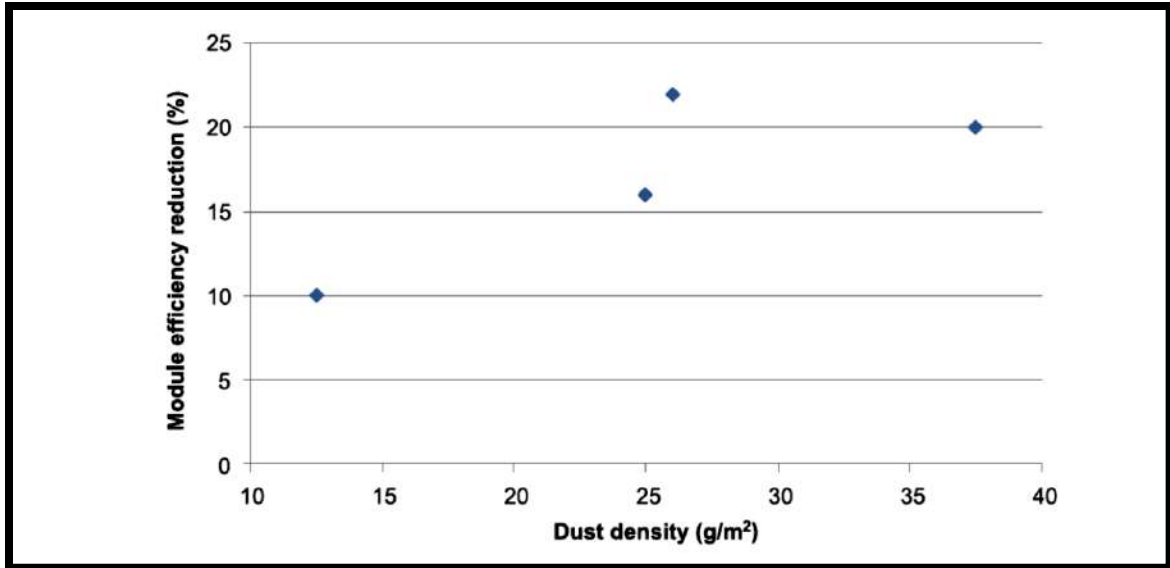
**Figure 2.11.** Power loss per week with mean dust density [107].

### 2.3.2. Reduction in the efficiency of PV module

The performance of PV modules typically declines with an increase in dust deposition [106], [108], [109] as a result of a reduction in the spectral and overall transmissivity of its cover[110], [111]. The distribution of dust particles on the PV cover, as seen in Figure 2.12, makes this connection less than perfectly linear. It demonstrates the connection

between the loss of solar modules and the amount of dust loaded onto the solar surface [83]. Varying studies have examined the degree of performance reduction in PV modules brought on by various rates of dust deposition. Ground clay (bentonite) was employed by Molki et al. [56] to evaluate how the efficiency of PV modules decreased. They applied up to  $4 \times 10^3$  mg of pulverized clay (bentonite) to PV modules. They discovered that the PV module's conversion efficiency decreased by 10%, 16%, and 20% for 100 mg, 200 mg, and 300 mg, respectively. They discovered a relationship between the rate of PV loss and the rate of dust buildup on the PV module that was negatively exponential.

The effect of dust in Mexico City was studied by Weber et al. [112]. They noticed the dust settlement rate changed between 24 and 102  $\text{gm}^2$  per day on flat surfaces. The effectiveness ratio decreases by about 15% after two months of dust accumulation on the PV modules without rain. Mejia et al. [113] investigated the effect of dust particles on photovoltaic panel efficiency. They discovered that the PV module's efficacy ranged from 7.2 percent to 5.6 percent throughout a 108-day period. They found that the influence of dust buildup on the PV module lowered its efficiency by roughly 2% in just 90 days. Klugmann-Radziemska [58] conducted an experimental study on the effect of dust on the performance rate of a  $37^\circ$  tilted silicon crystalline PV module in northern Poland. They observed that the overall reduction in PV module efficiency was 0.8 percent per 24 hrs. Experimental research on the effects of dust on the absorptivity and emissivity of absorber plates of PV modules was conducted by Li et al. [114]. They experimented with dust accumulation and ran simulations of dust deposition density over absorptivity loss. On the 110th day of dust exposure, which corresponds to an average dust deposition density value of surface  $7.07 \text{ g/m}^2$ , the greatest efficiency decline was measured as 19.23%.



**Figure 2.12.** Reduced module efficiency with dust concentration [72].

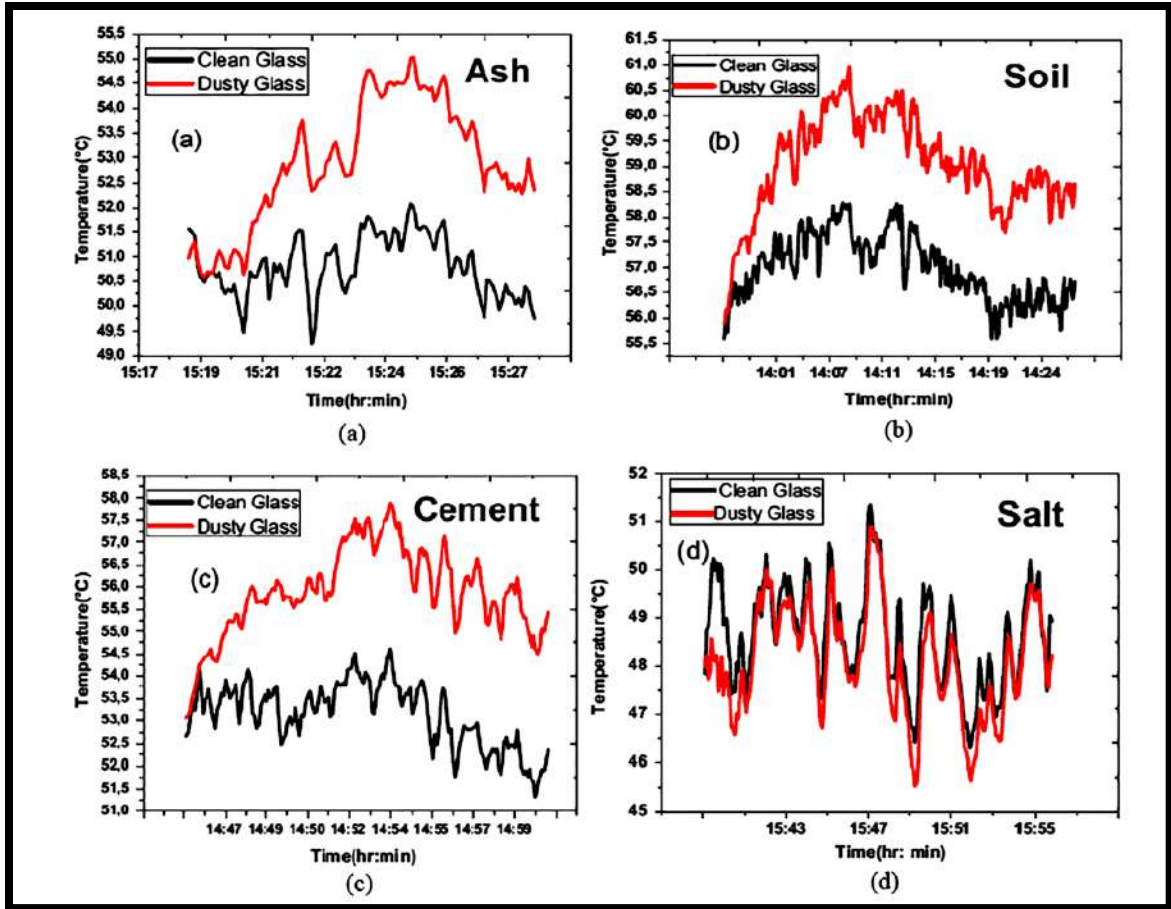
### 2.3.3. Reduction of PV transmittance module

The dust density does not simply grow with time spent in an exposed environment but is highly attuned to the prevailing weather patterns at that moment [115]. For example, the amount by which PV modules' transmittance is reduced is not uniformly linear but relies on environmental factors like the frequency of dust storms and the weather [50]. A hundred transparent glasses were evaluated by Elminir et al. [55] for dusting issues on a transparent cover of a PV module. For seven months, they measured the 100 glasses' transparency. At a zero-degree tilt angle, the density of dust deposited on the glasses was  $15.84 \text{ g/m}^2$ , but at a ninety-degree tilt angle, it was only  $4.48 \text{ g/m}^2$ . In both cases, transmittance was reduced by about 52.54 percentage points to a low of 2.38 percent. The impact of dust accumulation on PV cover transmittance was investigated by Adel A. Hegazy [54]. According to his findings, the solar model's glass cover transmissivity dropped by about 20% after just one month of exposure to the dust, and the module's power dropped by 60%–70% after six months. At dust deposition densities up to  $15.6 \text{ g/m}^2$ , Al-Hasan [116] analyzed the effect

of dust accumulation on the transmittance of light at the PV module over the wavelength range of 190 to 900 nm. They discovered that there was no wavelength dependence on the decrease in transmittance when dust deposition densities rose on the glass sample. The effects of dust deposition on photovoltaic (PV) module temperature, transmittance, and yield energy were investigated by Guan et al. [117]. They discovered that the top glass surface of PV modules lost transmittance due to dust accumulation.

#### **2.3.4. Increment the PV module temperature**

Different studies investigated the relationship between the rate of dust and the temperature of PV modules. According to Monto et al. [62], a few PV module cells are blocked by dust particles, bird droppings, leaves, and dirt marks. In this situation, blocked cells raise the PV module's temperature. These causes cause blocked cells to heat up and produce a hot spot that could damage a PV system. The relationship between the rate of dust particles and the temperature of the PV surface module was examined by Abderrezek et al. [108] using various types of dust particles. Salt, cement, soil, and ash were used. As can be seen in figure 2.13, they discovered that ash and soil raise the temperature of the module in comparison to other factors. According to this study, a hotspot created by erratically spaced dust particles on the PV surface raised the temperature of the PV module. Dorobantu et al. [118] studied surface contaminants' effect on PV module temperature. Any dust deposit on a PV module causes the afflicted area to heat up relative to the rest.



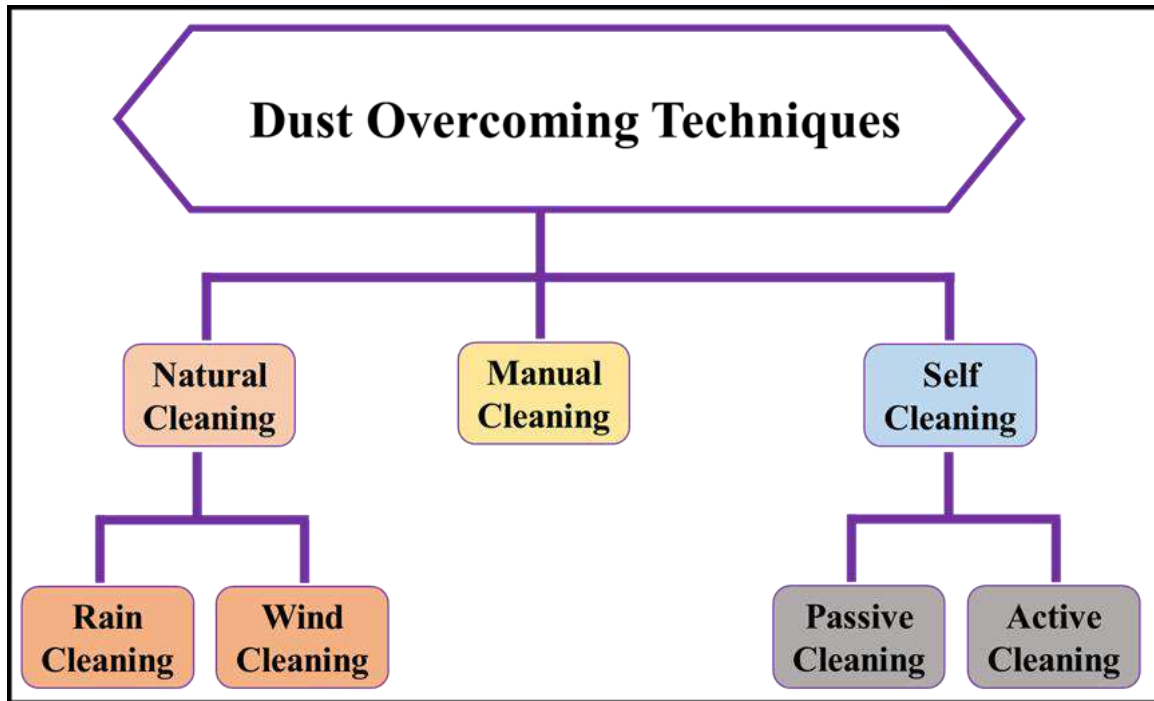
**Figure 2.13.** (a)Ash, (b)soil, (c)cement, and (d)salt particles affect PV module temperature [108].

A larger amount of dust accumulates over time, which degrades PV significantly. To regain maximum PV module production and mitigate the negative effects of environmental conditions, it is advised to adopt a suitable cleaning schedule. The appropriate frequency of cleaning is largely affected by the local climate [54], [55], [62], [97], [119].

## 2.4. Strategies for dealing with the dust problem

The efficiency, reliability, and cost of a PV system's deployment are all negatively impacted by dust accumulation on the surface of the PV modules. When dust accumulates on the surface of a photovoltaic module, it not only hinders the module's efficiency but also shortens its lifespan [11], [13]. Studying the links between physical dust properties,

chemical dust properties, and dust transport processes with solar panel performance is the key to designing efficient mitigation and prevention approaches that reduce dust particles from solar panels and boost efficiency [10], [120]. Figure 2.14 classifies cleaning approaches. Natural cleaning by rain and winds, manual cleaning by laborers, and self-cleaning by integrating a cleaning component into the PV system. There are two types of self-cleaning methods, active and passive technology. Technologies that are pre-treated physically or chemically in a lab to reduce dust attraction do not require any more effort beyond their initial installation. Surface modification is used in dust mitigation techniques to lessen the bond between the dust layer and the covered surface. This class includes both super-hydrophobic and super-hydrophilic surface treatments. Surfaces can be cleaned or protected against dust deposition with active technology. This class includes fluidic, mechanical, and electrodynamic/electrostatic approaches. The term "fluidal cleaning procedures" refers to techniques that use fluids like water to remove dirt and grime off surfaces. Wiping, blowing, vibrating, and ultrasonic-driven cleaning are all examples of mechanical processes. The electrostatic levitation process of the sun provides inspiration for electrodynamic/electrostatic cleaning techniques in dust reduction [13], [120]. Most of these technologies are discussed in the next sections.



**Figure 2.14.** Classification of soiling mitigation methods

#### **2.4.1. Cleaning dust particles using rainwater**

The functionality of the modules can be restored by using rainfall, which is thought to be the most effective natural cleaning solution for eliminating contaminants from PV surfaces [14]. Five millimeters of water can be considered sufficient for cleaning PV solar panels and restoring their output capability in some areas with frequent rain [121]. However, rainfall is in short supply in dry regions like the Middle East, particularly from April to November.

This indicates that human intervention is required to clean the panels to restore PV performance, as abandoning them to natural circumstances will result in performance degradation. Different experiments investigated the effect of rainwater on the efficiency of the PV module. The effectiveness of precipitation in removing dust particles from PV surfaces was investigated by Haeberlin et al. [122] and Appels et al. [123] in Leuven, Bern, and Eugene

located at latitudes of 50.88°N, 46.9°N, and 44°N, respectively. In these locations, the regular rainfall is rained over the course of the year, avoiding the need for manual cleaning; as shown by the results, rainwater sufficiently recovers the PV module performance. The effects of rain on the removal of dust particles from massive grid-connected PV modules in the United States were studied by Kimber et al. [124]. They discovered that in order to restore the PV module's functionality, at least 20 mm of rainwater must fall on its surface. The impact of tilt angles on the cleaning of PV modules by rainfall was researched by Qasem et al. [125]. They discovered that the inclined surfaces easily let dust fall because of gravity, whereas the horizontal surfaces are difficult to clean by rainfall. Rain's capacity to remove dust particles depends significantly on the PV surface's inclination. According to Bethea et al. [126], each PV module needs to be slanted in order to help clean the rainfall. Rainfall substantially impacts the process of dust deposition; however, light rain with short durations may accelerate dust deposition. Raindrops of low intensity can conglomerate with dust particles, which causes the module's surface to become dusty. The Middle East is one region where rain is insufficient for cleaning PV modules because rain resistance occurs when there are extended dry intervals between rainfalls [127]. Due to improved dust adherence on the PV module caused by the low rainfall, dust is transformed into mud that is difficult to remove by rain cleaning [126].

#### **2.4.2. Cleaning dust particles using wind**

The wind influences the effectiveness of PV cells. The wind transports dust and soils the PV solar module since it is the major mode of global transport for dust particles. Positively, wind can lower the total amount of dust deposited by clearing larger dust particles from PV surfaces. Additionally, as the wind speed

increases, the dust deposited falls, and the temperature of the PV modules' cells drops, increasing the system's efficiency [11], [14]. According to Mekhilef et al. [34], increasing wind velocity causes a larger thermal dissipation from the Photovoltaic surface leading to a decrease in the surrounding relative humidity, improving PV module efficiency. Although wind can improve the efficiency of PV modules, it cannot be relied upon because it has the potential to increase dust formation and is unreliable in areas with low wind speeds. The performance of PV modules is strongly influenced by wind speed and direction [50]. Jing et al. [128] evaluated how wind affected the PV cleaning procedure. They left behind dust on the plates of the solar units. They discovered that using natural wind to remove fine particles was ineffective because, in most cases, a high velocity was required to separate the dust particles from the surface. Therefore, in climates like the Arab Gulf States, where humidity also negatively affects the adhesion of dust particles to the panels, the natural wind cleaning of the PV modules is not a practical solution. How high altitude affects wind-driven PV cleaning was a topic of research for Cano [53]. The wind speed was greater than he had anticipated at the elevated PV module installation. An elevated PV module is better able to benefit from the wind's cleaning power.

#### **2.4.3. Cleaning dust particles using detergents**

Typically, water is utilized as the cleaning solution when removing dust. While rainwater can be used to achieve a cleaning effect, it is not always preferable as manual or automatic water cleaning due to the modules becoming dirty and the difficulty of mitigating the effects of prolonged untreated soiling. Water-cleaning PV modules have only one benefit: it reduces panel temperature, which in turn boosts electricity output [129], [130], [131], [132]. According to Krauter [133], water can lower PV cell temperatures to 22 °C and

decrease sunlight reflection by 2-3.6 percent. Additionally, Bahaidarah et al. [134] found that washing the solar module with water reduces the panel's temperature by 20% and increases its efficacy by up to 9%. Additionally, Odeh et al. [135] discovered that cleaning the solar cell with water improves the solar system's performance. It revealed a 15% increase in the PV module's output power when the sun was strongest.

Early works from the late 1970s and early 1980s describe washing photovoltaic modules with water and water mixed with detergents. According to reports from the Jet Propulsion Laboratory, MIT/Lincoln Laboratory, and NASA Lewis Research Center, washing PV modules using water and detergents is effective. The NASA facility used an Alconox-Tide solution and a scrub cloth to remove dust from the PV surface. After that, the PV module was washed with water and dried. The MIT lab utilized an Alconox solution and a toweling to reduce dust buildup on the PV module surface. Afterward, they rinse the PV surface with water and dry it with a squeegee. To remove dust, Propulsion Laboratory used a water-based degreaser that was applied with a toweling and then washed with water. These techniques for cleaning with detergent and water have been proven successful [14].

The impact of surfactants on eliminating dust particles and recovering the efficiency of PV panels was investigated by Abd-Elhady et al. [132]. In a lab setting, the impact of surfactants was investigated via them. They employed Tween-80 (zwitterionic), Cetylpyridinium Bromide (a cationic surfactant), and Sodium Dodecyl Sulphate (an anionic surfactant). They discovered that the cationic surfactant, zwitterionic surfactant, and anionic surfactant had the greatest effects on reducing collected dust particles from the surface. To achieve the greatest surface cleaning results for the PV module, the mix of cationic surfactant and anionic surfactant with water is advised. Surfactants with the

removing method were the subject of research by Moharram et al. [136]. They experimented to see how the non-pressurized water approach would reduce dust buildup on PV panels. Both were employed with surfactants in the non-pressurized water approach and one without surfactants. They employed Cetylpyridinium Bromide, a cationic compound, and Sodium Dodecyl Sulphate, an anionic compound. They discovered that using surfactants improves the performance of PV modules. In the end, they claimed that using water and a chemical mixture will increase the effectiveness of cleaning PV modules with tough stains.

This ionic cleaning method is more effective than water alone; some weaknesses include [13]:

1. Pressurized methods use more water than non-pressurized. Due to splashing water on the PV panel surface, this approach is not ideal in desert or semi-arid regions where water is scarce.
2. Surfactants can reduce water usage by improving cleaning efficiency; however, water evaporation is often excessive in hot climates. This could drain water and raise surfactant density. Consequently, it may cause the surfactants to adhere to the panels, which will have a soiling impact.

#### **2.4.4. Cleaning dust particles using a manual system**

The PV module could be cleaned manually using a soft cloth, water, and a person[11]. The conventional approach for removing dust buildup from a PV panel's surface is a manual system. The procedure is effective if set up on a regular schedule since it allows for the efficient cleaning of even difficult soiling from the PV panel, such as bird droppings or cement dust[13], [137]. In small-scale solar PV facilities, this procedure is the best for

cleaning the PV module [138]. Al-Shehri et al. [6], [139] tested the cleaning effectiveness of Photovoltaic panels using various brush substances, including silicon rubber foam, nylon, and cloth. They came to the conclusion that, despite some materials having a noticeable effect on solar panels, no material was determined to have a lasting or significant detrimental effect on solar panels' efficiency. Furthermore, using water and soft wipes to clean was more effective than using nylon brushes, which were less effective overall. Moreover, they concluded their subsequent research that choosing the best brush is crucial to achieving the necessary level of cleaning while avoiding harm to the solar panels' surface. The impact of brushing on the PV module surface following water cleaning was investigated by Pavan et al. [46]. They cleaned the two large PV plants in their trial using pressurized water. One power plant's panels were cleaned and then brushed. As a result of cleaning, the PV plants' output power improved by 1.1 percent without brushing and 6.9 percent with brushing, according to the results. Brushing removes the deeply adherent tiny particles that water washing alone could not remove.

Manual systems are superior at removing dust from photovoltaic panels but have two major downsides. First, consider the cleaning labor costs. Workers can be expensive, especially for large-scale PV systems [140], [141]. Different facets of labor must be addressed, including income, work health and safety issues, and government-related labor needs [141]. In addition, there are costs associated with manual cleaning that are similar to those associated with self-mechanical cleaning systems; these include water, tools (including cleaning and maintenance tools), and detergent. However, the PV panel surface could be damaged or cracked by improper handling of the labor-type cleaning approach that employs tools or other cleaning equipment. Scratches on the PV module's surface, caused

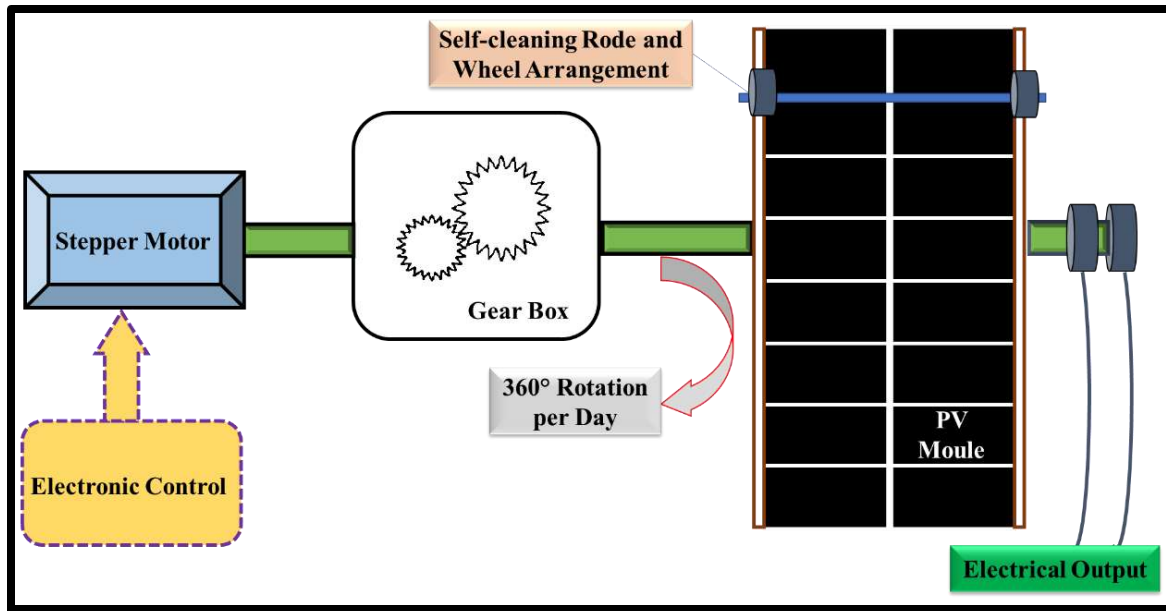
by repeated brushing, reduce the module's efficiency[13]. Second, substantial PV plants may not work with this strategy. This cleaning process is tedious and difficult because PV modules are mounted 2.5 to 4.5 meters above the ground; the safety of laborers must be considered [11],[13].

#### **2.4.5. Cleaning dust particles using an automated system**

On the surface of PV modules, automated technologies are utilized to remove dust particles. Mechanical brushing, wiping, blowing, vibrating, robots, detachable covers, and using subsonic or ultrasonic waves to break up dust adhesion are some techniques. Various mechanical methods are being developed for cleaning PV panels. Their designs vary according to factors, including the intended use of the PV system, personal choice, and the environmental conditions in which the PV module is installed [142]. These mechanical cleaning methods are powered by either human or mechanical energy. Machines have higher dust removal rates than humans, up to 95 percent, and can clean solar panels in a shorter time. However, a few factors must be taken into account before using the mechanical cleaning method; (1) A mechanical cleaning method uses a variety of hard goods. Although it reduces labor costs, this method has a high starting cost. As a result, the installation costs for a large-scale PV plant will be higher. (2) For the system to function at its optimum, the movable mechanical components of the device, such as the gear, chain, and spinning feature, need to be adequately maintained routinely. At this point, it is also necessary to incorporate maintenance costs. (3) Most mechanical systems come with brushes and wipers traveling over the panel. The wipers, brushes, or other pieces directly touching the PV surface will therefore begin to collect dirt. As a result, if this goes on for a long time without sufficient maintenance, the power effectiveness will suffer. (4) Most

mechanical clearing techniques rely on electrically powered, automatic, or programmable active cleaning devices. As a result, the power used comes either from an external battery that needs to be changed or from the PV system's feedback power, which will reduce the PV output while it is being cleaned. An automatic cleaning system, for instance, has been shown to use 2.22 percent of the power provided by the PV system, according to Ju et al. [143]. However, cleaning will necessitate a greater amount of energy in a large-scale PV facility. (5) For the mechanical system to effectively clean PV panels, most of its components must come into direct touch with the panels' surfaces. Brushing or wiping away dirt for an extended period, or doing so frequently, could cause severe harm to the panel's surface [13]. The majority of efforts have been directed at computer-based control of mechanical equipment [14]. Some mechanical tools are made to be employed as robotic cleaners, traversing the widest possible area in the least period, with as few human helpers as is necessary. For smaller Photovoltaic panels, there will be many robots with drier brushes [33]. Robotic cleaning systems have been developed with specifications nearly identical to non-robotic mechanical cleaning systems; robots operate completely autonomously via the designed programming algorithm. Simply put, they serve the same function as conventional mechanical cleaning systems but are guided by sensors and pre-programmed instructions from an "artificial brain." [144], [145], [146], [147], [148]. Robotic cleaning offers many benefits over traditional mechanical cleaning systems, including greater speed, efficiency, power efficiency, stability, and dependability. It can be used in situations where a high level of automated control is necessary or desirable [149]. The downsides of these robots include (a) the need for customization, (b) a substantial amount of costly installation, such as customized rails, and (c) complex repair under hot

temperature conditions, even though they offer autonomous cleaning and are usually quite tough [33]. The single-axis solar tracking system has a self-cleaning mechanism, which was invented by Tejewani et al. [150]. As seen in figure 2.15, this self-cleaning system consists of a stepper motor, microprocessor, and gearbox. The PV module is first positioned perpendicular to the ground in the morning. The system rotates in a way that keeps the solar radiation coming from the sun parallel to the PV module's surface. The PV module becomes perpendicular to the ground when the stepper motor turns 180°. During these moments, a brush cleans the PV module's surface as it spins as a result of gravity. The stepper motor has completed a full 360° turn before the PV module once more assumes a vertical position with regard to the ground. The PV module is cleaned by the brush. The PV module is cleaned twice daily in this manner. A comparison of daily energy production between the tracking module with cleaning equipment and a module equipped just with a tracking system demonstrated the effectiveness of the design, with the cleaning system seeing a 15% increase in the output power. Robotic cleaning, according to Ju et al. [143], raises installing and maintaining costs while lowering water demand for cleaning PV modules. In Shenzhen and China, they had two identical monocrystalline PV systems and were outside. In contrast to the other PV system, which was left unattended to be cleaned by natural weather, one of the PV systems had a motorized, mechanical cleaning that included an electric motor and a brush with water spray. Comparatively speaking, the PV system with a cleaning system produced greater output power than the PV system that was naturally cleaned. However, they discovered that the cleaning system's operational costs were higher throughout the same test time, including the water and energy used by the motors.



**Figure 2.15.** A mechanical device that is self-cleaning and has solar-tracking capabilities[150].

#### 2.4.6. Cleaning dust particles using the coating process

Coatings are naturally self-cleaning, which is a great way to protect your substrate from dust. The Coating technique has little energy and maintenance needs and is kind to the planet. Coating techniques have altered substrates' adhesion, wettability, corrosion resistance, and wear resistance. Substrates can have coatings applied to them in several different ways, including gases, solids, or liquids. Depending on the intended use, the substrate's surface can be generated hydrophilic or hydrophobic by the coating process. High surface energy materials, which have good wettability properties, must be considered to manufacture ultra hydrophilic surfaces. The photocatalytic process on these super-hydrophilic surfaces reduces pollution. Hydrophobic surfaces have low wettability, meaning water droplets don't readily adhere to the top layer. According to research, a surface's hydrophobicity is measured by the contact angle, and water droplets bounce off it. It depends on the surface's microstructure [151]. Materials with low surface energy, like

silanes, silicones, nanoparticles, and polymers, are employed for hydrophobic surfaces because of their ability to repel water. A super-hydrophobic surface is one with an exceptionally high level of hydrophobic capabilities. The water contact angle is the most crucial factor when designing a hydrophobic surface [13]. By changing the surface property of the PV module to be extremely hydrophobic, a better cleaning effect may be accomplished in the event of dust mitigation. Rainfall or a water-cleaning system can quickly remove mitigating dust particles from super-hydrophobic surfaces. Rolling water droplets scrape off contaminants and reduce dust accumulation from extremely hydrophobic surfaces. The probability of PV module surface recovery will improve as a result of this effect, and the maximum module effective area will be able to absorb more sunlight [13]. Numerous studies have looked at the modification of the PV surface module and confirmed that hydrophobic and hydrophilic surfaces lessen dust deposition from the PV module. Different titanium dioxide film thicknesses were placed on the glass surfaces by Hee et al. [50]. Due to the deposition of titanium dioxide, they saw less dust formation. They discovered that as film thickness increased, the effect of deposition became more noticeable. The dust particles did, however, raise the panel's temperature, which affected the voltage losses. Thus, employing self-cleaning nanomaterial on nano-coated PV modules can lower the rate of dust deposition but also improve thermal reduction, particularly in the hot environment of the Mena countries [152]. According to Yong Sheng et al. [153] .s research, only 71.8% of a PV module's effectiveness can be restored after being degraded by dust deposition using the ultra hydrophobic surface. A super-hydrophilic nano-structured glass with a contact angle of less than  $5^{\circ}$  was made by Verma et al. [74]. They enhanced PV performance by enhancing net optical transmission and

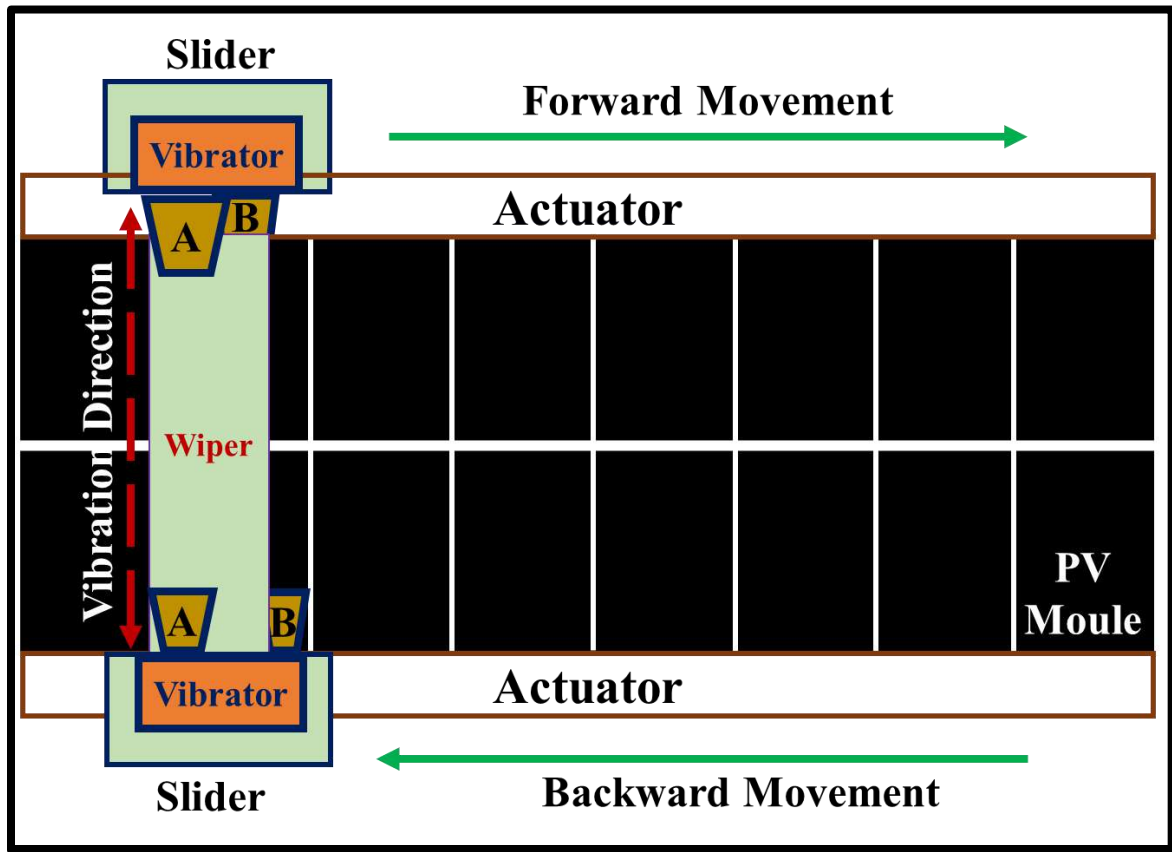
surface self-cleaning properties. For several months and in various climates, Arabatzis et al. [154] observed the exterior efficiency of coated and uncoated Photovoltaic cells and arrays. They employed an anti-reflective, self-cleaning, photocatalytic glass layer. Their findings demonstrated that the coated screen's superior hydrophobicity improved its ability to remove dust.

Generally, the coating application would result in a 5–6% power improvement for PV modules operating over an extended period. PV module-coated and uncoated surfaces were examined by Piliougine et al. [155]. They discovered that the average daily soiling loss for coated modules is 2.5 percent, compared to roughly 3.3 percent for uncoated modules. Despite the potential of the surface coating (superhydrophobic, super-hydrophilic) successfully dealing with the issue of dust accumulation on PV surfaces, this method remains unclear. According to Mitdal et al. [156], the cleaning effect of the superhydrophobic surface is not long life and can be used for three or four years. Furthermore, the polymer might be used to create the polymer film on the PV surface [157], [158], [159]. While some of these layers (polymers) may have high initial transmittance, research by Sarver et al. shows that they quickly become dirty due to the high surface energy of the polymer surfaces, suffer erosion damage, and deteriorate much more rapidly than glass when exposed to UV light [10].

#### **2.4.7. Cleaning dust particles using ultrasonic vibration**

The mechanical system driving elements are bulky and heavy design on photovoltaic panels. For these driving components to work properly, extra electrical energy is needed. Silent operation and flexible structure design must be taken into account while creating an effective mechanical system. In order to clean the surface of PV modules, the ultrasonic

vibration method was introduced. The effectiveness of ultrasonic vibration as a cleaning technique for PV modules was investigated by Lu et al. [160]. As seen in Figure 2.16, they cleaned the PV panels using piezoelectric actuators. The components of the piezoelectric system are shown in Figure 2.16. Between the foot, A and B plates are put into the piezoelectric plates. These plates have a y- and z-direction excitation. To vibrate the vibrator's parts and send a pulse to the slider, they applied voltages at resonance frequencies. With a forward speed of 117 mm/s and a reverse speed of 113 mm/s, Slider moves the wiper and the guide simultaneously. The outcomes showed that the PV module's output power increased to 1.29 W following ultrasonic vibration. In a related investigation, Williams et al. [161] also revealed that their piezoceramic actuators reduced the Martian dust from the PV cells.



**Figure 2.16.** Ultrasonic vibration mechanism of the piezo actuator [160].

#### **2.4.8. Cleaning dust particles using a drones system**

Drones are becoming a useful tool for the solar industry due to a number of benefits, such as large monitoring abilities, rapid data recording, and long-distance monitoring [162]. Drones have been proposed in recent research for PV monitoring applications [162], as well as aerial thermographic assessment of PV modules [163]. Drones are seen as a viable alternative to robotic installations that are permanently installed and manual cleaning methods. Drone systems are on the rise due to their adaptability and advantages in autonomous and human-free cleaning without the need for water. The overall cost of cleaning has a major impact when this technique is applied to large-scale PV power facilities. It's critical to remember that the drone is merely a platform for transporting various cargoes, such as cleaning equipment. One of the most critical parts of a drone is the power supply. The drone's other qualities and attributes can be determined or limited by having the correct power supply. The drone's high-capacity, lightweight power supply allows it to reach greater altitudes, travel larger distances, and carry heavier loads [33]. Drones used for solar panel cleaning have a lot of potential benefits, but they also have some drawbacks. Some of the potential benefits and drawbacks of deploying drones for PV cleaning. The advantages of the drone system include its automatic cleaning system, high mobility, and versatility, which allows it to be used on numerous PV solar panels and can be done without water. Capital costs and short flight times are downsides of this technology, and the need for power or fuel recharging stations and a new application necessitates study and research [33].

## **2.5. Review of the Electrodynamic Dust Shield (EDS) system**

Different approaches for cleaning solar panels have been developed by many researchers, some of which have been discussed in the preceding sections of this article. However, these approaches have several limits regarding clearing away dust and maximizing solar panels' effectiveness. In order to keep solar plants operating at peak performance in dusty settings, automated cleaning techniques are highly desirable. Most currently used methods rely on intricate mechanical and motorized components that have not been proven scalable, cost-effective, or reliable. Having a staff of experts on hand to keep the cleaning robots running smoothly is not always possible, especially for standalone installations in outlying places. Annually, vast amounts of water, the use of specially constructed vehicles, and an experienced operations crew are required for cleaning activities on a massive scale using water. According to Ju et al. [143], the price of water and labor has the potential to be a huge drawback in removing dust. Accordingly, the aforementioned approaches are both costly and labor-intensive to adopt.

Recently, a new method has been reached for cleaning solar panels using electrical energy, where dust particles are expelled using electrostatic forces. This method utilizes electrostatic forces called an electrodynamic dust shield system (EDS) [120]. Early in the 1967-1970's, the electrodynamic dust shield system (EDS) was proposed to the electrostatics research group, where the EDS concept has been investigated and examined by several scientific researchers for transporting unwanted charged or uncharged particles from dielectric surfaces [164], [165]. Masuda et al. [166], from the University of Tokyo, developed the basic idea behind the EDS system by demonstrating that a propagating electric field wave could transport charged aerosol particles in a transverse direction [167].

The working principle of EDS is based on applying the electrostatic principle by using electrostatic waves [31] and electrostatic forces to lift and expel particles of dust from the outside cover of solar panels and limit the gathering of dust particles on the EDS surfaces when the EDS system is stimulated [7], [168]. The EDS system is a candidate as one of the functional methods used in removing dust accumulation from transparent surfaces, not only PV modules [32]. Initially, EDS applications were designed for space missions only; however, when this method was used on the PV module surface, it showed an effective power for cleaning dust particles from the solar panel for solar power generation [16], [18], [19], [20], [23], [32]. The installation of the EDS system over the top transparent surfaces of photovoltaic solar panels has an efficient function in cleaning the solar panels from dust accumulation [3]. Integrating the EDS system with PV solar panels placed in desert regions increases the produced energy via daily cleaning of solar plants. This integration leads to a decrease in the utilization of water. It reduces the costs of using mechanical methods to clean PV panels from dust particles deposited on solar cell boards [3], [7]. In this chapter, we will delve into all the details of the EDS system as follows:

### **2.5.1. Items of the EDS technique**

The EDS system consists of an insulating substrate, conductive electrodes, dielectric covering materials, and an AC power supply. The set of conducting electrodes that are separated from one another by an insulating material is printed or deposited on the insulating substrate and embedded in a transparent dielectric material, then connected to an alternating high-voltage power supply [169], [170], [171].

### **2.5.1.1. Insulating Substrate**

The substrate material could be any insulating material. Still, in the EDS application, the substrate must be transparent for increasing sunlight harvesting by solar cells. The insulating substrate is a flat plate with high resistivity and high transparency. These transparent materials for the insulating substrate can be soda-lime glass, Poly (methyl methacrylate) (PMMA) which is called acrylic or acrylic glass, polyethylene terephthalate (PET), borosilicate glass, and insulating printed circuit board substrate (PCB). PCB boards are used in labs for more investigation of EDS applications [3], [20], [32], [172].

### **2.5.1.2. Conductive Electrodes**

The conductive electrodes (CE) are a series of parallel electrodes that are insulated and attached to a high alternating current (AC) power supply. These electrodes are printed or deposited on the insulating substrate by several methods, such as photolithography, ink-jet plotting, or screen-printing. The conductive electrodes are designed into different patterns, such as parallel spiral circular patterns, parallel spiral square patterns, parallel triangular patterns, and parallel rectangular patterns, which are the most manageable. The electrode material on the EDS system could be any material with high conductivity, low resistivity, and high transparency, which is needed for EDS applications in solar power generation. In past works, the researchers used different materials in the investigations of the EDS system; some of them are transparent, and some of these conductive electrodes are not transparent. The electrode materials that are used in the EDS system, such as Silver (Ag), Copper (Cu), Silver nanowire (AgNW), Chrome (Cr), Carbon nanotube ink or graphene ink, fluorine-doped tin oxide (FTO), indium tin oxide (ITO), aluminum-doped zinc oxide (AZO), and fluorine-doped zinc oxide (ZnO: F) [17], [20], [22], [30], [32], [170], [173], [174], [175].

The design, thickness, and width of the conductive electrodes in the EDS system and the interspacing between these electrodes are highlighted in table 3.1.

**Table 2.1.** A summary of the major attributes of the EDS system's electrodes

| References             | Width (mm)         | Spacing (mm)     | Design      | Height (mm)   |
|------------------------|--------------------|------------------|-------------|---------------|
| Sims et al. [176]      | 0.8                | 1.5              | Parallel    | 0.8           |
| Calle et al. [164]     | 0.3-0.4            | 0.48-0.67        | Cylindrical | --            |
| Sharma et al. [32]     | 0.127, 0.005, 0.01 | 0.508, 0.05, 0.1 | Parallel    | --            |
| Qixia et al. [177]     | 0.2                | 0.4              | Rectangular | 0.000032      |
| Mazumder et al. [19]   | 0.05-0.1           | 0.7-1            | Rectangular | 0.05          |
| Horenstein et al. [17] | 0.1                | 0.3-1.5          | Rectangular | --            |
| Mazumder et al. [4]    | 0.05-0.1           | 0.5-0.8          | Rectangular | --            |
| Sayyah et al. [30]     | 0-0.2              | 0-0.1            | Strip       | 0.005         |
| Mazumder et al. [94]   | 0.1, 0.0425, 0.08  | 0.5, 0.7         | Rectangular | 0.005, 0.0035 |
| Guo et al. [27]        | 0.3                | 7                | Rectangular | 0.005-0.01    |
| Kawamoto et al. [25]   | 1                  | 5                | Spiral      | --            |

### 2.5.1.3. Dielectric Cover

The dielectric cover is a very transparent thin layer covering the electrodes and substrate [3], [31]. It has excellent transparency, outside durability, and scratch impedance [19]. It protects the other components of the EDS system from coarse dust and water corrosion and stops the conductive particles in the atmosphere from reaching between the conductive electrodes [3]. Researchers advise using a dielectric cover to prevent electrical discharge and spark at high applied voltages. There are different types of dielectric coating materials, such as Polyurethane (PU) [32], polyester-urethane, Ethylene Tetrafluoroethylene (ETFE) [178], Urethane [3], Mylar 3M optically clear adhesive (OCA) [174], Borosilicate Glass,

acrylic glass, Polyethylene Terephthalate (PET), thin-film layer Neoprene [30], sticky scotch tape, smartphone and smartwatch screen protector [20]. The dielectric cover is attached to the EDS system by adhesive it over the electrodes/substrate or is applied as a coating on the conductive electrodes [18], [20], [179].

#### **2.5.1.4. Power Supply**

Multi A.C., a high-voltage generator, is connected to a series of conductive parallel electrodes in the EDS system to charge the deposited dust particles [168]. The EDS system's energy needs are dependent on the EDS system's operation, the dust-charging procedure, and the type of power supply utilized to activate the EDS [18], [25], [180]. A very modest amount of power, roughly  $10^{-5}$  W/mm<sup>2</sup> for each panel during activation time, is needed to activate the EDS electrodes and charge the deposited dust particles on the EDS surface. Additionally, no ongoing activation is necessary. It may only take a few minutes each day. The power needed by the EDS is a very small part of the overall power generated by the solar panel, which is significant during peak solar insolation hours.

#### **2.5.2. The function of the EDS system**

Electrostatic charging plays a significant function in the cleaning rate of the EDS system [7], [26]. As mentioned, the EDS system is a group of transparent conductive electrodes insulated from each other, deposited on the transparent insulating substrate, then coated by a transparent dielectric material that can protect the conductive electrodes from deterioration of the environment [14]. The EDS system's electrodes are turned on by connecting them to an AC high-voltage source. On the dielectric cover's surface, the activated electrodes create an electric field that changes with time and space. These conductive electrodes are surrounded by a non-uniform electric field [168]. Any particles

present on the surface were subject to electrostatic forces like Coulomb and dielectrophoretic forces due to the fluctuating electric field. These forces act on the dust particles close to the patterns of the electrodes on the EDS system [20], [25]. The electrostatic force is in charge of the expel of the dust particles after the dust particles become charged. Electrostatic force's effect powerfully depends on the dust particles' charge, if charged or uncharged particles [168].

### **2.5.3. Charging on the EDS system**

The dust particle charge by several electro-dynamic techniques contributes to setting and removing dust particles from the surfaces by the EDS system. These mechanisms are (1) contact charging, (2) Injection charging; (3) induction charging; (4) triboelectric charging.

#### **2.5.3.1. Contact Charging**

Uncharged (neutral) particles have an equal number of negative and positive charges on the surface. Uncharged particles can be charged before the EDS system activation by contacting these particles with each other and with the outer layer (dielectric cover) [164], [168]. The dielectric surface acts as a medium to charge the neutral particles, making the cover surface active for both conducting and neutral dust particles [26]. Mechanically, the contact between particles and the dielectric surface creates an exchange of charges between the particles and dielectric surface atoms, which raises the charge density of the particles [173], [181]. The connection of two materials leads to the transport of the charges between the surfaces of that materials. Following the transportation is separated, non-zero charges remain on each material, called the contact charging process [182], [183]. Since dust particles are dropped on the dielectric layer coated in the EDS system, contact charges are replaced on the dielectric surface. The charge exchange occurs between the contact

surfaces of atoms of the EDS dielectric surface and deposited dust particles. This transformation of charges depends on the contact atoms' surface states, where the pollution environment around the EDS system changes the atoms' surfaces in the dielectric surface. Because of that contamination, the contact charging mechanism takes the particles into the bipolar charging process. The exchange of charges between contact atoms makes one of the atoms positive and negatively charged [178],[179]. Often, the dielectric cover atoms have a great electro-negativity compared to the atoms of dust particles. In that case, the contact charging method makes the EDS system's top surface negatively charged and dust atoms positively charged. In other words, the atoms will be donor atoms (dust particle atoms) and acceptor atoms (dielectric surface atoms) [178]. The continuation of the deposition process for dust particles over the EDS dielectric surface depends on the acceptor atoms' saturation charge level. When the dielectric cover atoms reach a saturation level, no exchange charges will continue between the EDS surfaces and dust particles. In that case, the EDS power supply works to provide the EDS surface with positive and negative charges, to keep the charge transfer. This process called the charge injection process. The dielectric EDS surface must have non-zero conductivity to allow the driving electric field to transport charges between the dielectric cover and power supply to keep the exchange charges proceeding between the EDS surface atoms and dust particle atoms [178].

#### **2.5.3.2. Injection Charging**

The activation of the EDS system creates a local high electric field around the conductive electrodes. The tremendous electric field makes space charges surrounding the electrodes [184], [185], [186]; these space charges move into the EDS dielectric surface under the

impact of a high electric field, in which the space charges affect the distribution of charges on the dielectric surface. The injection charging plays a crucial role in charging dust particles dropped on the dielectric surface. The exchange of charges inside EDS components enhances the charging process of dust particles. The contact and injection charging functions are essential for charging and removing dust particles from the dielectric surface [178], [179].

### **2.5.3.3. Induction Charging**

Dust particles contain a concentration of metal oxides such as iron oxide, or soots, which means that dust particles have non-zero conductivity [178]. When uncharged dust particles drop on the EDS system's dielectric surface, they acquire electrostatic charges by the polarization charge process [21], [169]. Polarization or induction process is that method gaining electrostatic charges to the dust particles by the induction charging. The charge induction occurs over the EDS model's dielectric surface, which leads to increased surface charge density of dust particles, accordingly removing dust particles from the EDS surface [21], [169], [178].

Dust particles are assumed in EDS applications as dielectric materials with an amount of conductivity, like the dielectric surface covering the EDS electrodes. The dielectric surface has a significant amount of conductivity to avoid increasing charges on the dielectric surface and draining transported charges from the EDS dielectric surface. The surface conductivity of the dielectric surface is a crucial factor in the removal process of dust particles. Large surface conductivity of the dielectric surface will hauberk the electric field. Low conductivity will result in a high accumulation of dust charges on the dielectric surface. However, it will increase the dust particle adhesion force to the surface and decrease the particle's tribo-charging process on the EDS dielectric surface [26].

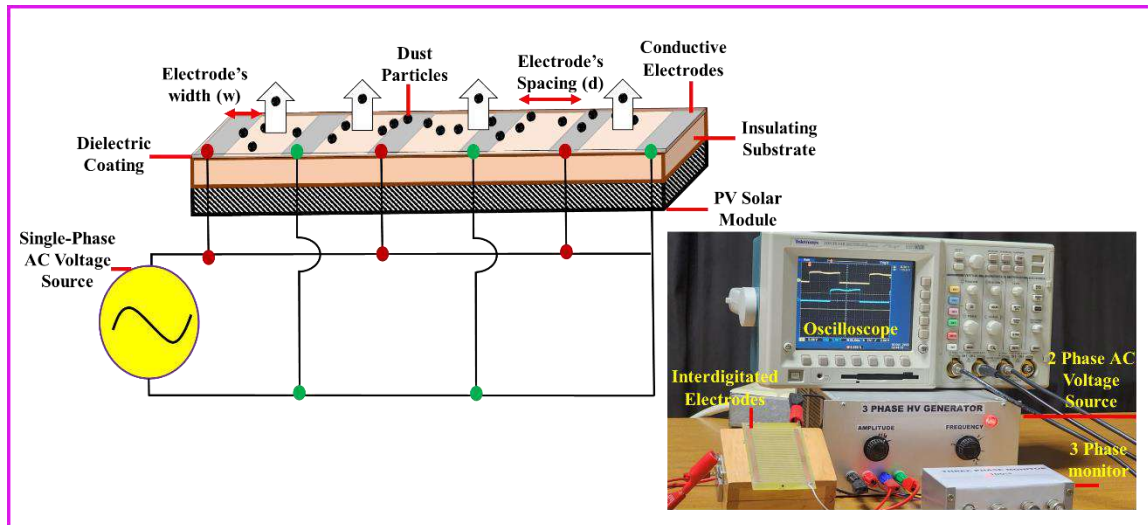
#### **2.5.3.4. Triboelectric Charging**

The winds cause triboelectric charging between dust particles when lifting off the dust particles from the surface in dry environments [26]. Mechanically, the collisions between the dust particles also cause triboelectric charging into the dust particles, leading to an increase in the surface charge density of dust particles [25], [31]. Uncharged dust particles resting on the dielectric surface of the EDS system are charged by the triboelectrification process when an alternating electric field is applied to the conductive electrodes. This electrode system will acquire a translational dielectrophoretic force that will create a rolling and frictional back-forth motion of dust particles on the EDS system's dielectric surface [26], [178]. Any dust particle movement on the dielectric surface leads to triboelectrification [21]. The triboelectric charging process starts in the EDS operation's initial moments, where dust particles are uncharged, or their charges are insignificant [30], [187].

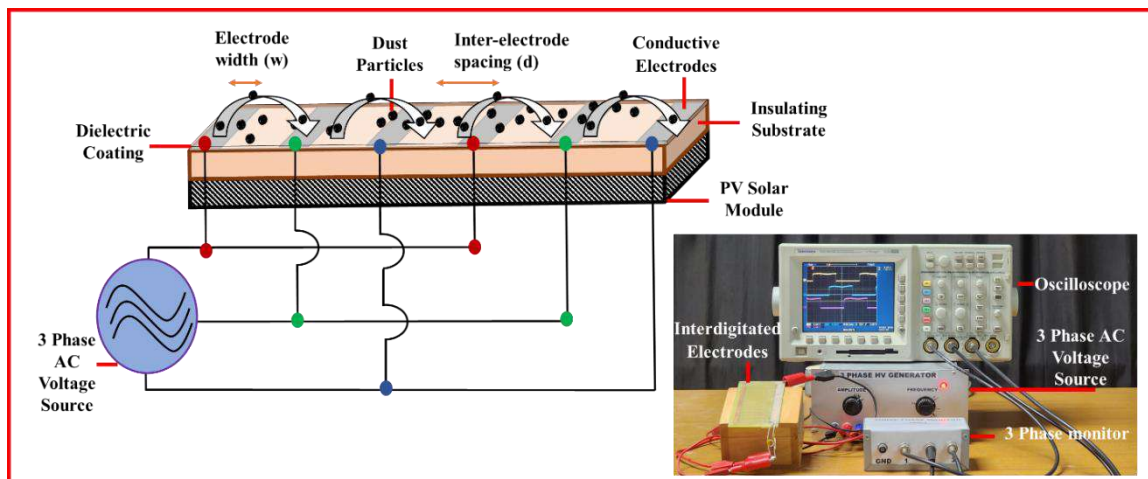
In summary, when the dielectric dust particles conducting with the dielectric surface will roll and oscillate on the surface, even with a small amplitude of motion, because of coulomb or dielectrophoretic forces. These particles are gaining triboelectric charges due to the friction factors with the dielectric surface. The magnitude of acquired charges in dust particles by triboelectric charging relies on the differences between the contacting dielectric surface's work functions of dust particles surface and dielectric surface. Finally, the dust particle's level of charge expands the amplitude of motion of dust particles until they reach enough level for removal from the dielectric surface of the EDS application. The removal of charged dust particles from the EDS system keeps the dielectric surface charged with opposite polarity, which needs to drain its charges (The injection-charging) to continue the exchange charges process between contacting surfaces [26].

#### **2.5.4. Waves on the EDS system**

To generate standing and traveling waves, a multi A.C. high voltage generator is connected to a series of conductive parallel electrodes in the EDS system. Standing waves generate by single phase-voltage, whereas traveling waves generate by three phase-voltage. As the voltage, frequency, and spacing distance were applied, standing waves moved in a vertical direction relative to an electric field, whereas traveling waves moved in a horizontal direction.[23]. The dust particles on the EDS surfaces are only lifted into the air by the standing wave; the traveling wave, on the other hand, transfers the dust particles along with it as it moves along the electric field. In the EDS system, standing waves cause dust particles subject to the Coulombic force to levitate in three different ways: rolling along with the dielectric plate, oscillating up and down suspended above the electrodes, and levitating in between the electrodes [24]. At a certain acceleration, the traveling waves can levitate and repel dust particles from the EDS surfaces. The dimension and density of dust particles significantly impact their acceleration [23]. The standing waves can limit the complexities of designing the conductive electrode patterns, especially for the third electrode, AC voltage source, and the number of interconnections created by traveling waves [18], [31], [168], [180], [188]. Figure. 2.17 and 2.18 show the effect of applied standing waves and traveling waves on the transportation of dust particles from surfaces on the EDS system, respectively.



**Figure 2.17.** A schematic diagram of the locally designed and fabricated single-phase EDS system and the inset shows the photograph of the EDS.



**Figure 2.18.** A schematic diagram of the locally designed and fabricated three-phase EDS system, and the inset shows the photograph of the EDS

### 2.5.5. Factors affected EDS performance

Several research teams have analyzed the evolution of the EDS system from a theoretical, numerical, simulational, and experimental perspective. Marshall's team at Vermont University, Mazumder's at Boston University, and most recently, Kawamoto's at Waseda have conducted most of the theoretical and experimental research into the EDS system.

These teams looked into various topics related to cleaning solar modules and surfaces on the moon, Mars, and other places that have deposited dust. They investigated the effect of the EDS components, voltage, frequency, and others on the EDS cleaning operation in PV modules. They found different parameters adversely affect the PV modules' cleaning performance of dust particles.

#### **2.5.5.1. Components of the EDS system**

To reduce the detrimental impacts of dust on lunar solar panels, NASA has suggested electrostatic methods. The surface of the PV module has been covered with an electrodynamic screen. Transparent plastic sheets, such as UV-resistant polyethylene terephthalate (PET), and conducting electrodes in a parallel or spiral pattern composed of transparent indium tin oxide are used to create the screen. These electrodes are implanted beneath a thin transparent layer. The electrodes are connected to a single- or multiple-phase AC power source, which creates an electromagnetic field on the surface that repels dust particles. The characteristics of the EDS components, such as the width of printed electrodes, the spacing between electrodes, the geometry of electrodes, and the thickness of the dielectric layer that shielded the EDS system, determine how well dust particles are repelled [16], [32], [142], [177]. After the dust particles levitate from the surfaces, Sayyah et al. [189] found that the influence of tilt angle at 20° and 30° adds to the moving of the dust particles in the lower section. At a tilt angle of 20°, the EDS was able to remove 40% of small dust particles (< 5 µm in size). They extended the interelectrode separation by 600 m and discovered that 40% of the leftover dust particles (size: 4–7 µm) still adhered to the glass. The findings demonstrated that the electric field intensity decreased as electrode separation increased, resulting in a lesser Coulomb force and, ultimately, a lower EDS dust

removal efficiency. They came to the conclusion that the interelectrode spacing has little effect because of the significant tilting angle of the solar panel ( $> 40^\circ$ ).

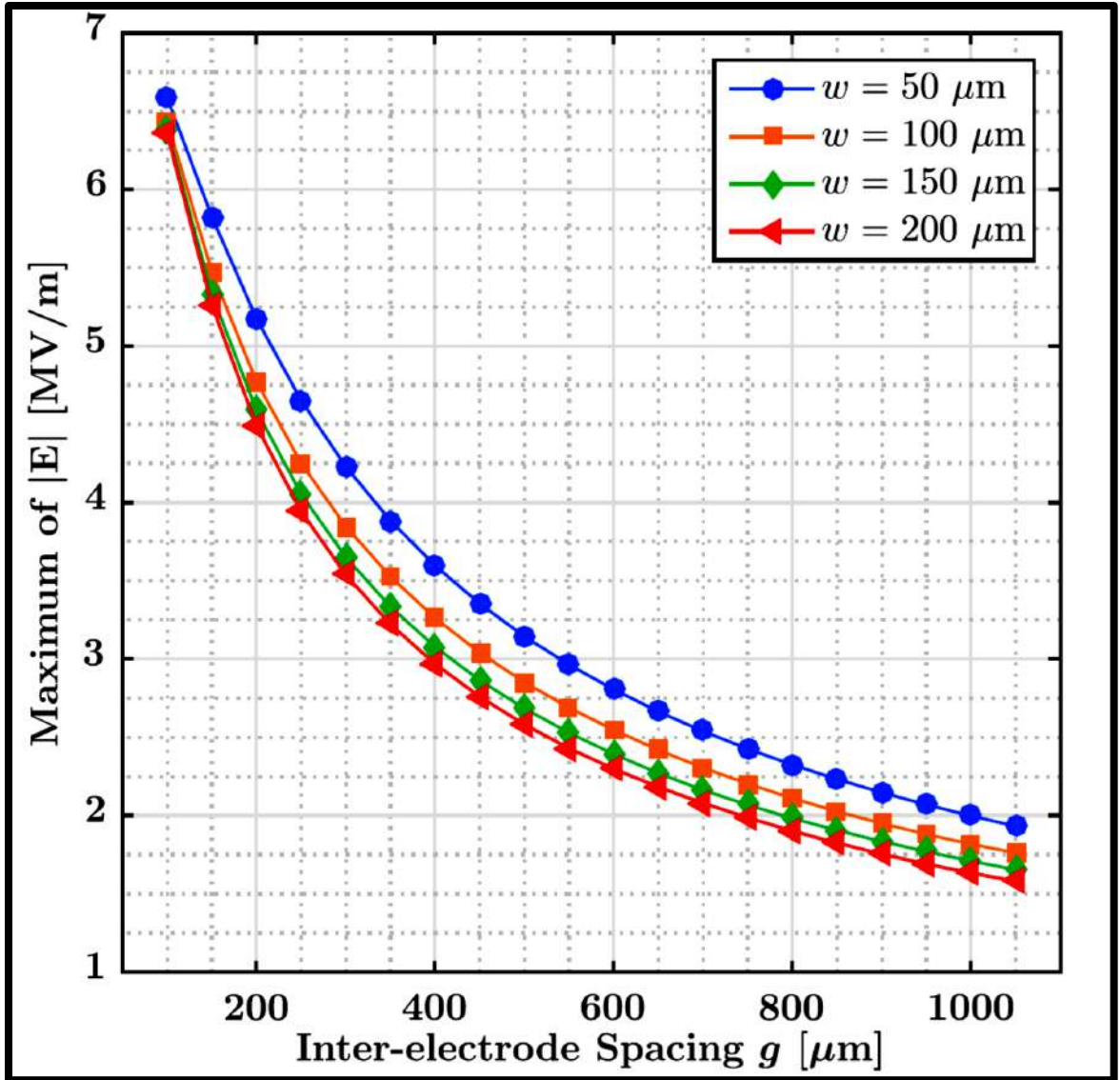
Saeidpour et al. [190] studied the intensity of the electric field in dielectric layers in the EDS system with different geometries. They used typical electrodes like rectangular or cylindrical electrodes, and spring rings electrodes in helix antennas. They observed that the change in the geometry of electrodes led to an increase in the electric field on the dielectric surfaces, thus increasing the EDS performance. According to the simulation results, the spring rings electrodes in helix antennas increased the electric field intensity by up to 50% compared with the typical electrodes.

Size, the thickness of the dielectric cover, dust loading amount, dust deposition methods, and particle size distribution were all factors that Bing Guo et al. [20] considered when analyzing the EDS's efficiency for use with solar power. They found that larger dust accumulations and thinner dielectric covers led to more effective dust removal [27]. They found that at a dust loading level of  $100 \text{ g/m}^2$  and a voltage level of 6 kVp-p, 90% efficiency in dust removal could be obtained in just 10 seconds after energization.

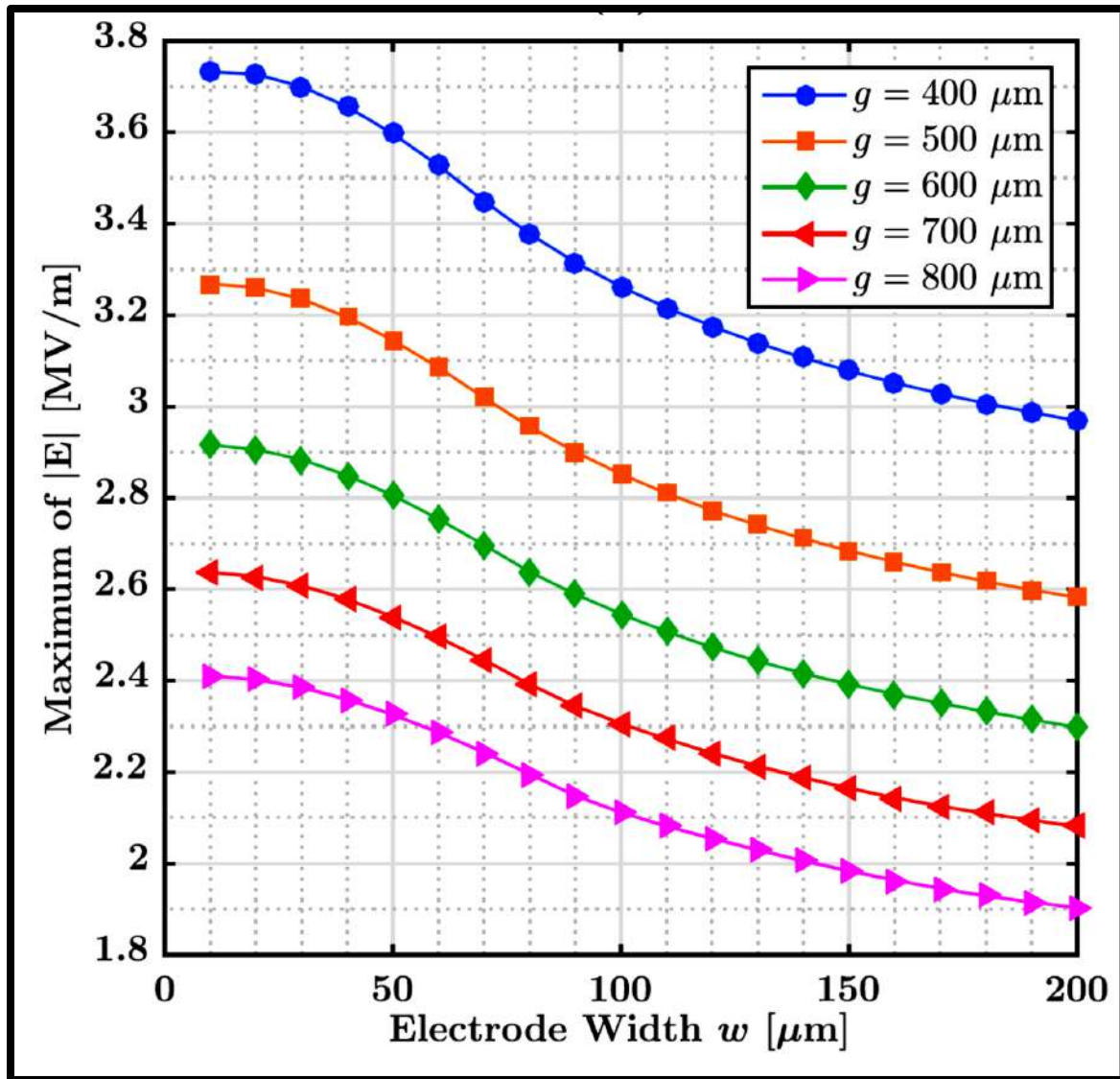
Single-phase voltage was used to power wire electrodes implanted in the cover glass plate of a solar panel in a recent work by Kawamoto et al. [18]. To prevent insulation failure, the electrodes were installed on a glass substrate 3 mm thick and then coated with a glass plate 0.1 mm thick. They found that the EDS's efficiency varied depending on the power source. They discovered that unlike the multi-phase power supply, which rejected dust particles in a certain direction (lateral mode), the single-phase power supply repelled dust particles in a random pattern. When the surface is tilted at an appropriate angle, the gravitational force

aids in the removal of dust particles, and the lateral mode of transport is more efficient than the random mode.

The solar panels have been upgraded with new transparent dust-shield technology. The electric field distribution in an EDS has been described in detail using analytical expressions presented by Sayyah et al. [30]. A transparent dielectric layer was used to cover electrodes arranged on a glass substrate. The EDS electrodes are powered by a three-phase power supply; they generate an electric field at the higher surface, where dust particles are located. This electric field produces electric power and Coulomb force which enters the dust particles. The particles accumulated along the PV cell are displaced by the motion of the transverse coulomb forces, and when they reach the edge of the panel, they are easily dismantled from the EDS surface. This team studied the effect of electrode width and inter-spacing between the printed electrodes on the EDS performance. They found as the electrode width or inter-spacing between the printed electrodes increases, the maximum electric field decreases, as seen in figure 2.19 & figure 2.20. which that effect the EDS performance. Sayyah and his team are revealed in figures 2.21 & 2.22. the effect of dielectric thickness and dielectric constant on the EDS performance. They showed that as the dielectric thickness increases, the maximum electric field decreases, but the maximum electric field increases as the dielectric constant increases (physically, the electrical field decreases as the dielectric constant increases). The EDS system performance relies on the value of the electric field, which is affected by up mentioned factors and other factors such as applied voltage and applied frequency.



**Figure 2.19.** A fundamental spatial period's effects of inter-electrode spacing ( $g$ ) on the maximal electric field norm (measured in MV/m) on the EDS surface [30].



**Figure 2.20.** Maximum electric field norm (in volts per meter) on the EDS surface as a function of electrode width ( $w$ ) over one spatial period [30].

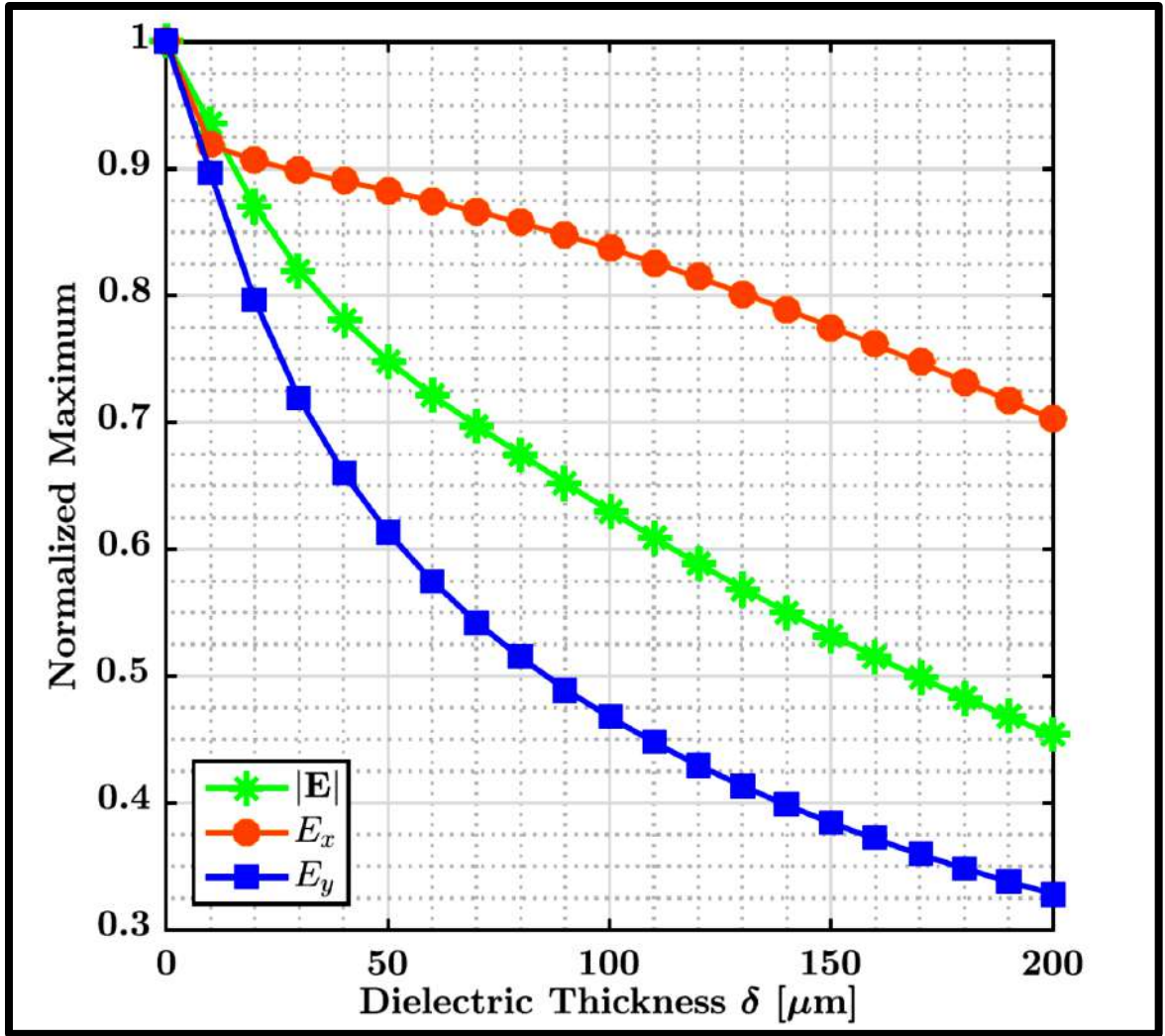
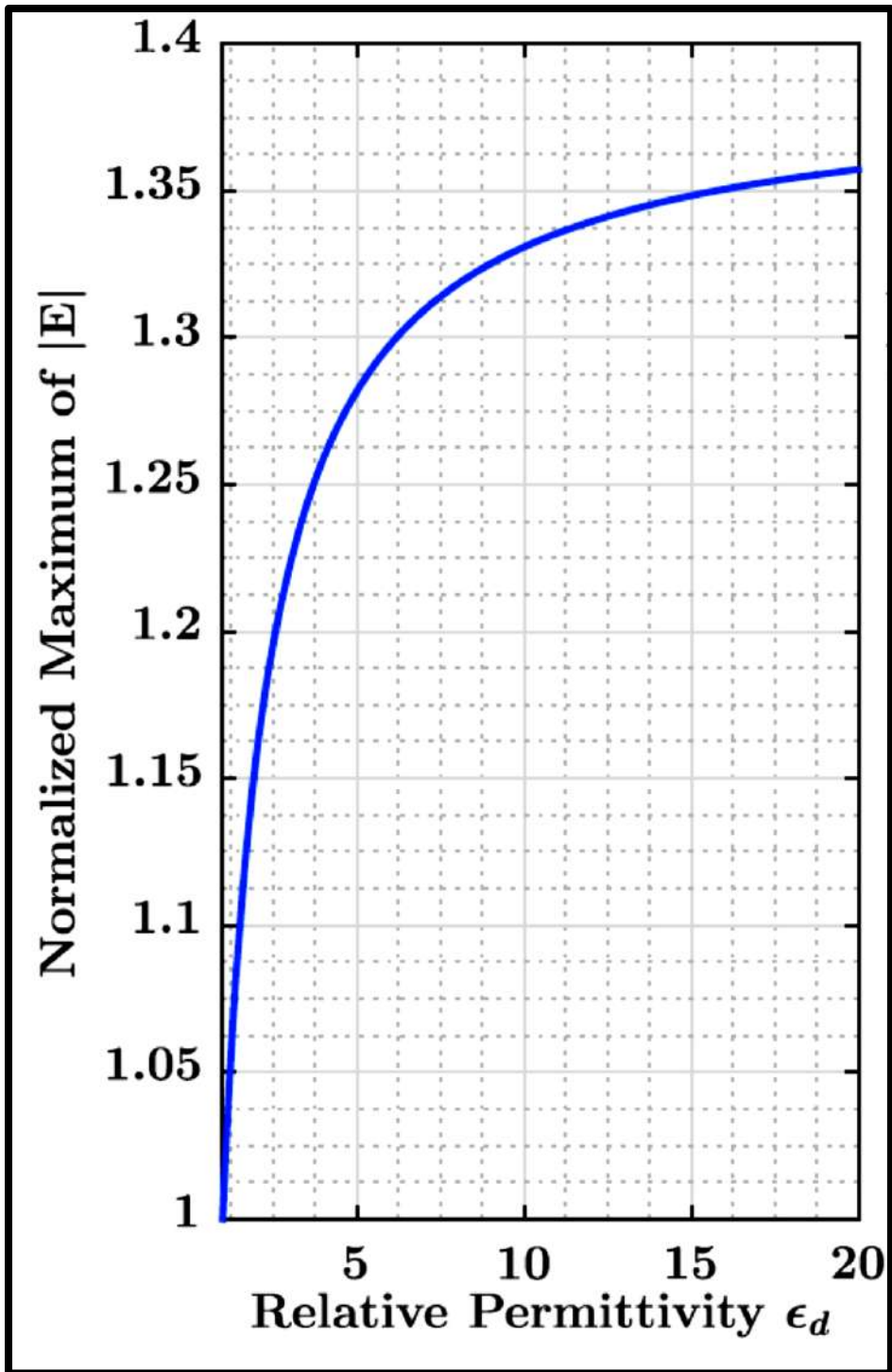


Figure 2.21. Influence of dielectric sheet thickness on electric field components [30].



**Figure 2.22.** Impact of relative permittivity on the maximum normalized electric field [30].

#### **2.5.5.2. Applied voltage and frequency on the EDS system**

The EDS system relies on transforming inert dust into active dust and generates electricity on a screen that charges dust particles and makes it easier for them to be removed by moving them over the edge of the plate surface [26]. The EDS system's capacity to clear dust is sensitive to variations in the applied voltage's amplitude, pulse (wave form), and frequency. Higher voltages, triangle signals, and pulsed signals all improve the effectiveness of dust removal. Low frequencies increase the shield surface's velocity, which increases removal effectiveness [176], [191].

The EDS system was built by Sims et al. [176] and comprised several parallel electrodes engraved on a printed circuit board. The EDS electrodes were joined to an AC power supply terminal. They applied AC voltage between 0-10 kV and a variable frequency of - 300 Hz. They used signal waveforms like sinusoidal, square, triangular, and pulsed forms. They utilized an electrode thickness of 0.762 mm with interspacing between the electrodes of 1.524 mm. The findings indicated that the applied AC voltage was the most important variable, and it was found that the removal efficiency and the applied voltage exhibited a linear connection. They demonstrated that the frequency determined how quickly the surface could be cleaned and that the pulsed waveform was far more effective at cleaning surfaces than the other waveforms.

The EDS system with traveling waves was created by Mazumder et al. [26], [178] to address the issue of dust collection on solar panels used on Earth [178] as well as on Mars missions [32], [192]. On printed circuit boards or glass substrates, they imprinted electrodes with a width of 50 to 100  $\mu\text{m}$ . Transparent polymers like polyurethane (PU) or ethylene tetrafluoroethylene (ETFE) were used to coat the electrodes. In order to generate

electrical forces that would outweigh gravity and viscous forces that would lift the dust particles from the surface, they applied an AC voltage of between 0.7 and 1.0 kVp-p. They discovered that by improving the frequency, voltage, and signal form, it was possible to obtain almost 90% of the cleaning efficiency of the EDS system. In order to create traveling waves with a rectangular form for the calculations of the electric field, Liu et al. [193] used a 4-phase AC voltage. On the EDS parts, 1.6 kV was applied on a set of conductive electrodes with an inter-spacing of 2.0 mm and a width of 1.0 mm. All the dust particle paths were plotted. They discovered that as the frequency decreased, the fraction of non-transported particles increased, and the forward-transported dust particles' surface charge was larger.

To prevent dust from settling on the PV, Biris et al. [191] employed the electric dynamic screen. The study found that boosting the voltage in the dust-removal system positively affected the total amount of dust collected.

According to the research of Bock et al. [169], voltage is the most important factor to consider when employing this cleaning strategy. Even at low voltage, the screen utilized in the study effectively removed a significant fraction of the built-up dust. Scientists found a direct correlation between increasing voltage and clearing away dust. The higher the voltage, the more dust is blown off the board's surface.

Atten et al. [194] looked into how well the EDS technology cleared solar panels of Martian dust. To clean the air of dust, they employed a single-phase power source to create standing waves. On insulating epoxy resin, they placed electrodes with widths of 0.25 to 0.7 mm and distances of 0.75 to 2.5 mm. They used a range of 20 Hz to 500 Hz in their applications. Everything was stored in a low-pressure CO<sub>2</sub>-filled chamber to simulate the Martian

environment. At 1 bar (terrestrial pressure), the required voltage for Martian simulant dust was roughly 4.8 kV, but at one mbar, the required voltage dropped to about 400 V. The researchers discussed in depth how the presence of fine dust particles necessitated a higher minimum voltage and how the EDS system improved with a higher voltage.

Calle et al. [195] explored the relationship between amplitude and frequency. Their investigations on three distinct EDS configurations (0.3, 0.5, and 0.6 mm electrode width with a matching electrode spacing of 1, 1.5, and 2 mm) indicated that raising the EDS amplitude needs a linear increase in frequency for a particular EDS configuration.

### **2.5.5.3. Dust particle trajectories**

The mechanism for dust removal in a standing-wave electric field was investigated by Sun et al. [177]. In their research, they used both numerical and experimental methods to examine the EDS system. As an early step in resolving Laplace's equation, they reduced the complexity of the electrodynamic field to Fourier series expansions, approximating the work of Masuda et al. [196]. The distribution of electrostatic fields over the EDS was then mapped using a MATLAB tool. They created a Lagrangian-based DEM model to trace the particles' motions; this model considers the governing forces acting on each particle. They found pockets of the EDS geometry that act as traps, preventing particles from being lifted. The trap regions formed because the forces (Coulomb force, Van der Waals force, and Dielectrophoretic force) around the borders and centerline of the electrodes are canceled out, reducing the effectiveness of the electric field and hence the efficiency of the EDS system.

Particle trajectories were examined by Horenstein et al. [165] using a simulation tool and subjected to various stresses. By inspecting the 2-D paths taken by the chosen particles,

they discovered the presence of EDS dead zones. As a result, these dead zones collect dust and reduce the efficiency of the EDS system.

#### **2.5.5.4. Diameters of dust particles on the EDS system**

A recent study on the movement of dust particles by standing waves was reported by Liu et al. [24]. They proved that smaller particles are trickier to eject, supporting the idea that countering surface forces is more difficult than fighting gravity.

Sayyah et al. [189] used transparent borosilicate glass and optically clear adhesive to construct the electrodynamic screen, which was then sequentially affixed to the electrode (electrode width: 80 m, inter electrode-spacing: 400-800 m). Their trials demonstrate that the EDS can clean the glass of particles with diameters of 50  $\mu\text{m}$  to 100  $\mu\text{m}$ . Results indicated that larger particles were more readily removed than smaller ones, indicating that dust diameter impacted the efficiency of the EDS system.

The impact of particle size distribution and particle charge on the effectiveness of the EDS dust removal process was researched by Johnson et al. [197]. They employed a 2-phase AC voltage and straight parallel electrodes with an electrode spacing of 1.27 mm for their EDS setup. They used a 5 Hz frequency and 6 kV amplitude to produce square waves. The EDS system was turned on for 15 seconds at a low vacuum (analogous to the Martian environment). On the surface, they dispersed a JSC Mars-1 dust simulant with various particle size distributions. According to their analyses, the average dust removal increased from 47.1 percent to 77.3 percent for uncharged particles and from 70.2 percent to 85.9 percent for tribo-charged particles, with a modest rise in dust particle width from 5.2  $\mu\text{m}$  to 5.8  $\mu\text{m}$ .

### **2.5.6. Influence of the EDS system on solar panel**

Various research looked into how the EDS system affected the PV module's power usage and efficiency. They demonstrated that the EDS system had no negative effects on the PV module's performance. The amount of electricity required to operate the electrodynamic screen is one issue that needs to be addressed [15].

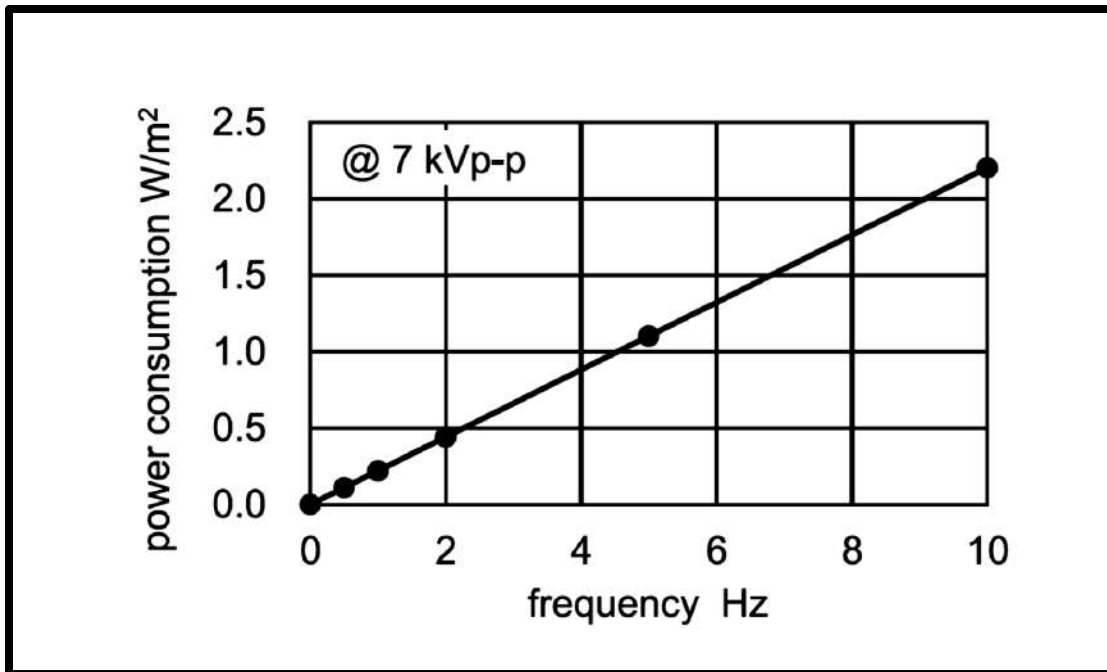
#### **2.5.6.1. Power consumption by the EDS system**

During the activation period, the EDS system only needs roughly  $10^{-5}$  W/mm<sup>2</sup> of electricity from every panel to charge the dust particles that have settled on the EDS surface and activate the EDS wires. Not only that, but it can function without being constantly activated. Daily sessions of only a few minutes may be all that is needed. During peak sun insolation, a typical solar panel generates about  $8 \times 10^{-4}$  W/mm<sup>2</sup> of power; the energy consumed by the EDS is a tiny percentage of this total [14]. The energy needed to remove the dust layer from the EDS system, according to experimental investigations, is less than 1 Wh/m<sup>2</sup> per removing cycle and less than 0.1 percent of the energy generated by a photovoltaic array with a surface area of 1.0 m<sup>2</sup>[13].

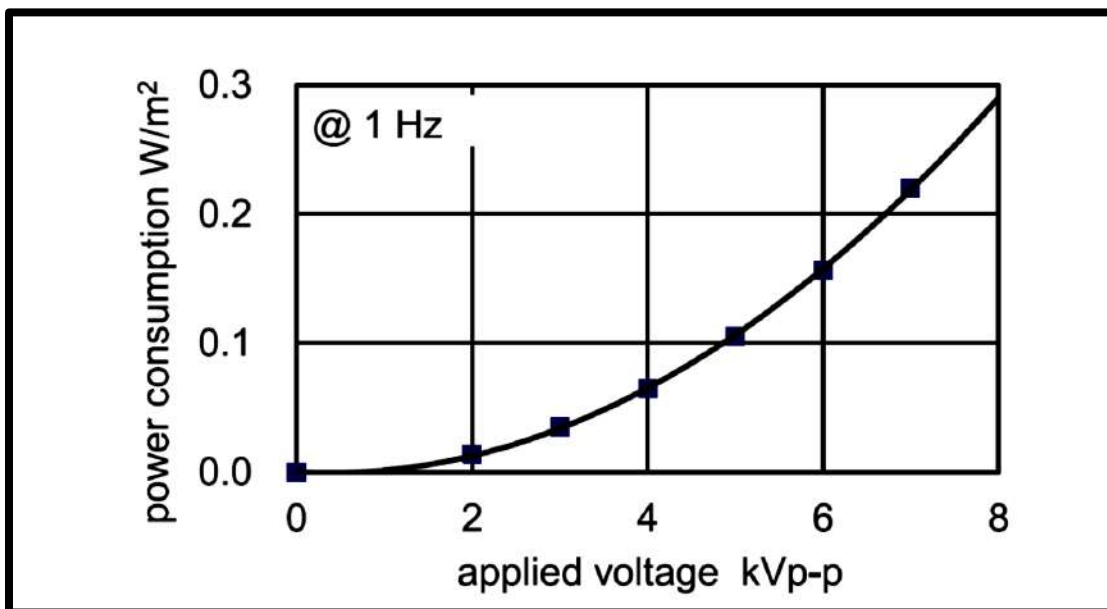
EDS power consumption was quantified by Sharma et al. [32]. They employed ITO electrodes implanted in a polyethylene terephthalate (PET) dielectric surface, with a width and a spacing of 0.127 nm & 0.508 nm, respectively. They subjected the EDS system to varying surface dust loading in a chamber replicating the Martian environment. They deposited 6.4 g/m<sup>2</sup> of dust continually for 35 minutes and deposited 3.7 g/m<sup>2</sup> depositing every 15 minutes for a total of 90 minutes. They were found to shield a 59 cm<sup>2</sup> area of the panel, and the average power consumed was  $1.02\text{--}2.87 \times 10^{-3}$  W. However, when the frequency rose, electricity consumed increased exponentially. The total amount of

electricity required was calculated to be  $10 \text{ W/m}^2$ , which includes  $5 \text{ W/m}^2$  for the source work and  $5 \text{ W/m}^2$  for dust removal[21], [169], [192].

Kawamoto et al. [18], [25], [180], [181], [198], [199] (2011-2019) studied the electric power consumption of an EDS system with different operational conditions. They used different operational voltages and frequencies such as [(800 V, 10 Hz), (4 kV, 10 Hz), (7 kV, 10 Hz), (2 kV, 10 Hz), (7 kV, 1 Hz), and (8 kV, 1 Hz)]. They found under these operational voltages and frequencies, the removing EDS system consuming power which is about [ 0.06 Wh, 7.3 mW,  $0.2 \text{ W/m}^2$ , 0.4 W, 10 W, and 11 W) respectively. Figures 3.7 and 3.8 by Kawamoto et al. [18] display the cleaning system's power usage. The cleaning plate's power consumption per unit area is shown in figures 2.23 and 2.24. If insulation failure does not happen, the power usage is proportional to the applied frequency and the applied voltage [180]. According to research conducted by Kawamoto et al., the number of operational cycles and operating period of an EDS system are the two most influential factors in determining the system's overall energy usage. If the system is used for 30 minutes every day, for instance, the daily energy consumption is only  $0.1 \text{ Wh/m}^2$ . When compared to the normal energy output of a solar cell, the EDS system has a very low energy requirement. In the end Kawamoto et al (2011-2019) proved that the performance of solar panels improved after applied the EDS system, where the rate of recovering up of solar panels was between 80% to more than 90%.



**Figure 2.23.** EDS system consumes power proportional to the applied frequency [18].



**Figure 2.24.** EDS system consumes power proportional to the square of the applied voltage [18].

#### **2.5.6.2. Efficiency consumption by the EDS system**

Soiling is a problem, and the EDS system shows great promise in addressing this problem. By fine-tuning the applied frequency, voltage, and signal shape and reducing the dielectric cover thickness and large dust agglomerations, the EDS system was able to increase its efficiency in removing dust [200].

The efficacy of EDS removal was found to be frequency and waveform-dependent by Sims et al. [176]. It was found that the frequency determined how quickly a surface could be cleaned and that pulsed forms were far more effective than the other waveforms in cleaning surfaces.

The three-phase electrodynamic screen model has a higher dust removal effectiveness than the single-phase model, according to Mazumder et al. [21], [26], and [178]. They investigated the effectiveness of the EDS system using a three-phase power supply to remove dust from Mars-like simulant dust particles. They discovered that the EDS efficiency was greater than 90%.

The impact of the EDS system on the PV module's efficiency was researched by Calle et al. [16]. They used four different solar panels to investigate the impact of the EDS system. They discovered that the solar panel's efficiency varied between 20 and 98 percent before and after the EDS was turned on.

Kawamoto et al. have studied lunar dust removal/mitigation since 2010. Electrostatic and magnetic cleaning systems/devices could remove 82 percent of lunar dust-off spacesuits and PV surfaces [188], [201], [202]. An electrostatic traveling wave dust cleaning system with low energy consumption was invented and enhanced to remove more than 90% of the dust from solar panels and other optical parts [31], [180], [199], [203].

The EDS approach was used by Kawamoto et al. [188] to free particles stuck in the astronaut suits' fibers. The plan was to use single-phase AC power to flash the material of the spacesuit by inserting parallel electrodes between the fibers. The spacesuit's outer layer was sewn with copper electrodes that had been tested and were covered in a thin polyester film for insulation. They added 10 mg of FJS-1 lunar dust particles to the spacesuit. The experiments were conducted between electrodes with an applied field of 1.5 MV/m and at a frequency of 10 Hz. They discovered that the highest removal effectiveness was roughly 75%. To increase cleaning effectiveness, they combined the EDS with a mechanical vibrator running at 10 V and 28 kHz. By up to 90%, the hybrid method improved cleaning effectiveness. Over the cloth surface, most of the residual particles were less than 10  $\mu\text{m}$ . It was impossible to remove particles smaller than 20 m using EDS alone (without motion). Using magnetic force delivered by a multipole magnetic roller, Kawamoto et al. [202] created a magnetic cleaning system to remove lunar dust from astronauts' spacesuits. This device had a separation rate of nearly 90%, a collection rate of just 10%, and an average washing performance of about 40%. Hybrid applications of electrodynamic and magnetic forces for the aforementioned cleaning technologies resulted in an 80% improvement in cleaning effectiveness.

Using a new set of criteria, Kawamoto et al. [203] reassessed EDS's usefulness for photovoltaic cells and lenses. They created two EDS setups, each with electrodes of ITO printed onto a glass substrate with a rectangular shape and spiral configuration. Their experiments used three different kinds of dust: FJS-1, JSC-A lunar dust simulants, and actual lunar dust brought back by the Apollo 11 lunar10 Pa mission. Their results

demonstrated that using a 4-phase AC voltage of 1000 V gives great cleaning efficiency under vacuum conditions up to 95.

Two EDS prototypes were tested by Guo et al. [204] to determine how well they collected dust in real-world conditions. Throughout two sets of tests, each set lasted four consecutive days; the EDS was stimulated once daily. EDS productivity dropped from 40 percent to 14 percent in just four days. They discovered that removal performance declines as dust atoms stay longer on the EDS face. The residue of previous cycles' dust is also typically not removed in the subsequent cycle. If the EDS is activated more frequently, more dust should be cleared from the air. At the outset of field exposure, EDS's removal efficiency depends on proximity to an electrode, although this dependence decreases as the number of EDS cycles grows.

#### **2.5.7. Advantages and disadvantages of the EDS system**

The method of moving the dust particles off any surface is crucial to the correct selection of the dust-removing technique. The surface area, material type, and functioning of the covered surface are other important considerations when determining the best dust-removing technology for use on the Moon, Mars, or Earth. Some removal technologies are better suited to smaller surfaces, while others may be more useful for larger ones. The designing of cleaning technology for settled dust particles is made more difficult when bigger surfaces must be protected using smaller ones, and vice versa. Because of these obstacles, cleaning performance is diminished, and surface blockage is raised; hence, it is crucial to choose the proper cleaning method for the covered area [120]. It is crucial to select the most efficient dust mitigation technology and optimize the chosen design based on the physical and chemical characteristics of the materials used in the shielded surface

(PV module). At the same time, other parameters are more important for selecting the suitable cleaning process for solar panels; for mechanical technology, the sensitivity of scratches and the level of fine residue dust should be considered, as the roughness properties of the surface and the work function of these surfaces are crucial for coating methods, and for electrical methods the consideration of thermal properties and surface conductivity is also critical. The cost of every removal procedure per panel unit should be assessed and considered before coming to any conclusion. Another key consideration when selecting dust-repelling technology is high-efficiency cleaning in a short period [14]. Modifications to the surface are acceptable; thus, they can be used for thermostats and other conductive opaque substrates. Due to the scarcity of optical coatings, surface modification approaches may not be the best option for maintaining solar panel edges. Since optical surfaces are typically in the sun's path, any deposited particles that are then hit by extremely powerful solar radiation will be difficult to wash off the protected surface. [120].

The key benefits of mechanical methods include low cost, the capacity to clean massive loads of suspended particles, minimal electrical power needed, and the lack of frequent bristle cleaning. It was found that the dust wiper's cleaning efficiency on dust particles never went beyond 93% in any of the tests conducted. Smaller particles with higher surface forces are predicted to result in less effective cleaning. Dust wipers shouldn't be used on surfaces when particles smaller than 5  $\mu\text{m}$  have been deposited due to the abrasion difficulties associated with this technique. When sensors are present, the mechanical levers holding brushes and wipers may block their field of view or prevent sunlight from reaching the solar cells. Therefore, mechanical methods can clean surfaces that do not easily scratch or collect dust [120].

As was previously indicated, mechanical techniques and other removal technologies are unsuitable for optical, solar panel, and PV cell surfaces since their cleaning efficiency decline with size, require a long time, a large number of personnel, a variety of materials, and a large volume of water [14]. Surfaces in photovoltaics and optics can benefit from electrodynamic techniques (EDS systems). Applying electrodynamic methods is useful for optical and PV surfaces [120]. In order to effectively address PV soiling issues, the EDS system is the best option. As a highly adaptable system, it requires few auxiliary resources for cleaning, such as an external power supply. The EDS system was initially designed to address the soiling on PV panels aboard Mars and lunar research probes [13]. The capacity of EDS technology to charge the uncharged particles as they fall on the EDS electrodes with their periodic non-uniform electric fields is the main benefit of employing EDS to remove dust particles from surfaces. This makes the EDS a great device for preventing dust buildup on non-conductive surfaces in both terrestrial and extraterrestrial environments. High vacuum testing of the EDS technology revealed excellent cleaning performance for eradicating adhered dust particles from the test surfaces [31]. With more than 90% efficiency, the EDS method is incredibly effective at returning the panel surface to its initial condition [3].

Although the EDS approach has been widely published, it does have some minor defects. The EDS system requires an AC electric field to generate a high voltage at variable frequencies in order to remove dust from the lunar, solar panel, and Martian surfaces. Atmospheric pressure and the insulator material surrounding the EDS electrodes could cause an electrical breakdown. EDS technology's economic viability on a broad surface area and cost-effectiveness must be examined because PV panels will need additional

processing and energy inputs [10], [205]. According to tests, the EDS system performs best with large dust particles larger than 20  $\mu\text{m}$  and performs less well with smaller dust particles between 0 and 5  $\mu\text{m}$ . [197]. Adding EDS as a dust barrier on top of solar panels has been shown to reduce power output by 15% by blocking some of the sun's rays via its transparent screen [32],[192]. Moreover, the fact that the EDS procedure calls for a dry ambient setting is a major drawback. Therefore, it can only be used in arid or semi-arid climates. Wet circumstances render it useless. High humidity makes it seem risky to use EDS on the PV system, and the danger of dust cementation that attaches to the screen makes things even worse [178].

As there are some critical issues in the EDS system, as with any technology, there are some solutions to overcome the drawbacks of the EDS system. The EDS system could be powered by supplied energy from the PV solar cells, and the EDS function could obey an optimal on/off method to ensure that generated power by the solar cells is adequate for energizing the EDS technology. The EDS systems require a remarkably little amount of energy for cleaning. Sharma et al. [32] and Kawamoto et al. [18] both provide average estimates of the power requirement of 10  $\text{W}/\text{m}^2$  or less [206]. The EDS does not operate continuously and may only need to operate for two minutes to clean the surface [18]. Integrating the EDS system with the hydrophobic coatings provided highly effective cleaning on wet soiling [10], [12]. This system works well in dry locations and can utilize polymer or weather-resistant glass in place of screens to boost the PV's longevity and minimize damage from ultraviolet radiation[8].

## CHAPTER 3

# THEORETICAL MODEL AND SIMULATION OF THE EDS SYSTEM

### 3.1. Introduction

We report here the development of the EDS system for the periodic cleaning of dust particles from solar panel surfaces. The EDS system consists of a clear dielectric cover surface with printed conducting electrodes linked to a multi-phase AC power source for generating electromagnetic waves, such as standing or traveling waves. The electromagnetic field generated by the electrodes on the EDS system's surface eliminates the dust particles accumulated on the solar panel surfaces and minimizes further deposition of charged and polarized dust particles. The pattern of dust deposition on the panel depends on the charge distribution of the dust particles. Dust particles' charge, polarity, and strength determine how it is distributed [207]. Electrostatic deposition forces build an uncharged dust layer that is more uniformly deposited on the panel surface and clings strongly to the surface. As each particle nears the surface, it experiences electrostatic attraction from image force and electrostatic repulsion from similarly charged particles. If the charge distribution is bipolar (charged dust particles), the dust particles will experience attraction due to both image forces and Coulombic forces between the dust particles approaching the surface and the surface due to positively and negatively charged particles on the surface [207]. The magnitude of these forces varies counterclockwise, with the square of the particle's distance

far from the PV surface. This means they are only useful at close range, where a charged particle is typically no more than a few micrometers from the surface. When a charged particle approaches the surface, the deposited layer of charged particles determines the electrostatic force of attraction or repulsion. The dust particles' movement on the EDS surfaces is influenced by electrical forces, coulomb force, magnetic force, image force, dielectrophoretic force, and non-electrical forces (mechanical forces) such as adhesion force, gravitational force, friction force, buoyant force, and particle-particle interaction force [207]. There have been a number of comparisons made between the forces exerted on charged and polarized dust particles based on various mathematical models proposed in the literature to check that the sum of repelling forces is bigger than the attracting ones in the control of exerted forces and to look into the effects of the forces' coefficients on the rate of cleaning efficiency of the EDS system. In the following sections, we discussed the affected forces on the EDS system's charged and polarized dust particles.

### **3.2. Electrical Forces**

The electrical forces are accountable for levitating the dust particles from the surface of the EDS system. These forces must be strong enough to overcome the adhesion and gravitational forces that also act upon the particles holding dust on the surface.

#### **3.2.1. Electrostatic Force**

The electrostatic force or Coulomb force ( $F_C$ ) is the primary driving force that transports dust particles outside the EDS surface and is considered the predominant one among the repelling forces on the EDS system [22], [30], [208]. The electrostatic force utilized an electric field acting on charged dust particles. The strength of the applied electric field is proportional to the applied voltage to the EDS system. Therefore, finely tuning the voltage

amplitude makes it possible to remove dust particles with a wide range of sizes with high efficiency [178], [209].

Assuming the dust particle has a spherical shape, the distance between the electrodes on the EDS system is  $d$ , and the applied voltage on the EDS system is  $V$ , the electric field is [209]

$$E = \frac{V}{d}, \left( \frac{\text{Volt}}{m} \right) \quad (3.1)$$

The electrostatic force ( $F_E$ ) that is influenced by the charged dust particle is proportional to the electrical field that is applied on a charged dust particle of charge  $q$  is equal to [209]

$$\vec{F}_E = q\vec{E} = \frac{qV}{d} \quad (3.2)$$

where  $q$  indicates the dust particle charge and  $\vec{E}$  Indicates the dust particle's localized electric field. Therefore, once the electric field for a particle with a particular charge  $q$  is known, the force  $F_E$  can be determined. [19].

The method for determining the dust particle's electric charge while it is floating in a medium under the impact of an electric field is

$$q = Ze \quad (3.3)$$

where  $Z$  indicates the charge number, and  $e$  is the electron's charge in coulombs.

In addition, if the surface charge density and radius of a charged spherical dust particle (as assumed) are  $\sigma_s$  and  $r$  respectively, then the charge of the dust particle is written as [21]

$$q = 4\pi\sigma_s r^2 \quad (3.4)$$

Where,  $\sigma_s$  is the surface charge density of charged dust particles ( $C/m^2$ ), and  $r$  is the radius of charged dust particles [21]. By substituting equations 3 & 4 in equation 2, the electrostatic force will be

$$\vec{F}_E = Ze\vec{E} = \frac{ZeV}{d} \quad (3.5)$$

$$\vec{F}_E = 4\pi r^2 \sigma_s E = \frac{4\pi \sigma_s V r^2}{d} \quad (3.6)$$

The electrostatic force must be substantially bigger than the sum of all attraction forces [19]. The experimentally observed strength of this force increases as the particle approaches the EDS system's electrodes [30]. In theory, this force is proportional to the dust particle's charge, but this quantity is typically not known [179]. When the EDS system is activated with dust particles on its interface, the dust particles acquire an electrical charge. As the electrical field distribution shifts, the charged dust particles will be driven away from the EDS system's interface. Particles' speeds as they travel down the EDS's surface are affected by the electric field's frequency and the distance between the electrodes [176], [208]. Uncharged particles will ultimately be removed from the shield by electrostatic Dielectrophoretic force. The explanation is that once the particles touch the surface of the EDS system, they will get charged due to tribo-charging. Due to triboelectric charging, the charge level can increase if the particles roll, slide, vibrate, or collide against the surface several times [176].

### 3.2.2. Dielectrophoretic Force

Though forces like electrostatic force (Coulomb force) are mainly accountable for the lifting of the particles, neutral particles (those without charges) can also be lifted off the surface [16]. Extrinsic electric dipole moment is a property of many bigger neutral particles due to the virtually equal distribution of positive and negative charges on their surfaces. Particles will feel a force if and only if the dipole moment is subjected to a spatially non-uniform electric field. The dielectrophoretic (DEP) force describes the motion of neutral particles

having interior electric dipole moments in an electric field that is not uniform [16]. The electric field around the particle is not uniform, resulting in DEP force. This force is much smaller than the Coulomb force for a highly charged particle; hence it is less likely to contribute to the particle's motion on a macroscopic scale. Particle and medium electrical characteristics, particle shape and size, and electric field frequency all play significant roles in determining the magnitude of the DEP force. [210], [211], [212].

Di-electrophoresis was initially documented as an effect appearing in the behavior of soil samples in the late nineteenth century. Herbert Pohl first used the word "di-electrophoresis" in 1951 to characterize the movement of biological particles subject to varying electric fields [213]. Micrometer-sized particles like cells and bacteria were separated from nanometer-sized particles like viruses and proteins using the dielectrophoretic force. However, in the late twentieth century, the dielectrophoretic force gained traction when used for cleaning dust particles on the PV modules. The DEP forces remove dust particles by charging the deposited particles through the triboelectrification process, particularly when the EDS system first starts up, and the particles have either no net charge or very little charge [30], [187].

A dust particle is exposed to the applied nonuniform electric field in the space above the EDS surface as it moves toward the EDS surface. In this instance, the contacts between the dust particle and the surrounding medium rearrange the electric dust charges. Maxwell-Wagner interfacial charge is the name given to this charge at the boundary between a particle and a medium [30]. The Maxwell-Wagner interfacial polarization is two dielectrics with different properties (conductivity and permittivity). The two dielectrics (dust particle and surrounding medium) have permittivity  $\epsilon_p$  for dust particle and  $\epsilon_m$  for medium and

conductivities  $\sigma_p$  and  $\sigma_m$ , for both, respectively [214]. The charge accumulation at the particle interface on both sides creates a net dipole moment throughout the particle [30]. A dipole moment is a primary electrostatic entity composed of two equal and opposite charges,  $+q$  and  $-q$  separated by a vector pitch  $\vec{r}$ . In this situation, the dipole moment is given by [178]

$$\vec{p} = q\vec{r} \quad (3.7)$$

Many particles possess fixed dipole moments; the dipole moments arise in a dielectric material, such as the dielectric layer in the EDS system: dust, dielectric cover, and the surrounding medium. All dipole moments with all particles are developing via the polarization process. The polarization process has different types, but orientational polarization is needed in our case. The particles are represented as having a permanent dipole moment and moving either with or against the electric field depending on how polarizable the dielectric layers are (dust particles, dielectric cover, and air) [210], [214]. The surface charge density at the particle's surface is caused by the differential polarizability of the dielectric layers in the EDS system. This charge induces a dipole in the particle by having opposite signs on either side of the particle in agreement with the electric field [214]. Due to the applied electric field's nonuniformity, the induced dipole experiences varying electric field strengths at its two ends, and this imbalance of forces results in particle motion [30].

The dipole suffers a net force as a result of the non-uniform electric field,  $E$ . Because the field  $\vec{E}$  at the dipole's two poles are not equal, resulting in a different Coulomb force. The force can be expressed as the total of the forces on the particle's two sides:

$$\vec{F} = q\vec{E}(x + \vec{r}) - q\vec{E}(x) \quad (3.8)$$

where,  $\vec{x}$  can be assumed to be -q's position vector without losing generality.

We can simplify this equation if  $|\vec{r}|$  is significantly less than  $|x|$  by utilizing a Taylor Series to extend the electric field about  $x$ , to give

$$E(x + \vec{r}) = E(x) + \vec{r} \cdot \nabla E(x) + \dots \quad (3.9)$$

where all phrases with a rank of  $\vec{r}^2$ , or above have been disregarded.

The dipole moment is given by  $p = q\vec{r}$ , then by substituting Eq. 9 into Eq. 8 gives

$$\vec{F} = \vec{p} \cdot \nabla \vec{E} \quad (3.10)$$

Equation 10 shows that this force only has a nonzero net value in a nonuniform electric field [214]. Di-electrophoresis (DEP) and dielectrophoretic force are terms used to describe the movement of particles in this non-uniform field [214].

The DEP  $\vec{F}_{DEP}$  is equal to the dot product of polarization ( $\vec{P}$ ) vector and gradient of applied non-uniform electric field ( $\vec{E}$ ). The relation of  $\vec{F}_{DEP}$  with  $\vec{P}$  and  $\vec{E}$  is given as [21].

$$\vec{F}_{DEP} = \vec{P} \cdot \nabla \vec{E} \quad (3.11)$$

Where  $\vec{P}$  Indicates the polarization vector is equal to

$$\vec{P} = N\vec{\mu} \quad (3.12)$$

where  $\vec{\mu}$  The induced dipole moment and N is the dipole number (particles per cubic meter).

The dipole moment is proportional to the electric field as

$$\vec{p} = \alpha \vec{E} \quad (3.13)$$

Where  $\alpha$  is the effective polarizability of the dielectric layer, and  $\vec{E}$  is applied electric field [214], [215].

Assuming the dust particle is a spherical dielectric particle, as mentioned, the spherical particle at an electric field has an induced dipole moment. The induced dipole moment  $\vec{\mu}$  of the sphere is the value of  $\vec{p}$  Multiplied by the sphere's volume, this result gives as [216]:

$$\vec{\mu} = v\vec{p} \quad (3.14)$$

Where  $v$  indicates the volume of the spherical particle. By combining equations 12,13 and 14, we found

$$\vec{P} = N\vec{\mu} = Nv\vec{p} = Nv\alpha\vec{E} \quad (3.15)$$

The nonuniform electric field source of this work is an AC source.

Assuming an applied potential of a single frequency ( $\omega$ ) can be defined as:

$$\phi(x, t) = \text{Re}[\tilde{\phi}(x)e^{i\omega t}] \quad (3.16)$$

where the  $\phi(x, t)$  Indicates the time-dependent potential in the mechanism that may be expressed using phasors. The tilde symbol ( $\sim$ ) denotes the phasor complex.

The complex phasor for the applied potential is given as:

$$\tilde{\phi} = \phi_R + i\phi_I \quad (3.17)$$

The electric field vector  $\tilde{E}$  Indicates the divergence of the applied potential so that it can be written as

$$\tilde{E} = -\nabla\tilde{\phi} = -(\nabla\phi_R + i\nabla\phi_I) \quad (3.18)$$

The dielectrophoretic force's derivation for a generic AC field is more complicated [45].

As assumed before, the dust particle is the spherical dielectric particle; the expression for the time-averaged dielectrophoretic force on the spherical particle is given as:

$$\langle \vec{F}_{DEP} \rangle = \frac{\text{Re}[(\vec{P} \cdot \nabla)\tilde{E}^*] - \text{Im}[(\vec{P} \cdot \nabla)\tilde{E}]}{2} \quad (3.19)$$

Where  $\text{Re} [\dots]$  and  $\text{Im} [\dots]$  indicate the real and imaginary parts of the function, respectively,

\* indicates the complex conjugate.

The combination between equations 15 and 19 results in the following equation

$$\langle \vec{F}_{DEP} \rangle = Nv \frac{\text{Re}[\tilde{\alpha}\tilde{E} \cdot \nabla\tilde{E}^*] - \text{Im}[\tilde{\alpha}\tilde{E} \cdot \nabla\tilde{E}^*]}{2} \quad (3.20)$$

Equation 20 can be rewritten by using vector identities as [214]:

$$\langle \vec{F}_{DEP} \rangle = N \left[ \frac{1}{2} v \text{Re}[\tilde{\alpha}] \nabla (\tilde{E} \cdot \tilde{E}^*) - \frac{1}{2} v \text{Im}[\tilde{\alpha}] (\nabla \times (\tilde{E} \times \tilde{E}^*)) \right] \quad (3.21)$$

This can be rewritten as:

$$\langle \vec{F}_{DEP} \rangle = \frac{1}{4} N v \text{Re}[\tilde{\alpha}] |\nabla \tilde{E}|^2 \quad (3.22)$$

As supposed that the particles of dust are spherical dielectric particles for the EDS system, the volume of the spherical particle is given as [30]:

$$v = \frac{4}{3} \pi R^3 \quad (3.23)$$

where R indicates the radius of the dust particle.

In the EDS system, the mechanism of removing dust particles depends on the polarizability of the dust particle and the surrounding medium. The effective polarizability of the dielectric layer in the EDS system is given as

$$\tilde{\alpha} = \frac{3\varepsilon_m}{N} \left( \frac{\tilde{\varepsilon}_r - 1}{\tilde{\varepsilon}_r + 2} \right) \quad (3.24)$$

where  $\varepsilon_m$  Indicates the medium permittivity, N indicates the number density of the particles (number per cubic meter), and  $\tilde{\varepsilon}_r$  Indicates the complex relative permittivity (dielectric constant) of the dielectric material [214], [217]. The dielectric constant of the dielectric materials strongly depends on the permittivity of the medium and particles, so it's written as

$$\tilde{\varepsilon}_r = \frac{\tilde{\varepsilon}_p}{\tilde{\varepsilon}_m} \quad (3.25)$$

where  $\tilde{\varepsilon}_p$  indicates the complex permittivity of the dielectric particle,  $\tilde{\varepsilon}_m$  indicates the complex permittivity of the surrounding medium [214], [218]

Complex permittivity of a material denoted  $\tilde{\varepsilon}$  written as

$$\tilde{\varepsilon} = \varepsilon - i \frac{\sigma}{\omega} \quad (3.26)$$

Where  $i$  indicates the imaginary unit,  $\sigma$  indicates the material's conductivity,  $\omega$  indicates the angular frequency of the applied electric field [30], [210].

By substituting Eq. 25 into Eq. 24 is then the effective polarizability of a spherical dielectric particle is

$$\tilde{\alpha} = \frac{3\varepsilon_m}{N} \left( \frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_m}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_m} \right) \quad (3.27)$$

The combination between equations 22, 23, and 27 will be the full expression for the time-averaged DEP force on a spherical particle and is then written as

$$\langle \vec{F}_{DEP} \rangle = \pi \varepsilon_m r^3 \text{Re} \left[ \frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_m}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_m} \right] \nabla |E|^2 \quad (3.28)$$

Equation 28 reveals that the magnitude of DEP force depends on the gradient of the electric field strength squared, the particle volume (  $r^3$  ), the permittivity of the particle, and the permittivity of the suspending medium [179], [219]. The direction of the force  $\vec{F}_{DEP}$  depends upon the sign of the term  $\left( \frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_m}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_m} \right)$  which called the Clausius-Mossotti factor ( $f_{CM}$ ) [16].

The direction in which the dielectrophoretic force acts can be either toward or away from an increasing field intensity, depending on whether the particle's effective polarizability is positive or negative [214]. If the particle has higher polarizability than the suspending medium ( $\text{Re}[f_{CM}] > 1$ ), then the particle will migrate toward places with a stronger electric field, resulting in a positive DEP. In the case of negative DEP, particles are repelled from high field regions because their polarizability is smaller than that of the suspending medium ( $\text{Re}[f_{CM}] < 1$ ) [214], [220], [221]. Typically, particles have a greater dielectric constant than the surrounding medium; dust particles undergo positive dielectrophoresis in the EDS

application and migrate to areas with stronger electric fields. If a neutral dust particle were to acquire a charge while moving along the insulated screen triboelectrically, it would be expelled from the screen by the greater  $q\vec{E}$  force. [16], [30], [179].

### 3.2.3. Image Force

The image charge method is a very useful method that helps in finding force on a charge when placed near a conductor. An image charge treats the conductor as a mirror.

In special, the concept "image force" has its roots in the electrostatics of wires, where a point charge  $Ze$  placed adjacent to an ideal infinite wire at a distance  $-z$  interacts with the metal surface in a way that mimics the behavior of an opposite charge ( $-Ze$ ) that is placed inside the metal at the same distance ( $z$ ), with the metal itself being ignored [222], [223].

When calculating image forces in an EDS system, the plane of the metal electrodes below the dielectric film is used as a ground plane. Particles with charges  $q$  and  $-q$  are separated by a distance roughly double the dielectric cover's thickness [179]. The image force ( $F_{IM}$ ) for a particle with a diameter  $D_p$  is expressed as

$$F_{IM} = \frac{q_p^2}{4\pi\epsilon_0\epsilon_r[2(t_0 + \frac{D_p}{2})]^2} \quad (3.31)$$

Where  $t_0$  is the dielectric thickness, and  $D_p$  is the particle diameter (m).

It's important to notice that this statement holds if the particle is substantially smaller than the electrode width. Very tiny dust particles have an image force defined as [30]

$$F_{IM} = \frac{q_p^2}{16\pi\epsilon_0\epsilon_r t_0^2} \quad (3.30)$$

### 3.3. Mechanical Forces

Calculating the net force generated on charged and polarized dust particles requires adding mechanical or non-electric forces on the particles. The most crucial forces are:

### 3.3.1. Adhesion Force

As previously mentioned, the dust accumulated on the PV modules integrated with the EDS system. To delete dust particles from PV modules, the EDS system needs to overcome a special type of force called Adhesion force. Adhesion force presents as the attraction relation between the dust layer and a horizontal EDS surface [178]. It depends on two main parameters; firstly, as dust particle size drops, especially for micro particles, the force of adhesion becomes significantly stronger, making it more difficult to remove dust particles from a given surface. Adhesion force depends on the density and radius of dust particles [26], [197]. Secondly, the adhesion force relies on atmospheric humidity, as reported by Mekhilef et al. [34]; the adhesion force between dust particles and surfaces was highly influenced by atmospheric humidity. As the relative humidity increased, the efficiency of solar panels decreased due to an increase in the adhesion force of dust particles to the surface [15]. Van der Waals, capillary, and chemical bonding forces combine to form the adhesion between the dust particles and the EDS substrate, with the chemical bonding force typically being absent in dry conditions [30], [178], [179].

#### 3.3.1.1. Van Der Waals Force ( $F_{VDW}$ )

Van Der Waals force is created between perfectly smooth particles and surfaces with no roughness. This force is expressed as [30]:

$$F_{VDW} = \frac{A_H D_p}{12r_{p-s}^2} \quad (3.31)$$

where,  $A_H$  Indicates the Hamaker constant, which values  $10^{-19}$  J in a vacuum; it depends upon the materials involved, where its value is approximated by  $5 \times 10^{-20}$  J for many common materials [179].  $D_p$  indicates the adhering dust particle diameter in meter unit,  $r$  indicates the equilibrium minimum range of separation between two solids surfaces of the

particle and the surface [30], [179], [177]. An intermolecular force is the van der Waals force. It is determined by the sizes of the dust particles and the separation between each one and the EDS surface, as shown in Eq. 31. It increases with increasing dust particle diameter [224], [225]. The van der Waals force increases with decreasing separation between dust and EDS surface, but it rapidly diminishes with increasing separation and becomes negligible at separations of  $z > 100$  nm. Assuming a typical spacing in the EDS system for van force approximately between 0.3-0.4 nm [30], [179].

### 3.3.1.2. Capillary Force ( $F_{cap}$ )

A capillary force is generated by the condensation of the moisture between the particles with a noticeable effect when the relative humidity exceeds approximately 50 %. The high moisture layer acts as a capillary bridge force between contacting surfaces due to forming a water droplet causing accumulation of particles on the EDS surface. When the moisture layer evaporates, the capillary force decreases, and the van der Waals force increases, which holds the particles strongly to the surface [224], [225], [226]. The added forces caused by increased RH above 50% are unfavorable for the electrodynamic removal of dust [179]. Because the EDS system must be operated in dry conditions with a relative humidity (RH) of less than 50 percent, the capillary force and the chemical bonding forces cannot be taken into account when it comes to practical applications of the EDS [178].

Capillary force is expressed as [227]:

$$F_{cap} = \pi \gamma_w D_p [\cos(\vartheta_p) + \cos(\vartheta_s)] \quad (3.32)$$

where,  $\gamma_w$  indicates the surface tension of water between the contact surfaces,  $D_p$  indicates the particle diameter (m),  $\vartheta_p, \vartheta_s$  Indicates the contact angles of the particle and the surface, respectively.

### 3.3.2. Friction Force

One of the factors restraining the repelling of a dust particle in the air is friction. When a small particle with a saturation charge approaches the EDS screen and is close to the electrode where the field is greatest, the velocity acquired by the particle can be computed if the particle motion obeys Stoke's law. The drag force of the particle in the Stokes law can be represented in terms of the dust particle velocity in the form of

$$F_D = 3\pi D_p v_p \zeta \quad (3.33)$$

Where the coefficient  $\zeta$  indicates the dynamic viscosity of air,  $D_p$  indicates the particle radius, and  $v_p$  Indicates the particle's velocity [12], [17], [22].

### 3.3.3. Gravitational Force

The gravitational force ( $F_G$ ) for a particle is expressed as

$$F_G = mg \quad (3.34)$$

Where  $m$  indicates the mass of the dust particle,  $g$  is the constant gravitational acceleration ( $9.8-10 \text{ m/s}^2$ ) [30], [178].

The mass of a particle can be expressed by its volume and density; the volume of a spherical dust particle is

$$v = \frac{4}{3}\pi R_p^3 = \frac{1}{6}\pi D_p^3 \quad (3.35)$$

Expression for the gravity force is:

$$F_G = \frac{1}{6}\pi D_p^3 \rho_p g \quad (3.36)$$

Where  $D_p$  indicates the dust particle diameter (m),  $\rho_p$  Indicates the dust particle density ( $\text{kg/m}^3$ ) [30], [228].

### 3.4. Total Force (Equation of motion)

In general, the net force acting on the dust particles on the EDS system to lift them above the surface can be represented as the sum of electrostatic forces ( $F_e$ ) and mechanical forces ( $F_m$ ). The general total force equation of motion of charged and polarized particles repelled and being transported out of the EDS system can be represented by [16], [26], [166], [176], [191].

$$F_t = F_e - F_m \quad (3.37)$$

The electrostatic forces included the coulomb force ( $F_C$ ), and image force ( $F_{IM}$ ) for charged particles and dielectrophoretic force ( $F_{DEP}$ ) for polarized particles, so the electrostatic force is expressed as

$$F_e = F_C + F_{DEP} + F_{IM} \quad (3.38)$$

While the mechanical forces included drag force ( $F_D$ ), gravitational force ( $F_G$ ), and adhesion force which is a summation of the van der Waal force ( $F_{VDW}$ ), and capillary force ( $F_{Cap}$ ), so the mechanical force can be expressed as

$$F_m = F_D + F_G + F_{VDW} + F_{Cap} \quad (3.39)$$

The total force equation of the particulate motion on the EDS system can be written as [12]:

$$F_t = (F_C + F_{DEP} + F_{IM}) - (F_D + F_G + F_{VDW} + F_{Cap}) \quad (3.40)$$

In terms of the dust particle acceleration, Eq. 42 can be rearranged as

$$m_p a_p = (F_C + F_{DEP} + F_{IM}) - (F_D + F_G + F_{VDW} + F_{Cap}) \quad (3.41)$$

where  $m_p$  indicates the dust particle mass, and  $a_p$  The dust particle acceleration.

The dust particles are influenced by different forces, as shown in equation 41. Nevertheless, there are special cases we can neglect some of these forces for logistic place and scientific reasons. It can be demonstrated that the force between a particular particle on the EDS

surface and its image charge is an order of magnitude lower than the force of gravity, allowing image force to be disregarded [229]. Due to the presumption that the EDS system was operated with a suitably low relative humidity or in a very dry sphere, the capillary force could also be disregarded. The threshold at which capillary force becomes significant for particles on an EDS system was estimated by Sayyah et al. [30] to be around ~40% relative humidity. However, in other publications, this threshold was thought to be around ~50% [7] or ~60% [230].

## **CHAPTER 4**

### **EXPERIMENTAL SETUP OF THE EDS SYSTEM**

The EDS system is a potential functional technique for clearing dust buildup from transparent surfaces, not only PV modules (see chapter 3). In this chapter, I will describe the experimental setup of the EDS system, then describe the dust removal efficiency's evaluation and the EDS system's theoretical mechanism. After that, I will describe the characterization techniques used to analyze the properties of dust particles.

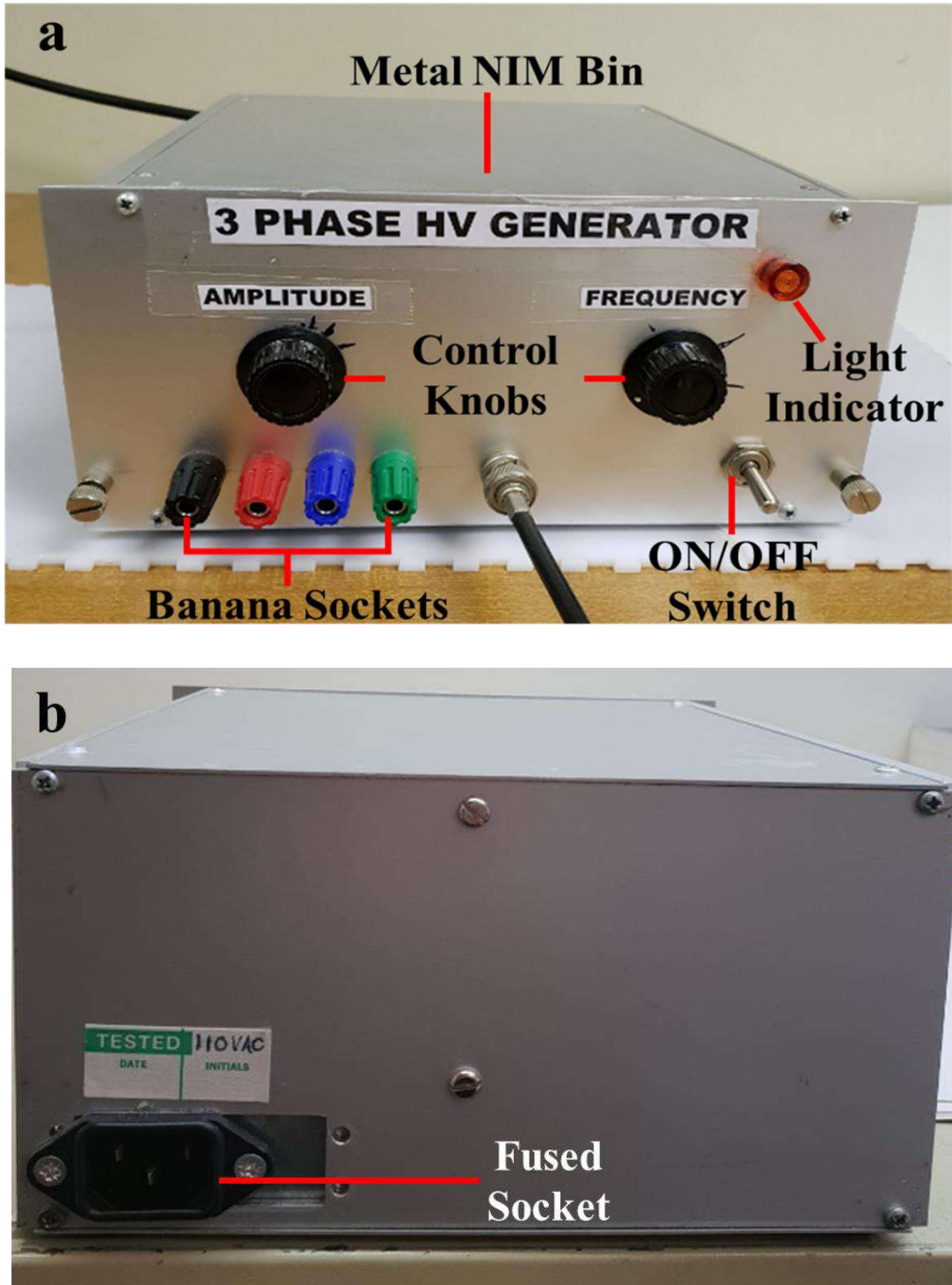
#### **4.1. Experimental setup of the EDS system**

The EDS system is composed of three essential parts: (i) High alternating current (AC) voltage source, (ii) Combined plate design of the EDS system, (iii) dust samples of the EDS system

##### **4.1.1. High AC voltage source**

We created a homemade multi-phase high voltage generator (HVG). It is designed as a part of the EDS system to produce high voltage used for removing dust particles from the EDS surfaces. The instrument can produce single and three-phase high-voltage pulses with an adjustable frequency, duty cycle, and amplitude. The frequency and amplitude of the output waveform are controlled by two control knobs provided on the HVG. The frequency can be varied from 1Hz to 1 kHz, and the output voltage could be varied from 0-1100V with a current output limited to 250  $\mu$ A for safety purposes. This instrument consists of three HV output connectors (banana sockets) and one connector to monitor the output waveform on the oscilloscope LeCroy 9350A. The mains supply 110 VAC 60Hz powers the instrument.

A 110VAC fused socket with a built-in noise filter is provided at the back of the HVG, where a cable connects the HVG to the mains power outlet. A separate power ON/OFF switch with an indicator has been provided to show if the instrument is ready to use. The instrument circuit board and components have been housed in a metal perforated NIM Bin casing as a complete circuit. Figure 4.1 shows the picture of the power supply of the EDS system in our lab.



**Figure 4.1.** Photograph of the diagram of high voltage generator (a) Front panel of the HVG, (b) Back panel of the HV.

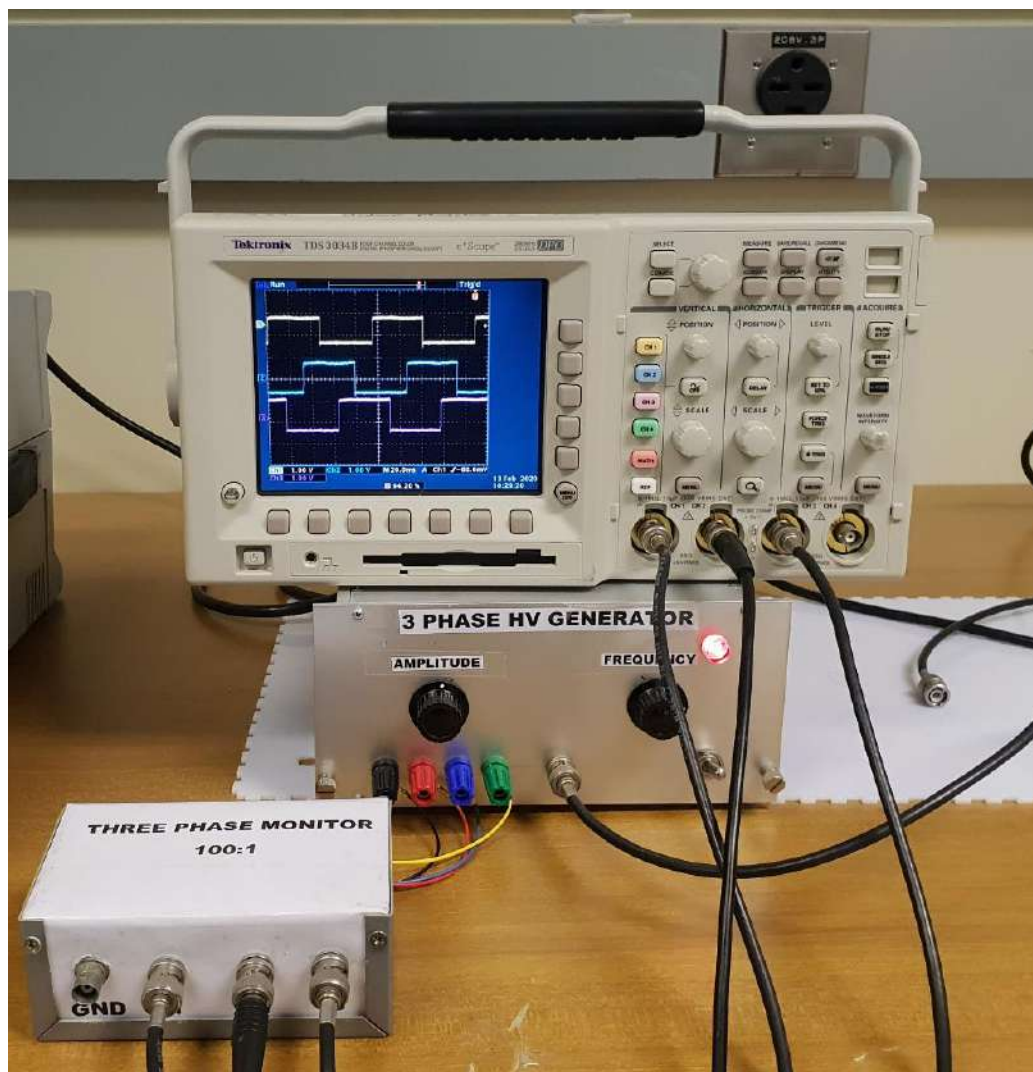
#### **4.1.1.1. Testing of High Alternating current voltage source**

The testing of the multi-phase high-voltage generator was done by using the setup shown in figure 4.2. The instrument was connected to the main power (110VAC, 60Hz) through the cable connected to the back socket. An oscilloscope was connected to the monitor output terminal. We kept the output voltage knob at the minimum position, counterclockwise direction, and the frequency control knob at the middle position; the front toggle switch turned ON the instrument, and the indicator light was illuminated. Immediately the waveform on the oscilloscope was observed. The effect of the two control knobs was observed, and the instrument appeared to work satisfactorily. In order to check all the outputs simultaneously, a special three-phase monitor was designed and fabricated, as shown in Figure 4.2. This high-impedance device divided the output by 100 times without loading the actual outputs to bring the voltage to a safe level for observation on the oscilloscope. A special four-input oscilloscope Tektronix TDS 3034B, was used for this purpose. The results are as shown on the oscilloscope display with all three outputs separated by 120 degrees with respect to each other.

#### **4.1.1.2. Operation of High Alternating current voltage source**

Connect the power cable to the back of the instrument to the 110VAC mains power supply. Turn the power switch on and observe the red light turning on at the front panel of the multi-phase HV generator. Connect a BNC cable at the monitor output and the other end to the oscilloscope LeCroy 9350A. Make sure that the two knobs to control the frequency and amplitude are set at a minimum, fully counterclockwise. Slowly rotate the Frequency knob clockwise to reach the middle point. Now slowly increase the amplitude control clockwise and simultaneously observe the waveform at the oscilloscope LeCroy 9350A.

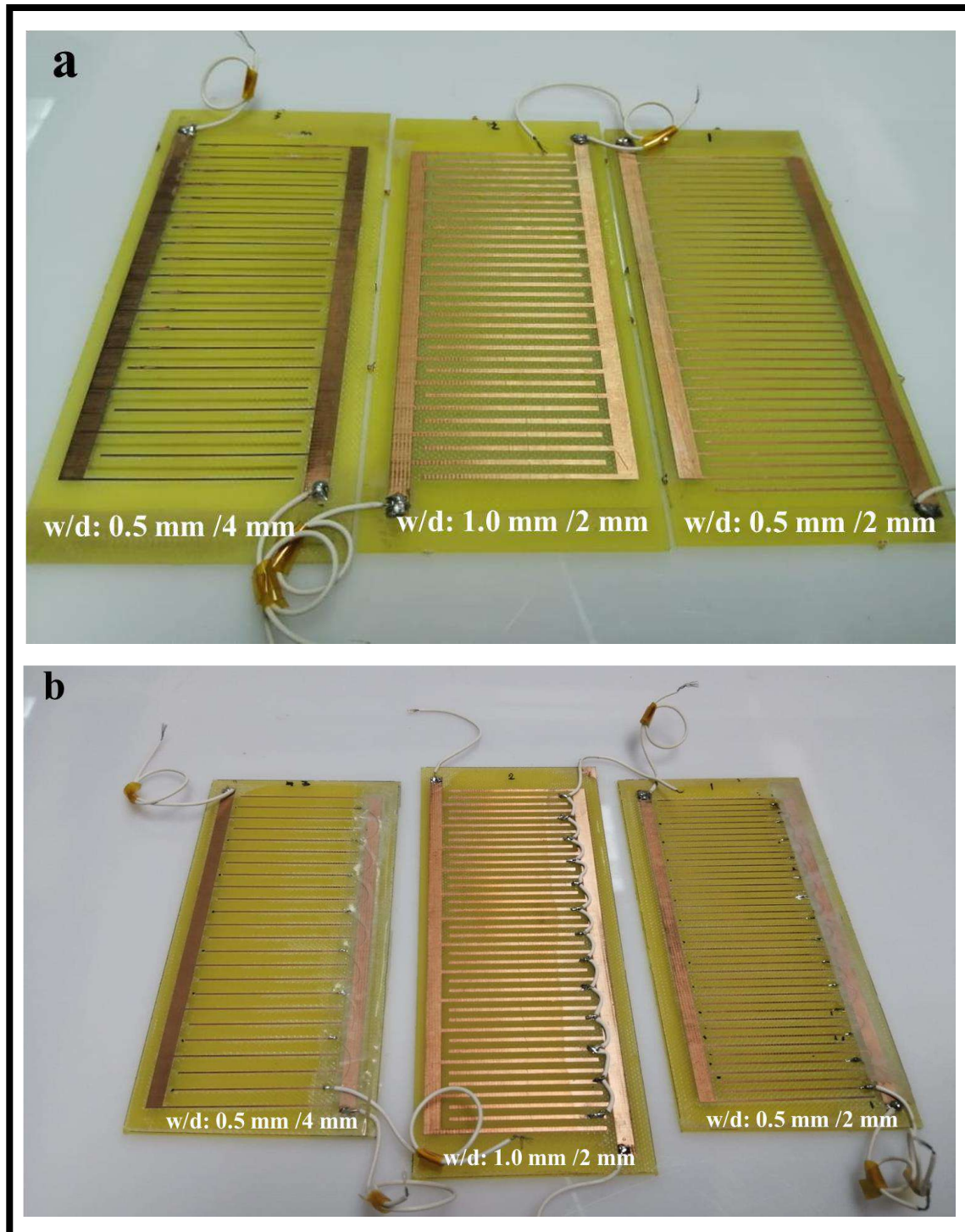
Finally, adjust the frequency and amplitude knobs at the desired frequency and amplitude. Note and mark the position of knobs at this position and turn OFF the power switch. Bring back the HV knob to a minimum, fully counterclockwise. Connect the multi-phase HV outputs to the device input points and turn ON the power switch. Now slowly increase the amplitude to the desired voltage and observe the monitor waveform to see if there is any distortion or jerks. If so, reduce the voltage, disconnect the output, and rectify any problems in the device under test.



**Figure 4.2.** The experimental setup for testing the activity of HVG by a four-input oscilloscope.

#### **4.1.2. Combined surface design of the EDS system**

We embedded the interdigitated copper electrodes with 0.018 mm thickness ( $t$ ) and with three different combinations of electrode width ( $w$ ) and spacing ( $d$ ) ( $w/d$ : 0.5 mm /2 mm; 1 mm /2 mm; 0.5 mm /4 mm) in 10 cm  $\times$  5 cm epoxy glass substrate by LPKF screen printing. The exposed metallic parts of the plate are properly insulated using Scotch tape with 0.065 mm in thickness, which also serves as the functional dielectric coating for the EDS system. We keep the electrode thickness low to minimize the casting of the shadow of the electrode on the solar panel, which could reduce the solar light intensity [18], as shown in figure 4.3. Figure 4.3 shows the different combinations of electrodes at different widths and spacing between the electrodes in two different phases (single phase and three phases).



**Figure 4.3.** Different combinations of electrodes at different widths and spacing for (a) single-phase and (b) three-phase.

#### **4.1.3. Dust samples of the EDS system**

The dust samples for evaluating the EDS system efficiency were collected from the natural dust storm that hit Dharan in the Kingdom of Saudi Arabia in March 2021. The average size of the collected dust particles in Saudi Arabia was approximately 28  $\mu\text{m}$  in diameter, as found in the dust characterization.

Hot temperatures, dry air, and frequent dust storms are typical of the Saudi Arabian desert. The Dharan city is situated about 10 kilometers inland from the Arabian Gulf Coast at the coordinates (26 ° 32' N, 50 ° 13' E), in the eastern coastal plain of Saudi Arabia, just north of the Tropic of Cancer. Dhahran is in a desert climate, despite its proximity to the shore. Seasonal changes in this area include an extremely hot period (May–October) and a cold period (November–April) (November-April). During the warmest months, average daily highs approach 37 degrees Celsius, while during the coldest months, average daily highs decrease by around 20 degrees Celsius. Around the clock, the relative humidity displays a huge diurnal cycle of 60 percent [6], [231].

#### **4.2. Evaluation of dust removal efficiency and processing**

The EDS system (plates of a combination of the epoxy glass substrate with copper electrodes, and dielectric cover material (Scotch tape), with different electrode widths and different interspacing between electrodes) was carefully cleaned by wiping the plate surface of the EDS system using a cloth wipes® and weighed before dust loading. High-accuracy electric balance (SAG105, Mettler Toledo International, Tokyo) with a minimum reading of 0.0001 g was used for all the weighted measurements in our work. A measure of 100 mg of dust particles was evenly scattered on the EDS system by manual shaking for each experiment, and the dust-deposited electrode was weighed to note the initial mass. The EDS

system was carefully connected to the high AC voltage source and energized for 90 seconds in all experiments. After electrification, the EDS system is weighed again to find the final mass to estimate dust removal efficiency. The percentage of decrease of dust mass after standard 90-second electrification by AC voltage source with appropriate source voltage and frequency estimated the dust removal efficiency of the EDS system. The Experiments were repeated in the 400-1000V potential range and 3-36 Hz frequency range. The EDS system was cleaned after each run, and each trial started with loading dust onto a clean EDS system. Then, the EDS system was carefully returned to the high-voltage source to start a new experiment. Each data point, corresponding to the dust repulsion efficiency for a set of experimental parameters, was repeated five times, and the statistical standard deviation was found to be very small, indicating that the measurements were accurate. Hence the measurements are reproducible and repeatable under the same experimental condition.

### **4.3. Experimental Characterization Techniques**

The dust particles' properties were analyzed using various characterization methods. One or more of these methods are:

#### **4.3.1. Chemical Analysis**

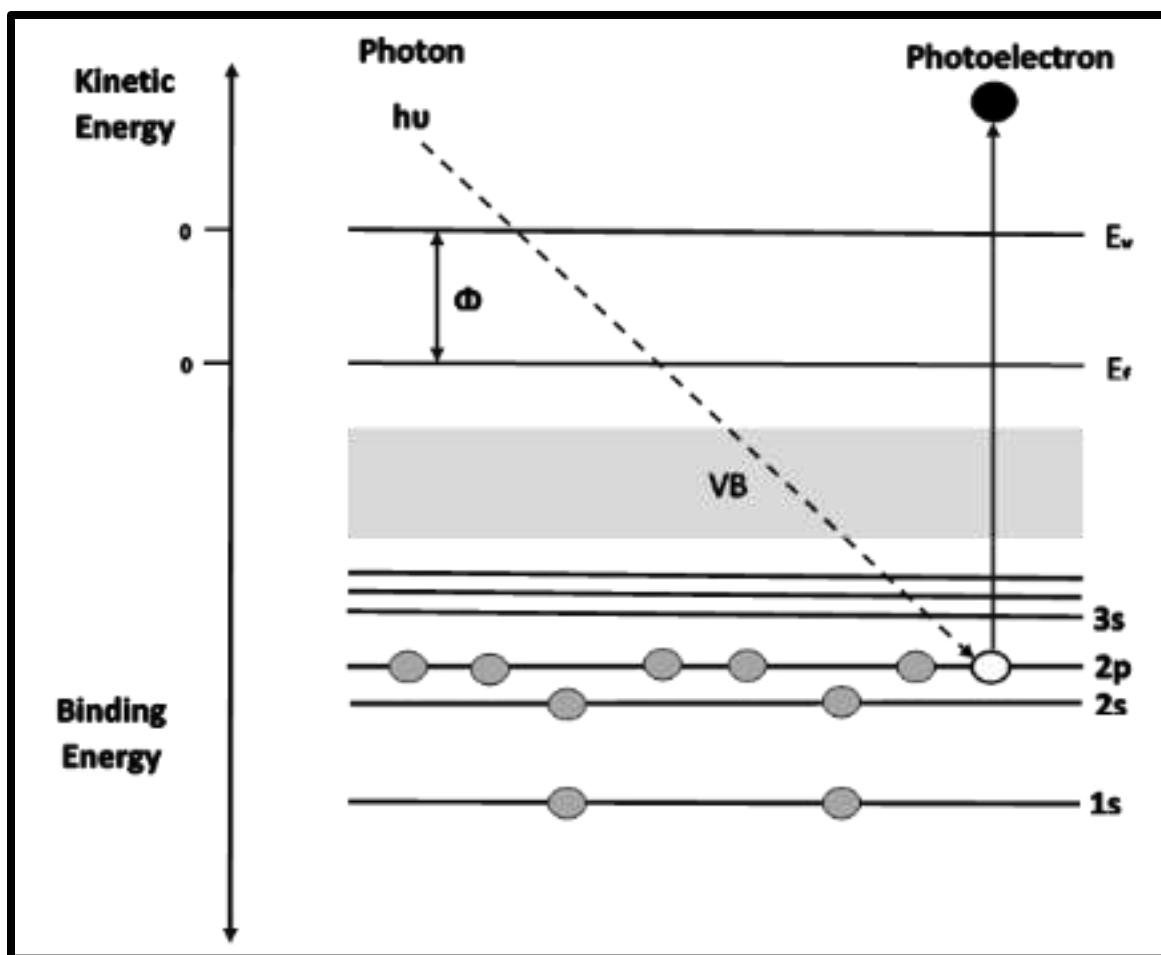
X-ray photoelectron spectroscopy, sometimes known as XPS, is one of the most potent and widely used methods for conducting chemical analysis [232]. XPS is a non-destructive method for investigating the electronic structure of molecules, solids, and individual atoms. The atomic-scale chemical composition of surfaces and interfaces is crucial to developing many material characteristics. High-resolution spectra in binding energy areas for the chemical state of the samples can be acquired by XPS. The photoelectric effect is essential for XPS to function. Each atom's core electrons have unique binding energy, the same as the electron's

ionization energy. Photons with energy ( $h\nu$ ) are shone on a sample kept in a very low-pressure environment [233]. Whenever an X-ray beam is focused on a specimen's surface, the core electron of an atom absorbs all of the photon's energy. When the photon's energy ( $h\nu$ ) is higher than the electron's binding energy ( $E_b$ ), and the electron's energy ( $E$ ) is higher than the solid's work function ( $\phi$ ), the core electron will be free to leave the atom. This released electron has a kinetic energy of  $E_k$  and is known as a photoelectron. The Einstein relation determines the binding energy of the core electron.

$$h\nu = E_k + E_b + \phi \quad (4.1)$$

$$E_k = h\nu - E_b - \phi \quad (4.2)$$

Where  $h\nu$  is incident photon energy,  $h$  is the plank's constant ( $6.62 \times 10^{-34}$  J.s),  $\nu$  is the photon's frequency,  $E_b$  is an electron's binding energy,  $\phi$  is the work function which is the minimum energy needed to remove an electron from a solid. The basic principle of XPS is shown in figure 4.4.

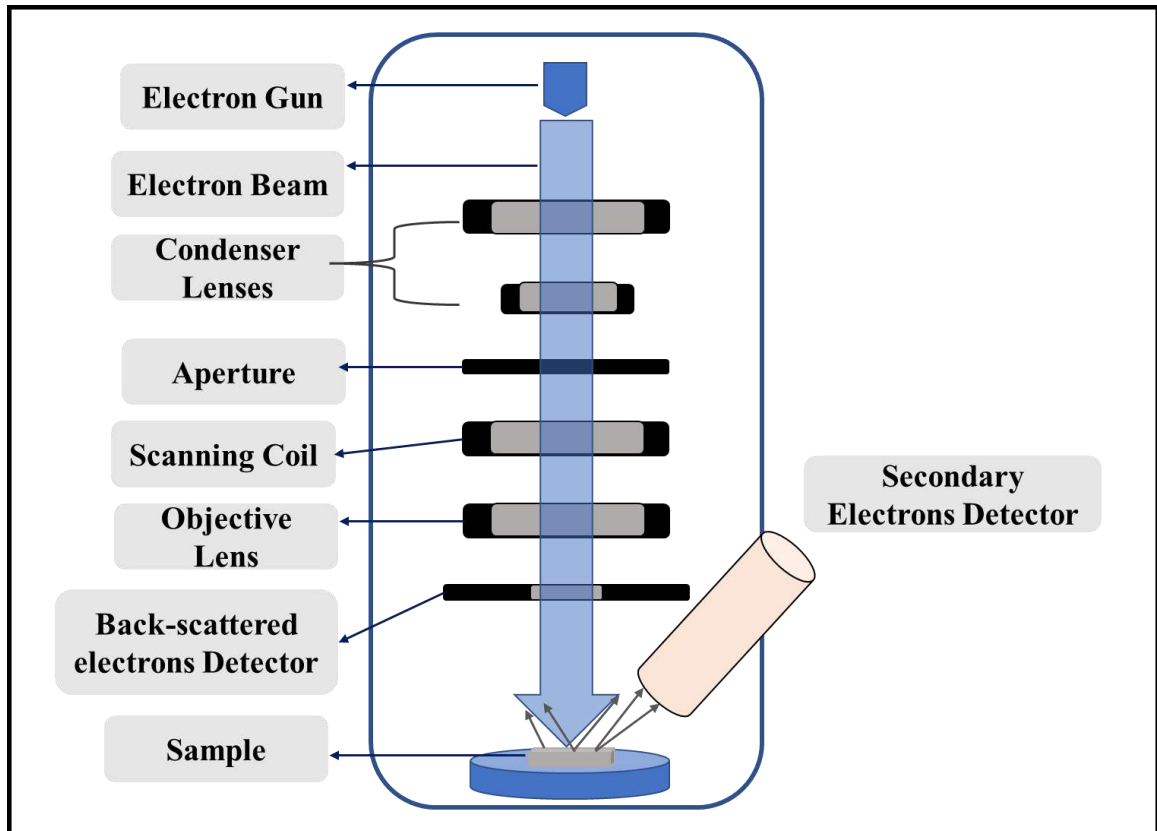


**Figure 4.4.** An illustration demonstrating the XPS fundamental principle

### 4.3.2. Morphological Analysis

In order to create an image of a sample, a scanning electron microscope (SEM) sends a focused beam of electrons across the specimen surface[234]. The basic idea behind SEM is that the electrons hit atoms in the sample, and those atoms send out different signals that reveal things like surface topography and composition. Interactions of the electron beam with atoms at different depths inside this object generate the signals an SEM utilizes to create an image [234]. Crystallized elements and photons can be observed using the various signals generated, such as secondary electrons, backscattered electrons, and diffracted backscattered electrons. The image is created by using secondary and backscattered

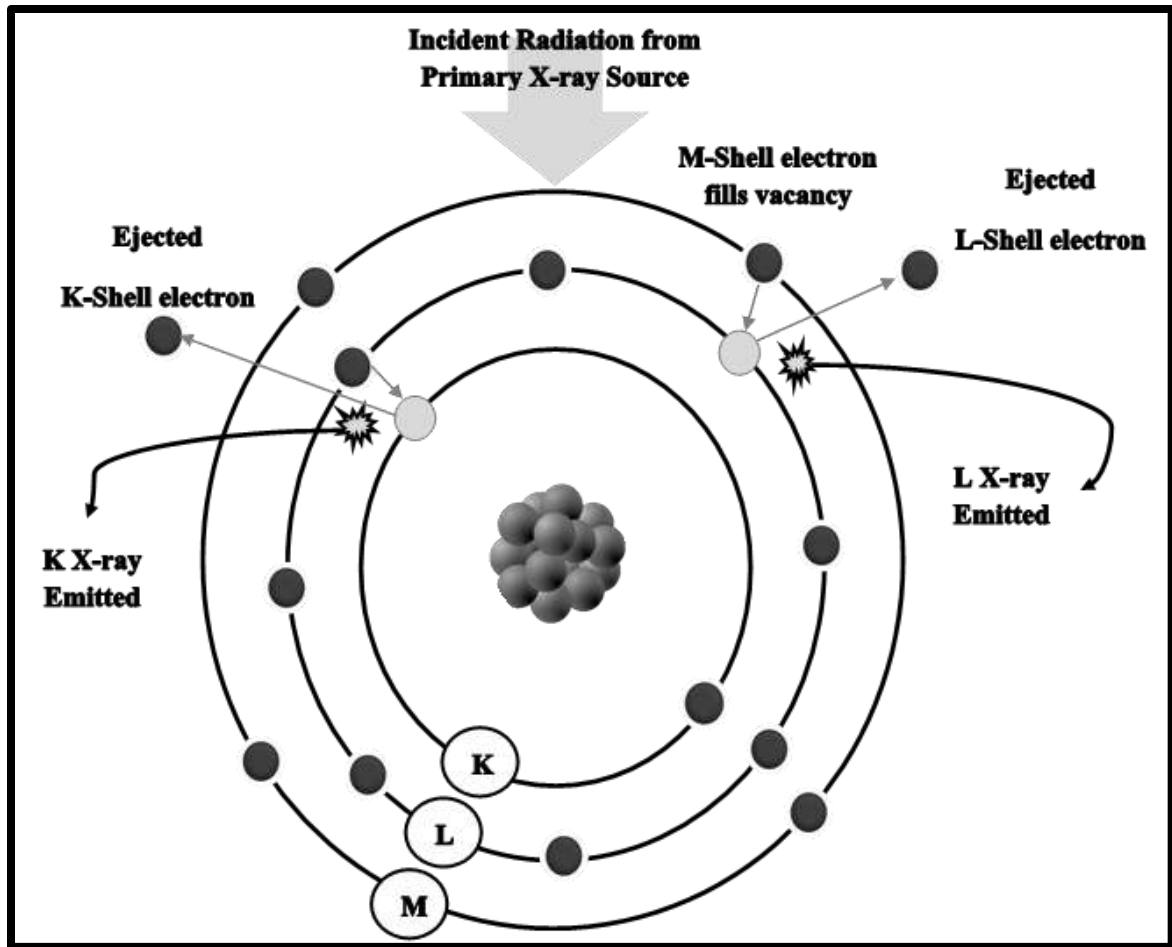
electrons. Backscattered electrons display contrast in the composition of the specimen's elements, while secondary electrons released from the specimen are primarily responsible for detecting the specimen's morphology and topography.[234]. The primary parts of a scanning electron microscope (SEM) are its electron source, lenses, scanning coil, detector, display device (data output devices), power supply, and vacuum system [234]. A schematic diagram showing the geometry of SEM components is given in figure 4.5. The morphology of our samples was investigated by Scanning Electron Microscope (JEOL SEM-JSM6610LV).



**Figure 4.5.** A simplified representation of SEM's core features.

### 4.3.3. Elemental Analysis

Elements in a sample can be determined or identified using energy-dispersive X-ray spectroscopy (EDX). It is based on studying how an X-ray source interacts with a sample. The basic concept of the EDX is that each element has a unique atomic structure permitting a distinct collection of peaks on its X-ray spectrum to find its characterization capabilities. Atoms in the top few microns of the sample are excited to emit distinctive x-rays when the electron beam of the SEM is traversed across the sample. Each x-ray has a unique amount of energy based on the type of atom it radiated away from the atom. The EDX system takes in the x-rays, organizes them according to energy, and plots the results. Electronic capture and display/processing of a qualitative EDX spectrum. Electron diffraction X-ray spectrometry (EDX) is based on the principle of the emission of distinctive X-rays from a specimen, wherein a high-energy beam of charged particles (electrons, ions, or X-rays) is transmitted through the sample under investigation. While in its resting state, an atom in the sample has its electrons confined to one of several predetermined energy levels, or "shells," around its nucleus. An electron in a lower shell could be ejected from the shell after being excited by the incident electron beam, leaving behind an electron-hole. If an electron from a higher-energy shell further out fills the void, the energy of the higher-energy shell compared to the lower-energy shell could be released as an X-ray [235]. Figure 5.6 is a simplified schematic depicting the EDX working principle.



**Figure 4.6.** A simplified representation of EDX's principle.

#### 4.4. Theoretical Characterization Technique

To find the best settings for the EDS's design and functioning, a series of simulations were run with a wide range of setups and parameters. COMSOL Multiphysics and Wolfram Mathematica are utilized for theoretical characterization to look into the EDS system's features. The word COMSOL is not an acronym. It's inspired by the words "Computer" and "Solution" [236], [237]. COMSOL Multiphysics is a cross-platform finite element analysis, solver, and Multiphysics simulation software. It is a comprehensive simulation software environment for many real-world applications. The COMSOL Multiphysics program aims to mimic, as closely as possible, the effects observed in real applications.

Mathematica is a programming language that does a lot of symbolic computation and is a good tool for mathematicians or applied mathematicians (physicists, etc.). It is designed to carry out complex mathematical computations and calculations; the Wolfram Language is the programming language used in Mathematica [238], [239], [240], [241].

## CHAPTER 5

### RESULTS & DISCUSSIONS

#### 5.1. Discussion of the mechanism of the EDS system

In a three-phase EDS system, a three-terminal interdigitated electrode is powered by a three-phase square wave AC voltage source that creates a non-uniform electric field between the electrodes and sets up a traveling wave propagating in the horizontal direction (positive x-direction). The net potential field ( $\phi(x, y, t)$ ) in between the electrodes is the superposition of the potentials of three square waves with the mutual phase difference of  $\frac{2\pi}{3}$  and the negative gradient of this time-varying net potential is the established non-uniform electric field ( $E(x, y, t) = -\nabla\phi$ ) in between the electrodes [30]. The dust particles in the EDS system experience different kinds of electrostatic forces (Coulomb force, DEP force, and image force) and different mechanical forces (adhesive force, gravitational force, drag force, capillary force, and Van der Waal force) [16], [26], [191]. The net effect of these forces leads the particles to acquire a net acceleration. Based on the vertical component of the net acceleration, the particles either levitate or adhere to the EDS surface. In contrast, the horizontal component determines the direction of the propagation with respect to the wave direction. The charged ( $q$ ) dust particles in the electrostatic field ( $E$ ) in between the electrodes experience Coulombic force ( $qE$ ). The neutral particles in the non-uniform electric field get polarized and experience the dielectrophoretic force  $F_{DEP}$ , whose magnitude is proportional to the gradient of the field ( $\nabla E$ ), the cube of the particle radius ( $r$ ), and the numerical value of the real part of the Clausius-Mossotti ( $CM$ ) factor in the square bracket

of equation (5-a) [16], [179], [209]. The direction of  $F_{DEP}$  is toward regions of increasing electric field (positive  $F_{DEP}$ ), if the polarizability of a particle is greater than that of the medium, and the direction of the DEP force is towards the decreasing electric field (negative  $F_{DEP}$ ), if the polarizability of a particle is less than that of the medium. In most of the cases, the polarizability of the particles is higher than that of the medium, and hence the dust particles experience positive  $F_{DEP}$  force and move towards the regions of increasing electric field. During this movement along the dielectric surface, the neutral dust particles triboelectrically acquire charge, and as a result they are lifted from the dielectric surface by Coulomb's force. Another force of electrostatic origin is the image force due to particle's image over the dielectric surface of thickness ( $t_0$ ), image force can be approximated as in equation b, considering that radius ( $r$ ) of the particle is much smaller than  $t_0$  [178], [214].

$$F_{DEP} = 4\pi\epsilon_m r^3 \text{Re} \left[ \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*} \right] E \nabla E \quad (5. a)$$

Where  $\epsilon_p^*$  and  $\epsilon_m^*$  Indicate the frequency-dependent complex dielectric constants of the particle and the medium.

$$F_{IM} = \frac{q^2}{16\pi\epsilon_0\epsilon_p t_0^2} \quad (5. b)$$

Where  $q$  is the particle charge,  $\epsilon_0$  and  $\epsilon_p$  are the dielectric constants of the free space and particle.

$$\phi = \frac{3\pi\gamma r}{2qE} \quad (5. c)$$

The factor ( $\phi$ ) that describes the relative importance of adhesive force to Coulomb's force is given in equation (5-c) [193], [242]. Among the mechanical forces in action, the adversely acting adhesive force tends the particles to stick to the dielectric surface, and this force increases with the surface energy ( $\gamma$ ) of the dielectric surface and the radius of the dust

particle ( $r$ ). In addition to the adhesive force, the particle size-dependent Van der Waal force also tends the particles to stick to the dielectric surface, and the magnitude of this force is inversely proportional to the square of the distance of separation between the particle and the surface [30], [179]. Since the Van Der Waals force is weak for large particles, these particles are often easier to be levitated because the growth rate of Coulomb force with particle radius is more significant than that of the adhesive force[243]. However, Van Der Waals force can be considered negligible when the separation distance between the particle and the surface is less than 100 nm, and the particle size becomes larger than 40  $\mu\text{m}$  in diameter [30],[178]. Also, when the particles acquire velocity, the adverse drag force is inevitable, and the magnitude of this force is proportional to the particle radius ( $r$ ) and its velocity, and this force impedes the repulsion of particles into the air [17], [22]. When the level of humidity in the environment exceeds a certain limit, the capillary force (due to the surface tension) between the contacting surfaces through water droplets comes into play, and the capillary force depends on the particle radius, the water wettability, and particle wettability on the dielectric surface [227]. However, the capillary force becomes negligible in dry and low-humid conditions (less than 40% relative humidity) [178].

In addition to the forces discussed above, the waves generated by the AC voltage source on the electrode surface are important agents levitating and transporting dust particles from the PV panels [23]. Single-phase AC voltage source generates the standing wave, which levitates the dust particles that are lifted by the net electrostatic forces in the direction perpendicular to the electric field [23]. In the standing wave, the dust particles roll back and forth along with the dielectric plate, oscillate up and down above the electrodes, and levitate in between the electrodes. On the other hand, a three-phase AC voltage source generates a

traveling wave that moves in the horizontal direction of the electric field [7]. The traveling wave is generated in the three-phase supply because of the potential rhythmic change at each electrode due to the systematic 120-degree phase shift [25]. In the case of the three-phase EDS with an electrode of width  $w$  and the inter-electrode spacing  $d$ , the spatial periodicity ( $\lambda$ ) of the generated traveling wave is  $\lambda = 3(w + d)$ , and when the AC voltage source frequency is  $f$ , the speed of the traveling wave is  $V_T = f\lambda$  [30].

Interestingly, in the context of dust repulsion from the EDS surface, all the forces of electrostatic origin work together to remove the dust from the surface, and at the same time, all the mechanical forces impede the repulsion process. So the net force is the difference between the forces of electrostatic origin and the mechanical forces, and this net force gives the necessary horizontal and vertical components of the acceleration to the particles [26], [191]. Also, the forces of electrostatic origin contribute to both horizontal and vertical components of the acceleration, depending on the charge, electric field, gradient of the electric field, and the nature of the dielectric properties of the medium and the particles [12], [214]. On the other hand, the mechanical forces contribute to the vertical component of the acceleration, depending on the mass, speed, size of the particles, and environmental conditions. The vertical acceleration is strong enough to lift the dust particle against the opposing mechanical forces when the applied field is above a particular value at a given frequency. This acceleration is expected to increase with the increasing electric field at a particular frequency [25], [30]. The horizontal component of the acceleration can be either positive or negative, depending on the relative charge state of the particles. If we assume that the traveling wave is moving in the positive x-direction, the positive horizontal component of the acceleration drives the particles along the direction of the traveling wave;

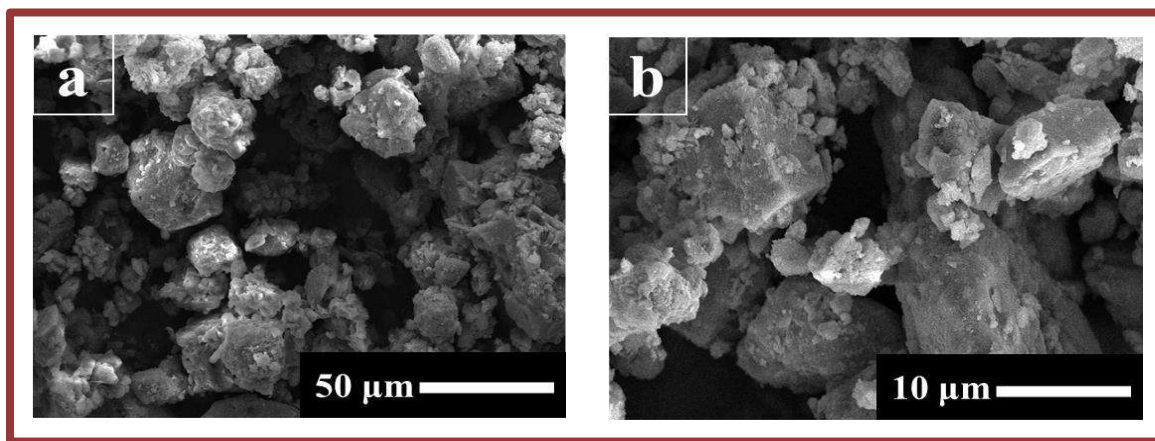
and also in phase with the traveling wave, provided the speed acquired by the particle is the same as the speed of the wave [12], [17], [22]. On the other hand, if the horizontal component of the acceleration is negative, the particle moves opposite to the direction of the traveling wave with its acquired speed. The frequency and the voltage of the AC source, the geometry of the interdigitated electrode, the charge state and size of the dust particles, and the environmental conditions are the vital functions in deciding the final magnitude and the direction of the vertical and horizontal components of the acceleration that are instrumental in lifting and sweeping the particles away.

## **5.2. Three-Phase Experimental Work**

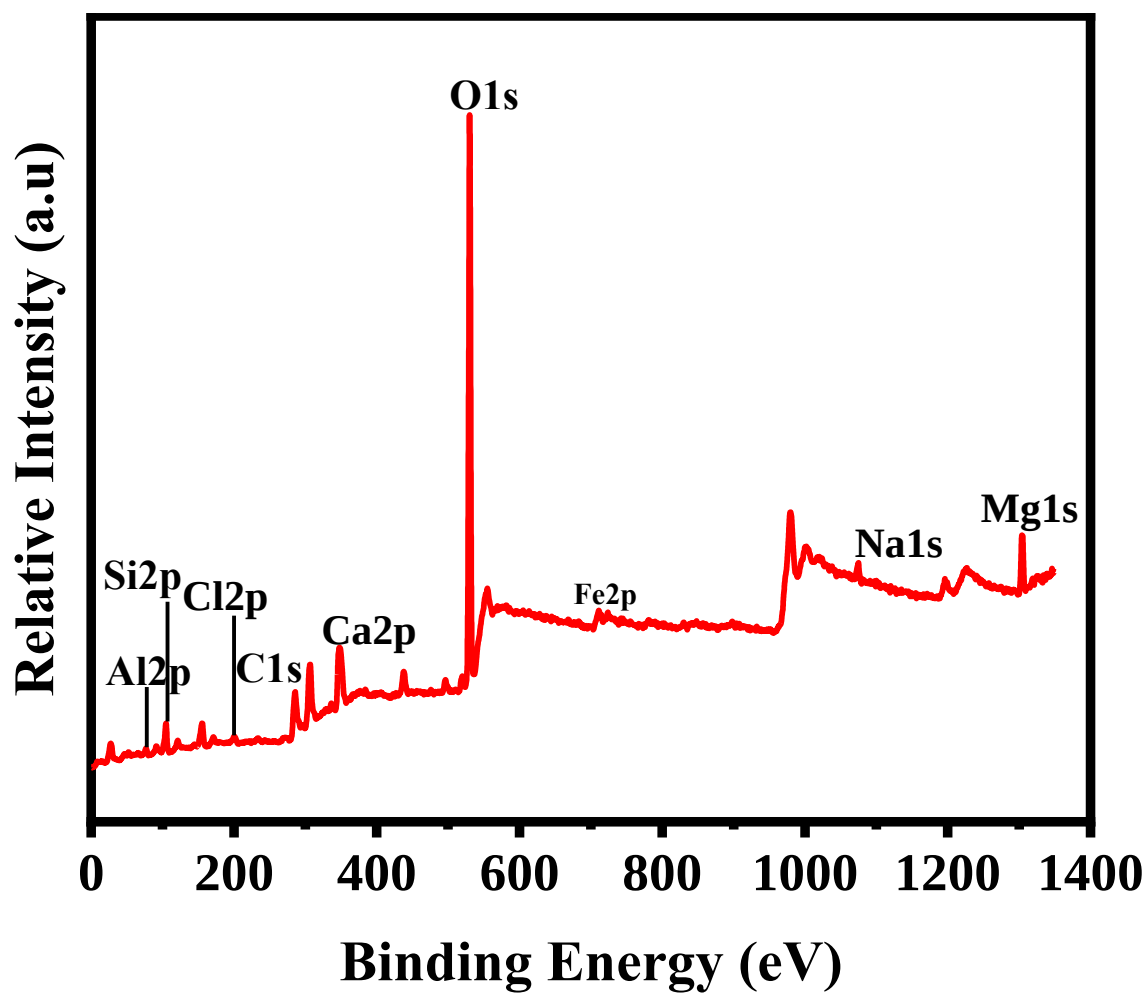
### **5.2.1. Characterizations of the desert sand used in the EDS system**

The dust particles in the EDS system are subjected to different kinds of mechanical and electrostatic forces, and hence the dust removal efficiency of the EDS system vastly depends on the elemental composition, charge state, size, and shape of the experimental dust particle [12], [244]. This motivates us to carry out the morphological characterizations, elemental analyses, and particle size analyses of the dust particles to correlate their roles in deciding the eventual dust removal efficiency of the EDS system. The adhesive force that holds the particles on the PV panel surface, their relative strength concerning the Coulomb's force, the impeding drag force, dielectrophoretic (DEP) force experienced by the neutral particles in a non-uniform electric field with a gradient are all dependent on the particle size. Even sometimes, the shape of the particles comes in contact with the EDS system [16], [20], [22], [29], [245]. SEM micrographs of the dust particles used in this work are shown in Fig.5.1. a and Fig.5.1.b in two different magnifications, where it is quite evident that the particle sizes are in the range of 10-50 microns, and as for the shapes; also

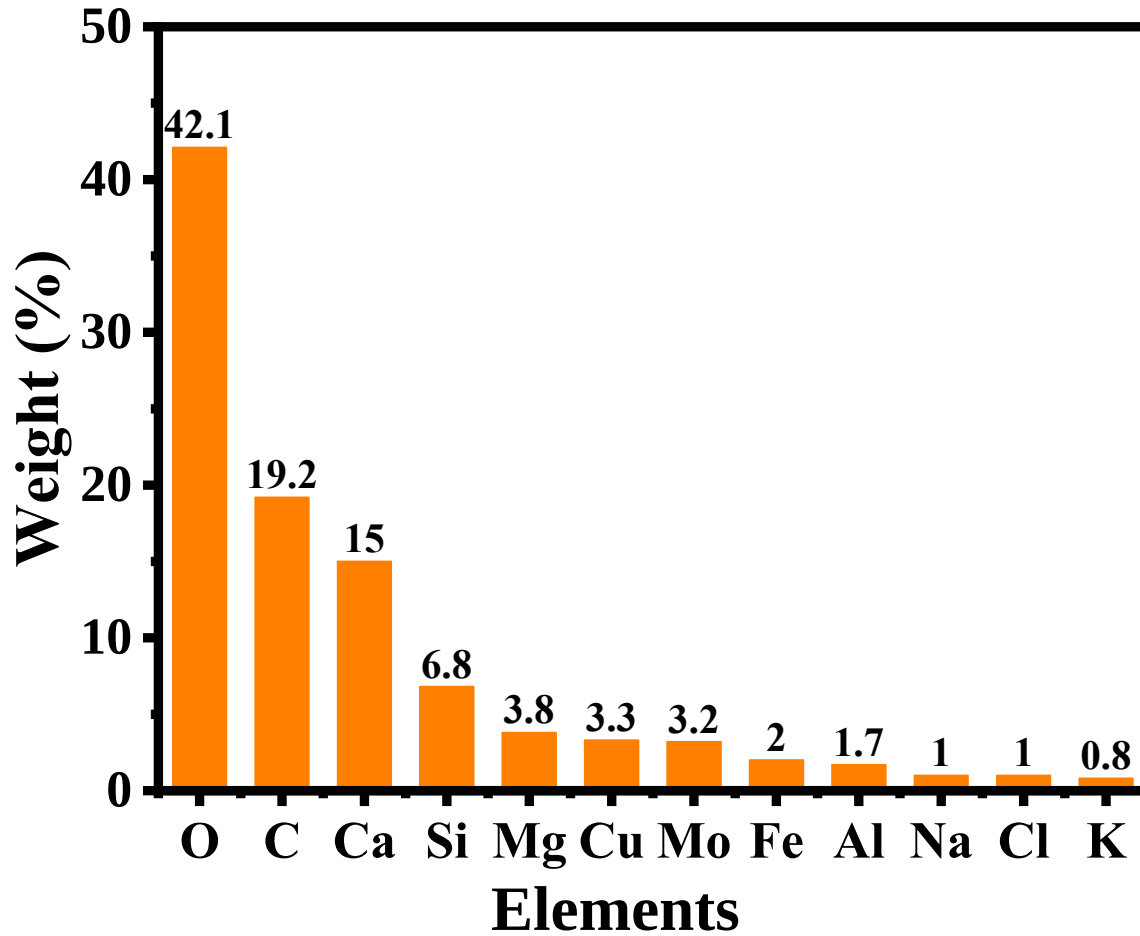
it can be observed that they are quite irregular, and the smaller particles are anchored on the surface of the bigger ones. This anchoring of the particles on one another could indicate that some dust particles acquired charges due to triboelectric charging through collision or attached to some ions. These charged particles are subjected to simple Coulombic force due to the electric field in between the electrodes of an operating EDS [24], [26], [181]. In addition to the size and shape of the particles, the elemental composition of the dust particles is also an important parameter that decides the particles' susceptibility to different charging processes due to their unique electronegativity and oxidation states in the compound they are attached. The XPS survey scan and the EDX spectrum taken from the SEM are shown in Fig.5.2. and 5.3. These results indicate the presence of oxygen (O), carbon (C), calcium (Ca), silicon (Si), magnesium (Mg), Copper (Cu), molybdenum (Mo), iron (Fe), aluminum (Al), sodium (Na), chlorine (Cl), and potassium (K), which is qualitatively in agreement with the elemental compositions of sand reported in similar works, allowing for some geographical variation [245], [246], [247], [248]. For example, the presence of sodium and potassium in our dust sample can be attributed to the coastal proximity.



**Figure 5.1.** SEM micrographs of dust particles in two magnifications (a & b).



**Figure 5.2.** XPS survey scan showing the different elements present in the dust particles



**Figure 5.3.** EDX elemental analysis of dust particles.

## 5.2.2. Parametric optimization of the EDS system

### 5.2.2.1. Dependence of the dust removal efficiency on electrode geometry at varying AC source frequency

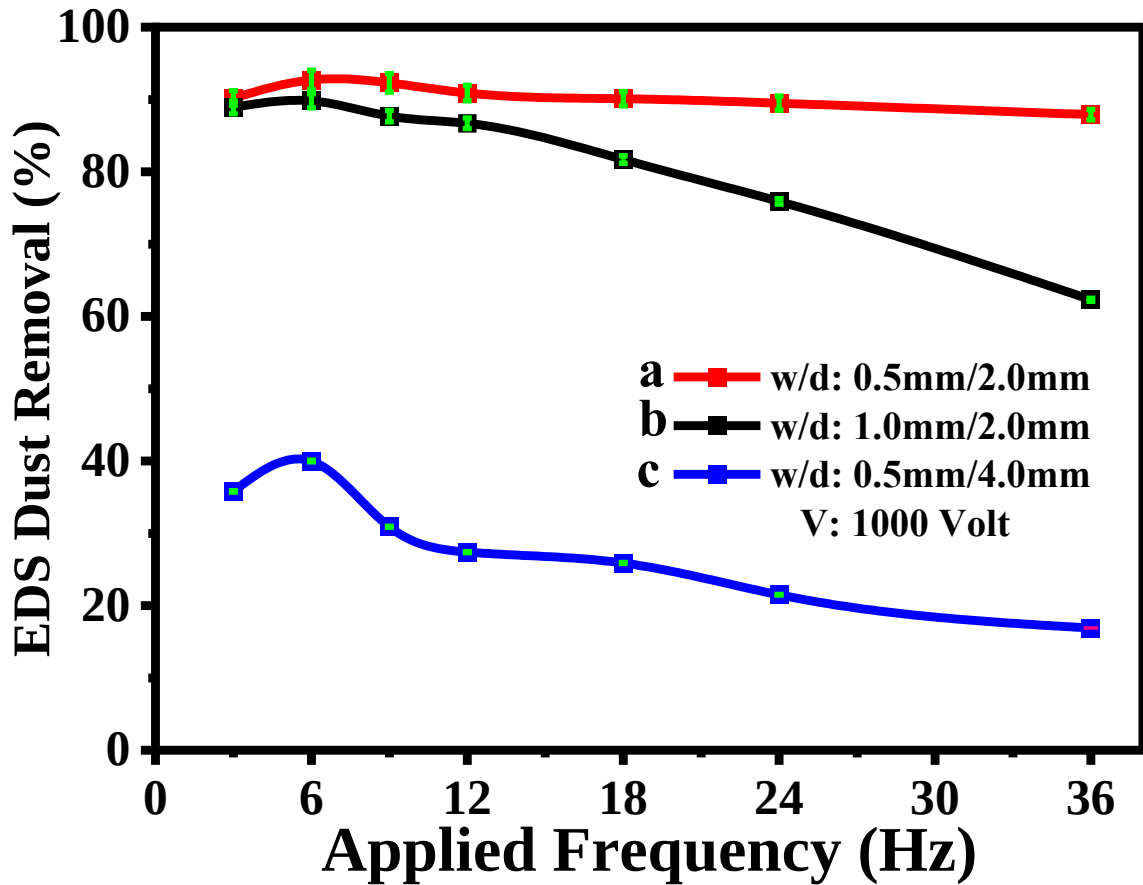
As discussed in section 5.3., the Columbic force on the charged particles depends on the intensity ( $E$ ) of the electric field, the DEP force on the field gradient ( $\nabla E$ ) and particle size, and the strength of most of the mechanical forces involved increase with the particle size [12], [22], [214]. In addition to the AC source voltage, the electrode geometry and the AC source frequency play an important role in deciding the nature of the non-uniform electric field between the electrodes. Hence, electrostatic forces mediated by the electric

field ( $E$ ) and field gradient ( $\nabla E$ ) provide the necessary acceleration to the charged and neutral dust particles to win over the impeding mechanical forces [18], [19], [30]. Also, spatial periodicity  $\lambda$  and the speed of the traveling wave established on the EDS system changes with the electrode's geometry and the AC source's frequency. Finally, the dust removal efficiency of the EDS depends on the combined effects of the particle acceleration acquired through the action and counteraction of the electrostatic and mechanical forces and the parameters of the traveling wave generated by the three-phase voltage source. In addition to the instantaneous voltage and the inter-electrode spacing, the strength of the electric field in between the electrode is affected by the dielectric nature of the dust particles. This is because the original electric field polarizes the dielectric medium between the electrodes and sets up a dipole-induced electric field opposite to the original field, reducing the net electric field [214]. The charged dust particles in between the electrodes experience the Coulomb's force and get deflected in the direction according to the charge states of the individual dust particle. Also, the spatial periodicity ( $\lambda$ ) and the speed of the traveling wave ( $V_T$ ) on the EDS system are defined by the electrode width ( $w$ ), inter-electrode spacing ( $d$ ), and the AC source frequency ( $f$ ) as  $\lambda = 3(w + d)$  and  $V_T = f\lambda$ . Hence, the combined effects of the electrode geometry and the AC source frequency jointly decide the speed of the traveling wave, which is another crucial parameter to reckon with in the process of dust repulsion. Finally, combining all, the magnitude and the direction of the horizontal component of the acquired velocity of the dust particle (due to the horizontal component of the acceleration), relative to the direction and speed of the traveling wave, influence the efficiency of dust removal.

Fig. 5.4 a–c shows the dust removal efficiency at varying frequencies, respectively, for the electrode geometrical configurations:  $w=0.5\text{mm}/d=2\text{mm}$ ;  $w=1\text{mm}/d=2\text{mm}$ ; and  $w=0.5\text{mm}/d=4\text{mm}$ . It is obvious from Fig.5.4 that in all three geometrical configurations, the dust removal efficiencies are the highest at the AC source frequency of 6 Hz, above which the efficiency declines at different levels. In each geometrical configuration of the electrode, the spatial periodicity  $\lambda$  of the traveling wave is the same, and the speed of the wave  $V_T$  in each case changes with the varying frequency. As the acceleration and the speed acquired by each dust particle are already defined, only the varying speed of the traveling wave relative to the speed acquired by each dust particle decides the final efficiency of the dust removal. The inter-electrode spacing considered in Fig. 5.4a and Fig. 5. 4c are 2mm and 4mm, respectively. The electric field between the 2mm spacing is approximately double that of 4mm. As the electric field in the case of Fig. 5.4c is less than that in Fig. 5.4a, the particles in Fig. 5.4c acquire less horizontal velocity component than those in Fig. 5a (due to lower acceleration). At the same time, due to the larger electrode spacing, the speed of the traveling wave in the case of Fig. 5.4c is higher than those of Fig. 5.4a. For the electrode configuration specified in Fig. 5.4c, at the peak frequency of 6Hz, the wave speed is 8.1 cm/sec, and the same in the case of Fig. 5.4a is 4.5 cm/sec.

Hence, for the particles in Fig. 5.4a, due to the combined effects of higher particle speed and less wave speed, more dust particles can catch up with the traveling wave speed, resulting in a higher dust removal efficiency of  $92\pm 1\%$ . On the hand, the combined effects of the lower particle acceleration due to the low electric field and the higher traveling wave speed of the dust particles result in the lower dust removal efficiency of  $42\pm 1\%$  in Fig. 5.4c. In Fig. 5.4b, although the electric field remains the same as in Fig 5.4a (due to the

same electrode spacing), as a result of a slight increase in electrode width, the spatial periodicity  $\lambda$  and speed  $V_T$  of the traveling wave in Fig. 5.4b is slightly higher than that in Fig. 5.4a at any given frequency. For example, at 6 Hz peak frequency,  $V_T$  in Fig. 5.4b is 5.4 cm/sec compared to 4.5 cm/sec in Fig.5.4a. and this combination renders the peak dust removal efficiency of  $89\pm1$  %. The less compatible wave speed with respect to the particle acceleration at higher and lower frequencies makes the dust removal efficiency less at both ends of the peak frequency. It should be noted that the effect of the electrode width on the dust removal efficiency is quite nominal compared to the drastic change brought about by the variation in inter-electrode spacing.



**Figure 5.4.** Dependence of the dust removal efficiency on different electrode geometrical configurations: (a)  $w=0.5$  mm/ $d=2$  mm, (b)  $w=1$ mm/ $d=2$ mm, and (c)  $w$

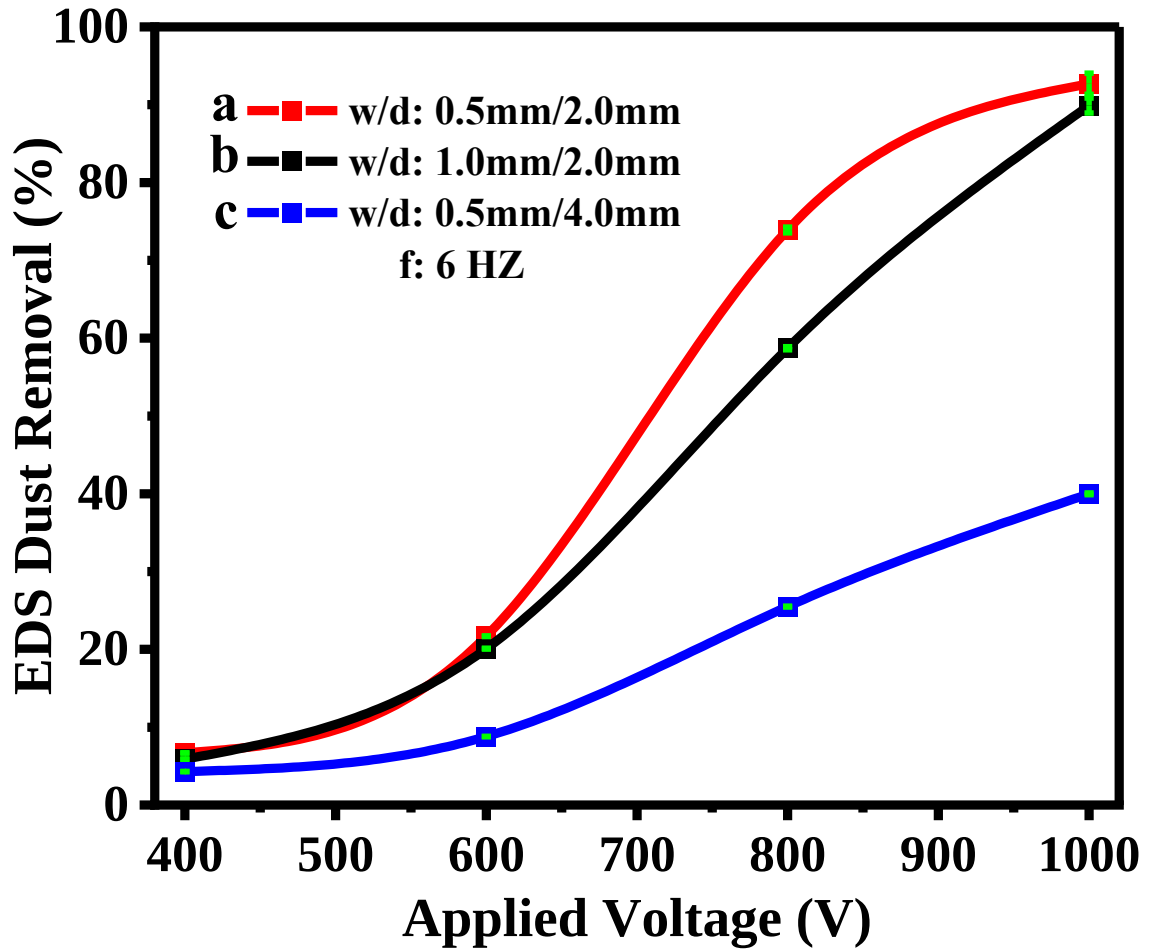
=0.5mm/d=4mm, and, at varying AC source frequency, and the fixed source voltage of 1000V, and 30 g/m<sup>2</sup> surface loading.

#### **5.2.2.2. Dependence of the dust removal efficiency on electrode geometry at varying AC supply voltage**

The same setup of electrode configurations as in the previous section was used here. Fig. 5.5a–c shows the dust removal efficiency at the constant source frequency of 6 Hz and varying AC source voltage for three variants of electrode geometrical configurations:  $w=0.5\text{mm}/d=2\text{mm}$ ;  $w=1\text{mm}/d=2\text{mm}$ ; and  $w=0.5\text{mm}/d=4\text{mm}$ . It is obvious that, in each of the three cases, the dust removal efficiencies increase almost linearly with AC source voltage, but in a different trend. It should be noted that the horizontal and vertical components of the acceleration of the dust particle and the consequent particle speed increase with the increase of the electric field, but for each case of electrode geometry, the spatial periodicity  $\lambda$  and speed of the traveling wave  $V_T$  remain constant. If we compare Fig. 5.5a and Fig 5.5c, for each value of source voltage, the electric field between the electrodes in Fig. 5.5c should be approximately half of that in the case of Fig 5.5a (due to the twice the inter-electrode spacing). The reduced electric field in Fig.5c leads up to the reduced particle acceleration and consequent reduction in the dust removal efficiency to  $40\pm1\%$  compared to nearly  $90\pm1\%$  at 1000 V in Fig. 5.5a.

On the other hand, by comparing Fig. 5.5a and Fig. 5.5b, the electric field at every supply voltage remains the same (due to the same electrode spacing), leading to the same particle kinetics in Fig. 5.5a and Fig. 5.5b. Hence, the dust removal efficiency in Fig. 5.5a and Fig. 5.5b are almost identical at 1000 V source voltage. In section 5.3, it was described that all the mechanical forces involved in the dust removal process contribute negatively to the

vertical components of forces of electrostatic origin. Hence, at lower AC supply voltages, the electrostatic forces are too weak to dominate the stronger mechanical forces to levitate the dust particles from the EDS surface, and the traveling waves have nothing to carry along, resulting in poor dust removal efficiency. Kawamoto et al. [180] studied the lunar dust with traveling waves. They concluded that the adhesion force is the main reason for the lower dust removal efficiency on the surface of the EDS system.



**Figure 5.5.** Dependence of the dust removal efficiency on different electrode geometrical configurations: (a)  $w=0.5$  mm/ $d=2$  mm, (b)  $w=1$ mm/ $d=2$ mm, and (c)  $w=0.5$ mm/ $d=4$ mm, and, at varying AC source voltage for the fixed source frequency of 6 Hz and 30 g/m<sup>2</sup> surface loading.

### **5.2.2.3. Dependence of the dust removal efficiency on dust Parameters (particle size, dust loading) and angle of inclination**

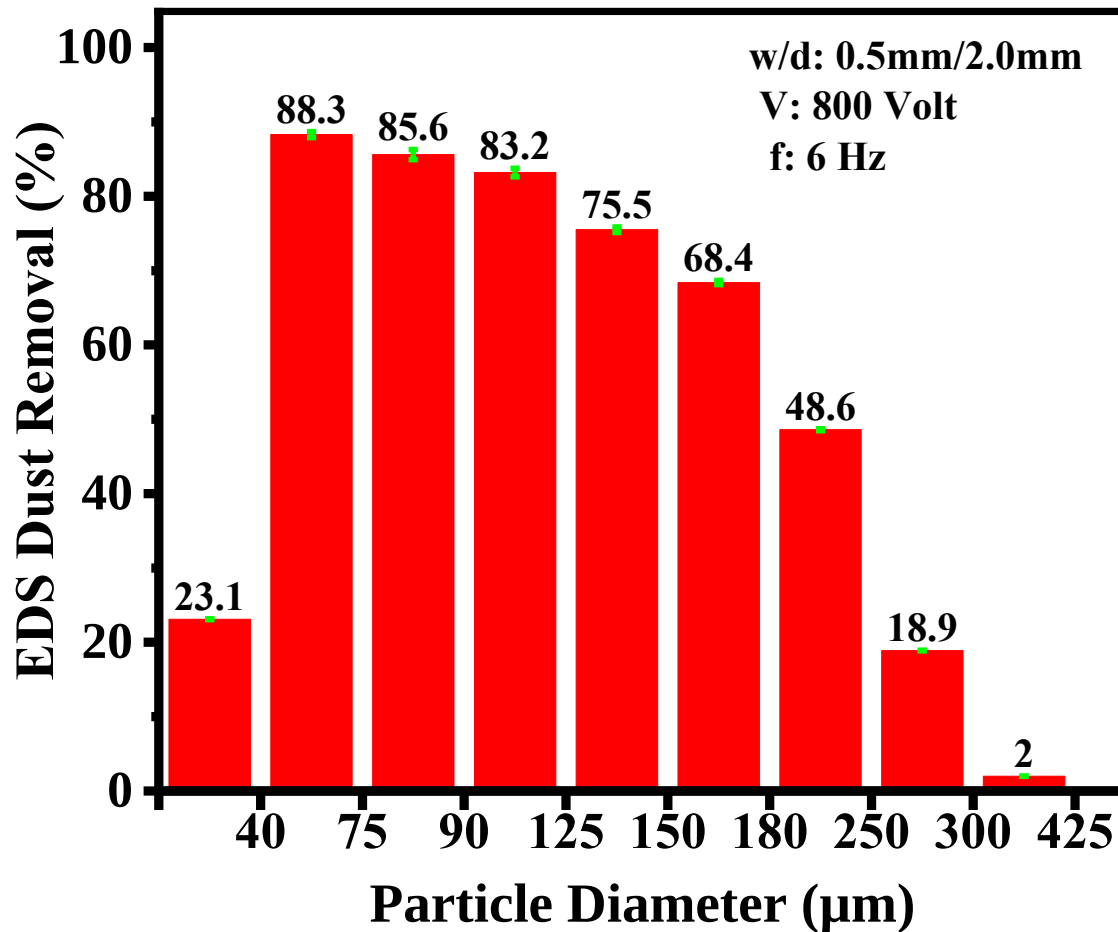
All the adversely acting mechanical forces involved in the dust removal process discussed in section 3 depend primarily on the size of the particle. Hence, the accumulated dust's size will affect the net vertical component of acceleration needed to levitate the dust particles from the EDS surface. The relative dominance of adhesive force over Coulomb's force and drag force is directly proportional to the particle size. In contrast, Van der Waals force is indirectly proportional to the particle size. In the case of electrostatic forces, the dipole-induced DEP force is directly proportional to the cube of the particle size (equation 1). Also, when the particle size gets quite bigger (comparable to the distance between the electrodes), the electrostatic force between the dust particles and the conductive rectangular electrodes is minimized, and the dust particles are not transported [18], [180]. Fig. 5.6 shows the efficiency of dust removal recorded for different dust particles segregated by their average sizes in the electrode configuration of  $w=0.5\text{mm}$ /  $d=2\text{ mm}$ , and with the supply voltage and frequency of 800 V and 6 Hz, respectively. It is quite obvious in Fig. 5.6 that the particles in the size range of 40-75 microns are most efficiently ( $90\pm1\%$ ) removed, while the removal efficiency of particles size below 40 microns is only  $22\pm1\%$  due to the weak DEP force of small particles compared to strong Vander Waals force holding the particles on the dielectric surface. On the other hand, for the particle sizes above 75 microns, the dust removal efficiency starts to gradually decline, which of course can be attributed to stronger mechanical forces, like gravitational force, the relative dominance of adhesive force over Coulomb's force. As the particle size gets bigger, this unfavorable situation prevails more, and eventually, at particle sizes above 250 microns, the dust

removal efficiency becomes very low. Finer dust particles have a greater impact than larger dust particles on the performance of a solar panel [62]; for this reason, the cleaning EDS system and its operational scheme are improved and optimized to enhance its performance in cleaning small particles from solar panels.

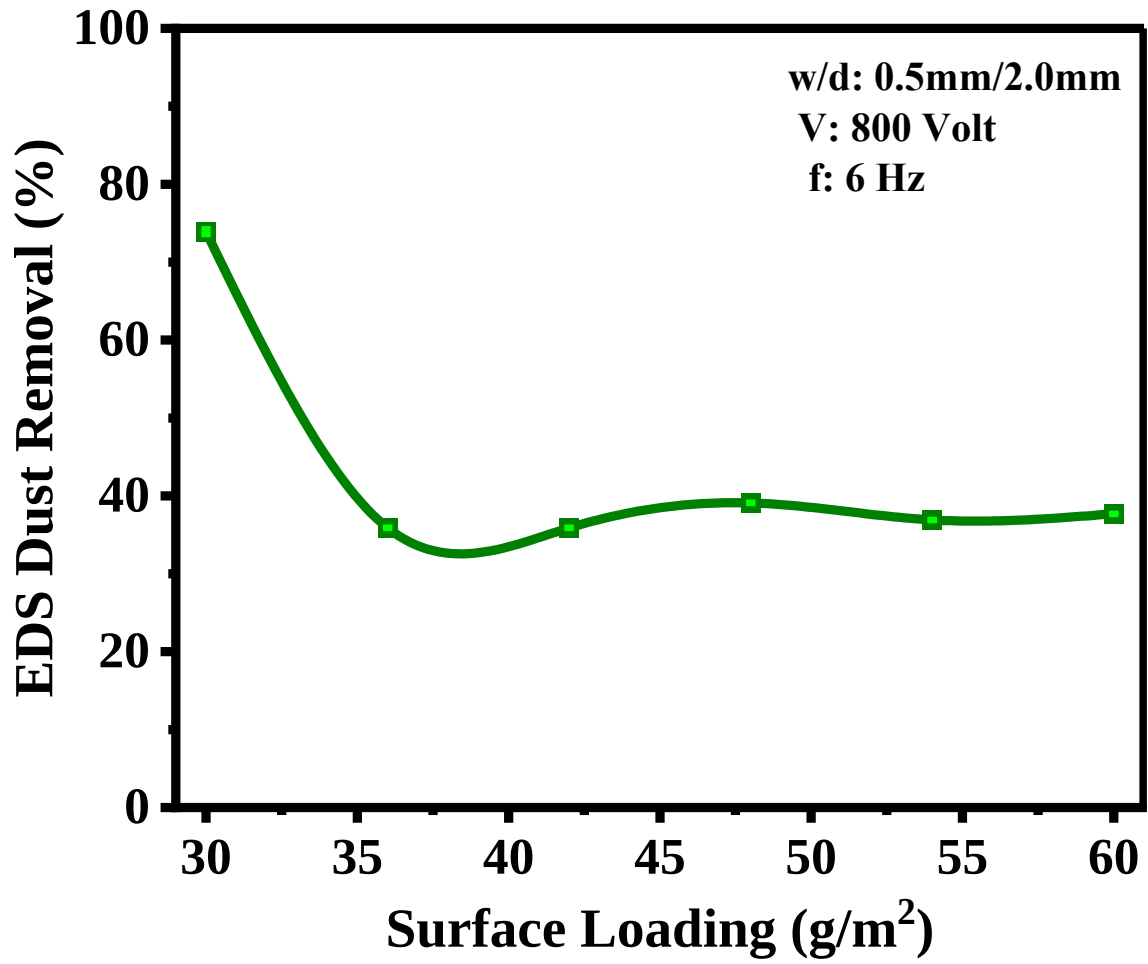
The amount of dust deposition in the unit time ( $\text{gram}/\text{m}^2$  per day) and the consequent dust removal efficiency differ from place to place depending on the geographical location and meteorological condition of the place of installation. In order to include this factor in our study, the dust removal efficiency for different dust loading levels in the range of  $30 \text{ g}/\text{m}^2$  to  $60 \text{ g}/\text{m}^2$  was investigated, and the results are shown in Fig.5.7. It is quite clear from Fig. 5.7 that the dust removal efficiency drastically decreased from  $74 \pm 1 \%$  in the case of the dust loading of  $30 \text{ g}/\text{m}^2$  to  $35 \pm 1 \%$ , even for a slight increase in dust loading. This is because the force applied to the lower particles is insufficient to overcome the mass packed on the top [197]. The solution for this situation is to incline the EDS system, where tilt angle plays an essential role in sweeping away the dust particles, especially at higher tilt angles, by increasing the gravity forces concerning the adhesion forces [173].

In the previous section, we have seen that as the particle size becomes large on an un-tilted EDS surface, the gravitational force holds the particle to the surface and makes the levitation of the particle by the electrostatic forces quite difficult. This problem can be mitigated by inclining the PV panel to a certain angle, evident from increased dust removal efficiency with the inclination angle depicted in Fig. 5.8. For this study, electrode configuration of  $w = 0.5 \text{ mm}$ /  $d = 2 \text{ mm}$ , and the supply voltage and frequency of  $800 \text{ V}$  and  $6 \text{ Hz}$ , respectively, were used. As we increased the inclination angle, the dust removal efficiency increased from  $77 \pm 1 \%$  to  $87 \pm 1 \%$ , and this value still increased when the dust

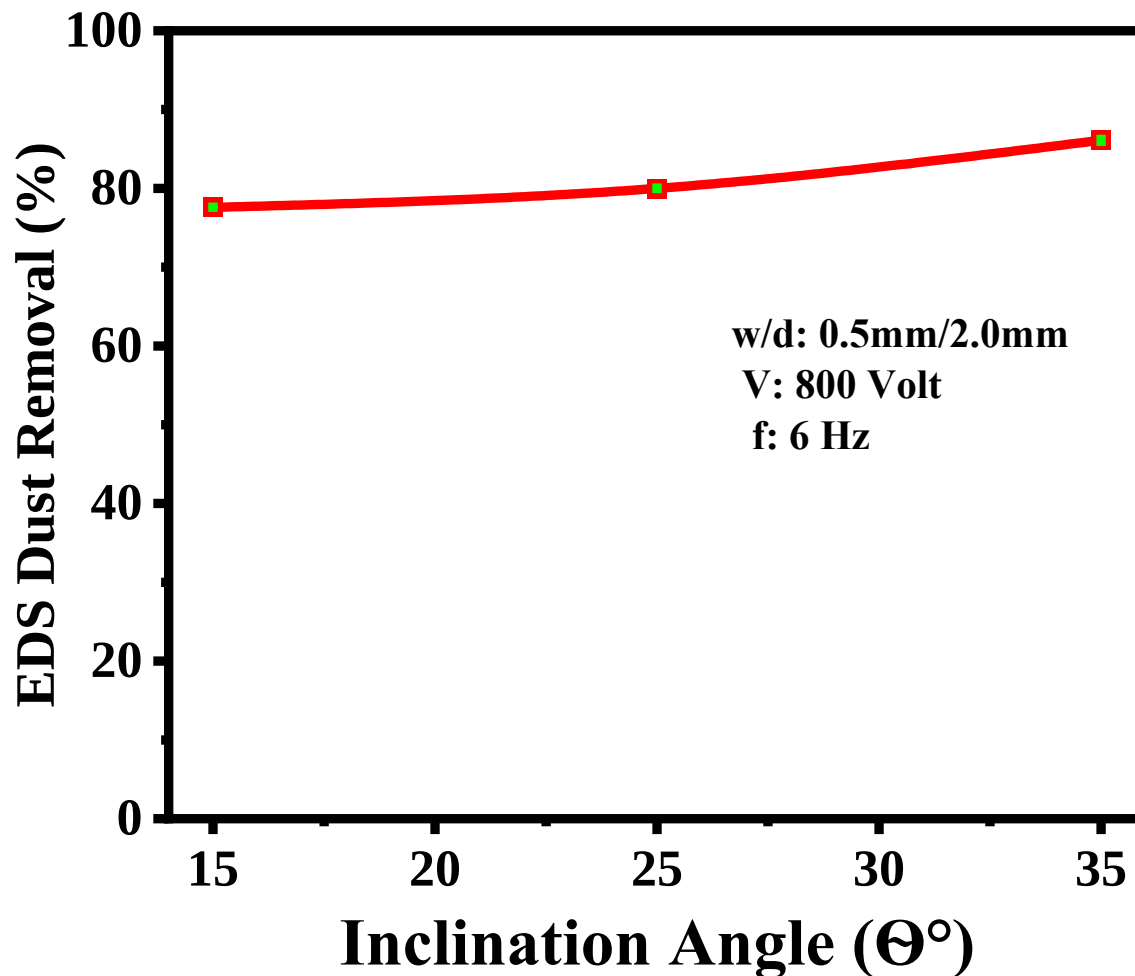
particle loading was increased from 100 mg to 200mg. The inclination of the EDS system has a significant advantage in increasing the dust removal efficiency of deposited dust particles from the EDS system, thus increasing the PV module performance. The dust removal efficiency increased when the inclination was high, and this is because the gravitational force effectively assisted the removal of the dust particles with larger particle sizes [173], [198].



**Figure 5.6.** Dependence of the dust removal efficiency on dust particle size for the electrode geometry of  $w=0.5$  mm/ $d=2$  mm, AC supply voltage 800V, frequency 6 Hz, and surface loading  $30$  g/m<sup>2</sup>.



**Figure 5.7.** Dependence of the dust removal efficiency on surface dust loading for the electrode geometry of  $w=0.5$  mm/ $d=2$  mm, AC supply voltage 800V, frequency 6 Hz

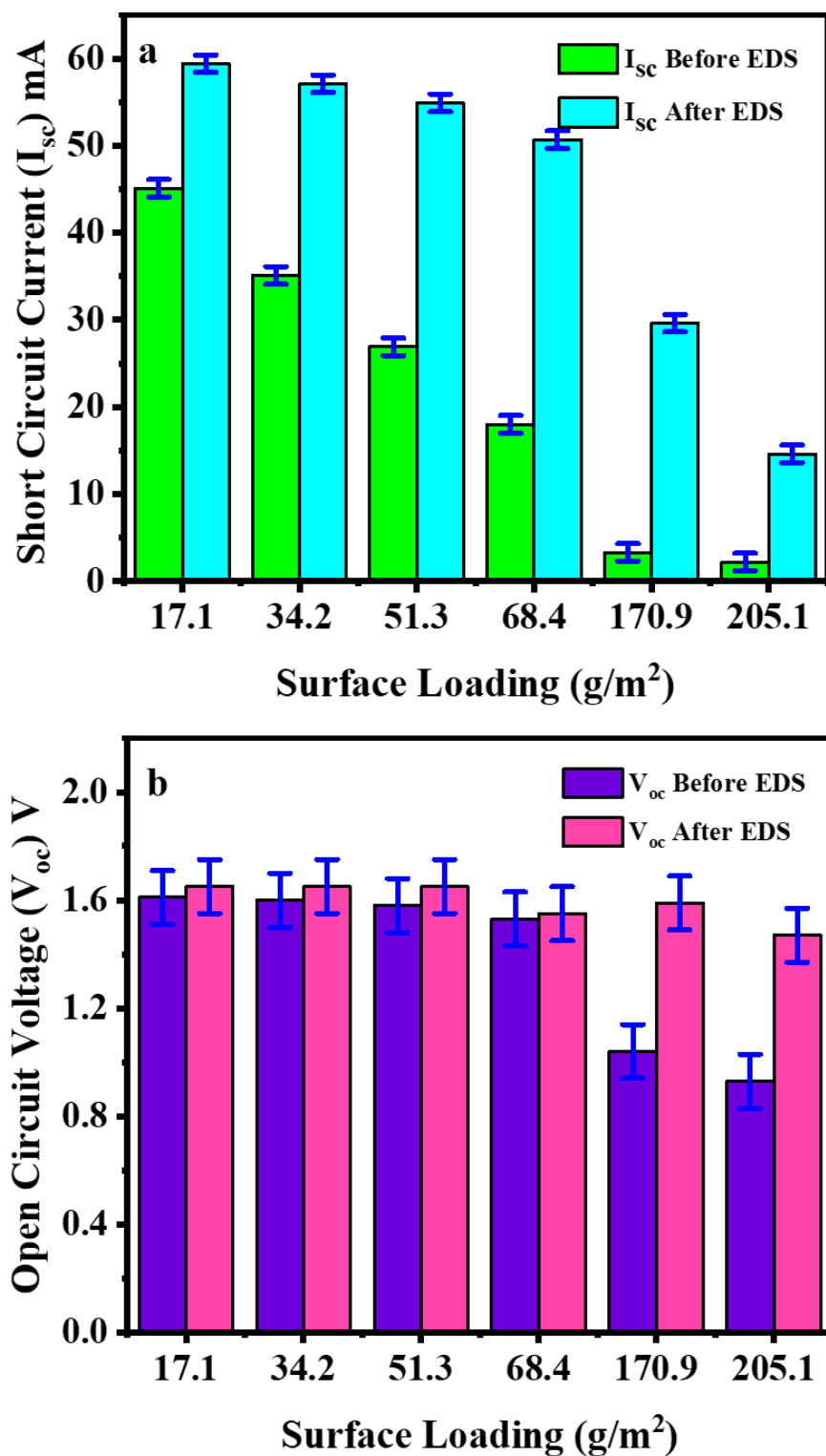


**Figure 5.8.** Dependence of the dust removal efficiency on the angle of inclinations for the electrode geometry of  $w=0.5$  mm/ $d=2$  mm, AC supply voltage 800V, frequency 6 Hz, and surface loading  $30 \text{ g/m}^2$ .

#### 5.2.2.4. Performance of EDS on Solar panels under actual working conditions

As the dust accumulation on solar panels gets thicker, the solar light transmission on the active area of the solar panel becomes proportionally less, leading to the decline of the important photovoltaic figures of merits like short circuit current ( $I_{sc}$ ), open circuit voltage ( $V_{oc}$ ), fill factor (FF), and the photovoltaic efficiency ( $\eta$ ). Fig. 5.9a shows the short circuit current ( $I_{sc}$ ) before and after the application of electrodynamic dust repulsion for various levels of dust loading on the commercially available polycrystalline Si solar panel, exposed

to the natural solar irradiance of 9.4 klux ( $1380 \text{ w/m}^2$ ), which is slightly above the normal testing condition of  $1000 \text{ w/m}^2$ . It is quite clear from Fig. 5.9a that the short circuit current ( $I_{sc}$ ) generated due to photo-induced electrons reduces linearly with the reduced solar irradiance as a result of increased dust masking, and also after electro-dynamic dust repulsion for every level of dust loading, the short circuit current ( $I_{sc}$ ) gets back to its characteristic standard value, which indicates that the EDS system helps to improve the performance of the solar cell in terms of photo voltaic power output. It is known that unlike the short circuit current ( $I_{sc}$ ), the open circuit voltage ( $V_{oc}$ ) of the solar cell remains constant for a wide range of light irradiance below the standard irradiance of  $1000 \text{ w/m}^2$ , as shown in Fig. 5.9b and below a certain level of illumination, the open circuit voltage ( $V_{oc}$ ) deteriorates to a very low value, which is attributed to reduced shunt resistance, and increased serial resistance of the solar panel. The reduction of open circuit voltage ( $V_{oc}$ ), accompanied by the undesired shunt and serial resistances, leads to the reduction of important photovoltaic parameters like fill factor (FF) and the characteristic photovoltaic efficiency ( $\eta$ ). Fig.5.9b also shows the restoration of open circuit voltage ( $V_{oc}$ ) to its characteristic value for each level of dust loading once electro-dynamic dust repulsion is applied. This study demonstrates the effectiveness of the EDS repulsion in the process of improving the photovoltaic performance of the solar cell.



**Figure 5.9.** Improve performance of solar cells due to EDS dust repulsion in terms of (a) Short circuit current ( $I_{sc}$ ) and (b) Open circuit voltage ( $V_{oc}$ ) at different dust

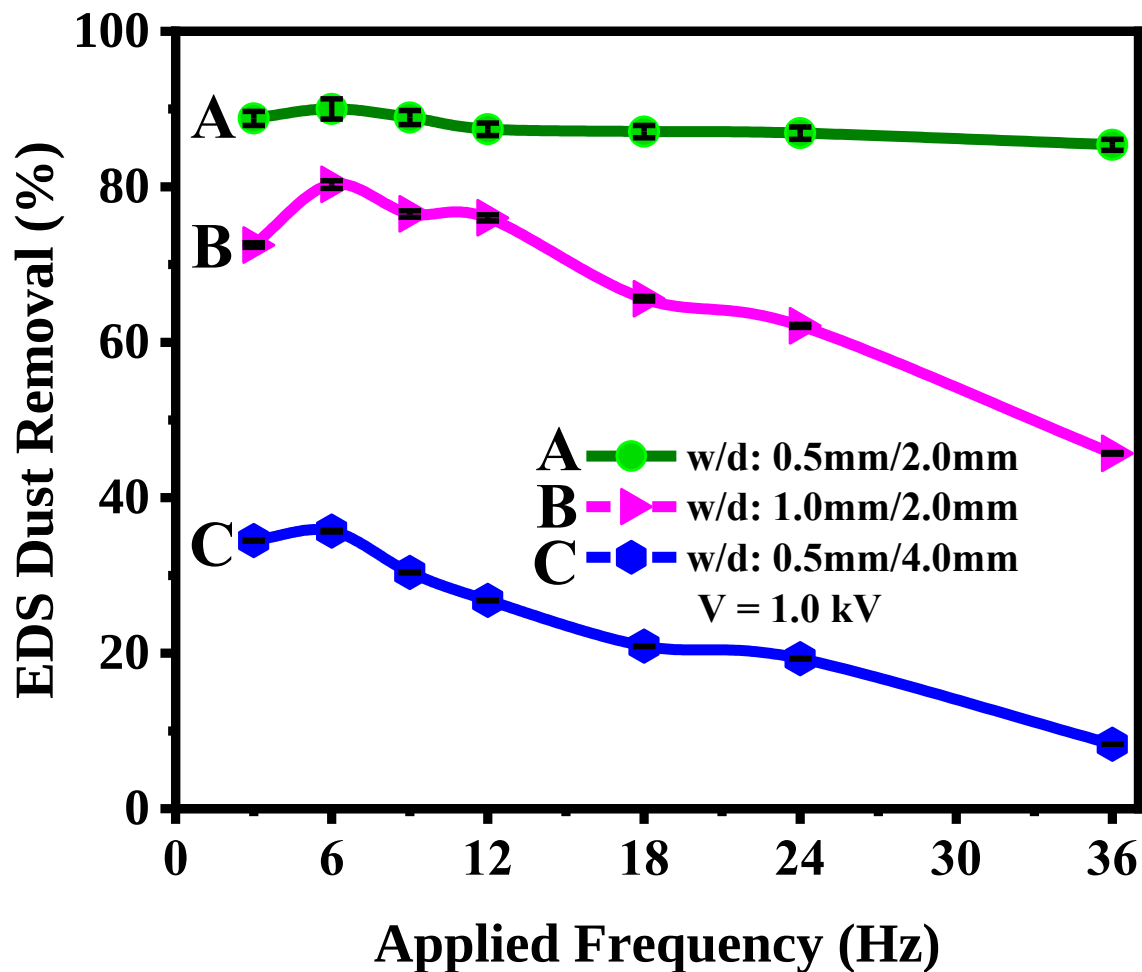
loading at the solar irradiance of  $1380 \text{ w/m}^2$ . The selected frequency and voltage are 6 Hz and 800V, respectively.

### **5.3. Single-Phase Experimental Work**

#### **5.3.1. Dust removal efficiency at varying AC source frequency**

The effectiveness of removing dust at different frequencies is displayed in Fig. 5.10A-C for the following electrode geometrical configurations:  $w = 0.5\text{mm}/d = 2.0\text{mm}$ ,  $w = 1.0\text{mm}/d = 2.0\text{mm}$ , and  $w = 0.5\text{mm}/d = 4.0\text{mm}$ . Maximum efficiency in removing dust is achieved in all three geometries at an alternating current (AC) source frequency of 6 Hz and then gradually decreases with increasing frequency. The standing wave's speed varies with frequency, but its spatial periodicity remains constant across all possible electrode geometries. How well dust is removed depends on how fast the wave changes and how fast each particle moves. In Fig. 5.10A and 5.10B, the electrode widths of 0.5mm and 1.0mm are taken into account. The minor increase in electrode width from figure 5.10A to figure 5.10B causes the standing wave's spatial periodicity and speed to be slightly greater in figure 5.10B at any given frequency. For instance, the peak dust removal effectiveness of  $80\pm1\%$  is achieved by combining the standing speed of 3.6 cm/sec in Fig. 5.10B with a 6 Hz peak frequency compared to 3.0 cm/sec in Fig. 5.10A. Fig. 5.10A and 5.10C show 2.0mm and 4.0mm inter-electrode separation. As the electric field in Fig. 5.10A is greater than in Fig. 5.10C, the particles in Fig. 5.10A levitate more and gain more collisions leading to more velocity. Due to smaller electrode spacing, Fig. 5.10A's standing wave is slower than Fig. 5.10C's. At 6Hz, the wave speed for Fig. 5.10A's electrode design is 3.0 cm/sec, while Fig. 5.10C's is 5.4 cm/sec. So, in Fig. 5.10A, more dust particles may catch up with standing wave speed due to increased particle levitation

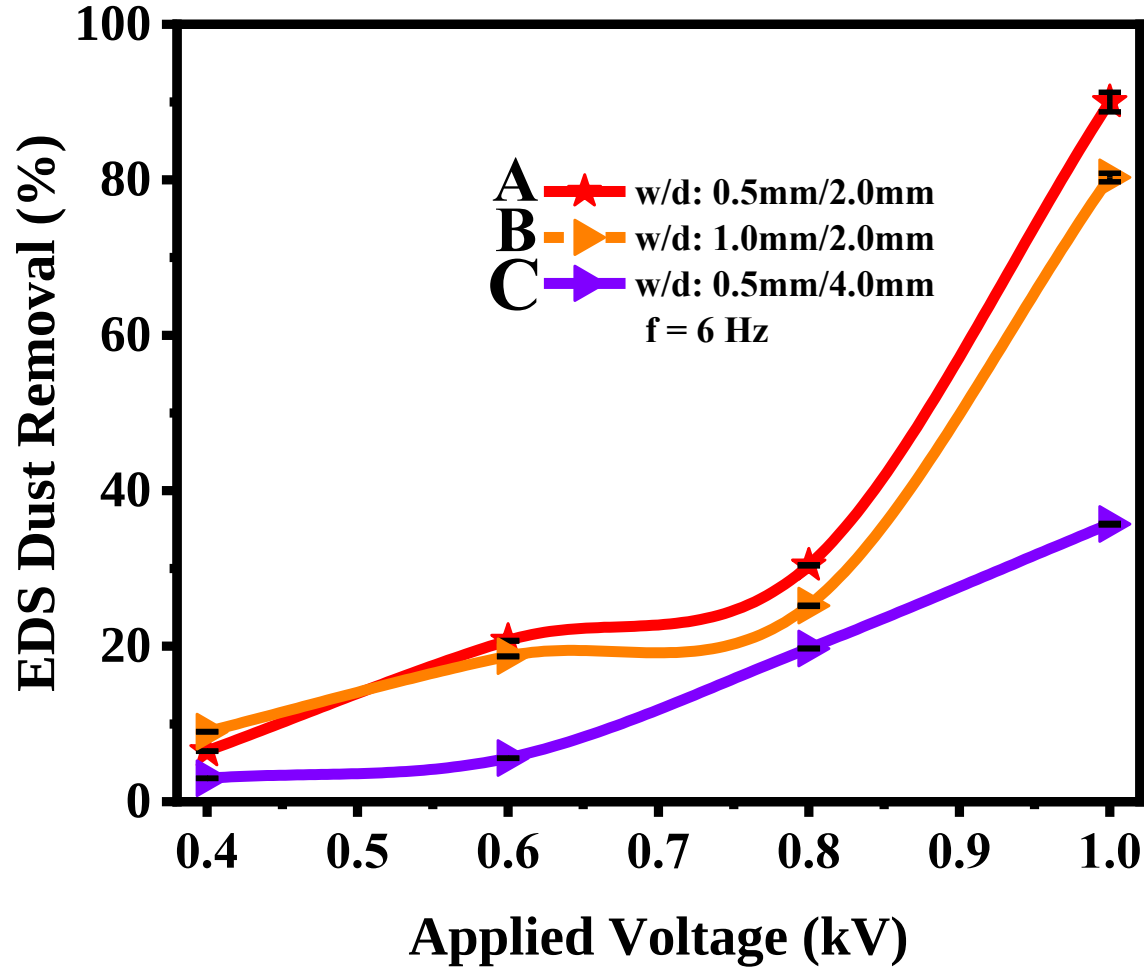
resulting in the collisions between particles that lead to faster particle speed and less wave speed, resulting in  $90\pm1\%$  dust removal effectiveness. On the other hand, as can be seen in Fig. 5.10C, the reduced dust removal effectiveness of  $35\pm1\%$  results from the combined impacts of the greater standing wave speed of the dust particles and the lower particle levitation due to the low electric field. Lower and higher frequencies are less effective in removing dust because their wave speeds are less compatible with the particle levitation at those extremes. It is important to notice that the difference in inter-electrode spacing has a much larger impact on dust removal effectiveness than does the electrode width itself.



**Figure 5.10.** Dust removal effectiveness as a function of AC source frequency, the fixed source voltage of 1.0 kV, and surface loading of 30 g/m<sup>2</sup>, for three distinct electrode geometrical configurations: (A)  $w=0.5\text{mm}/d=2.0\text{ mm}$ ; (B)  $w=1.0\text{ mm}/d=2.0\text{mm}$ ; and (C)  $w=0.5\text{mm}/d=4.0\text{mm}$ .

### 5.3.2. Dust removal efficiency at varying AC source voltage

Similar electrode setups to those described before were used. Three alternative electrode geometrical configurations ( $w=0.5\text{mm}/d=2.0\text{mm}$ ,  $w=1.0\text{mm}/d=2.0\text{mm}$ , and  $w=0.5\text{mm}/d=4.0\text{mm}$ ) are shown in Fig. 5.11A-C, each with their respective dust removal efficiencies at a constant source frequency of 6 Hz and variable AC source voltage. Contrary to what one might expect, the efficiency with which dust is removed rises practically linearly with increasing AC source voltage. While the spatial periodicity and speed of the standing wave are unaffected by the electrode geometry, the vertical component of the dust particle's levitation and the resulting particle speed rise with an increase in the electric field. Particle dynamics in Fig. 5.11A and Fig. 5.11B are the same because the electric field is constant for all supply voltages (since the electrode spacing is constant). Therefore, the dust removal efficiencies shown in Figure 5.11A and 5.11B are  $90\pm1\%$  and  $80\pm1\%$ , respectively, for a source voltage of 1.0 kV. However, if we compare Figure 5.11A and Figure 5.11C, we can see that the electric field between the electrodes in Figure 5.11A should be larger than that in the case of Figure 5.11C for all source voltage values (due to the twice the inter-electrode spacing). Dust removal effectiveness is improved from around  $35\pm1\%$  at 1.0 kV in Fig. 5.11C to  $90\pm1\%$  when the electric field is raised, as shown in Fig. 5.11A.

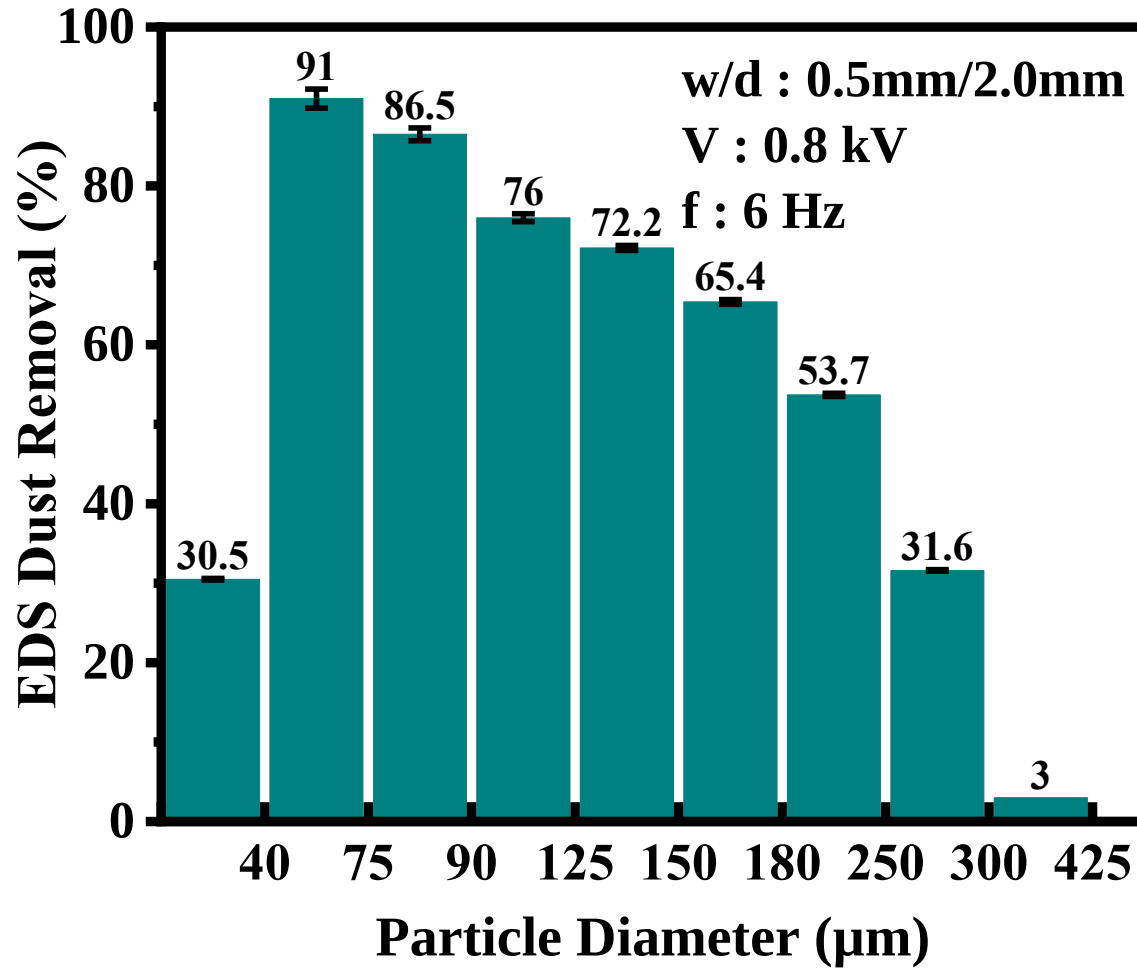


**Figure 5.11.** Dust removal effectiveness as a function of AC source voltage, the fixed source voltage of 1.0 kV, and surface loading of  $30 \text{ g/m}^2$ , for three distinct electrode geometrical configurations: (A)  $w=0.5\text{mm}/d=2.0 \text{ mm}$ ; (B)  $w=1.0 \text{ mm}/d=2.0\text{mm}$ ; and (C)  $w =0.5\text{mm}/d=4.0\text{mm}$ .

### 5.3.3. Dust removal efficiency at varying dust particle size

The mechanical forces (adhesive, drag, and gravity) that work against dust removal are generally proportional to the particle's size. Therefore, the net vertical component of levitation required to lift the dust particles from the EDS surface will be affected by the size of the deposited dust. Particle size directly correlates with the relative dominance of adhesive force over Coulomb's force and drag force and an indirect correlation with Van

der Wall's force. When it comes to electrostatic forces, the dielectrophoretic force (DEP) force is proportional to the cube of the particle's size. Also, the electrostatic force between dust particles and the conductive rectangular electrodes is less when the particles are bigger (compared to the distance between the electrodes) [21], [249]. Dust removal effectiveness was measured for particles of varying sizes using a supply voltage and frequency of 0.8 kV and 6 Hz and a  $w=0.5\text{mm}/d=2\text{mm}$  electrode arrangement (see Fig. 5.12). As can be seen in Fig. 5.12, particles between 40 and 75 microns in size are removed with an efficiency of  $90\pm1\%$ , while particles below 40 microns in size are removed with an efficiency of only  $29\pm1\%$ . This is because small particles' DEP force is weak compared to the strong Vander Walls force holding the particles on the dielectric surface. However, dust removal effectiveness begins to drop off sharply once particles reach diameters greater than 75 microns, which is understandable given because of the large mechanical forces in the removal process, such as gravity and the relative strength of adhesion force compared to Coulomb's force. This adverse scenario becomes more prevalent at larger particle sizes, and at particle sizes beyond 250 microns, the efficiency of dust removal drops dramatically. Since finer dust particles are more detrimental to a solar panel's efficiency than bigger dust particles [176], the cleaning EDS system and its operational scheme are developed and adjusted to increase the efficiency in clearing away dust and dirt from solar cells.

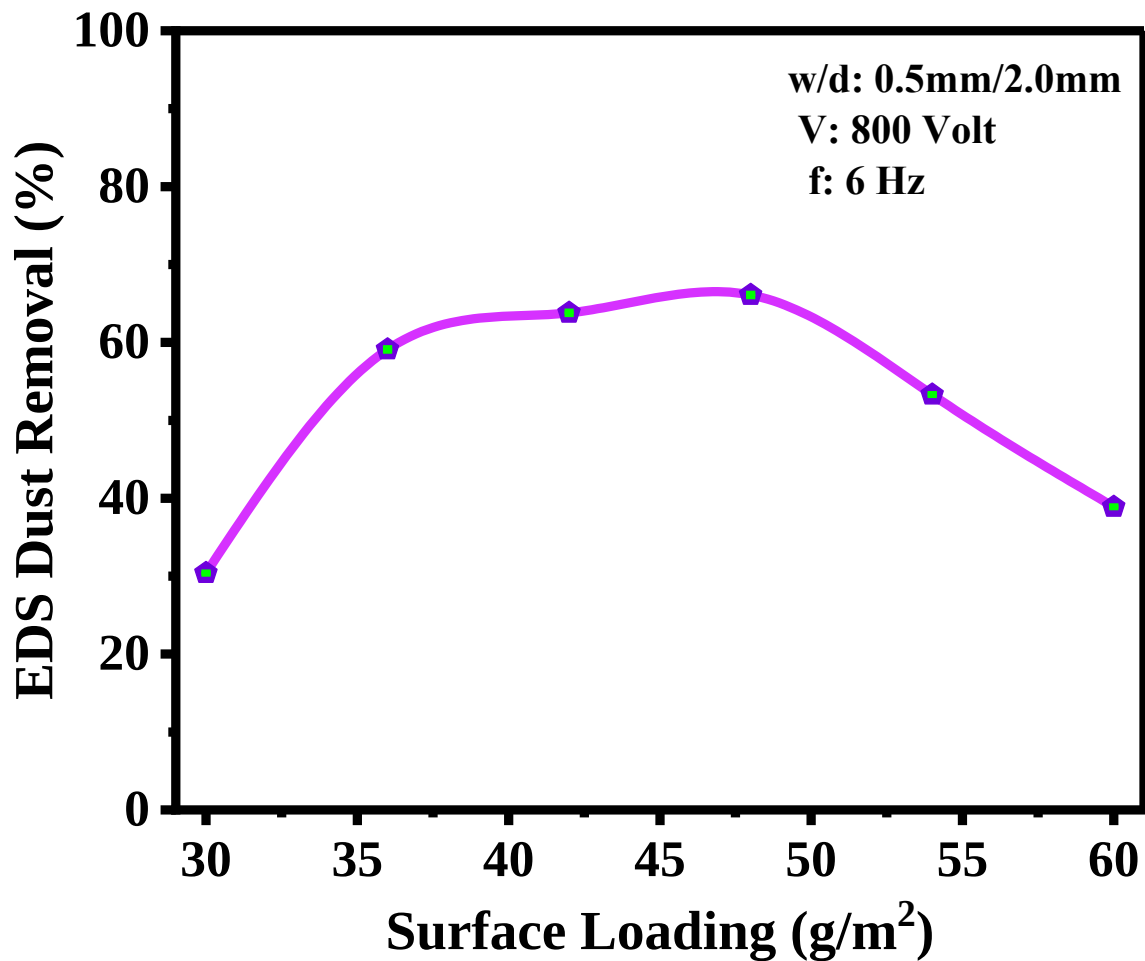


**Figure 5.12.** Dust removal effectiveness as a function of dust particle size at fixed AC source frequency of 6 Hz, voltage 0.8 kV, and surface loading of  $30\text{ g/m}^2$  for the electrode geometry  $w=0.5\text{mm}/d=2.0\text{ mm}$ .

#### 5.3.4. Dust removal efficiency at varying dust loading

Location and climate significantly impact how much dust is deposited per unit of time (grams per square meter per day) and how effective dust suppression systems are. To account for this variable, we measured the efficiency of dust removal at various dust loading densities (from  $30\text{ g/m}^2$  to  $60\text{ g/m}^2$ ), and the results are presented in Fig.5.13. The efficiency of the EDS system was shown to be significantly lower at low dust loading levels, then increased with increasing dust loading, and in some cases decreased with

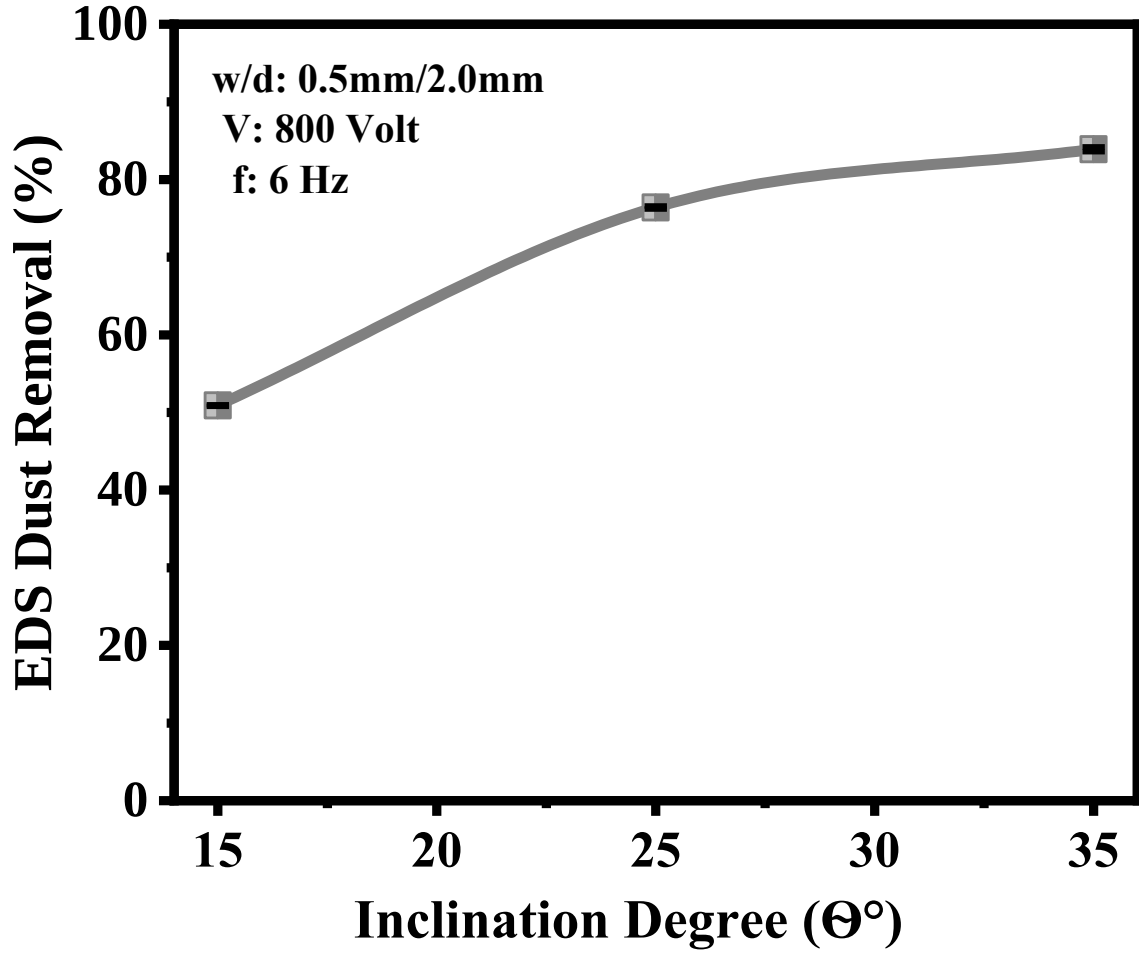
further increase in dust loading as shown in Fig. 5.13. [20], [250]. This is because when the dust density at the surface rises, the particles within the EDS move vertically, up and down, then jump out of the surface via collisions. Particles in the upper layer move about more often due to the increased collision interaction between dust particles as the dust deposition rises. Efficiency rises as the movement does, particularly at the points (30-45)  $\text{g/m}^2$  then start the efficiency decrease as shown in the figure between (50-60)  $\text{g/m}^2$  due to the force applied to particles being insufficient to overcome the mass packed on top [197], [251]. The EDS efficiency was about  $30.4 \pm 1\%$  at the lightest dust loading (about  $30 \text{ g/m}^2$ ). So, a single-phase might be the best option for extreme dust loads.



**Figure 5.13.** Dust removal effectiveness as a function of surface dust loading at fixed AC source frequency of 6 Hz, voltage 0.8 kV, and surface loading of 30 g/m<sup>2</sup> for the electrode geometry w=0.5mm/d=2.0 mm.

### **5.3.5. Dust removal efficiency at a varying inclination angle**

The performance of the PV modules can be improved via the EDS system's inclination, which improves the cleaning rate efficiency of deposited dust particles. At a steeper angle, gravity helps do the work of cleaning by drawing out dirt and debris. When the degree of tilt is raised, the EDS system's cleaning efficiency also increases [173], [252], as shown in Fig. 5.14. Fig. 5.14 shows the mitigated dust particles by inclining the PV panel to a certain angle. It describes the increase in dust removal efficiency as the inclination angle increases. This analysis utilized an electrode configuration of w=0.5 mm/ d=2 mm, a supply voltage of 0.8 kV, and a frequency of 6 Hz. When the inclination angle was raised from 50.9±1 % to 83.9±1 %, the effectiveness of collecting dust particles rose, and this trend continued when the dust particle loading was raised from 100 mg to 200 mg.



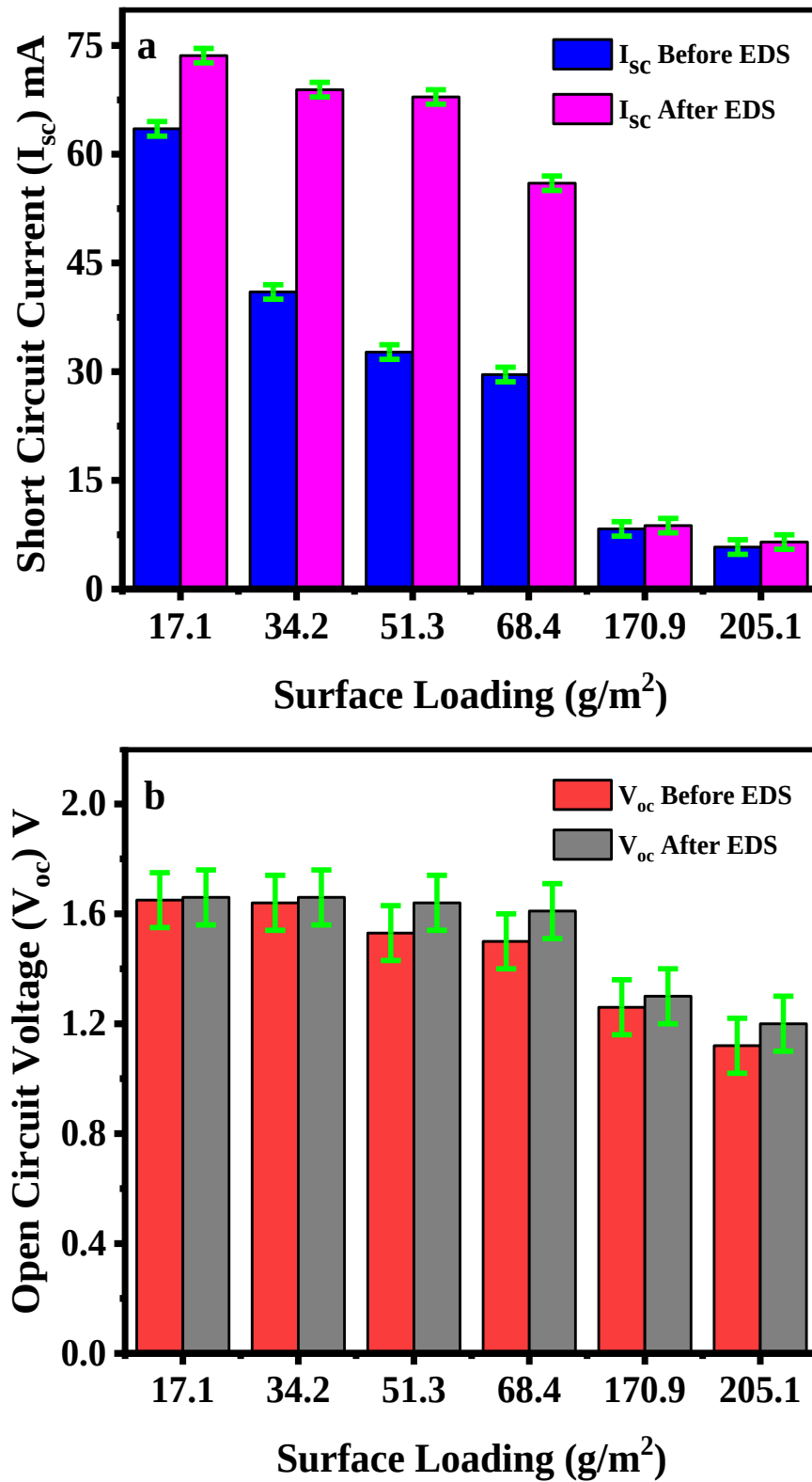
**Figure 5.14.** Dust removal effectiveness as a function of inclination of the angle at fixed AC source frequency of 6 Hz, voltage 0.8 kV, and surface loading of 30 g/m<sup>2</sup>, for the electrode geometry w=0.5mm/d=2.0 mm.

### 5.3.6. EDS performance on solar panels under real-world operating circumstances

The solar light transmission on the solar panel's active area decreases proportionally as the amount of dust buildup increases, which results in a decline in key photovoltaic performance metrics like short circuit current ( $I_{sc}$ ), open circuit voltage ( $V_{oc}$ ), fill factor (FF), and the photovoltaic efficiency ( $\eta$ ). On a commercially available polycrystalline Si solar panel exposed to a 550 W laboratory lamp, Fig. 5.15a displays the short circuit current ( $I_{sc}$ ) before and after applying electrodynamic dust repulsion at various degrees of dust

loading. It is evident from Fig. 5.15a that the short circuit current ( $I_{sc}$ ) caused by photo-induced electrons decreases with reduced solar irradiance as a result of increased dust masking, and that the short circuit current ( $I_{sc}$ ) returns to its standard value after electro-dynamic dust repulsion for every level of dust loading, indicating that the EDS system aids in improving the performance of the solar cell in terms of photovoltaic power output.

The solar cell's open circuit voltage ( $V_{oc}$ ) is known to remain constant across a large range of light irradiance, in contrast to the short circuit current ( $I_{sc}$ ). The open circuit voltage ( $V_{oc}$ ) decreases to a very low value below a specific degree of illumination, as shown in Fig. 5.9b, which is related to the solar panel's lowered shunt resistance and increased serial resistance. Important solar characteristics like fill factor (FF) and typical photovoltaic efficiency ( $\eta$ ) are reduced as a result of the decrease in open circuit voltage ( $V_{oc}$ ), together with the undesirable shunt and serial resistances. Once the electro-dynamic dust repulsion is applied, the open circuit voltage ( $V_{oc}$ ) returns to its typical value for each dust loading level, as shown in Fig. 5.15b. This research proves that EDS repulsion is a viable method for enhancing solar cells' photovoltaic performance.



**Figure 5.15.** Improve performance of solar cells due to EDS dust repulsion in terms of (a) Short circuit current ( $I_{sc}$ ) and (b) Open circuit voltage ( $V_{oc}$ ) at different dust

loading. The selected frequency, voltage and lamp power are 6 Hz, 800V and 550W, respectively.

## 5.4. Simulation Work

### 5.4.1. Theory

The electric field's effect in the EDS system was computed by the maximum value of the electric field on the EDS system. In other words, one value at the top point in the graph of the electric field where the electric field is max [30]. However, the electric field is not a fixed point. It changes simultaneously along the EDS system's spatial period (non-uniform electric field). In this case, the electric field is computed by finding the electric field's average value at all instants on the EDS system.

In our work, we will approximate our electric field function as if it was constant at various intervals. The approximation leads us to a more precise value for the electric field. The approximations get better and better as the spatial period change ( $d\lambda$ ) is smaller and smaller. The approximation can involve adding a massive number of tiny intervals of ( $d\lambda$ ). The value of these approximation approaches can be described simply as the area under the curve.

Assuming the area under the curve represents the potential applied to the EDS system along the EDS system's spatial period as in figure (5.16 - a). Choosing a sliver to present the approximation value of the potential along the spatial period as in figure (5.16-b). The little ( $dU$ ) represents the area of this sliver. The sliver's height is the electric field ( $E$ ) which is the graph's height. The width of the silver is the changing interval of the spatial period ( $d\lambda$ ). By considering that a sliver is a rectangle, the area under the graph is approximately

$$dU = E(\lambda)d\lambda \quad (5.1)$$

The derivative of any function giving the area under the graph is equal to the function for the chart itself. The derivative of the area function under the curve at a specific interval must equal the graph's height at each point between that interval. In other words, the integration of the graph's height at a particular interval must equal the area function under the graph, which is called the fundamental theorem of calculus [253]. The applied potential is equal to

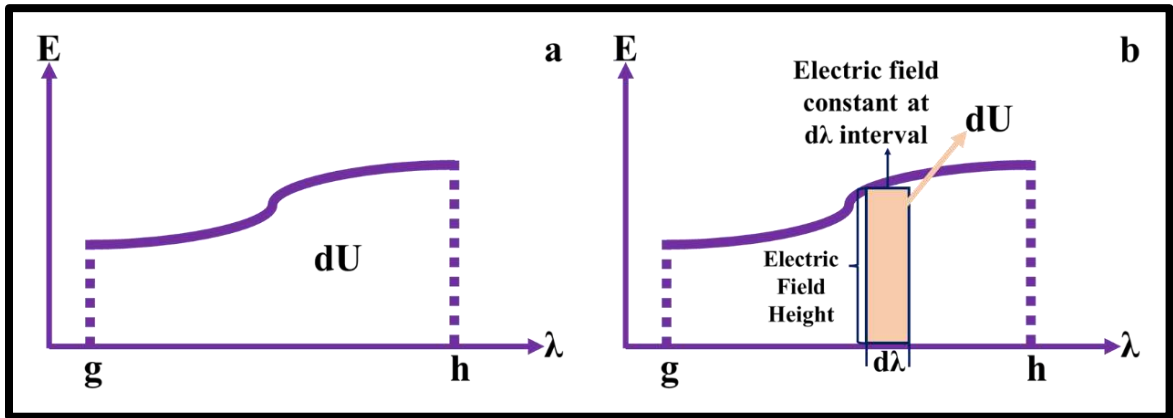
$$U = \int_{\text{Lower bound}}^{\text{Upper bound}} E(\lambda) d\lambda = U(\text{Upper bound}) - U(\text{Lower bound}) \quad (5.2)$$

In summary, the average value for any function  $f(x)$  at some interval between the upper bound ( $h$ ) and lower bound ( $g$ ) is the integral of the function on that interval divided by the width of that interval.

$$\text{Average } f(x) = \frac{\text{The area under the graph}}{\text{Width of the area}} = \frac{\int_g^h f(x) dx}{h - g} \quad (5.3)$$

In the end, the average value of the electric field equal to

$$\text{Average } E(\lambda) = \frac{dU}{d\lambda} = \frac{\int_g^h E(\lambda) d\lambda}{h - g} \quad (5.4)$$

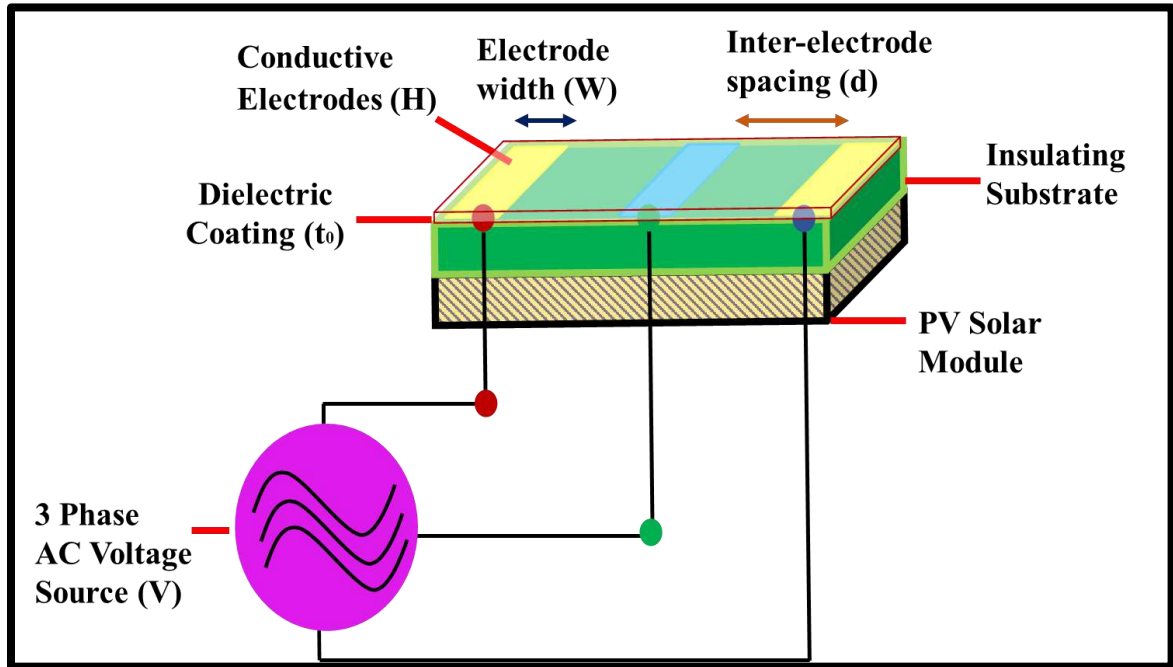


**Figure 5.16.** (a-b) A schematic diagram explains the theoretical formula to compute the average electric field (V/m).

### 5.4.2. Model

The EDS design involves a lot of parametric variables. Using modeling can determine the optimum design to remove dust particles from PV surfaces while optimizing most variables of the EDS system that affect the electrical field strength. Our main model was developed using the simulation programs Mathematica and COMSOL Multiphysics®. The parametric variables and the electric field strength on the EDS configuration were modeled in three dimensions for simulation with the real experimental work. The computational geometry for the effect of the parametric variables of the EDS system is illustrated in Fig. 5.17. Figure 5.17 shows all the EDS systems without dust particles. The EDS's electrodes can be connected to a multi-phase power supply to produce traveling waves or to a single-phase to create standing waves. All these waves can transfer dust particles from the surface of solar cells. Also, they repel the dust before reach to the surface of EDS. The power supply's output waves can repel the dust particles from EDS's surface in any form of waves, such as square waves, sinusoidal waves, sawtooth waves, and rectangular waves. The power supply energizes the conductive electrodes with high voltages [17], [26], [30], [164], [172], [176], [254]. Our work's power supply is a three-phase power supply that produces traveling waves to mitigate the dust particles from the structure periodically. The EDS system produces the electric field from a periodic array of conductive parallel rectangular electrodes that each had a width of ( $w$ ), an interspacing distance ( $d$ ) between axes of symmetry of neighboring electrodes, and thickness ( $H$ ). The electrodes were deposited on a substrate and embedded below a dielectric cover sheet at a distance ( $t_0$ ) below the EDS top surface. The substrate and dielectric cover material are the same materials (Borosilicate material). Electrodes were energized by applied voltage with peak-to-peak amplitude ( $V$ ),

the three consecutive electrodes were made of copper and activated as the first and third electrodes were energized (with yellow color), and the second electrode was grounded (with blue color).

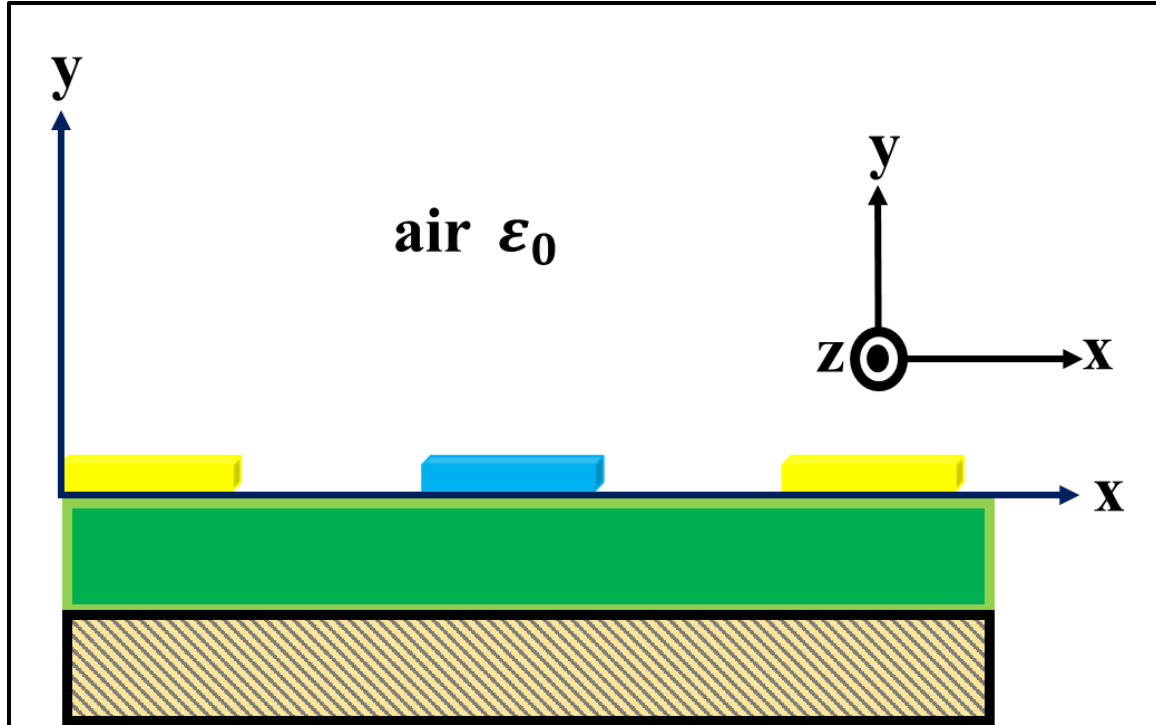


**Figure 5.17.** Complete schematic diagram of the EDS system with all parts.

### 5.4.3. Electric Field Analysis

Compared to a particle tracking model, the EDS system's electric field strength is much easier to calculate computationally [255]. It is useful to compute the electric field without taking into account any particle mobility in the EDS system. To explore the relationship between the electric field and the configuration of the EDS system, many pertinent measurable measures can be readily calculated. The electric field on the EDS system depends on the potential applied to the EDS system. It depends on the EDS system configuration, especially on the electrode design. Therefore, the theoretical solutions of electric distribution for the potential and electric field were computed in two aspects, one

without a dielectric layer on the conductive electrodes, as shown in figure 5.18, and the other by adding one layer of dielectric material, as shown in figure 5.19. Figure 5.18 shows a cross-section of the EDS system on the XY-plane without dielectric surface covering, direct exposure to the free space exists for the deposition electrodes, and the z-direction of the deposited electrodes is presumptively limitless (normal to the page).



**Figure 5.18.** A simplified diagram of the cross-section of the EDS system for direct exposure to the free space for the deposited electrodes in the infinite z-direction.

Assuming the dust particles are deposited on the conductive electrodes with no charge, that means no net charge in the space up the deposited electrodes, so for this particular case, the electric potential's Laplacian equation can be written in cartesian coordinate in XY-plane as following [30]:

$$\nabla^2 U(x,y) = \frac{\partial^2 U(x,y)}{\partial x^2} + \frac{\partial^2 U(x,y)}{\partial y^2} = 0 \quad (5.5)$$

$$0 \leq x \leq \lambda, 0 \leq y < \infty$$

At boundary condition (BC)  $y = 0$ , the distribution of electric potential on the EDS surfaces is directed by the periodic distribution of conductive electrodes on the EDS surface in the x-direction. In BC  $y \rightarrow \infty$ , the distributed electric potential on the EDS surfaces is zero in all the x-direction.

The electrode's potential on the EDS surface is periodic in time and space. The potential of electrodes  $U(x,y,t)$  is calculated theoretically at any time (t) as the solution of the Laplacian equation at two dimensions without any change in the z-axis. We can assume the placed electrodes are infinitely periodic on the x-axis. Hence, the electrode potential can be expressed as a Fourier series of the spatial sinusoidal waves (sine and cosine forms) used to analyze non-sinusoidal waves [256]. The general form of the Fourier series of spatial sinusoidal is given as:

$$f(t) = \frac{1}{2}a_0 + \sum_{k=1}^{\infty} a_k(t) \cos(k\omega t) + b_k(t) \sin(k\omega t) \quad (5.5)$$

The Fourier form in eq (7) is divided into two terms; DC term, which is  $a_0$  and AC term, which is  $a_k$  and  $b_k$ . The DC term is used to locate the position of the wave on the positive and negative axis. However, in our work, we deal with AC terms so that  $a_0$  will be neglected in all analyses of the Fourier equation. From all that, we will analyze the AC terms of the Fourier equation in the detective analysis for the potential of periodically placed electrodes [257]. The Fourier series of spatial sinusoidal at x-direction for the potential of the periodic electrodes can be denoted as

$$U(x, y, t) = \sum_k [a_k(t) \cos(k\omega x) + b_k(t) \sin(k\omega x)] e^{-\omega k y} \quad (5.6)$$

Where:  $\omega = \frac{2\pi}{\lambda}$ ,  $\lambda$  is the fundamental spatial period in the x-axis [256],  $a_k$  and  $b_k$  the Fourier coefficients are time-dependent.

The fundamental spatial period in the x-axis for the three-phase is denoted as

$$\lambda = 3w + 3d \quad (5.7)$$

(w) is conductive electrode width deposited on the substrate, and (d) is the inter-spacing between the conductive electrodes on the substrate.

The electric potential at BC  $y = 0$  in the x-direction will be

$$U(x, 0, t) = \sum_k [a_k(t) \cos(k\omega x) + b_k(t) \sin(k\omega x)] \quad (5.8)$$

For simplicity, we can drop the time parameter (t) in eq (7), so the equation will be

$$U(x, y) = \sum_k [a_k \cos(k\omega x) + b_k \sin(k\omega x)] e^{-\omega k y} \quad (5.9)$$

Equation (10) shows (i) The electric potential expression, which is written in the form of the Fourier series in both sinusoidal terms (cosine and sine) that indicate the electric potential has neither odd nor even symmetry. (ii) The electric potential or electric field's solution decreases exponentially in the y-direction, reducing the potential [17]. The Fourier coefficients  $a_k$  &  $b_k$  are computed by [17], [30].

$$a_k = \frac{2}{\lambda} \int_0^\lambda U(x, y) \cos(k\omega x) dx, \quad b_k = \frac{2}{\lambda} \int_0^\lambda U(x, y) \sin(k\omega x) dx \quad (5.10)$$

The gradient operator of the electrode's potential can give us the linear analytical form of the electrical field in the x-direction in the spacing between the electrodes and the edges of

conductive electrodes. Hence, the electric field can be computed as follows [17], [30], [172].

$$\vec{E} = -\nabla U(x, y) \quad (5.11)$$

$$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} \quad (5.12)$$

$$E = -\left(\frac{\partial U(x, y)}{\partial x} + \frac{\partial U(x, y)}{\partial y}\right) \quad (5.13)$$

$$E_x = -\left(\frac{\partial U}{\partial x}\right), \quad E_y = -\left(\frac{\partial U}{\partial y}\right) \quad (5.14)$$

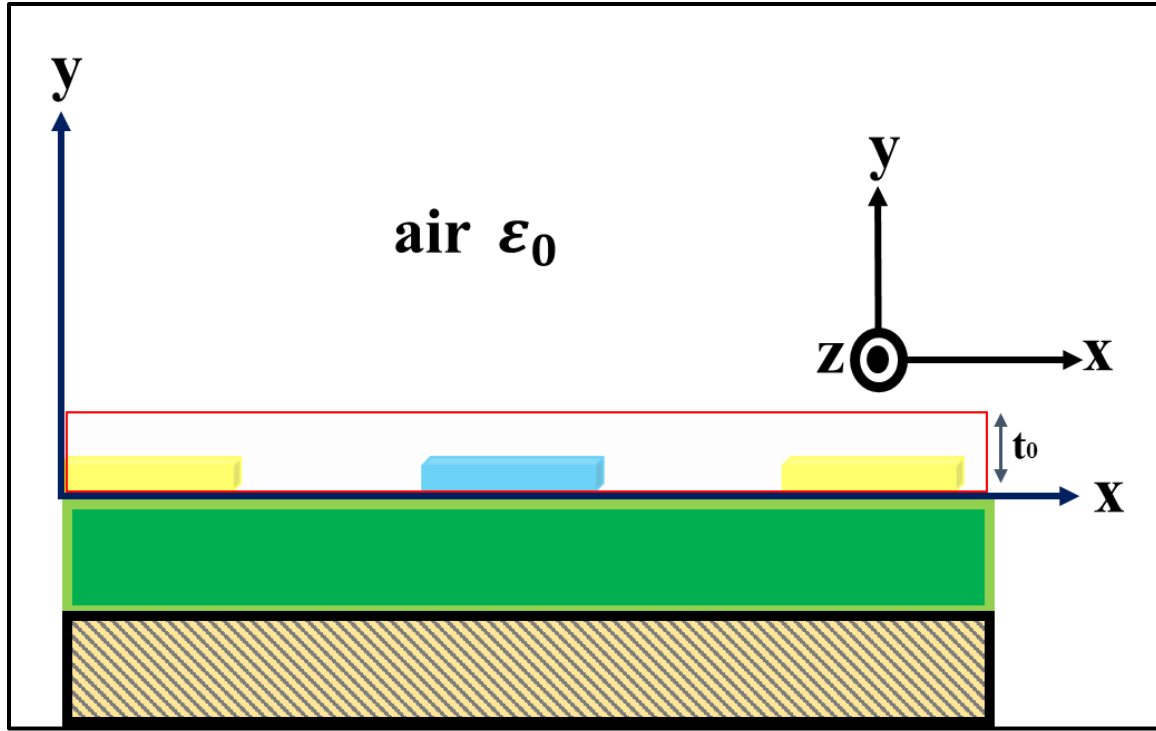
Equation (16) shows the electric field component in x-y directions. The electrical field computed in both axes as

$$E_x = -\left(\frac{\partial U}{\partial x}\right) = \sum_k \omega k e^{-\omega k y} [a_k \sin(k\omega x) - b_k \cos(k\omega x)] \quad (5.15)$$

For the second component, the electric field is written as

$$E_y = -\left(\frac{\partial U}{\partial y}\right) = \sum_k \omega k e^{-\omega k y} [a_k \cos(k\omega x) + b_k \sin(k\omega x)] \quad (5.16)$$

The equations (16-17) show the electric field components on the EDS system without dielectric covering material; by adding covering material with the thickness ( $t_0$ ) with relative permittivity ( $\epsilon_r$ ) on the electrodes of the EDS system, it will impact the electric potential and field distribution [30]. When the top of the conductive electrodes on the EDS surface covering by a transparent dielectric material, as shown in figure (5.19), the thickness of the transparent dielectric layers will be computed with the analytical solution not neglected like electrode thickness. The electrode's microscopic thickness is very small compared to the transparent covering materials' millimetric height [30]



**Figure 5.19.** A simplified diagram of the cross-section of the EDS system for the deposited electrodes covered by transparent dielectric covering material (TDC).

The electric potential and field distribution inside the transparent dielectric covering (TDC) and in the space where the dust particles collected up the EDS surface. The electric field and electric potential are denoted inside TDC and in space as  $E_D$ ,  $E_s$ ,  $U_D$ , and  $U_s$ , respectively, indicating the area where the electric field and the electric potential are computed in the EDS application. We supposed that electric potential as a function of  $(x)$  in both areas inside the TDC [ $Q(x)$ ] and outside TDC in space or air [ $P(x)$ ] at BC [ $y = 0, y = t_0$ ] were symbolized by Fourier series of spatial sinusoidal respectively as [30], [172]:

$$P(x) = \sum_k [a_k \cos(k\omega x) + b_k \sin(k\omega x)] \quad (5.17)$$

$$Q(x) = \sum_k [m_k \cos(k\omega x) + r_k \sin(k\omega x)] \quad (5.18)$$

Where  $a_k, b_k, m_k, r_k$  are Fourier coefficients,  $a_k, b_k$  are known Fourier coefficients for space but  $m_k, r_k$  are unknown Fourier coefficients for TDC computed in the expression of  $a_k, b_k$  coefficients.

Firstly, in our problem, we are looking for an expression of electric potential inside the TDC. Secondly, looking at the electric potential outside TDC in space (air & atmospheric gasses). The expression of the first case should be satisfied with both boundary conditions  $[y = 0, y = t_0]$ , so in that case, we suppose that the electrical potential inside TDC is a summation of two functions of P and Q variate in the x-direction and the y-direction as:

$$U_D(x, y) = f_1(P) + f_2(Q) \quad (5.19)$$

We try to find each function of P, Q in equation (21); we start with the function  $f_1(P)$  and we suppose the general form of function  $f_1(P)$  as

$$f_1(P) = P(\alpha e^{-\omega ky} + \beta e^{\omega ky}) \quad (5.20)$$

Where  $\alpha$  and  $\beta$  are constants that need to compute but, initially at the boundary condition  $[y = 0]$ , the function  $f_1(0)$  must equal to 0 lead to

$$f_1(P) = P \Rightarrow \alpha + \beta = 1 \quad \text{at } y = 0 \quad (5.21)$$

and at the second boundary condition that  $y = t_0$  the function must equal zero, which leads to

$$f_1(P) = 0 \Rightarrow \beta e^{k\omega t_0} + \alpha e^{-k\omega t_0} = 0 \quad \text{at } y = t_0 \quad (5.22)$$

By using equations (22), we can compute the value of  $\alpha, \beta$  respectively, as following

$$\alpha + \beta = 1 \Rightarrow \beta = 1 - \alpha \quad (5.23)$$

By substituting in equation (23), we get

$$(1 - \alpha)e^{k\omega t_0} + \alpha e^{-k\omega t_0} = 0 \quad (5.24)$$

$$\alpha(-e^{k\omega t_0} + e^{-k\omega t_0}) = -e^{k\omega t_0}$$

By using simple equations (identities) of  $\sinh(x)$  and  $\cosh(x)$  as [258]

$$\sinh(x) = \frac{e^x - e^{-x}}{2} \quad (5.25)$$

$$\cosh(x) = \frac{e^x + e^{-x}}{2} \quad (5.26)$$

We reach to

$$\alpha = \frac{e^{k\omega t_0}}{2\sinh(k\omega t_0)} \quad (5.27)$$

Through similar steps, we reach to

$$\beta = \frac{-e^{-k\omega t_0}}{2\sinh(k\omega t_0)} \quad (5.28)$$

By using equations (28) and (29) the  $f_1(P)$  will be

$$f_1(P) = P\left(\frac{e^{k\omega t_0}}{2\sinh(k\omega t_0)}e^{-k\omega y} + \frac{-e^{-k\omega t_0}}{2\sinh(k\omega t_0)}e^{k\omega y}\right)$$

$$f_1(P) = \frac{P}{2\sinh(k\omega t_0)}(e^{k\omega t_0}e^{-k\omega y} + -e^{-k\omega t_0}e^{k\omega y}) \quad (5.29)$$

$$f_1(P) = \frac{P}{2\sinh(k\omega t_0)}(e^{-k\omega(y-t_0)} - e^{k\omega(y-t_0)})$$

$$f_1(P) = -\frac{P \sinh(k\omega(y-t_0))}{\sinh(k\omega t_0)}$$

Now the second term of electric potential in equation (20) should satisfy the following

$$f_2(Q) = 0 \text{ at } y = 0, \quad f_2(Q) = Q \text{ at } y = t_0 \quad (5.30)$$

Which lead to

$$\alpha + \beta = 0 \text{ at } y = 0, \quad \alpha e^{-k\omega t_0} + \beta e^{k\omega t_0} = 1 \text{ at } y = t_0 \quad (5.31)$$

By the similar steps as in the first term to compute  $\alpha$  and  $\beta$ , we reach to

$$\alpha = -\frac{1}{2 \sinh(k\omega t_0)} \quad (5.32)$$

$$\beta = \frac{1}{2 \sinh(k\omega t_0)} \quad (5.33)$$

By using equations (34) and (35) for the second term as in equation (22)

$$f_2(Q) = Q(\alpha e^{-k\omega y} + \beta e^{k\omega y}) \quad (5.34)$$

$$f_2(Q) = Q\left(\frac{e^{k\omega y}}{2 \sinh(k\omega t_0)} - \frac{e^{-k\omega y}}{2 \sinh(k\omega t_0)}\right)$$

$$f_2(Q) = \frac{Q}{2 \sinh(k\omega t_0)} (e^{k\omega y} - e^{-k\omega y}) \quad (5.35)$$

$$f_2(Q) = \frac{Q \sinh(k\omega y)}{\sinh(k\omega t_0)}$$

By substituting equations (30 & 36) in equation (20), we will get the expression of electric potential inside TDC, so the expression of potential is written as:

$$U_D(x, y) = \left(-\frac{P \sinh(k\omega(y - t_0))}{\sinh(k\omega t_0)} + \frac{Q \sinh(k\omega y)}{\sinh(k\omega t_0)}\right)$$

$$U_D(x, y) = \sum_k \left( \frac{[\sinh(k\omega y)][m_k \cos(k\omega x) + r_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right) \quad (5.36)$$

$$- \left( \frac{[\sinh(k\omega(y - t_0))][a_k \cos(k\omega x) + b_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right)$$

As we know, the electric field is equal to the gradient of electric potential as

$E = -\nabla U(x, y)$ , for this case, we have electric potential in two directions, the  $x$ , and  $y$  components with unit vectors for each axis used for electric field expression to indicate the place of derivation for each axis, the electric field components written as:

$$E_D(x, y) = E_{D_x} \hat{i} + E_{D_y} \hat{j} \quad (5.37)$$

From equation (38), the electric field in side TDC in the x-axis (tangent component) is written as follows:

$$E_{D_x} = \frac{-\partial U_D(x, y)}{\partial x}$$

$$E_{D_x} = \sum_k \left[ \frac{[k\omega \sinh(k\omega y)][m_k \sin(k\omega x) - r_k \cos(k\omega x)]}{\sinh(k\omega t_0)} \right] + \left[ \frac{[k\omega \sinh(k\omega(y - t_0))][b_k \cos(k\omega x) - a_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right] \quad (5.38)$$

The second is the normal components of the electric field as

$$E_{D_y} = \frac{-\partial U_D(x, y)}{\partial y}$$

$$E_{D_y} = \sum_k \left[ \frac{[k\omega \cosh(k\omega(y - t_0))][a_k \cos(k\omega x) + b_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right] - \left[ \frac{[k\omega \cosh(k\omega y)][m_k \cos(k\omega x) + r_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right] \quad (5.39)$$

The total electric field inside TDC can be written from eq (39 & 40) as follows

$$E_D(x, y) = \sum_k \left( \left[ \frac{[k\omega \sinh(k\omega y)][m_k \sin(k\omega x) - r_k \cos(k\omega x)]}{\sinh(k\omega t_0)} \right] + \left[ \frac{[k\omega \sinh(k\omega(y - t_0))][b_k \cos(k\omega x) - a_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right] \right) \hat{i} + \left( \left[ \frac{[k\omega \cosh(k\omega(y - t_0))][a_k \cos(k\omega x) + b_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right] - \left[ \frac{[k\omega \cosh(k\omega y)][m_k \cos(k\omega x) + r_k \sin(k\omega x)]}{\sinh(k\omega t_0)} \right] \right) \hat{j} \quad (5.40)$$

The expression of electric potential in space outside TDC can be given with the same changes in equation (10) with the unknown Fourier coefficients; the change in equation (10) indicates to use of all of the environments outside TDC as follows:

$$U_S(x, y) = \sum_k e^{-k\omega(y-t_0)} [m_k \cos(k\omega x) + r_k \sin(k\omega x)] \quad (5.41)$$

The electric field in the space outside TDC in the direction above the TDC surface can be computed by the following steps used inside TDC

$$E_S(x, y) = E_{S_x} \hat{i} + E_{S_y} \hat{j} \quad (5.42)$$

$$E_{S_x} = \frac{-\partial U_S(x, y)}{\partial x}, E_{S_y} = \frac{-\partial U_S(x, y)}{\partial y} \quad (5.43)$$

For the first term in eq (44)

$$E_{S_x} = \sum_k k\omega e^{-k\omega(y-t_0)} [m_k \sin(k\omega x) - r_k \cos(k\omega x)] \quad (5.44)$$

For the second term, eq (44)

$$E_{S_y} = \sum_k k\omega e^{-k\omega(y-t_0)} [m_k \cos(k\omega x) + r_k \sin(k\omega x)] \quad (5.45)$$

The total electric field in space outside TDC will be as follows:

$$E_S(x, y) = \sum_k k\omega e^{-k\omega(y-t_0)} ([m_k \sin(k\omega x) - r_k \cos(k\omega x)] \hat{i} + [m_k \cos(k\omega x) + r_k \sin(k\omega x)] \hat{j}) \quad (5.46)$$

Equation (47) of the electric field outside TDC in space shows that electric field distribution depends on the thickness of TDC and Fourier coefficients; and in spatial period shows that electric field depends on the width of electrodes and the distance between the

electrodes in EDS application.

The electric field depends on the Fourier coefficients  $m_k, r_k$  in eq (41) and eq (47), which they can compute by using equations of the electric field on both sides of TDC by equations (41) and (47) at B.C ( $y = t_0$ ).

For equation (41), we get

$$E_D(x, y) = \sum_k ([k\omega][m_k \sin(k\omega x) - r_k \cos(k\omega x)] \hat{i} + [\frac{[k\omega][a_k \cos(k\omega x) + b_k \sin(k\omega x)]}{\sinh(k\omega t_0)} - \frac{[k\omega \cosh(k\omega t_0)][m_k \cos(k\omega x) + r_k \sin(k\omega x)]}{\sinh(k\omega t_0)}] \hat{j}) \quad (5.47)$$

For equation (47), we get

$$E_S(x, y) = \sum_k k\omega ([m_k \sin(k\omega x) - r_k \cos(k\omega x)] \hat{i} + [m_k \cos(k\omega x) + r_k \sin(k\omega x)] \hat{j}) \quad (5.48)$$

Comparing the tangential components and normal components of the electric field in equations (48) and (49), we can get the computed value of Fourier coefficients  $m_k, r_k$ . In the normal component compression, we have a condition at BC ( $y = t_0$ ) could satisfy

$$\epsilon_0 E_{S_y}(x, t_0) = \epsilon_0 \epsilon_r E_{D_y}(x, t_0) \Rightarrow E_{S_y}(x, t_0) = \epsilon_r E_{D_y}(x, t_0) \quad (5.49)$$

Where  $\epsilon_0$  is space permittivity outside TDC, and  $\epsilon_r$  is the relative permittivity of TDC.

Hence:

$$\begin{aligned}
& \frac{\epsilon_r}{\sinh(k\omega t_0)} \sum_k ([a_k \cos(k\omega x) + b_k \sin(k\omega x)] \\
& \quad - [\cosh(k\omega t_0)][m_k \cos(k\omega x) + r_k \sin(k\omega x)]) \\
& = \sum_k [m_k \cos(k\omega x) + r_k \sin(k\omega x)]
\end{aligned} \tag{5.50}$$

In the tangential compression, we have a condition at BC ( $y = t_0$ ) could satisfy given as

$$E_{S_x}(x, t_0) = E_{D_x}(x, t_0) \tag{5.51}$$

Hence:

$$\sum_k [m_k \sin(k\omega x) - r_k \cos(k\omega x)] = \sum_k [m_k \sin(k\omega x) - r_k \cos(k\omega x)] \tag{5.52}$$

As we see in equation (53), both sides are satisfied. We can set the terms in equation (51) as

$$\begin{aligned}
& \frac{\epsilon_r}{\sinh(k\omega t_0)} [a_k \cos(k\omega x)] + \frac{\epsilon_r}{\sinh(k\omega t_0)} [b_k \sin(k\omega x)] \\
& \quad - \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} [m_k \cos(k\omega x)] \\
& \quad + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} [r_k \sin(k\omega x)] \\
& = [m_k \cos(k\omega x)] + [r_k \sin(k\omega x)]
\end{aligned} \tag{5.53}$$

By collecting unknown Fourier coefficients together as

$$\begin{aligned}
& \frac{\epsilon_r}{\sinh(k\omega t_0)} [a_k \cos(k\omega x)] + \frac{\epsilon_r}{\sinh(k\omega t_0)} [b_k \sin(k\omega x)] \\
& = ([m_k \cos(k\omega x)] + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} [m_k \cos(k\omega x)]) \\
& \quad + ([r_k \sin(k\omega x)] + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} [r_k \sin(k\omega x)])
\end{aligned} \tag{5.54}$$

By equating each coefficient, we will get

$$\begin{aligned} \frac{\epsilon_r}{\sinh(k\omega t_0)} [a_k \cos(k\omega x)] \\ = \left( [m_k \cos(k\omega x)] + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} [m_k \cos(k\omega x)] \right) \end{aligned} \quad (5.55)$$

$$\begin{aligned} \frac{\epsilon_r}{\sinh(k\omega t_0)} [b_k \sin(k\omega x)] \\ = \left( [r_k \sin(k\omega x)] + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} [r_k \sin(k\omega x)] \right) \end{aligned} \quad (5.56)$$

Then the first coefficient  $m_k$  in eq (56) will be

$$\begin{aligned} \frac{\epsilon_r a_k}{\sinh(k\omega t_0)} = m_k \left( 1 + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} \right) \\ m_k = \frac{\epsilon_r a_k}{\epsilon_r \cosh(k\omega t_0) + \sinh(k\omega t_0)} \end{aligned} \quad (5.57)$$

The first coefficient  $r_k$  in eq (57) will be

$$\begin{aligned} \frac{\epsilon_r b_k}{\sinh(k\omega t_0)} = r_k \left( 1 + \frac{\epsilon_r [\cosh(k\omega t_0)]}{\sinh(k\omega t_0)} \right) \\ r_k = \frac{\epsilon_r b_k}{\epsilon_r \cosh(k\omega t_0) + \sinh(k\omega t_0)} \end{aligned} \quad (5.58)$$

From equations (58) & (59), we conclude that Fourier coefficients  $m_k$  &  $r_k$  are functions of relative permittivity  $\epsilon_r$  of TDC at provided  $a_k$  &  $b_k$  Fourier coefficients.

The theoretical solutions in equations (37, 41, 47, 58, 59) can be applied to the simulation program, but we have first to compute the known Fourier coefficients  $a_k$ ,  $b_k$ .

Simplicity, we determine  $a_k$ ,  $b_k$  at BC  $[y = 0]$ . The electric potential is supposed at  $[y = 0]$  as linear potential between the electrodes in the EDS application. The electric potential can be expressed for three electrodes connected with a three-phase power supply in one fundamental spatial period in the x-direction as follows:

$$U_D(x, 0) = \begin{cases} \phi_1 & , \quad 0 \leq x \leq (W) \\ \frac{\phi_2 - \phi_1}{d} (x - W) + \phi_1 & , \quad (W) \leq x \leq (W + d) \\ \phi_2 & , \quad (W + d) \leq x \leq (2W + d) \\ \frac{\phi_3 - \phi_2}{dD} (x - 2W - d) + \phi_2 & , \quad (2W + d) \leq x \leq (2W + 2d) \\ \phi_3 & , \quad (2W + 2d) \leq x \leq (3W + 2d) \\ \frac{\phi_1 - \phi_3}{dD} (x - 3W - 2d) + \phi_3 & , \quad (2W + 2d) \leq x \leq (3W + 3d) \end{cases}$$

The known Fourier coefficients  $a_k, b_k$  can be computed by using equation (11) at  $[y = 0]$  as following

$$a_k = \frac{2}{\lambda} \int_0^{3W+3d} U(x, 0) \cos(k\omega x) dx, \quad b_k = \frac{2}{\lambda} \int_0^{3W+3d} U(x, 0) \sin(k\omega x) dx \quad (5.59)$$

By using the following integral rules, we can compute the value of  $a_k, b_k$  for preceding theoretical calculations

$$\begin{aligned}\int \cos[ax] \, dx &= \frac{1}{a} \sin[ax] \\ \int x \cos[ax] \, dx &= \frac{1}{a^2} \cos[ax] + \frac{x}{a} \sin[ax] \\ \int \sin[ax] \, dx &= -\frac{1}{a} \cos[ax] \\ \int x \sin[ax] \, dx &= \frac{1}{a^2} \sin[ax] - \frac{x}{a} \cos[ax]\end{aligned}\tag{5.60}$$

Firstly for  $a_k$  Computed applying eq (61) as follows:

$$\begin{aligned}
 a_k = & \frac{2}{T} \left[ \int_0^W \varnothing_1 \cos[k\omega x] dx + \int_W^{W+d} \left( \frac{\varnothing_2 - \varnothing_1}{d} (x - W) + \varnothing_1 \right) \cos[k\omega x] dx \right. \\
 & + \int_{W+d}^{2W+d} \varnothing_2 \cos[k\omega x] dx \\
 & + \int_{2W+d}^{2W+2d} \left( \frac{\varnothing_3 - \varnothing_2}{d} (x - 2W - d) + \varnothing_2 \right) \cos[k\omega x] dx \\
 & + \int_{2W+2d}^{3W+2d} \varnothing_3 \cos[k\omega x] dx \\
 & \left. + \int_{3W+2d}^{3W+3d} \left( \frac{\varnothing_1 - \varnothing_3}{d} (x - 3W - 2d) + \varnothing_3 \right) \cos[k\omega x] dx \right]
 \end{aligned} \tag{5.61}$$

$$\begin{aligned}
a_k = \frac{T}{2\pi^2 k^2 d} [ & (\phi_2 - \phi_1)(\cos[k\omega(W + d)]) - \cos[k\omega W]) + (\phi_3 \\
& - \phi_2)(\cos[k\omega(2W + 2d)]) - \cos[k\omega(2W + d)]) + (\phi_1 \\
& - \phi_3)(1 - \cos[k\omega(3W + 2d)])]
\end{aligned} \quad (5.62)$$

Then the expression of  $a_k$  will be

$$\begin{aligned}
a_k = \frac{T}{2\pi^2 k^2 d} [ & (\phi_1 - \phi_2)(\cos[k\omega W] - \cos[k\omega(W + d)]) + (\phi_2 \\
& - \phi_3)(\cos[k\omega(2W + d)] - \cos[k\omega(2W + 2d)]) + (\phi_3 \\
& - \phi_1)(\cos[k\omega(3W + 2d)] - 1)]
\end{aligned} \quad (5.63)$$

Secondly for  $b_k$  Will be computed by substituting eq (61) in eq (62) as follows:

$$\begin{aligned}
b_k = \frac{2}{T} [ & \int_0^W \phi_1 \sin[k\omega x] dx + \int_W^{W+d} \left( \frac{\phi_2 - \phi_1}{d} (x - W) + \phi_1 \right) \sin[k\omega x] dx \\
& + \int_{W+d}^{2W+d} \phi_2 \sin[k\omega x] dx \\
& + \int_{2W+d}^{2W+2d} \left( \frac{\phi_3 - \phi_2}{d} (x - 2W - d) + \phi_2 \right) \sin[k\omega x] dx \\
& + \int_{2W+2d}^{3W+2d} \phi_3 \sin[k\omega x] dx \\
& + \int_{3W+2d}^{3W+3d} \left( \frac{\phi_1 - \phi_3}{d} (x - 3W - 2d) + \phi_3 \right) \sin[k\omega x] dx]
\end{aligned} \quad (5.64)$$

$$\begin{aligned}
b_k = \frac{T}{2\pi^2 k^2 d} [ & (\phi_2 - \phi_1)(\sin[k\omega(W + d)] - \sin[k\omega W]) + (\phi_3 \\
& - \phi_2)(\sin[k\omega(2W + 2d)] - \sin[k\omega(2W + d)]) - (\phi_1 \\
& - \phi_3)(\sin[k\omega(3W + 2d)])]
\end{aligned} \quad (5.65)$$

Then the expression of  $b_k$  will be

$$b_k = \frac{T}{2\pi^2 k^2 d} [(\phi_1 - \phi_2)(\sin[k\omega W] - \sin[(k\omega(W + d))]) + (\phi_2 - \phi_3)(\sin[(k\omega(2W + d))] - \sin[(k\omega(2W + 2d))]) + (\phi_3 - \phi_1)(\sin[(k\omega(3W + 2d))])] \quad (5.66)$$

By substituting equations (64& 67) in equations (58 &59), we can compute the value of  $m_k$  and  $r_k$  as following:

$$m_k = \frac{\epsilon_r T}{(2\pi^2 k^2 d)(\epsilon_r \cosh(k\omega t_0) + \sinh(k\omega t_0))} [(\phi_1 - \phi_2)(\cos[k\omega W] - \cos[(k\omega(W + d))]) + (\phi_2 - \phi_3)(\cos[(k\omega(2W + d))] - \cos[(k\omega(2W + 2d))]) + (\phi_3 - \phi_1)(\cos[(k\omega(3W + 2d))] - 1)] \quad (5.67)$$

$$r_k = \frac{\epsilon_r T}{(2\pi^2 k^2 d)(\epsilon_r \cosh(k\omega t_0) + \sinh(k\omega t_0))} [(\phi_1 - \phi_2)(\sin[k\omega W] - \sin[(k\omega(W + d))]) + (\phi_2 - \phi_3)(\sin[(k\omega(2W + d))] - \sin[(k\omega(2W + 2d))]) + (\phi_3 - \phi_1)(\sin[(k\omega(3W + 2d))])] \quad (5.68)$$

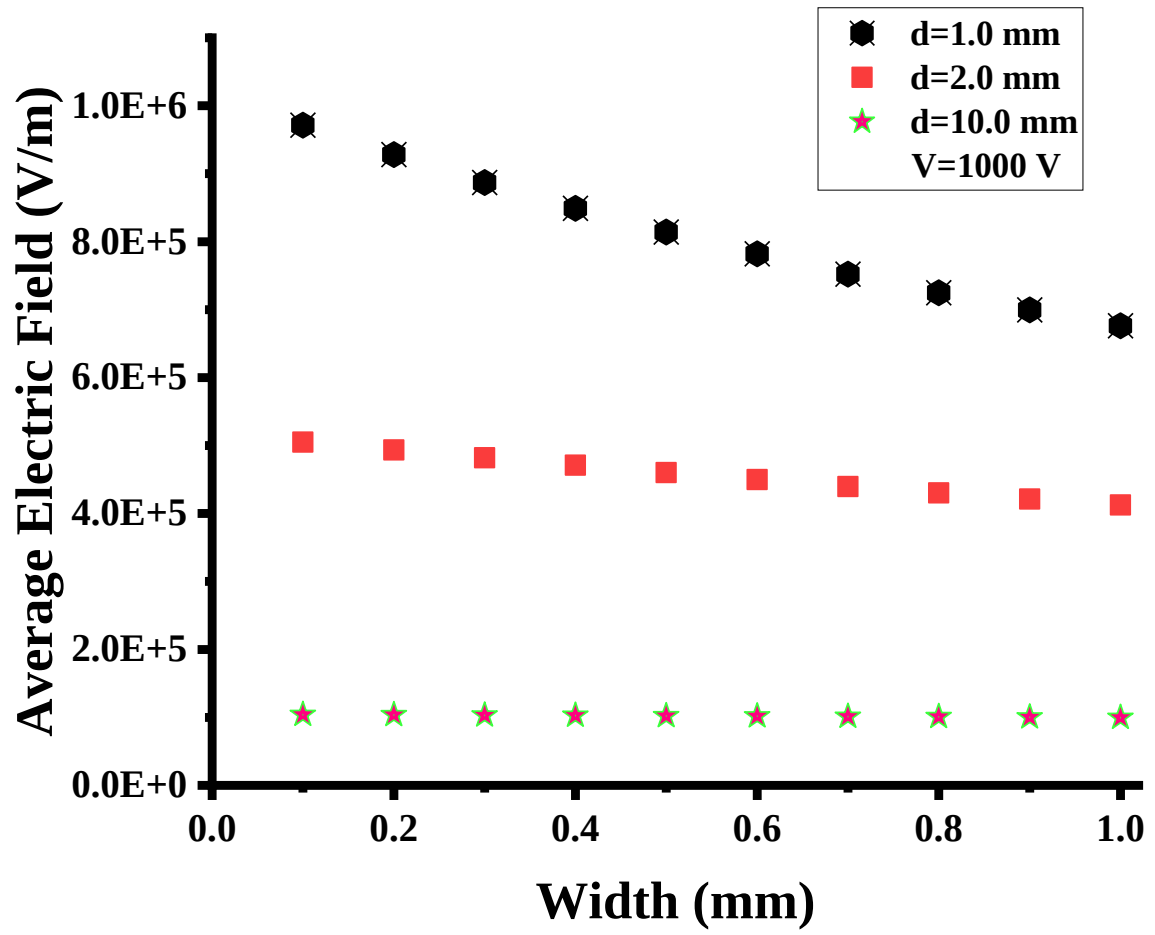
Combined and applied equations (47, 64, 67, 68, 69) together would prove the effectiveness of EDS parameters like width and spacing affected the performance of the electric field. The electric field distribution is also affected by the dielectric constant, dielectric thickness electrode thickness, grounded, and activation of the electrodes. Any impact on the electric field efficiency would be inverse to the EDS system's removal efficiency of dust particles. All mentioned parameters and others will discuss in the following section.

#### 5.4.4. Effect of electrode dimensions

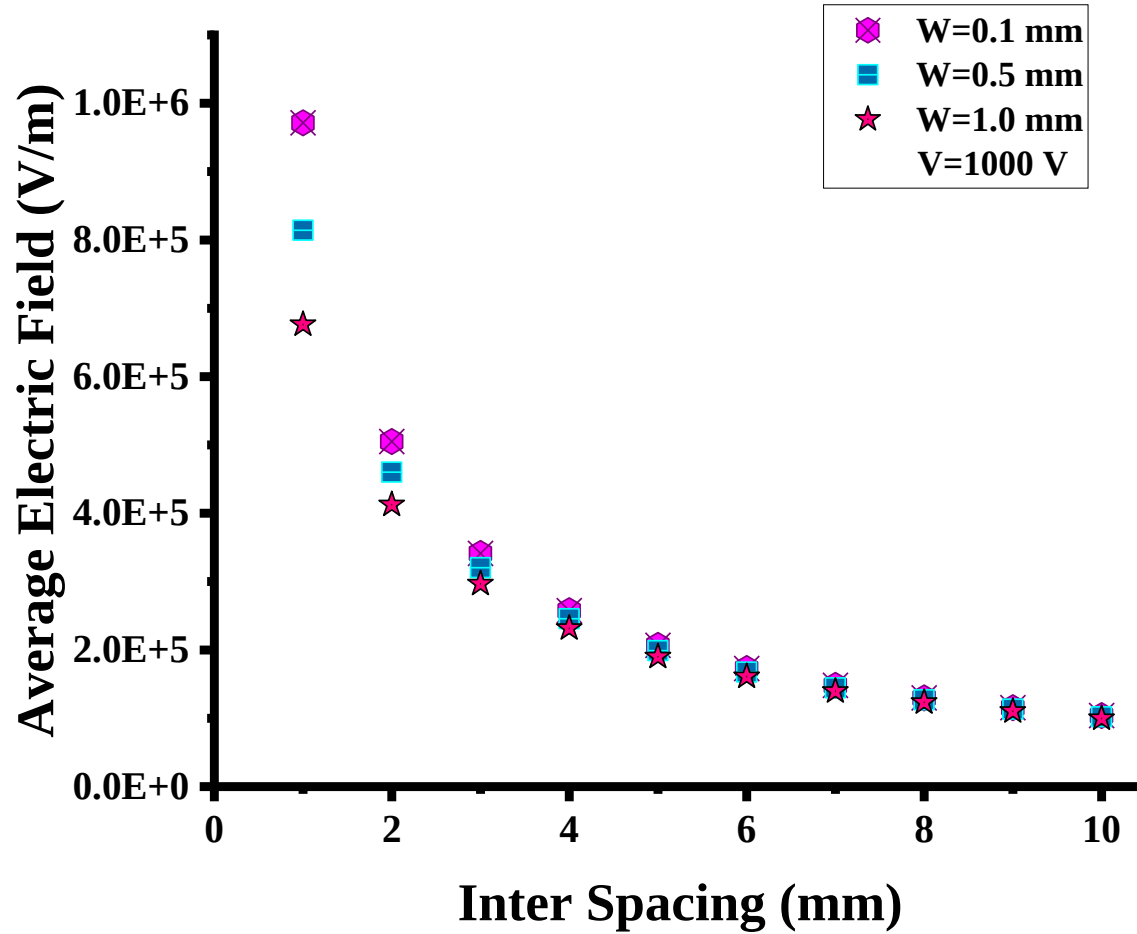
The electrode width and inter-electrode spacing determine how the electric field is distributed on the EDS surface through the equations (47, 64, 67, 68, 69). In Figures 5.20

and 5.21, we see how varying the width and inter-spacing parameters affect the average electric field magnitude on the EDS surface throughout a single fundamental spatial period. As shown in Figure 5.20, as the electrode width increases, the average electric field decreases for a specific value of inter-spacing ( $d$ ). For instance, when  $d = 1.0, 2.0$ , and  $10$  mm, the percentages of decreasing the average electric field for width between  $0.1$  mm and  $1.0$  mm are  $30.4\%$ ,  $18.4\%$ , and  $4.1\%$ , respectively. As shown, the effect of width on the average electrical field is more significant for smaller values of  $d$ .

Figure 5.21 provides the average electric field as a function of  $d$ ; For a given electrode width, the average electric field falls as the interspacing between the electrodes increases. The effect of change in the interspacing is more significant than the effect of the width parameter; in figure 5.21, when  $W = 0.1, 0.5$ , and  $1.0$  mm, the percentages of decreasing the average electric field for interspacing between  $1.0$  mm and  $10.0$  mm are  $89.3\%$ ,  $87.4\%$ , and  $85.2\%$ , respectively. As shown, the effect of spacing on the average electrical field is more significant for smaller values of  $W$ .



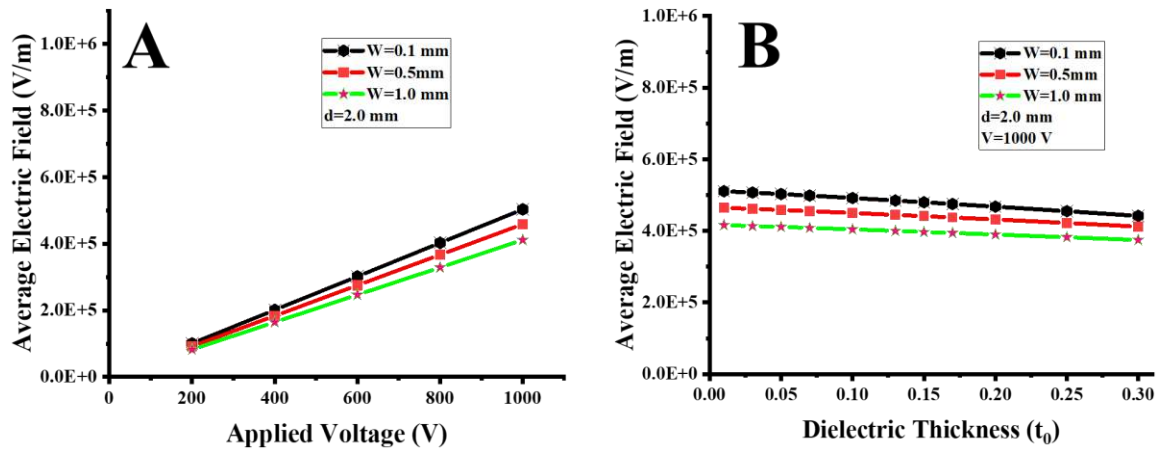
**Figure 5.20.** The width's electrode impacts the average electric field (V/m) on the EDS surface in one fundamental spatial period.



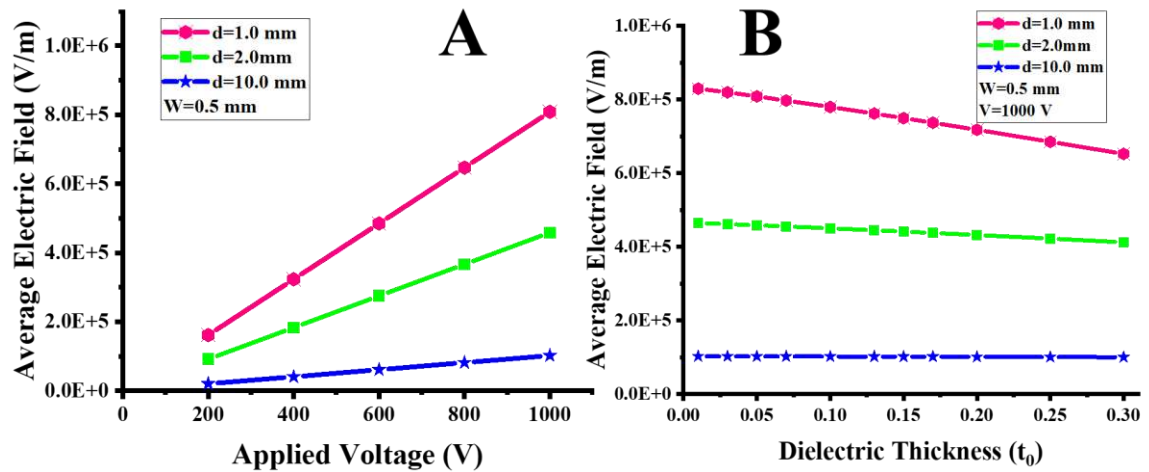
**Figure 5.21.** Impact of inter-electrode spacing on the average electric field (V/m) on the EDS surface in one fundamental spatial period.

The effect of change in the distance between the electrodes is more powerful in decreasing the electric field than any other parameter. These words can be proven in the following figures (5.22-5.23) at different parameters, applied voltage, and dielectric thickness. Figure 5.22-A show the effect of width at different applied voltages. It proves that the effect of width in decreasing the average electric field at fixed spacing ( $d=2.0$  mm) reaches 18.3% between the width of 0.1 mm and 1.0 mm at 1000 volts. At changing the dielectric thickness of the cover material, the average electric field decreased by 15.2% at 1000 volts at the dielectric thickness of 0.3 mm in figure 5.22-B.

In figure 5.23, we prove that the effect of spacing is the controlled parameter in decreasing the average electric field. The average electric field decreased by 87% at ( $W=0.5$  mm,  $V=1000$  volt) for figure 5.23-A. Figure 5.23-B, the effect of interspacing still controlled the decreasing of the average electric field by 85% at ( $W=0.5$  mm,  $V=1000$  volt, and  $t_0=0.3$  mm).

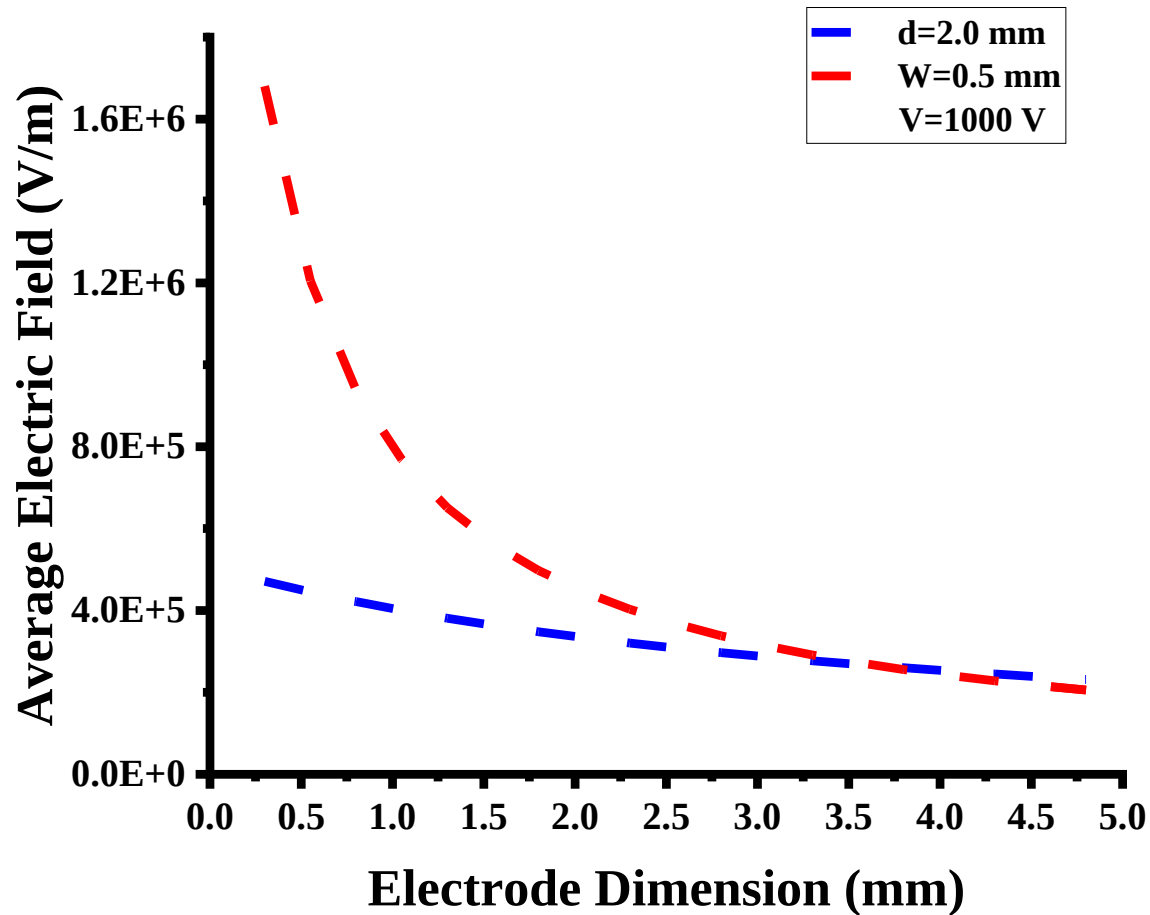


**Figure 5.22.** Impact of electrodes width on the average electric field (V/m) with variable voltage and dielectric thickness on the EDS surface in one fundamental spatial period.



**Figure 5.23.** Impact of inter-electrode spacing on the average electric field (V/m) with variable voltage and dielectric thickness on the EDS surface in one fundamental spatial period.

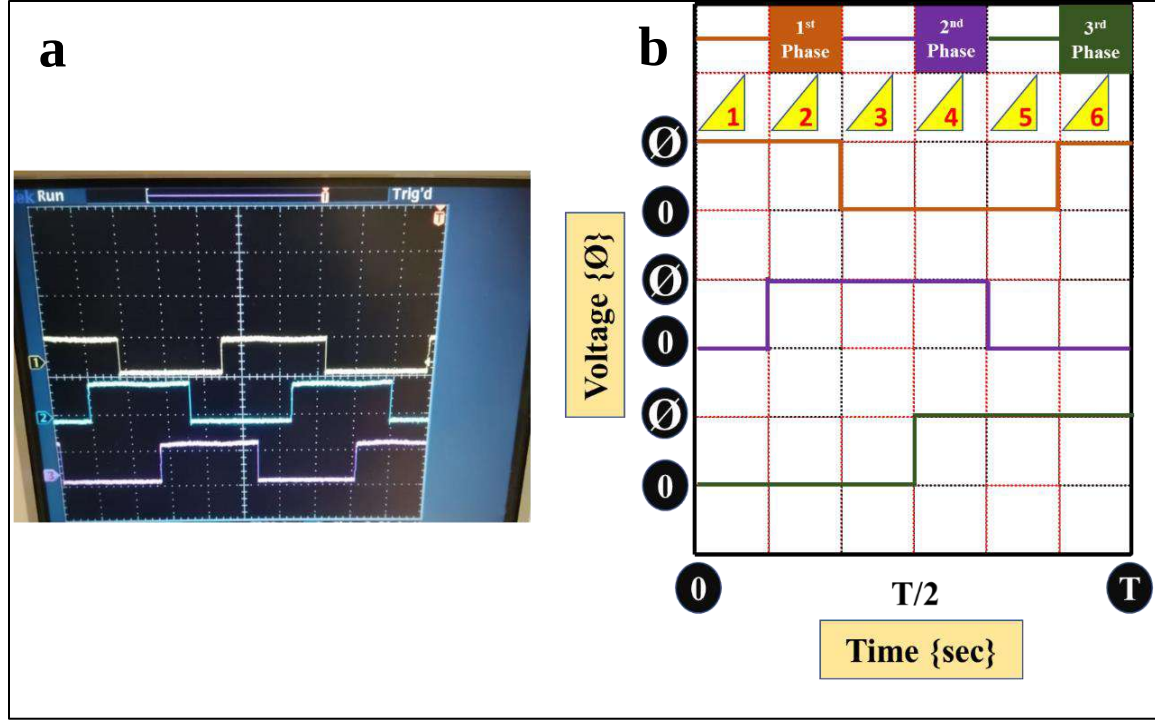
In a special case for changing the width of the electrode as the change in the inter-spacing between the electrodes, in this case, we prove that the interspacing parameter is the dominant parameter in the EDS system, as shown in figure 24. Figure 24 proves that the influence in the average electric field is controlled by the change in distance between the electrodes between (0.3 mm- 5.0 mm) and fixed voltage of 1000 volts for borosilicate cover material, which reaches about 88%, but in the same case for change in width the decreasing reach to 51 %.



**Figure 5.24.** Impact of electrode dimensions on the average electric field (V/m) on the EDS surface in one fundamental spatial period with three dielectric materials.

#### **5.4.5. Impact of electrode activation**

A single-phase or three-phase power supply energizes the conductive electrodes on the EDS system's surface. The produced waves from power supplies can be used directly to remove dust particles from the EDS surface. The solutions of electric potential and electric field are utilized to find how the electric field is affected by the activation of the EDS system. In our work, the electrodes are distributed on top of EDS's substrate. The three-phase power supply energizes the electrodes in our work, which produces traveling waves to repel dust particles. It has a rectangular pulse, as shown in figures (5.25-a and 5.25-b). Figure (5.25-a) shows the waveform pulse of our lab oscilloscope screen, and figure (5.25-b) shows the named voltages for three electrodes on the surface of the EDS system. The pulse of the three-phase power supply has a different voltage combination, as mentioned up. Each pulse has six various voltage combinations, as shown in figure (5.25-b), in which they switch between grounded value (zero volts) to activation value (volt); these voltage combinations are  $\{(\emptyset, 0, 0), (\emptyset, \emptyset, 0), (0, \emptyset, 0), (0, \emptyset, \emptyset), (0, 0, \emptyset), (\emptyset, 0, \emptyset)\}$ .

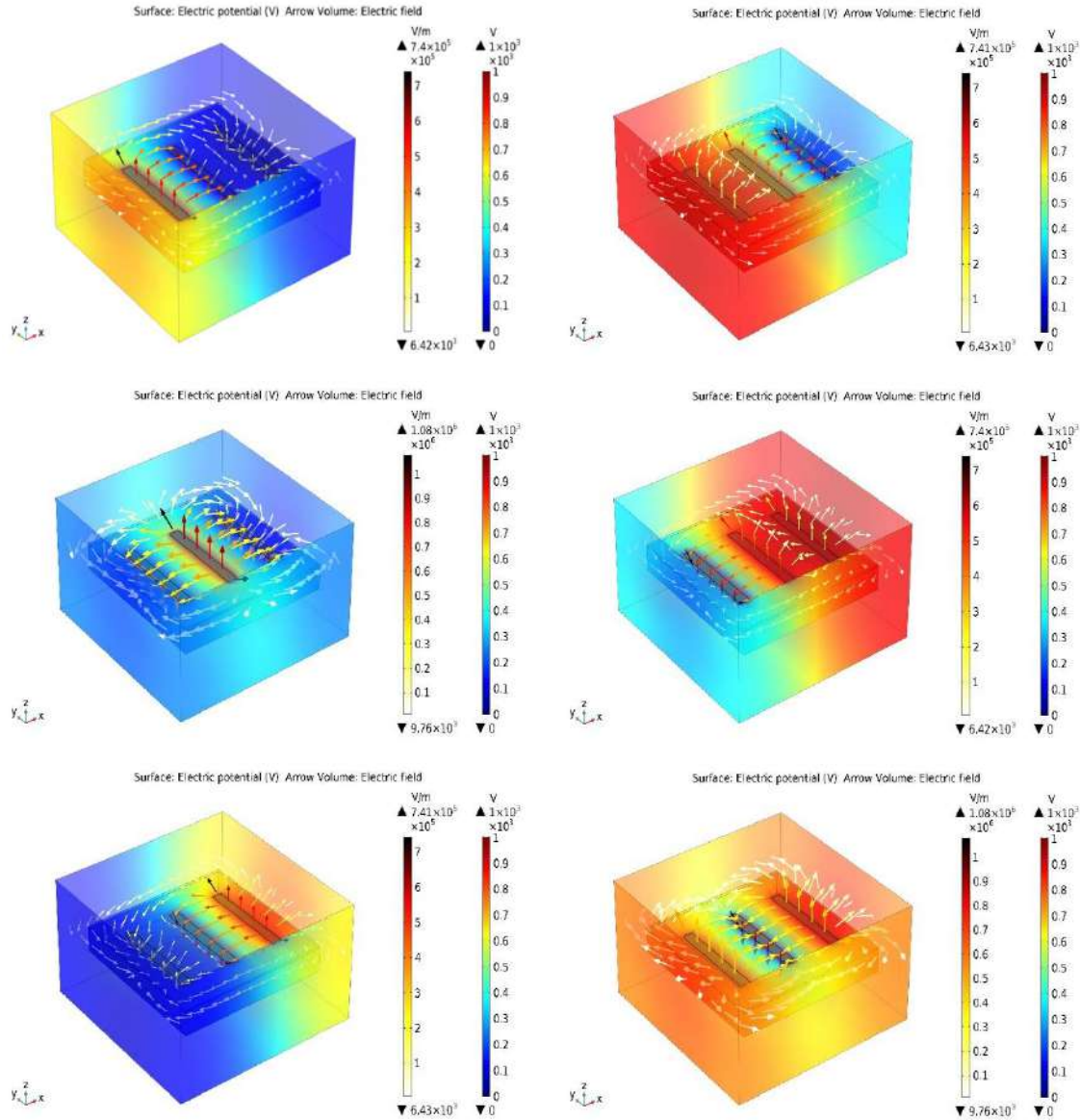


**Figure 5.25.** Rectangular voltage pulses of Three-phase power supply (a) The waveform pulse of our lab oscilloscope screen (b) The named voltages for three electrodes on the surface of EDS application with six various voltage combinations  $\{(\emptyset, 0, 0), (\emptyset, \emptyset, 0), (0, \emptyset, 0), (0, \emptyset, \emptyset), (0, 0, \emptyset), (\emptyset, 0, \emptyset)\}$ .

We assume that every phase has some electrodes connected with it with different volts in the spatial period. The volts in the connecting electrodes are sorted as  $\emptyset_1, \emptyset_2$ , and  $\emptyset_3$ , for three electrodes in one fundamental spatial period. The change in the combinations of applied voltages between the electrodes results in changes in the electric field, affecting the removal of dust particles. This change in the electric field produces a moment change in the arrangements of charges of dust particles. This charge has an opposite sign on either side of the particle in line with the electric field, therefore producing an induced dipole in the particle [214]. The induced dipole experiences different strengths of the electric field at both ends because of the nonuniformity of the applied electric field, and this imbalance

of forces (dielectrophoretic force and Coulomb force) gives rise to the particle movement [16], [30], [214].

To show the effect of the voltage combination on the electric field, the EDS system has been investigated in the COMSOL Multiphysics finite element analysis software, as shown in figure 5.26. Figure 5.26 shows the six various voltage combinations  $\{(\emptyset_1, 0, 0), (\emptyset_1, \emptyset_2, 0), (0, \emptyset_2, 0), (0, \emptyset_2, \emptyset_3), (0, 0, \emptyset_3), (\emptyset_1, 0, \emptyset_3)\}$  in three dimensions. The voltages applied to the copper electrodes are set to be 1000 V and zero, respectively. The electrode deposited on borosilicate material with width, inter-electrode spacing, and thickness of the electrode has been considered to be 0.5 mm, 2.0 mm, and 0.02 mm, respectively. The thickness of the dielectric coating is 0.1 mm, and the dielectric constant of the covering material is 4.8 for borosilicate covering. The electric potential is 1000 volts on the EDS surface. It is constant for all combinations. As expected, the figure's electric field vectors originate from the activated electrodes and terminate in the electrode with zero potential. The electric field value was  $7.41 \times 10^5$  V/m in combinations  $\{(\emptyset_1, 0, 0), (\emptyset_1, \emptyset_2, 0), (0, \emptyset_2, \emptyset_3), (0, 0, \emptyset_3)\}$  respectively, however the value of electric field was  $1.08 \times 10^6$  V/m for combination  $\{(0, \emptyset_2, 0), (\emptyset_1, 0, \emptyset_3)\}$  as shown in figure 5.26. the reason for that is the inverse relation between electric field and distance.



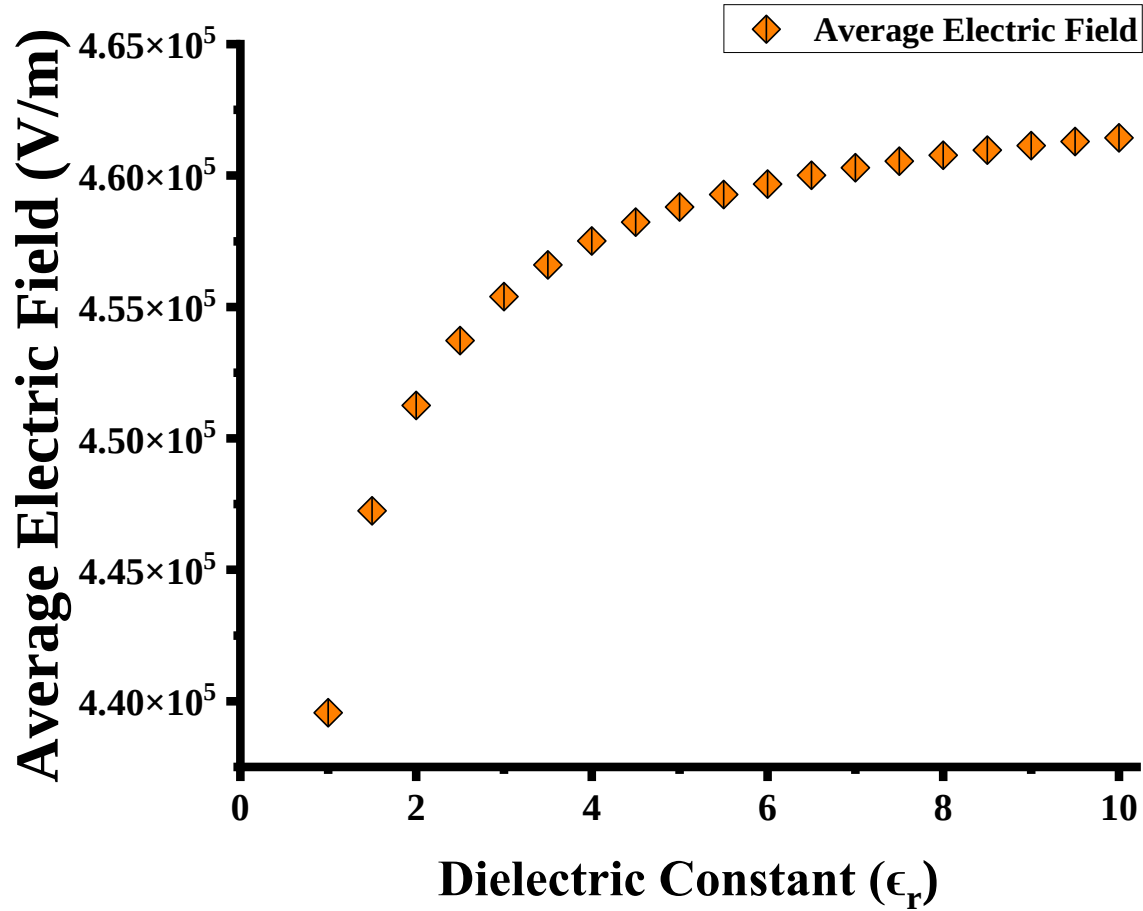
**Figure 5.26.** The impacts of various voltage combinations on the electric field (V/m) on the EDS surface in one fundamental spatial period.

#### 5.4.6. Effect of Dielectric constant

A material's dielectric constant is the ability to store electrical potential energy under the influence of an electric field. The capacitance concept treats the dielectric constant concept in the EDS system. Figure 5.27 shows a capacitor created by the EDS arrangement of two neighboring electrodes. The translucent dielectric layer and air make up the analogous

capacitor's dielectric medium. The dielectric constant is also called relative permittivity [259].

The sensitivity of the dielectric constant ( $\epsilon_r$ ) of the transparent dielectric cover on the EDS system measured theoretically in the equations (47, 64, 67, 68, 69). This dielectric constant is one of the parameters that affect the electric field strength, as shown in figure 5.27. Figure 5.27 shows the average electric field as a function of the dielectric constant; it shows the dielectric constant's effect on increasing the electric field's average value. The electric field is sensitive to any change in the covering material in the EDS system. As the dielectric constant of the covering material increases, the average electric field increase, but the percentage of decreasing the electric field is very low. By comparison, the increase of the electric field in the dielectric constant between 1 to 10 is about 4.5%. The changeable dielectric constant of the cover material has a low effect on the performance of the electric field. In summary, the effect of the dielectric constant is not making much sense in the performance of removing dust particles from the EDS surface because this parameter does not affect the electric field source.

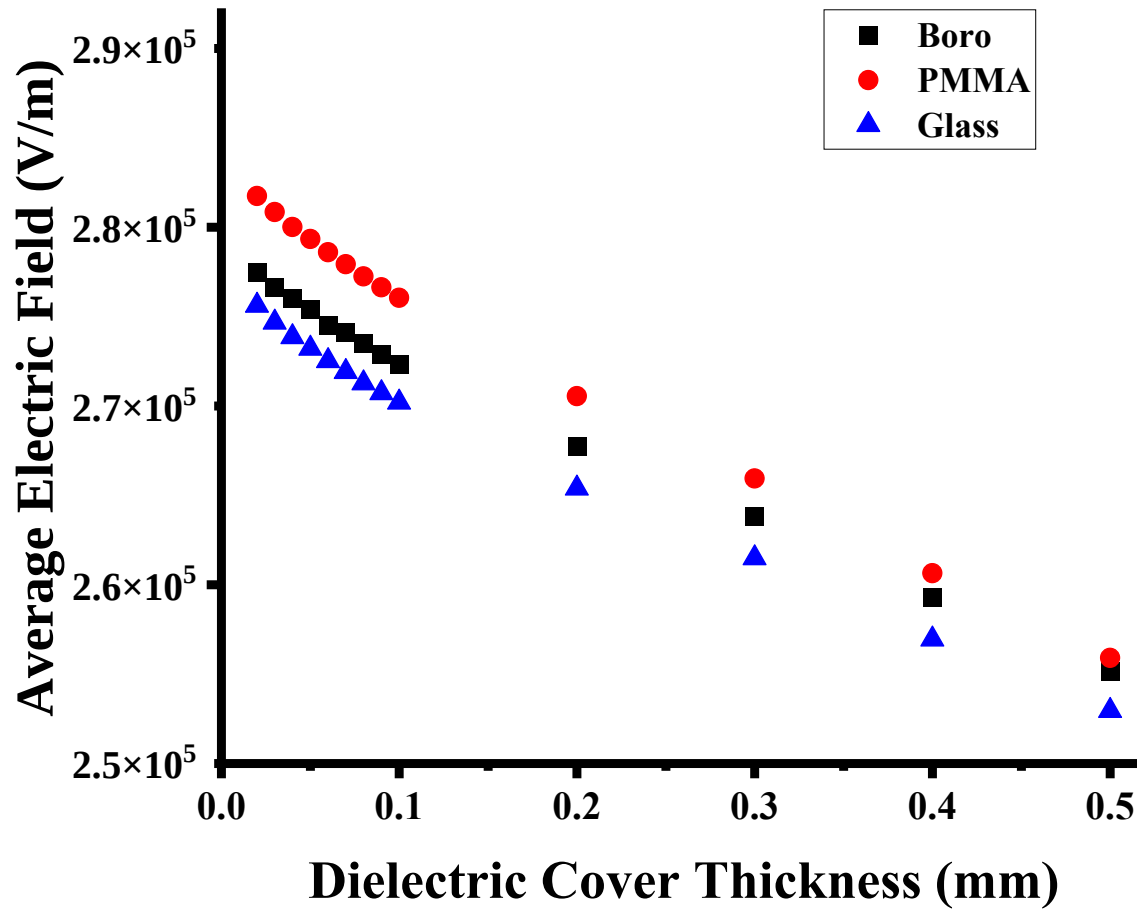


**Figure 5.27.** Impact of dielectric constant on the electric field (V/m) on the EDS surface in one fundamental spatial period.

#### 5.4.7. Effect of Dielectric Thickness

The thickness of the dielectric material that covers the EDS system affects the averaged electric field. The increase in dielectric thickness decreases the performance of averaged electric field between the electrodes, thus decreasing the cleaning efficiency of the EDS system versus the dust particles. The decrease in the electric field happened because of the increasing distance between the source of the electric field (electrodes) and the surface of the EDS system.

The investigation of increasing dielectric thickness was considered COMSOL software at constant inter-spacing (2.0 mm), constant width (0.5) mm of the deposited electrodes on the substrate on the EDS system, and at a fixed applied voltage (1000 V) for three dielectric materials, Polymethylmethacrylate (PMMA), Borosilicate (Boro), and Glass. The results are shown in figure 5.28. In this figure, two important points were proven. Firstly, the EDS system will not reach the breakdown state of an electric field in the surrounding air. Secondly that the decrease in the average electric field percentages is 8.0%, 9.2%, and 8.2% for Boro, PMMA, and glass, respectively, but the change in the dielectric constant does not have much effect on the performance of the average electric field as shown in figure 5.28, which support the results in figure 5.27. The percentage of an effective dielectric constant between PMMA-Boro and PMMA-glass at a fixed dielectric thickness of 0.3 mm is 0.8% and 1.7%, respectively.

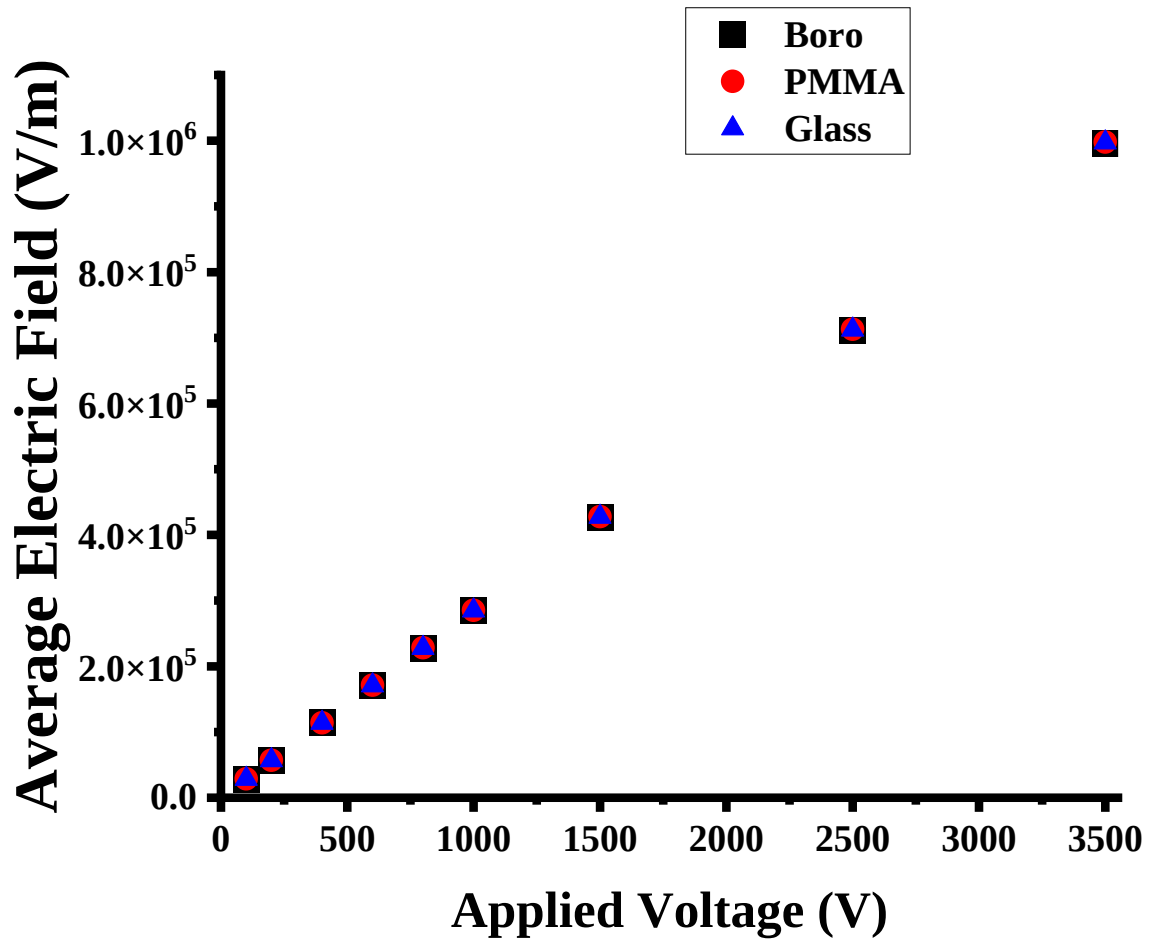


**Figure 5.28.** The average effect of the thickness of the dielectric materials on the performance of the electric field (V/m) on the EDS surface in one fundamental spatial period with three dielectric materials.

#### 5.4.8. Effect of applied potential

The applied voltage on the EDS system greatly impacted the electric field performance. The electric field depends on the value of the applied voltage. As the applied voltage increases, the average electric field efficiency increase, thus increasing the efficiency of the EDS system in removing dust particles from the PV surfaces by increasing the forces (Coulomb and dielectrophoretic forces). Figure (5.29) shows the mentioned explanations. It also shows that the dielectric constant change does not affect the performance of the resulting average electric field. The reason for this is that the dielectric material directly

affects the surface of the EDS system and does not affect the source of the electric field, which is the conductive electrodes. Still, the effect of the applied voltage is more significant than the dielectric constant because of its effects directly on the electrodes of the EDS system.

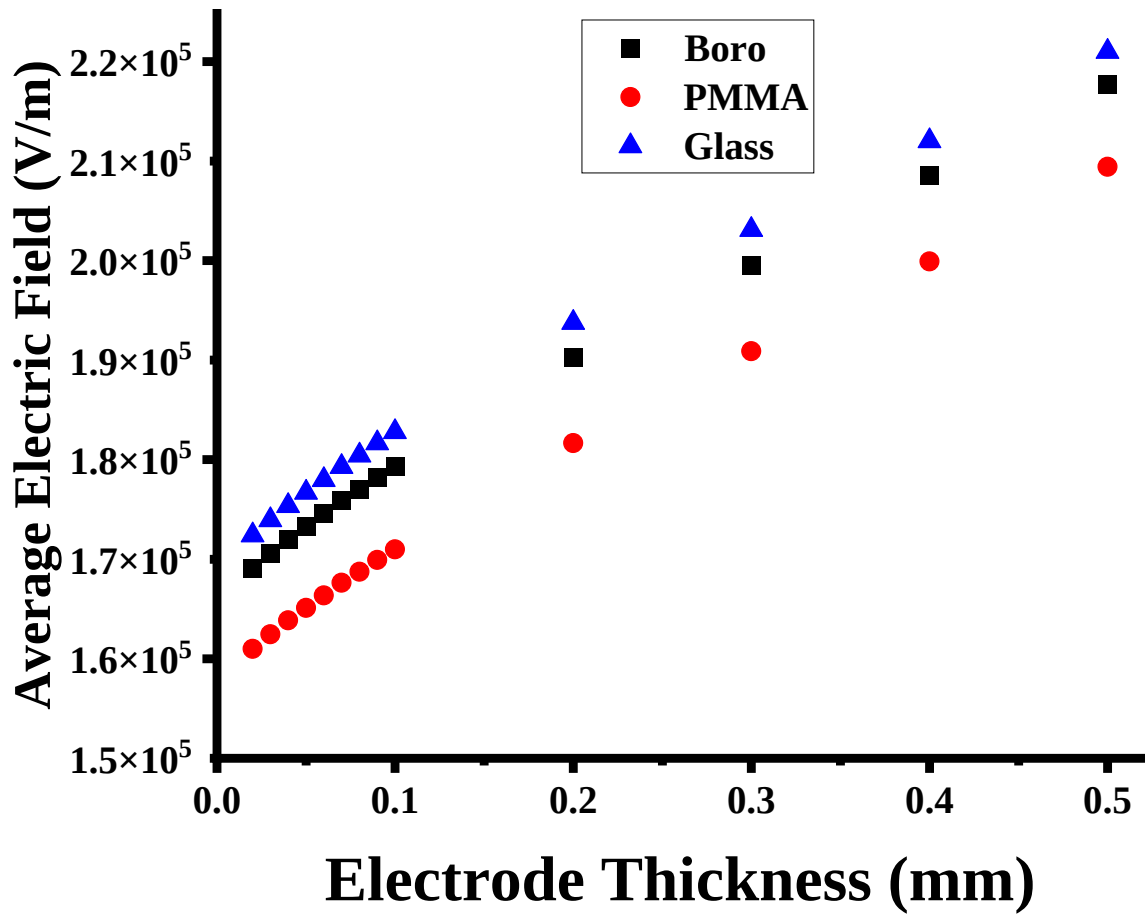


**Figure 5.29.** Impact of applied voltage on the electric field (V/m) on the EDS surface in one fundamental spatial period with three dielectric materials.

#### 5.4.9. Effect of electrode thickness

The conductive electrodes deposited on the insulating substrate of the EDS system under the transparent dielectric material are the source of the electric field. They are the source of driven force (Coulomb force) that work to remove the dust particles from the surface.

Any modifications to the dimension of these electrodes will directly affect the performance of the average electric field, thus affecting the efficiency of the PV solar cells due to the impact on the removal process of the dust particles from the PV surfaces. The surprising here is that adjusting these electrodes leads to either increase or decrease in the value of the average electric field. The investigation of increasing electrode thickness was considered COMSOL software at constant inter-spacing (2.0 mm), constant width (0.5) mm of the deposited electrodes on the substrate on the EDS system, and at a fixed applied voltage (1000 V) for the mentioned dielectric materials. The results are shown in figure 5.30, in this figure; when the height of the electrodes increases, the average electric field in all-dielectric materials increases. The percentage of increasing electric field by modification of the electrodes are 22.3%, 23.1%, and 21.9% for Boro, PMMA, and glass, respectively.



**Figure 5.30.** The average effect of the thickness of the electrode materials on the performance of the electric field (V/m) on the EDS surface in one fundamental spatial period with three dielectric materials.

## CHAPTER 6

### CONCLUSIONS AND FUTURE SUGGESTIONS

#### 6.1. Conclusion

Electrodynamic dust-repellent surfaces have been developed for photovoltaic solar panels by utilizing the electrodynamic dust shield (EDS) system. The EDS system was designed and developed locally as an anti-dust solution for different surfaces. From work, the following conclusions can be made.

- ✚ Our research facilities have been responsible for developing a multi-phase power supply, which includes both single-phase and three-phase.
- ✚ The elemental analysis, chemical composition, SEM imaging, and particle size distribution investigations were carried out for the dust samples.
- ✚ Three combinations of electrode width/inter-electrode spacing (0.5mm/2 mm, 1mm/2 mm, and 0.5 mm/4 mm) were fabricated and tested at varying frequencies (3-36 Hz) and varying voltages (400-1000V).
- ✚ The dust removal efficiency was increased as the applied voltage increased, but the dust removal efficiency was optimized at six hertz for applied frequency.
- ✚ The EDS system was parametrically optimized to achieve the highest dust removal efficiency of  $92\pm1\%$  and  $90\pm1\%$ , and the highest dust removal efficiency was achieved for 0.5mm/2 mm geometrical combination at the supply voltage of 1000V and the frequency of 6 Hz for both single-phase and three-phase respectively.
- ✚ The dust removal efficiencies for both power supplies were also studied for dust parameters like dust particle size, dust surface loading, and inclination angle; the

highest efficiency was observed for the particle size of 40-75 microns, the dust surface loading of 30 gram/m<sup>2</sup>, and 35° degree of the tilt angle.

- ✚ The efficiency of the EDS system increased with increasing the tilt angle of the photovoltaic solar panel, decreasing the surface loading of dust particles, and decreasing the relative humidity.
- ✚ The EDS system was integrated with photovoltaic cells, which increased the efficiency of the photovoltaic solar panel when exposed to natural sunlight.
- ✚ The force analysis on the dust particle removal via the EDS system was achieved in this work, where coulomb force is the dominant force in removing dust particles.
- ✚ The average electric field was investigated theoretically and numerically; it was sensitive to the EDS system configuration.
- ✚ The average electric field decreases as the dielectric covering thickness, electrode's width, and the spacing between the electrodes increase; however, the average electric field increases as the dielectric constant and the electrode's height increase.
- ✚ The modification in the source of the electric field applied potential and electrode dimensions are the dominant parameters in the electric field performance.

## 6.2. Suggestions

In order to proceed with this job, the recommendations that are provided below may be of assistance.

1. Build a model that describes all the affected parameters on the EDS system efficiency.
2. Form a mathematical model for the affected forces on the EDS system performance to describe the job of each force and how to increase the EDS efficiency by this force model.
3. Utilize transparent electrode materials and investigate their impacts on the EDS system efficiency.
4. Investigate the operation of the power supply of the EDS system from the solar panel.
5. Investigate the EDS system on the PV solar panel for a long time, more than one year, to optimize the activity of the EDS system.

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## Publications

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- **Saeed A. Baqraf**, Mohammed A. Gondal, Mohamed. A. Dastageer, Muhammad Raashid, Abdulaziz Al-Aswad “High Development of Electrostatics of the Automatic Single-Phase Dust Shield to Engage Renewable Photovoltaic Panels with Dusty Atmospheres and Space Implementations”, *IEEE Journal of Photovoltaics* (under submission).
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