

Investigation of Dust-Related Energy Losses in Rooftop Solar PV Systems: A Case Study in Chittagong Town

(Master of Science in EEE)



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Session 2021-22

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CHATTOGRAM-4349, BANGLADESH
2024

Declaration

I, Rashmi Roy, hereby declare that the work presented in this thesis titled "Investigation of Dust-Related Energy Losses in Rooftop Solar PV Systems: A Case Study in Chittagong Town" is the result of original research carried out by me under the guidance and supervision of Dr. Nipu Kumar Das, Professor, Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology (CUET).

This work has been conducted as part of my Master of Science (MSc) degree in Electrical and Electronic Engineering at CUET. I affirm that this thesis has not been submitted in whole or in part to any other academic institution for any other degree. The results presented herein are based on the data collected during my research, including experimental results, analysis, and observations. All sources and references used in this work have been properly acknowledged and cited.

Furthermore, I declare that the content of this thesis represents my work and is free of any form of plagiarism. Any assistance received during the preparation of this thesis and any contributions made by others have been explicitly stated and acknowledged.

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List of Publications

- **Rashmi Roy**, Israt Jahin Fariha, Nadira Shobnom, N. K. Das (March 2024): Financial Feasibility and Environmental Sustainability of Rooftop Solar PV in Chattogram: A Case Study on Residential, Commercial, and Industrial Buildings. DOI: 10.1109/iCACCESS61735.2024.10499585. IEEE Conference paper: International Conference on Advances in Computing, Communication, Electrical, and Smart Systems (iCACCESS).
- Md Alauddin Bhuiyan, M. J. Rahman, **Rashmi Roy**, N. K. Das (December 2023): Energy-Neutral Cricket Stadium: The Zahur Ahmed Chowdhury Stadium, Analytical Design, and Computational Modeling. DOI: 10.1109/EICT61409.2023.10427967. IEEE Conference paper: 6th International Conference on Electrical Information and Communication Technology (EICT).
- **Rashmi Roy**, N. K. Das, Mrinmoy Dey, M A Matin (October 2023): Evaluating Solar Energy as a Viable Solution to Bangladesh; Energy and Environmental Challenges: Opportunities, Constraints, and the Path Forward. Conference paper: 7th International Conference on Mechanical Engineering and Renewable Energy 2023 (ICMERE2023).
- Rashmi Roy, N. K. Das, Syed Farid Uddin Farhad, Nazmul Islam Tanvir: A Case Investigation Dust-Related Energy Degradation in Rooftop Solar PV Systems in Chattogram City. (Plan to submit in a journal for a full paper publication).

Approval by the Supervisor

This is to certify that the thesis submitted by **Rashmi Roy** to the Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology (CUET), in partial fulfilment of the requirements for the degree of Master of Science (MSc) in Electrical and Electronic Engineering, has been carried out under my supervision.

I have reviewed the thesis and found it to be an original piece of work, and I hereby approve it for submission. The thesis is suitable for presentation and fulfils the necessary standards of research in the field.

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Acknowledgement

I would like to express my deepest gratitude to my supervisor, **Dr. Nipu Kumar Das, Professor, Department of EEE, CUET**, for his invaluable guidance, constant encouragement, and insightful suggestions throughout this research. His expertise and support were instrumental in the successful completion of this thesis.

I am also profoundly thankful to **Dr. Syed Farid Uddin Forhat, PSO, BCSIR**, for his expert advice, assistance with the experimental setups, and for providing the necessary resources that significantly contributed to this work.

My gratitude also goes out to **Nazmul Islam Tanvir, SO, BCSIR**, for helping me with the experimental settings that were a big help with this effort.

I extend my sincere thanks to all the institutions (CUET, AECC, BPDB, and NMI) that facilitated the necessary space for my experimental setup and also helped me in the collection of dust samples for analysis. Your cooperation and support have been essential to this study.

Finally, I would like to acknowledge the support of my family, colleagues, and, friends whose encouragement and patience have been a constant source of strength throughout this journey.

Abstract

The accumulation of dust on rooftop solar photovoltaic (PV) systems is a critical factor that reduces the overall energy output, particularly where the dust accumulation rate is higher. This thesis investigates the impact of dust accumulation on the efficiency of rooftop solar photovoltaic (PV) systems in Chittagong City in four key locations which represent different types of environmental conditions throughout the city. Like- CUET is located in a semi-urban area, AECC is located in an industrial area, BPDB is located in a commercial area and NMI is located in an EPZ area respectively, focusing on how dust reduces solar light transmittance and, consequently, energy output and analyzes the elemental composition of the dust contributing to it. Dust samples were collected from these four locations, and analyzed using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDX) spectroscopy, and UV transmittance tests. And also set up two 550wp solar panels on the rooftop of the CUET's professor building block to investigate the real scenario of degradation of efficiency in a regular clean panel and unclean panel.

The SEM and EDX analyses revealed significant variations in dust composition: CUET samples showed high carbon content (13.09% to 62.71%) with high light absorbing properties which originate from vehicular emissions, burning fossil fuel and industrial activities, while NMI samples had high oxygen that often bound with other elements in the form of oxides (e.g., silica as silicon dioxide, calcium oxide, iron oxide, aluminium oxide) (41.74% to 44.92%). The AECC location showed the highest silicon (commonly present as silica (SiO_2) in sand) content (up to 38%), which correlated with a notable decline in transmittance. BPDB locations also varied, with silicon, iron, and calcium being prominent in certain locations. These elements significantly affected solar transmittance, reducing the panels' energy output. The study found that dust accumulation can reduce solar light transmittance by 10% to 42%, depending on the dust composition, location and also seasonal variation — in the dry season solar transmittance is lower and in the wet season is higher. Energy output data from two 550 Wp solar PV systems at the CUET location showed the highest efficiency drop of 21.28% in April due to dust accumulation.

The findings highlight the necessity for regular cleaning and maintenance of solar panels, especially in environments like Chittagong where dust accumulation is prominent. Based on the analysis, cleaning intervals and methods tailored to each location's dust composition are recommended to optimize energy output. This research provides practical insights into improving the performance of rooftop PV systems, contributing to enhanced renewable energy efficiency in urban settings.

সারাংশ

এ গবেষণার প্রয়োজনীয়তা মূলত শহুরে পরিবেশে ছাদে স্থাপিত সৌর প্যানেলের ওপর ধুলার সঞ্চয়ের প্রভাব বুঝতে সাহায্য করে। চট্টগ্রাম শহরের মতো ঘনবসতিপূর্ণ, বন্দরনির্ভর ও শিল্পায়িত এলাকায় বায়ুমণ্ডলে প্রচুর পরিমাণে ধূলিকণা ও অন্যান্য কণা বিচরণ করে। এই ধূলিকণা সৌর প্যানেলের পৃষ্ঠে জমা হয়, যা সৌরশক্তি থেকে বিদ্যুৎ উৎপাদনের কার্যকারিতাকে ব্যাপকভাবে প্রভাবিত করে। ফলে, সৌর প্যানেল থেকে শক্তি উৎপাদন উল্লেখযোগ্য হারে হ্রাস পায়, যা শহুরে এবং শিল্প এলাকা, বিশেষত বিদ্যুৎ নির্ভরতা বাড়ানোর জন্য অপরিহার্য হয়ে উঠছে।

গবেষণার মাধ্যমে আমরা জানতে পারি, ধুলার প্রভাব কেবল প্যানেলের আলোক শোষণের ক্ষমতা হ্রাস করে না, বরং প্যানেলের দীর্ঘমেয়াদি কর্মক্ষমতার ওপরও নেতিবাচক প্রভাব ফেলে। ধুলার উপাদানসমূহ যেমন সিলিকন, কার্বন, অক্সিজেন, অ্যালুমিনিয়াম ইত্যাদি, প্যানেলের উপরিভাগে জমে আলোর প্রতিসরণ ঘটিয়ে বিদ্যুৎ উৎপাদন কমিয়ে দেয়। গবেষণার মাধ্যমে এই সমস্যার প্রকৃত কারণ চিহ্নিত করে, উপযুক্ত পরিষ্কার পদ্ধতি এবং প্রতিরোধক ব্যবস্থা নেওয়া যেতে পারে, যা ভবিষ্যতে সৌর প্যানেলের কার্যক্ষমতা বৃদ্ধি করতে সহায়তা করবে।

এছাড়াও, বাংলাদেশে নবায়নযোগ্য শক্তি উৎসের ব্যবহার বাড়ানোর যে পরিকল্পনা, তার জন্য এই গবেষণা গুরুত্বপূর্ণ। বিদ্যুৎ উৎপাদনে নিরবচ্ছিন্নতা নিশ্চিত করতে এবং সৌরশক্তির কার্যকর ব্যবহার বাড়াতে ধূলা সঞ্চয়ের প্রভাব এবং তা প্রতিরোধের উপায় জানা অপরিহার্য। এই গবেষণা কেবল একটি তাত্ত্বিক বিশ্লেষণ নয়, বরং সৌর প্যানেল রক্ষণাবেক্ষণের জন্য একটি বাস্তবসম্মত সমাধানের দিকেও দিকনির্দেশনা প্রদান করে, যা বাংলাদেশের মতো উন্নয়নশীল দেশের জন্য অত্যন্ত প্রয়োজনীয়।

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Chapter 1: Introduction

1.1 Background

During the era of international trade, every action has unintended consequences and is acknowledged as essential to reducing poverty and enhancing the socio-economic conditions of individuals. Globally, there have been changes in the kinds of energy sources and how they are used. Before the latter half of the 19th century, wood was the main source of energy. Wood had been supplanted by coal by the end of the same century. By the mid-1900s, petroleum and natural gas were two of the globe's main sources of energy. Gas oil, and coal are fossil fuels that have contributed significantly to the development of contemporary civilization over the last 100–150 years. Conversely, it affects all living things on Earth and produces serious environmental problems (such as a change in climate) at every stage of production, manufacturing, and consumption. Furthermore, other adverse environmental impacts such as acid rain, global warming, low water quality, and groundwater pollution, using fossil fuels pollute the environment and produce over 800 distinct compounds [1]. There is a limited amount of fossil fuels on Earth and nearly every one we consume now comes from nonrenewable sources.

Based on IEA projections, burning fossil fuels produces 60% of the electricity produced globally [2]. Fossil fuels release enormous amounts of CO₂ alongside other toxins into the environment. The impacts of greenhouse gases have intensified due to industrial operations and the burning of fossil fuels for power or transport, which generate large amounts of CO₂. Figure 1.1 shows the causes of greenhouse gas emissions. These emissions have the potential to raise Earth's temperature and produce unstable environmental conditions. This could have serious consequences for humanity's future, especially in less developed rural areas where people are more susceptible to disasters such as drought and flooding [3]. However, the evidence is unambiguous: emissions must be halved by 2030 and brought to a net-zero level by 2050 to prevent the most serious impacts of environmental change.

Given the present energy shortage, the depletion of fossil fuels, and the greenhouse gas emissions they produce, people are looking for practical alternatives that are reliable, inexpensive, easily accessible, clean, long-lasting, and sustainable. Renewable energy has become more and more popular over the past few years. An untapped natural resource is

considered "renewable energy" if it comes from those resources and won't run out or change appreciably for millions of years. In 2021, the total amount of power generated from renewable sources exceeded 8000 TWh, a record that surpassed the mark of 500 TWh from the year before [2].

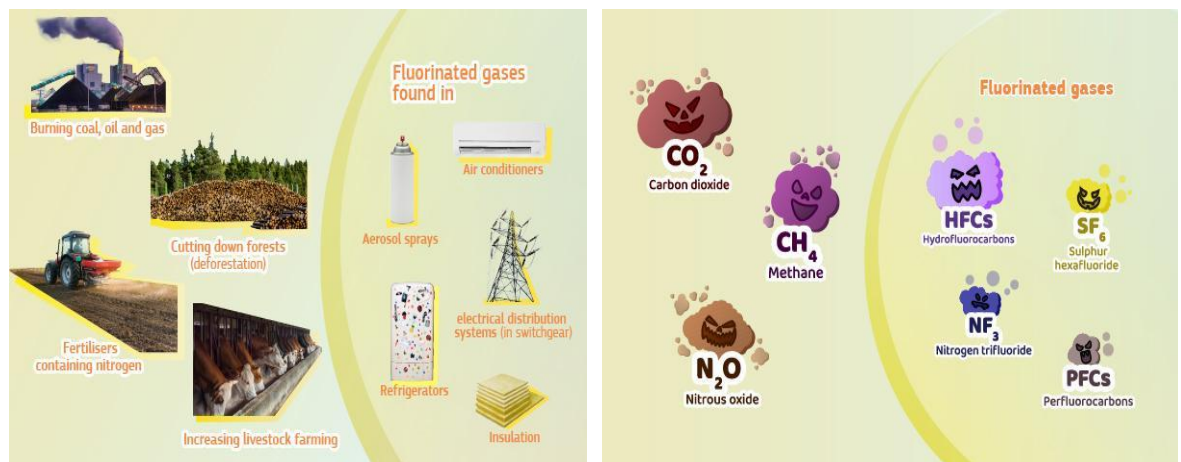


Figure 1.1: The causes of greenhouse gas emissions.

Furthermore, our planet is supposed to be transformed by the Sustainable Development Goals (SDGs). They serve as a wake-up call to eradicate poverty and inequality, save the environment, and guarantee that everyone has access to justice, wealth, and good health. In the meantime, SDG 7 states to ensure access to affordable, reliable, sustainable and modern energy for all. So, as part of SDG goal 7 the Bangladeshi government hopes to have power available to everyone. The government has prioritized the power sector and created short-, medium-, and long-term power generation strategies to achieve the aim. For that, the government sets as its objective in the new strategy to gradually implement generate 10%, or 2,500 MW, of power by 2025 and 20%, or 6,500 MW, by 2030, and forty per cent (40%) of electricity from environmentally friendly sources/renewable resources by 2041 [4]. As low-carbon electricity emerges as the primary energy carrier (Figure 1.2), the proportion of electrical power utilized in final-use sectors must increase from roughly 20% in 2015 to 40% in 2050 [5].

As solar energy emerges as a leading renewable energy source, ensuring its efficiency and longevity becomes crucial. The buildup of dust on the top of panel surfaces is one of the significant issues with preserving the functionality of solar photovoltaic (PV) systems. Dust accumulation can significantly reduce solar transmittance, lowering the panels' energy output and overall efficiency. This observation is especially pertinent in urban areas like Chittagong City, where dust levels can vary greatly based on the place and environmental factors.

Determining the level of energy losses and creating focused cleaning techniques require an analysis of the makeup and effects of dirt on solar panels. Without proper Maintenance can

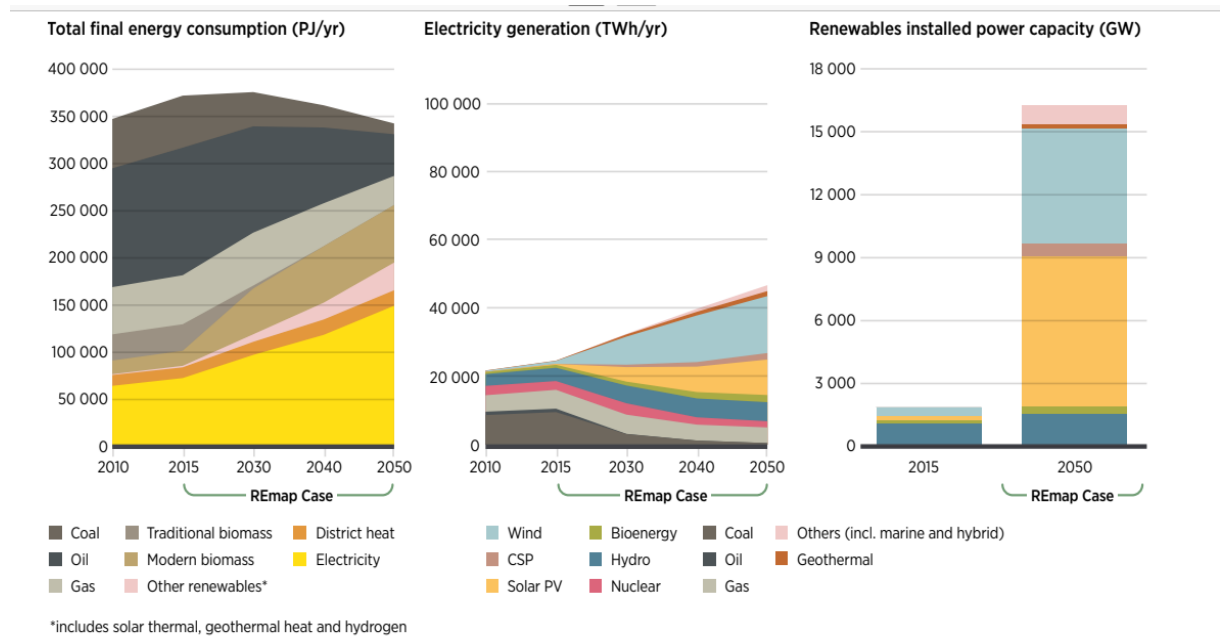


Fig. 1.2: The rising importance of electricity derived from renewable energy.

diminish the effectiveness of solar PV systems over time, leading to higher costs and reduced sustainability. So, it is necessary to study the dust types of accumulate on solar panels and their effect on solar transmittance. Moreover, developing effective cleaning methods tailored to the specific dust composition of different locations can enhance the solar panel's performance, contributing to the broader goal of maximizing renewable energy output and reducing reliance on fossil fuels.

This study addresses these challenges through the setup of dust collectors in four key locations and evaluates the seasonal impact of dust accumulation on solar panels in Chittagong City, analyzes the characteristics and accumulation rates of dust, and assesses the effectiveness of natural cleaning through rainfall. Additionally, it proposes efficient cleaning methods to maximize energy output. This pioneering research addresses a critical yet underexplored aspect of solar energy optimization in the region.

1.2 Objectives

This paper aims to fulfil three key objectives-

- Quantify the impact of dust accumulation on the energy yield of rooftop solar PV systems under different climatic conditions.
- Investigate the characteristics of dust particles that accumulate on solar panels, such as size, shape, and composition.
- Evaluate the effectiveness of different cleaning methods and frequencies for rooftop solar PV systems in various regions and climates.

When designing photovoltaic systems, this study will help developers, engineers, scientists, technicians, PV industry stakeholders, and solar project ownership to incorporate an exact pollution adjustment factor. Pollutant loss evaluations can additionally enhance the projection of solar electrical energy generation, enabling the improved design of the plant and aiding in the prediction of how a PV array or field will perform and the investment return's effects.

1.3 Solar Photovoltaic Energy

Converting sunlight into electrical energy starts with understanding solar radiation and how it interacts with Earth. Solar energy begins its journey as electromagnetic radiation emitted by the Sun. This radiation travels through the vacuum of space and reaches Earth's atmosphere, where a portion is absorbed, scattered, or reflected. The remaining radiation reaches the surface, providing the energy required for generating electricity for photovoltaic (PV) systems.

1. **Solar Energy Reaching Earth:** The Earth orbits the Sun at an average distance of 149.6 million kilometres. The Sun emits energy uniformly in all directions, with Earth receiving a fraction of it, approximately $1,361 \text{ W/m}^2$ (solar constant) outside the atmosphere [6]. However, the energy received on the surface depends on factors such as time of day, season, latitude, and atmospheric conditions.

2. **Longitude and Optimal Solar Energy Collection:** Solar energy varies across longitudes due to the Earth's rotation and its tilt (23.5°). Regions closer to the equator receive more direct sunlight, maximizing energy capture. For example, areas between 20°N and 40°N are often ideal for high solar energy yield because they combine strong sunlight intensity with longer daylight hours.

3. **Atmospheric Effects and Air Mass:** The "air mass" (AM) represents the relative path length sunlight takes through the atmosphere before reaching a surface. It is expressed as $AM = 1/\cos(\theta)$, where θ is the solar zenith angle as shown in Figure 1.3. When $\theta = 48.2^\circ$, it is denoted as AM 1.5, representing the scenario of sunlight shining on the Earth's surface on a typical clear day. This standard air mass condition for solar panel testing, closely resembles actual human living conditions, with an irradiance of 1000 W/m^2 , which represents average atmospheric conditions at mid-latitudes. This condition is widely used for PV performance measurements because it approximates the energy available on a sunny day.

4. **Photovoltaic Conversion Process:** Solar panels, made of semiconductor materials like silicon, absorb sunlight. Most of the time, photons, or light energy, energize the electrons in the atoms of a semiconductor substance when they impact photovoltaic cells. When sunlight, composed of photons, strikes silicon, the energy from the photons excites electrons in the

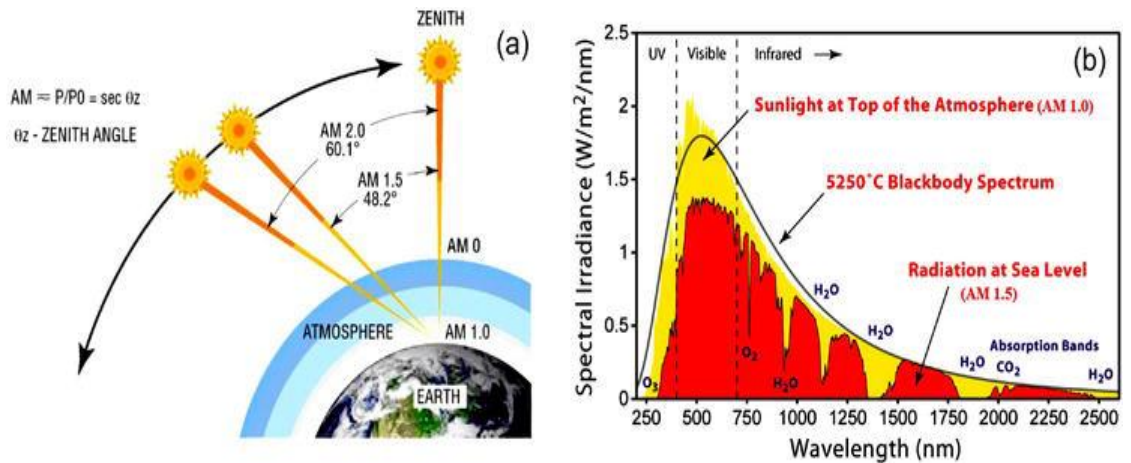


Fig. 1.3: AM 0, AM 1.5 Diagrams and AM 0, AM 1.5G Spectral Graph

material. If the photon energy is greater than the semiconductor's bandgap energy, it promotes electrons from the valence band to the conduction band, creating electron-hole pairs. These charge carriers are separated by an electric field at the p-n junction of the semiconductor, where the p-side contains an abundance of holes (positive charge) and the n-side has an abundance of electrons (negative charge). The electric field drives electrons toward the n-side and holes toward the p-side, generating a flow of charge or current when the circuit is closed, as illustrated in Figure 1.4. This flow of electrons is captured as direct current (DC), which is later converted to alternating current (AC) by an inverter for practical use.

Particularly rooftop solar PV installations have gained popularity due to their accessibility, high flexibility, simplicity, scalability, ease of installation, ability to capture abundant sunlight, and clean and secure use that can lower future electricity costs and reduce reliance on grid power. Photovoltaic cells have an extremely extended lifetime. The first solar power system was set up in the US in 1954, and it still stands today.

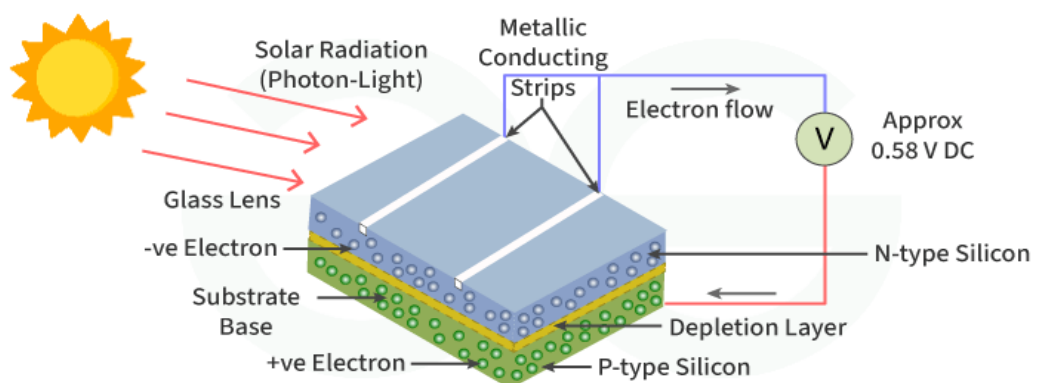


Fig. 1.4: Photovoltaic Cell.

Systems that use solar energy have different output voltage, current, and power depending on how much sunshine they get. The total global absorption of solar energy is nearly

1.8×10^{11} MW [7], which is enough to meet the current power demands of the world. Figure 1.5 illustrates that the solar energy generation capacity has increased significantly in the last decade, and further extrapolation demonstrates that its future capacity could increase up to 1700 GW by 2030 [8]. The International Energy Agency (IEA) calculated that photovoltaic (PV) may supply eleven per cent (11%) of all green power produced worldwide. This equates to a substantial annual decrease of 2.3 gigatonnes of CO₂. Bangladesh is a subtropical nation that receives an estimated 1,900 kWh/m² of solar energy annually, or 4 to 6.5 kWh/m² daily, which is a substantial amount of solar radiation [9]. Thus, solar photovoltaic is the most potential renewable energy source. Presently, Bangladesh produces 1084.49 MW of solar energy out of 1378.48 MW of total renewable energy [10]. Although there is no denying that solar energy has the potential to transform the energy landscape, over time completely, several external variables may compromise the effectiveness and performance of PV systems.

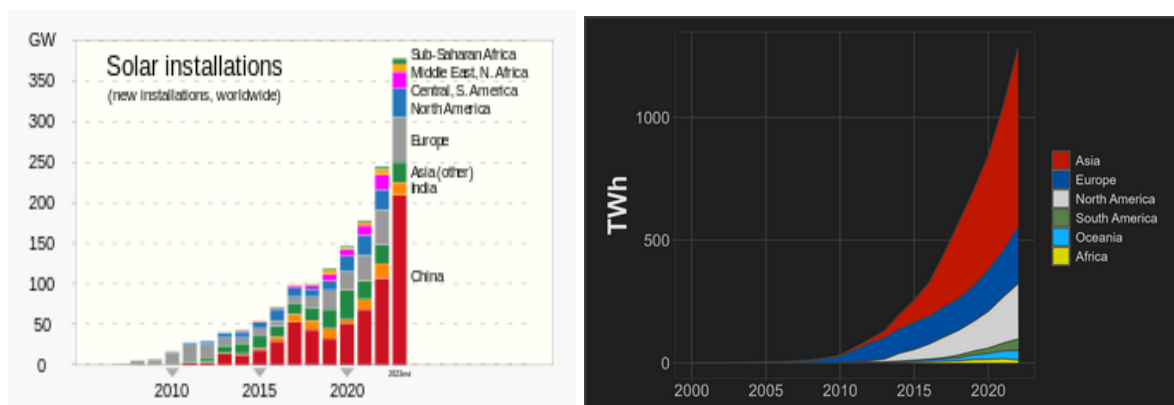


Fig. 1.5: Photovoltaic energy generation capacity over the years.

This deterioration is contingent upon various aspects, including panel quality, ambient circumstances, upkeep, and technological advancements, as shown in Figure 1.6. For example, when a photovoltaic cell's temperature goes up, the panel's efficiency output power significantly drops. Again, wind speed may also influence how well photovoltaic (PV) panels work. By removing warm air and allowing more cool air to enter, wind may help to boost the convective cooling of the PV system, which may help to lower the temperature of the PV cells. Photovoltaic efficiency is also impacted by humidity. If the temperature of the solar cells is lower than the ambient air at the point of dew, high humidity could result in precipitation. When this happens, ambient water vapor may condense and produce minuscule water droplets on the PV panel's surface. The capacity of these water droplets to absorb and disperse light lowers the quality of sunshine that enters the PV cells. Additionally, high relative humidity can cause electrical connections to corrode and the photovoltaic system to malfunction. Solar panels deteriorate at a rate of 0.5% per year on a typical basis, according to the National

Renewable Energy Lab. This means that after twenty years of service, a panel will provide energy at roughly 90% of its initial peak output.

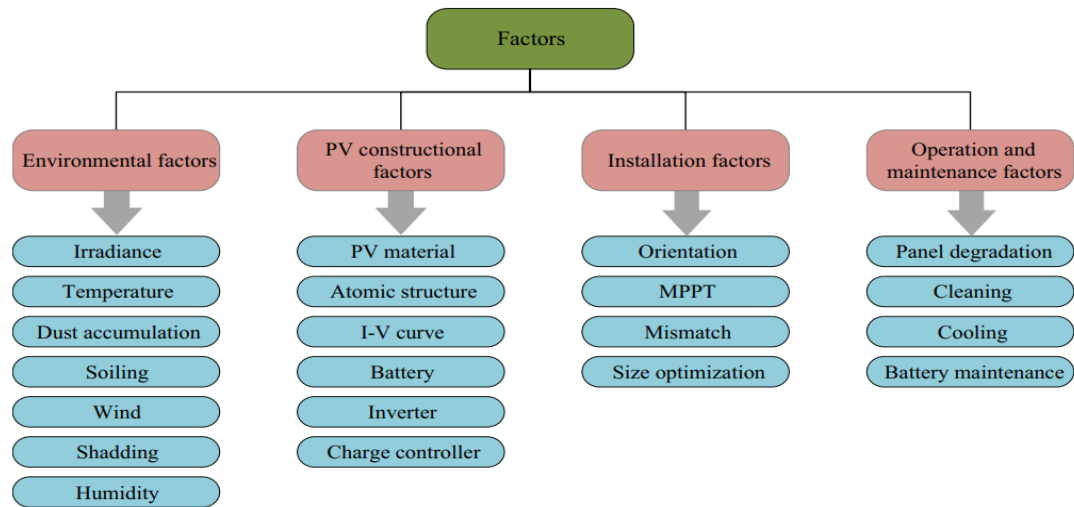


Fig. 1.6: PV panel efficiency degradation factors.

1.4 Dust

Usually are two different forms of shading: mild shading, which occurs when dust, haze, or fog lowers the solar radiation intensity, causing the current to fall in proportion to the radiation intensity. The efficiency of the PV system is significantly affected by this shadow type. Hard shadowing is the process of anything blocking the light in a certain area. A solar cell that is fully shaded produces no current; when it is slightly shaded, just the section of the cell that is slightly shaded is impacted, and the current production drops correspondingly. The accumulation of dust on PV panels is posing a growing threat to their dependability. By slightly obscuring the sunlight irradiance incident on the surfaces of PV modules, the persistent and flying dust in the sky makes a shadow that blocks sunlight and drastically lowers the amount of electrical energy produced as well as overall system productivity [11]. Furthermore, dust accumulation on solar cell surfaces prevents light from entering the cells, which heats the cell's internal components and drastically lowers the output efficiency of PV modules [12]. Quantifying the effect of pollution is crucial wherever PV systems are to be placed, and long-term, on-site tests are preferred. The impact of dust (or soiling) deposition and shadowing on PV module output has been investigated by specialists worldwide [13]. Nonetheless, dust and air pollution are widespread, particularly in areas like China and India where solar PV markets are expanding quickly and where solar PV power generation is much lower [14]. The air pollution effect on environmental transparency is shown in Fig. 1.7 (a). The generation of solar electricity is threatened by atmospheric pollutants because they can, as Attenuate solar radiation that reaches the PV surface through absorption, scattering, and reflection, as depicted in Fig. 1.7 (c). Bangladesh ranks

seventh globally in terms of air pollution, according to the IQ Air Report 2022. Particulate matter concentration is measured in parts per million (ppm) or micrograms per cubic meter. The Air Quality Index (AQI) is derived from the amounts of carbon monoxide, nitrogen dioxide, sulfur dioxide, and PM2.5 and PM10 particles, among other contaminants. The aerodynamics of PM2.5 and PM10 particles are, respectively, 2.5 and 10 micrometres or less. PM2.5 and PM10 are the two pollutants that have the worst effects.

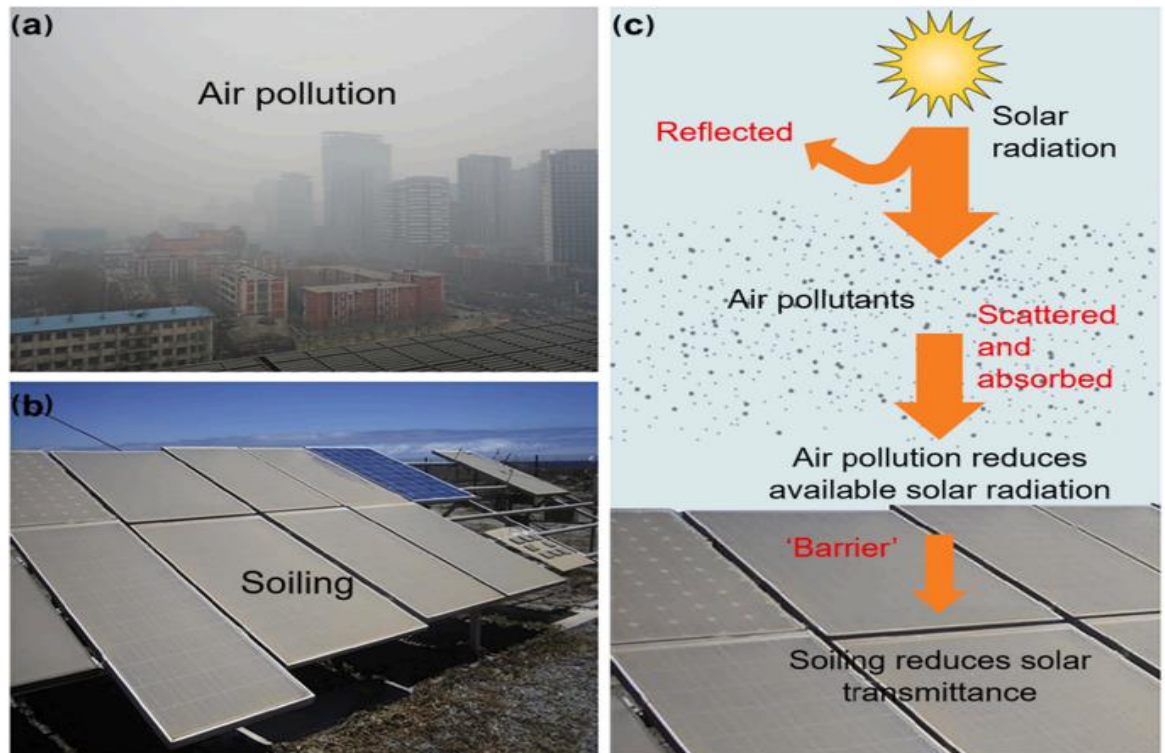


Figure 1.7: An illustration of a) pollution in the environment, b) soiling of PV modules, and c) how soiling and air pollution reduce the amount of solar energy that reaches the PV surface [14].

The mean pollution level in Chittagong is $39.2 \mu\text{g}/\text{m}^3$ at PM2.5, which is below the recommended threshold of $12 \mu\text{g}/\text{m}^3$ for health, according to most studies [15]. If the air quality exceeds $35 \mu\text{g}/\text{m}^3$ for a full day, it is deemed unhealthy [16]. The sources of dust in the study included open waste dumping, automobiles, brick kilns, burning rubbish, industrial emissions, and road dust, all of which contribute to air pollution in metropolitan areas. The impact is worse on the solar unit during the season of dry when the atmosphere is dirtier and leads to a drop in energy, voltage, and current due to the buildup of dust with particular mass fractions [17]. Little research has been done so far on the extent to which Bangladesh's dust deposition has reduced solar energy output in indoor setups. To that end, an analysis is carried out in this work to determine how dust particles can impair the performance of solar panels and also quantify

the effect and features of dust particles that build up on solar panels, including their shape, size, and composition.

1.5 Dust intensity around the world

The dust concentration is more significant in areas that are darker in Figure 6, which depicts the world's distribution and intensity of dust. Regarding dust protection, it has been noted that the nations in the Middle East and North Africa (MENA) are significantly affected, followed by regions such as portions of Asia [18]. The world's dustiest region is the MENA region [19], with Saudi Arabia, Sudan, Iraq, the Persian Gulf, and the region experiencing the most strong frequency of severe storms of dust globally [20]. Most of the dust storms caused by the Shamal winds are recorded in the dry months in the Persian Gulf, Iran, Syria, the southern Arabian Peninsula, and Iraq; in winter, dirt storms are documented in the regions of Mediterranean northern Egypt. In addition, storms of dust primarily occur in the springtime in the Mediterranean regions of northern and southern Jordan, Egypt, Lebanon, western Iraq, and the northern Arabian Peninsula [21]. Frequency of dirt worldwide with an annual production of between 60 and 200 million tons of mineral dust, the Sahara Desert is well known for being the earth's largest dust supplier. According to research, the amount of dust released into the Sahara desert is almost 400% higher than that of the Arabian deserts [22]. With regard to the frequency of dust storms, South West and North East Asia, and MENA are the most frequented locations. The global dust frequency scheme based on synoptic meteorological records for 1974–2012 is displayed in Fig. 1.8 [23].

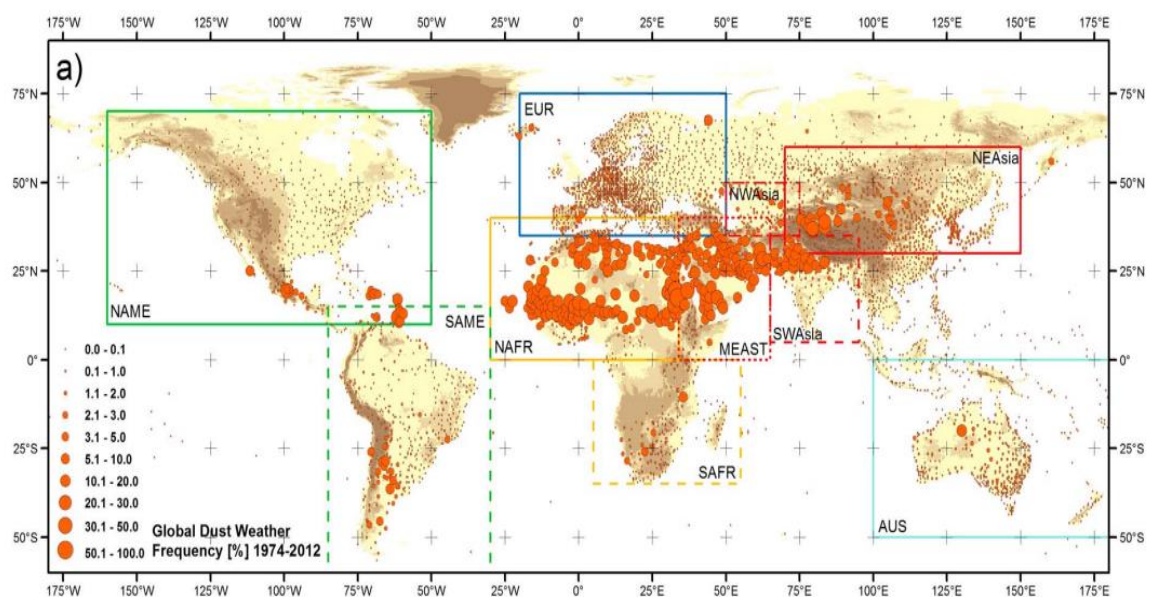


Fig. 1.8: The pattern of dust frequency worldwide from 1974 to 2012 based on comprehensive weather records [23].

1.6 Causes of dust accumulation

A number of variables, including air pollution, temperature, wind direction and speed, sun irradiation, shade, and neatness, have a significant impact on how much energy solar panels generate. Climate fluctuations can impact ambient temperature and sun irradiation, which can change the amount of energy produced by photovoltaic panels [24].

Depending on the environment, type of dust, location, and solar plant installation, dirt—which may be measured in layers of micron—may build up on the PV panels over time [25]. The rate at which dust collects on the solar panel's surface is also influencing the degree of tilt. Fig. 1.9 provides a particular view of the reasons behind accumulation of dust. The weight and size of the dust particles deposited on the solar panel's surface affect its efficiency.

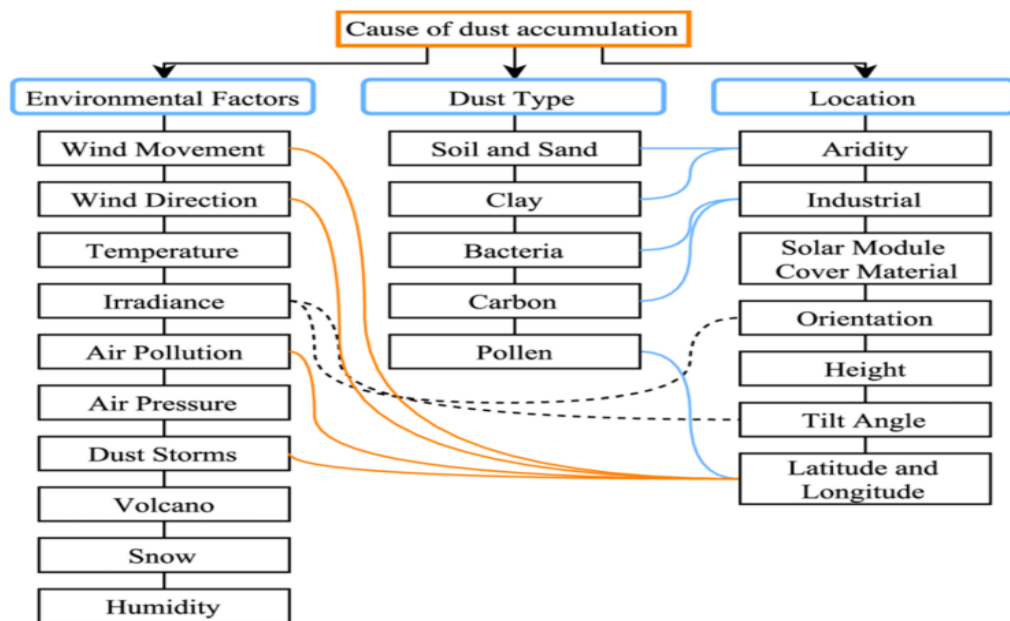


Fig. 1.9: A detailed view of dust accumulation causes [25].

Numerous research have thoroughly examined the relationship between the quantity of dust that has been placed on the Photovoltaic panel's surface and losses of power from the panel [26]. The two factors were shown to be linearly related; the more the dust particles that are deposited get smaller, the loss in power generation increases with the amount of radiation that is obstructed from reaching the PV module surfaces [27]. Pollutants that have been deposited include ash, silica, sand, and red soil. Numerous environmental conditions, like as wind speed, humidity, and air temperature, affect these pollutants' phase, size, physical, and chemical properties along with how they aggregate on the panel's surface [28].

Although the soiling impact increases as the tilt angle of the solar PV panel decreases, or, to put it another way, increases as the panel becomes more horizontal, pollutants in the atmosphere may still drastically impair the energy production of the panel., as illustrated in

Fig. 1.10. This research can be linked to the observation that while the gravitational force increases in eliminating accumulated dust as the tilt angle decreases, it does so less effectively [29]. Because of soiling, this accumulated dirt shades the PV modules, which lowers the output power that is produced. Nevertheless, the output power increases once again if the modules are cleansed.

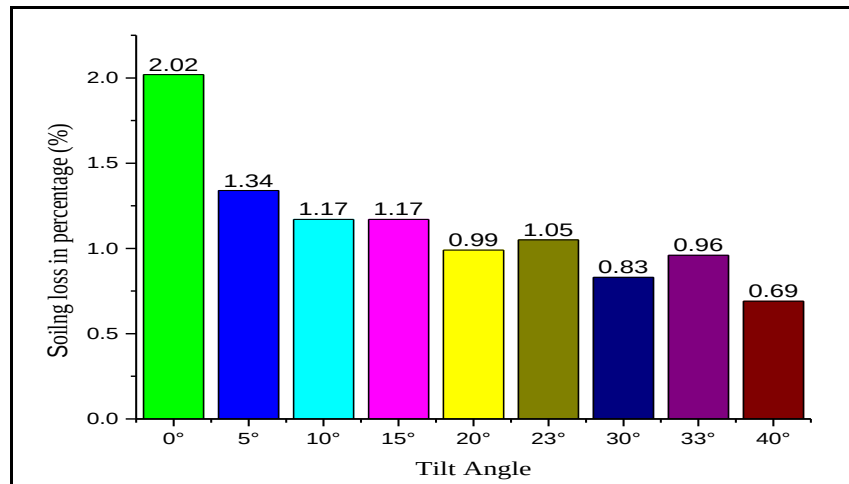


Fig. 1.10: Soiling losses at different tilt angles [29].

1.7 PV Performance Based on Dust Particle Size

Dust particle size has a considerable impact on the performance of photovoltaic (PV) modules. Smaller particles aggregate more easily due to wind and air currents, resulting in increased deposition on PV surfaces. Dust particle size relates to the size of particles deposited on PV systems, which can range from submicrometers to millimetres. These tiny particles consist of diverse components with variable diameters, volume, chemical composition, and form. The dust collection's particle size distribution ranges from 0.003 μm for clay particles to 190 μm for soil particles, with 83% falling within the 0.3 to 60 μm range [30]. Experimental measurements of the dust's size showed that it ranges from 0.1 to 1000 μm , with the majority of the particles collected (43%) having diameters between 100 and 500 μm and 15% having sizes between 10 and 50 μm [31]. Moreover, smaller particles have a greater impact on reducing solar energy transmission due to their larger surface area. For example, Larger particles predominated in the dust from Babuin, Indonesia, compared to Perth, Australia, according to the size on two samples of dust from two different nations [26]. According to the researchers, larger dust particles that stuck to PV glass surfaces tended to be irregularly distributed, creating huge spaces between them that allowed more light to pass through. Nevertheless, the small particles absorb more solar energy and perform worse in terms of PV power because of their higher surface area-to-volume ratio. However, the soil particle size can

affect PV module power output differently. The smaller particle sizes (75 μm and smaller) had a greater impact on power output at low irradiance levels (300–500 W/m^2) but the larger particle size (150 μm) had a greater impact at higher irradiance levels (1000–1200 W/m^2) [32]. Understanding the size arrangement of dust particles on the panel is essential for forecasting how dust will impact PV system performance.

1.8 Effect of Shaded Solar Cells and Hot Spots in PV Panels

Partial shading is a critical issue in photovoltaic (PV) panels, as it significantly impacts their performance and longevity. When a portion of a solar panel is shaded, the affected cells produce less current than the unshaded cells. Since solar cells within a panel are typically connected in series, the reduced current from the shaded cells limits the overall current flow in the circuit. This leads to a reduction in the panel's power output, even if the shaded area is minimal.

In addition to power loss, shading can cause localized heating known as hot spots. Hot spots occur when shaded cells are forced to dissipate excess energy as heat rather than contributing to power generation. This happens because the current generated by unshaded cells passes through the shaded cells, causing them to operate in reverse bias. Over time, hot spots can degrade the performance of the affected cells, reduce the efficiency of the PV panel, and potentially lead to permanent damage, such as delamination or cell cracking.

Modern PV panels often include bypass diodes to mitigate the effects of shading and hot spots. These diodes provide an alternate path for current to flow around shaded cells, preventing reverse bias and reducing the risk of damage. However, the use of bypass diodes may result in the loss of power from the shaded portion of the panel, which still affects overall efficiency.

Understanding and addressing the effects of shading and hot spots is crucial in the design, installation, and maintenance of PV systems. Proper site analysis to minimize shading, the use of advanced materials, and innovative technologies such as smart panels can help mitigate these issues and enhance the reliability and performance of PV systems.

1.9 The severity of the dust issue

Figure 1.11 summarizes the influence of dust accumulation on the output performance of the panel, including the maximum and minimum values for monthly reduction in various locations. The power reduction and efficiency degradation numbers provided are derived from real measurements; the location and timing of the measurements are responsible for any discrepancies in the values. For the North Africa, Middle East, and the Far East, the soiling impacts are significant and crucial. Depends on the data shown in Figure 1.11, the difficulty of

dust deposition over the solar panels is extremely severe all over the world. In Egypt, the monthly decline in efficiency can vary from 11 [33] to 17% [34]. This implies that the efficiency of Photovoltaic panels can declines by 50% within a span of 3-5 months. Consequently, it becomes imperative to purely clean the PV panels to retain their efficiency and ensure a consistent power output [35]. This sharp decline in Egypt's efficiency applies to several other nations as well, Pakistan included. The monthly worsening of the solar panels' effectiveness in Pakistan owing to dirt collection can differ from 16 up to 57% [36], that's it fairly substantial and again shows that additional research should be done to decrease dust deposition over PV panels. It is evident that the monthly decrease is significant and occasionally reaches 65% [37]. Using dust components such as sand, red soil, wood power, and bird dropping, one study in Bangladesh evaluates an inside experiment setup with an artificial solar simulator to observe the PV performance. Bird droppings, wood powder, red soil, and sand decompose at levels of 8.1%, 10.3%, 22%, and 24.5% under dry conditions and 3.6%, 9.5%, 18.3%, and 17.2% under wet conditions [38] and another study show efficiency can degrade maximum 35% and minimum 22% in the one-month interval [17]. That will have a major effect on the power output and payback time. For this reason, it's critical to routinely purify the PV panels at a cheap cost and with fewer resources.

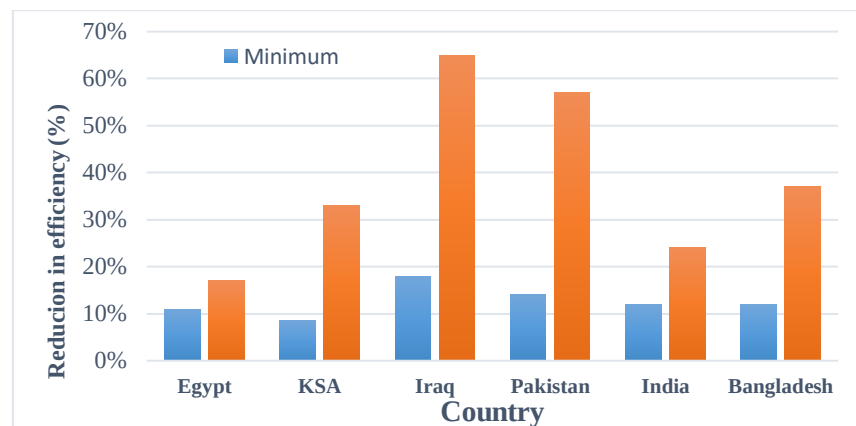


Fig. 1.11: The maximum and minimum monthly drop in Photovoltaic panel efficiency due to dust collection for a few countries.

Chapter 2: Literature Review

Solar photovoltaic (PV) systems have emerged as a critical alternative in the quest for clean and renewable energy. The installation of these systems has been demonstrated to dramatically reduce dependence on greenhouse gas emissions and fossil fuels, particularly in regions with high solar insolation. Nonetheless, one of the most significant environmental problems that can impair the effectiveness and performance of solar PV systems is dust deposition. Because dust has greatly decreased the efficiency and longevity of Photovoltaic modules, researchers worldwide have focused a great deal of emphasis on dust-related energy losses in solar PV systems. Understanding the causes behind dust formation and its harmful effects on energy output is essential, especially in regions like Chittagong, Bangladesh, where there is a high prevalence of dust deposition. To maximize the performance of rooftop solar PV installations, it is also essential to determine appropriate cleaning techniques that are specific to the local environmental conditions.

The literature review chapter thoroughly summarises the body of knowledge regarding the origins, consequences, and various cleaning techniques for dust on solar PV panels. Additionally, this chapter will highlight region-specific perspectives and useful suggestions for raising the sustainability and efficiency of rooftop solar PV installations in comparable settings. The following themes will be methodically examined in this chapter:

2.1 Dust Deposition Mechanisms and Their Effects on PV Performance

Comprehending the process of accumulation of dust on solar panels and the variables impacting the rates of deposition is essential. According to earlier research, dust deposition lowers light transmission and raises surface reflectance, which lowers PV systems' overall efficiency. Studies have additionally demonstrated that the kind, dimensions, and makeup of dust particles can differ greatly, impacting the degree of energy dissipation. The shape and size of the extracted dust particle arrangement has both an immediate and considerable impact on the reduction of solar cell performance [32]. The quantity and size of dust accumulations have an impact on how light enters PV modules and how it is absorbed, scattered, and reflected. They additionally possess an enormous effect on how wind speed interacts with

them. While small particles tend to stick to the solar cell's surface and each other, big particles volatilize and cling to the air even in mild prevailing breezes [39]. the effect of dust particles on the performance of concentrated solar power (CSP) in semi-arid and arid regions. Experimental and numerical studies are used in the study to comprehend the soiling rate and how it affects CSP functionality. Results show that the soiling rate is influenced by wind direction and speed, with the highest decrease observed in March. The study also found a 63% drop in specular reflectivity after three months of exposure. A parabolic trough solar collector's thermal performance and power soiling loss were measured; the thermal efficiency decreased by 36%. The soiling effect is more noticeable in CSP systems, leading to a three to five times decrease in performance, according to the study's comparison of power soiling loss with that of PV technology [40]. A comprehensive review [41] paper on the use of solar energy in various industries, emphasizing the significance of understanding dust deposition mechanisms. It highlights how dust particles adhere to solar PV surfaces, reducing efficiency and increasing maintenance costs. The authors discuss various factors influencing dust accumulation, including particle size, surface, environmental conditions and roughness. Among the various pollution depositions are silica, ash, red soil, sand, and calcium carbonate. The energy yield of photovoltaic panels can be severely reduced by air pollution; even after a little outdoor exposure (such as two months) without proper cleaning, the panels' power generation can be decreased by about 6.5% [42].

Among the several types of analysis, the most common and challenging is that of environmental influences.. Thus, unlike other conditions, this is faced regularly throughout the year. When it comes to PV panels, pollution is the grownup of particles of dust on the surface of the modules. These particles, which correspond to the area where the panel has been stored, can include sand, ash, etc. [43]. This category's experiment includes an investigation of the dust-induced decrease in solar radiation.

Researchers found in another study that the less recognized component that has the biggest impact on PV installation effectiveness is dust [44]. They evaluated the state of the art in the examination of dust's impact on PV system performance and noted obstacles to more relevant study. Nonetheless, certain researchers suggested and talked about how dust affects the solar collectors' transparent cover. [45][44]. They proposed a concept for electrical performances and conducted an experimental study into the impact of accumulated dust particles on PV modules. The research focused on factors like effective operating techniques, radiation availability and these systems' design and sizing. The output efficiency of solar PV modules is greatly decreased by dust, it was found. The decrease in glass regular

transmittance is significantly influenced by the dust deposition density, plate tilt angle, and surface orientation with respect to the prevalent wind direction. Changes in power fluctuation when PV cell pollution increases. A decline in output power of around 17.4 percent per month is suggested by the slope of the best straight line that passes across the data points of the solar cell positioned at a 45° angle facing south. After conducting an investigation into the impact of dust on the exacerbated environment in the Greek city, Athens, researchers concluded that the effects of dust are site-specific [46]. Similarly, other researchers studied the fundamental impacts of dust fouling on the glass covers of PV modules [47]. The findings showed that the total transmittance was about 20% and the spectral transmittance declining was about 35%. Additionally, the typical spherical nature of the deposited dust particles was noted. One more author [48] offers a simulation approach to forecast how dust may affect PV performance. The model illustrates how varying dust densities impact energy output and has been verified by experimental data. The study's findings emphasize the need for efficient cleaning techniques since even small amounts of dust can result in significant efficiency losses.

Hegazy investigates [49] how dirt accumulation affects the solar transmittance of glass covers used in solar collectors. The findings indicate a notable decrease in transmittance with increasing dust deposition, leading to reduced collector efficiency. The paper emphasizes the need for regular cleaning to maintain optimal performance. Another research [50] quantifies the energy yield reduction of PV panels due to natural air pollution and dust deposition. The authors conducted field measurements and found that areas with higher pollution levels experience more significant efficiency losses, underlining environmental factors' impact on PV performance. This paper also presents [51] experimental results on the effect of dust on PV panel energy yield. The study shows a clear correlation between dust density and performance reduction. The findings' implications for PV maintenance procedures and the advancement of dust mitigation devices are covered in the research.

2.2 Quantifying Energy Losses Due to Dust Accumulation

Quantitative evaluations of energy losses shed light on how serious the issue is. Research has revealed differing levels of reduced efficiency; in severely dusty regions, some studies have reported losses as high as 30%. These results highlight the need of routine maintenance and efficient cleaning techniques.

A thorough assessment of the impact of soiling on Photovoltaic performance in California is shown in the research [52]. To calculate the energy losses brought on by dust accumulation, the researchers employed statistical models in addition to field data. According to the study,

annual energy yield might be greatly increased by routine cleaning. This conference piece of writing discusses the consequences of soiling on large-scale solar installations in California and the Southwest United States [53]. The author's present data showing significant performance degradation due to dust and pollution, highlighting the importance of regular cleaning for maintaining system efficiency.

This comprehensive review paper [54] summarizes historical and contemporary research on dust impacts on solar energy systems. The authors discuss various methodologies for quantifying energy losses due to dust, as well as mitigation strategies. The review highlights the need for standardized testing procedures to accurately assess soiling effects.

Dust deposition on photovoltaic panels causes energy yield losses, which are measured in this thorough study [27]. The impact was estimated by the scientists using both experimental and modelling methods, and they discovered that dust can result in significant losses in efficiency. The study highlights how critical it is to create efficient cleaning technologies. Dust deposition on PV panel surfaces is particularly high in desert regions. Dust on photovoltaic panels reduces solar effectiveness by about 40%. Different PV system cleaning techniques are currently used in this area [55].

Additionally, a performance assessment of the environmental impacts of PV modules was conducted by Zeki.A. Darwish et al. [28]. According to the study, dust accumulation on the solar panel's surface results in an average annual energy loss of about 4.4% per day. During extended dry spells, daily energy losses can exceed 20 per cent. Phase, kind, physical and chemical characteristics of dust particles differ based on different environmental factors. Apart from the speed of the wind, temperature, humidity, and air all significantly affect how isolated dust behaves and builds up on the PV cell.

Based on actual observations, researchers provided a notion regarding the impact of dust accumulation on the performance of multi-crystalline Photovoltaic modules [56]. The impact of dirt on the performance of PV modules (multi-crystalline) and the deterioration of PV performance as a result of various pollutants deposition and accumulation were examined by the authors. The density of dust accumulated on PV modules and the variations in efficiency in composite climates have been linked by the authors [57]. They came to the conclusion that there was a substantial decline in PV module power, about 10-15%, when heavy layers of dust deposition. Additionally, they claimed that a very few quantity of dust on the solar PV modules' covers seldom ever interferes with the sun's ability to reach the silicon photovoltaic module. Scholars carried out investigations into the impact of diverse relevant factors on the

effectiveness and functionality of solar photovoltaic cells. None, though, have considered all three of these factors at once.

Researchers examined how dirt buildup affected PV module performance and examined how particles affected solar module performance [58]. According to the study, external resistance can cut PV performance by as much as 85%. This study also found that raindrops would not have a substantial effect on PV module performance. Approximately 30% of the energy coming from the sun is absorbed or reflected by clouds, oceans, and land, according to an investigation that was conducted [59]. Furthermore, it has been reported that absorption or reflection losses cause a portion of the solar energy that enters the solar cell to be lost; these losses are believed to account for 15 to 30 per cent of the total energy gathered. The aluminium/steel bimetallic strips operate as a passive activator for the experiment-based solar tracker. Efficiency gains of up to 23% are realized over installed solar panels. Excellent agreement exists between the results and the artificial intelligence model [60]. The design, testing and modelling of an active single-axis solar tracker are presented. By using a light-dependent resistor (LDR), the smart tracker system functions in many modes to enable flexibility to accommodate varying environmental conditions.

Additionally, an investigation conducted through experimentation demonstrates a concurrence with the MATLAB/Simulink model's performance [61][62]. The authors supplied data from experiments on 5 W polycrystalline and amorphous PV modules [63]. The voltage and current are used to conduct the performance evaluation. An assessment of the PV module's energy, electrical, and thermal characteristics has been attempted. For a thorough analysis, factors including fill factor, voltage, current, heat loss, and module temperature are taken into account [64]. An extensive examination of the energy and building-integrated photovoltaic modules' analysis is evaluated alongside electrical performance [65].

The writers went into detail on the yearly performance in terms of performance ratios and other kinds of power losses. The PV-SYST and PV-GIS software programs are used to compare the PV plant's obtained results. A hostel building's isolated rooftop solar PV system was designed by the authors [66], and simulation was used to assess the system's performance. The entire cost is estimated, including labour, controller, maintenance, and cabling. Studies on the effect of dust accumulation on PV module surfaces were conducted by the majority of researchers. It has been demonstrated that during a six-month trial, dust collection could cause power drops of up to 50%. Additionally, the authors examined the behavior of a solar energy collector drop when dust gathered on its surface. In order to assess PV performance over a specific time period, the scientists chose rooftop PV panels. Additionally, they computed how

different settlement of dust thicknesses affected the energy yield and financial performance of tiny power plants. It may be concluded that the performance of environmental circumstances is based on the studies that the researchers are conducting. Isolated dust and its behaviour in accumulating on the PV cell are largely determined by air, humidity, temperature, and wind speed.

Another examination [34] of the dust deposition mechanism on solar photovoltaic modules showed that the fine grain, which has a diameter of less than 0.05 mm, the medium grain, which has a diameter of 0.05 e² mm, and the coarse grain, which can range from 2 to 57 mm, are related to the distribution, shape, orientation, size, and deposition types and orientation of dust particles on the module top surface. Again, another study looks into how much sand dust there is and how that affects photovoltaic panel efficiency. It was observed that when dust particles accumulate up to 1 g/m², the maximum output power and short circuit current fall dramatically; however, the rate of decrease slows down at higher concentrations. Roughly 40% less short circuit current is used, and approximately 34% less maximum output power is produced. Open circuit voltage, however, is not affected by the buildup of sand dust [67].

A different study by the same researchers concluded that fly ash samples, limestone deposition, and red soil deposition all had a significant effect on the performance of the solar PV module, with dust being the less well-known issue although it was an indoor experiment.[68] A study was designed with these facts in mind to find the effects of different dust particles on the functionality of solar photovoltaic modules and determine the correlation between particle sizes and solar photovoltaic performance.

2.3 Dust Cleaning Methods (Economic and Practical Considerations)

Research into more sophisticated cleaning systems with effective techniques must include dust cleaning on PV panels. One important consideration in the use of various cleaning techniques is their cost-effectiveness. Understanding the trade-offs between higher energy output and the expenses of implementing and sustaining these solutions is made easier with the aid of economic evaluations of cleaning procedures. Here are some key cleaning techniques that are covered.

Investigating more sophisticated cleaning systems with effective techniques requires a thorough understanding of dust cleaning on photovoltaic surfaces. Investigating more sophisticated cleaning systems with effective techniques requires a thorough understanding of dust cleaning on photovoltaic surfaces. The cost-effectiveness of different cleaning

methods is a crucial factor in their adoption. Economic analyses of cleaning strategies help in understanding the trade-offs between increased energy output and the costs associated with implementing and maintaining these solutions. Some of the important cleaning methods are discussed as follows.

Solar photovoltaic module washing procedure shielded the solar cell and increased efficiency. The authors compiled all of the dust elimination techniques, including electrostatic, self-cleaning nanofilm, mechanical, and natural ways [69]. In the industrial setting, a linear piezoelectric actuator-based method for cleaning solar panels is used to provide the most electricity. In an attempt to efficiently clear the layer of dust from the top surface of the solar PV module, a mop/wiper is fixed with the activator for linear movement. This cleaning technology is lightweight and compact [70].

One of the main research topics for the viability of solar plants is lowering the cost of cleaning solar panels. A. Fernández-García et. al. concentrated on improving outside cleaning techniques for solar plants in semi-desert climates. Various cleaning techniques are employed, and based on the outcomes, the water and brush cleaning method is the most successful. The concept was supported by the findings, which showed an average effectiveness of 98.8% during rainy seasons and 97.2% during dry ones. [71].

The investigators designed a novel receiver tube research to track how well cleaning techniques for solar panels worked. After testing five different cleaning techniques, it was determined that the receiver tube method was the most successful. When compared to the other tried and proven procedures, this one is more conventional. An enhanced cleaning method that employs electrostatic force to eliminate sand from solar panel surfaces has been created by Kawamoto et. al. [72]. Over 90% of the remaining sand is driven away from the solar power module surface by the developed cleaning mechanism, as illustrated. Even in situations where there was an excessive amount of sand accumulation and deposition on the panel, the system's output performance was enhanced. The proven technology is expected to enhance the output efficiency of MW solar power plants located in desert areas.

An extensive analysis covers dust-related issues and highlights the latest advancements in automated washing systems for solar photovoltaic modules [73]. The authors have successfully developed a robotic arm with electromechanical system designed for cleaning the top surface of solar PV modules. Through meticulous analysis and optimization, they have achieved high effectiveness. During 50 W solar panels testing time, they observed an enhancement in efficiency. Dust, bird droppings, and dirt significantly diminish the performance of PV systems. Regular maintenance is crucial to ensure optimal

efficiency. Another review assesses [74] different kind of cleaning methods for solar photovoltaic modules, focusing on recent technological developments and comparing traditional manual cleaning with automated and robotic systems, analyzing their economic feasibility. The study concludes that automated cleaning (Electrostatic cleaning) can significantly reduce operational costs and improve efficiency.

By delving into these areas, this literature review not only synthesizes the existing body of knowledge on dust deposition mechanisms, energy losses, and cleaning techniques but also highlights a critical research gap. Previous studies have predominantly focused on arid or semi-arid regions, leaving subtropical areas with high humidity and diverse dust compositions underexplored. Notably, no prior studies have comprehensively evaluated the effectiveness of natural cleaning—such as rainfall—in removing dust from PV systems or quantified the energy recovery achieved without relying on artificial or advanced cleaning technologies. This absence of data leaves an important gap in understanding the baseline efficiency that can be attained under natural conditions.

Motivated by this gap, the current study introduces a novel approach by empirically examining the role of natural cleaning and how much output energy can be gained by this process without additional intervention establishing a critical benchmark for PV system performance, in Chittagong’s environmental context. This investigation lays a foundation for proposing optimized, sustainable, and cost-effective strategies, to mitigate dust-induced energy losses in rooftop solar PV systems. These efforts will not only advance knowledge in the field but also provide actionable insights for enhancing solar energy efficiency in similar regions. The findings from this study will form a robust foundation for the methodologies and analyses detailed in the subsequent chapters.

2.4 Different country’s study on dust accumulation:

As Fig. 2.1 illustrates, the majority of studies on the soiling and dust collection effect on solar panels came from Asia. According to some research reports, Saudi Arabia leads the globe in the quantity of research and studies looking into the soiling effect on photovoltaic panels [75]. The dominance of Asia in dust accumulation investigations on PV panel surfaces can be attributed to two main factors. First, a startling 60% of all newly installed PV systems worldwide were located in Asia, accounting for a sizable portion of all new installations [76]. Secondly, Africa is thought to be one of the worst regions on Earth for sand and dust accumulation, and numerous proposals for assistance collaboration for renewable energy between Africa and the European Union countries. Asia is regarded as one of the world's driest, windiest, and dustiest regions, and the region's climate is significantly influenced by

the interaction of dust and clouds [77]. Regretfully, the proportion of research conducted in Africa is only about 12%, meaning that there are sadly very few equivalent studies throughout the continent. However, Europe is listed as the second continent in terms of dust accumulation studies, with about 23% of published studies, nearly twice as many as the studies surveyed in Africa. However, given that Europe does not much experience as many severe dust storms as the MENA or Asia region does, the comparatively lower percentage of research carried out in Europe when compared to Asia is thought to be typical and unsurprising [78].

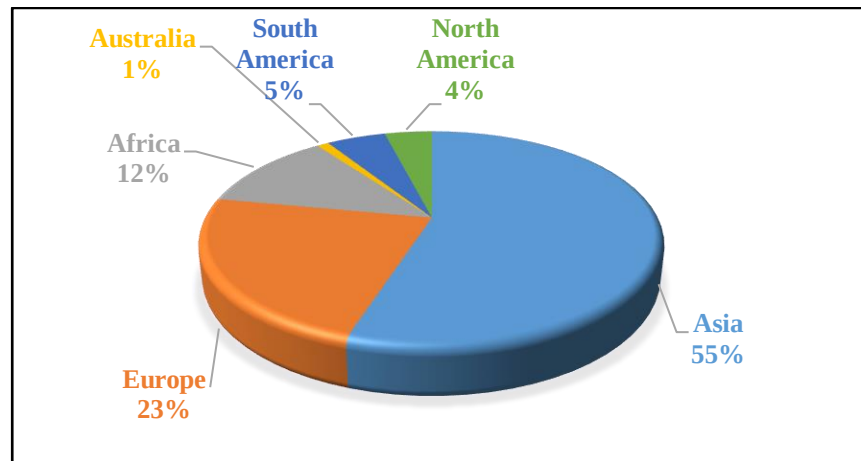


Figure 2.1: Different continents' contribution percentage to the studies on the influence of dust on PV panels [75].

Chapter 3: Materials and Methods

3.1 Purpose of the Chapter

This chapter details the materials used and the methodological approach adopted in this research. It aims to provide a clear and comprehensive description of the procedures and techniques employed to investigate dust-related energy losses in rooftop solar PV systems and evaluate suitable cleaning methods within the specific context of Chittagong Town, Bangladesh.

3.2 Overall Approach and Structure of the Chapter

The study area is described in this chapter with a focus on how relevant it is to the research goals. The items used are then described, including dust samples, solar PV panels, cleaning supplies, and measuring tools. The methods, experimental design, and data analysis methods are then covered in detail in the methodology section. The application of the case study in Chittagong, ethical issues, and the study's shortcomings are also covered in this chapter. This methodical technique guarantees the reproducibility and dependability of the research findings.

3.3 Study Area

The city of Chattogram, which is in southeast Bangladesh, has a tropical monsoon climate with heavy dust deposition during certain seasons. This area was chosen because it has a lot of solar potential and frequently experiences dust collection, which makes it a perfect place to research how dust affects rooftop solar PV systems.

3.4 Climatology of the test region:

Test apparatuses were located on the roof of the four key selected areas, which gives a comprehensive review of the total city, one of them is the professor's building block of Chittagong University of Engineering and Technology at 22°27'26.09'' north latitude and 91°58'13.55'' east longitude. The second one is Atomic Energy Centre, Chattogram at 22°37'19' north latitude and 91°8'168' east longitude. The third one is Bangladesh Power

Development Board, South Zone distribution, Agrabad, Chattogram at 32°43'00'' north latitude and 51°31'45'' east longitude. The last is the National Maritime Institute, Chattogram at 32°43'00'' north latitude and 51°31'45'' east longitude. These four spots were picked because they reflect a variety of contexts and environment, such as the EPZ region (NMI), commercial area (BPDB), industrial area (AECC), and university campus semi-urban area (CUET).

These habitats serve as an overview of Chattogram's topography and geography, and because of their variance, installing PV stations in any of them requires a separate analysis of the site's environmental variables. The contrasting characteristics of their particular products is made clearer by the selection of four locations with varying ecological circumstances. Figure 3.1 shows the location of the study areas on the map, sample location 1 is CUET, sample location 2 is AECC, sample location 3 is BPDB, and sample location 4 is NMI respectively.

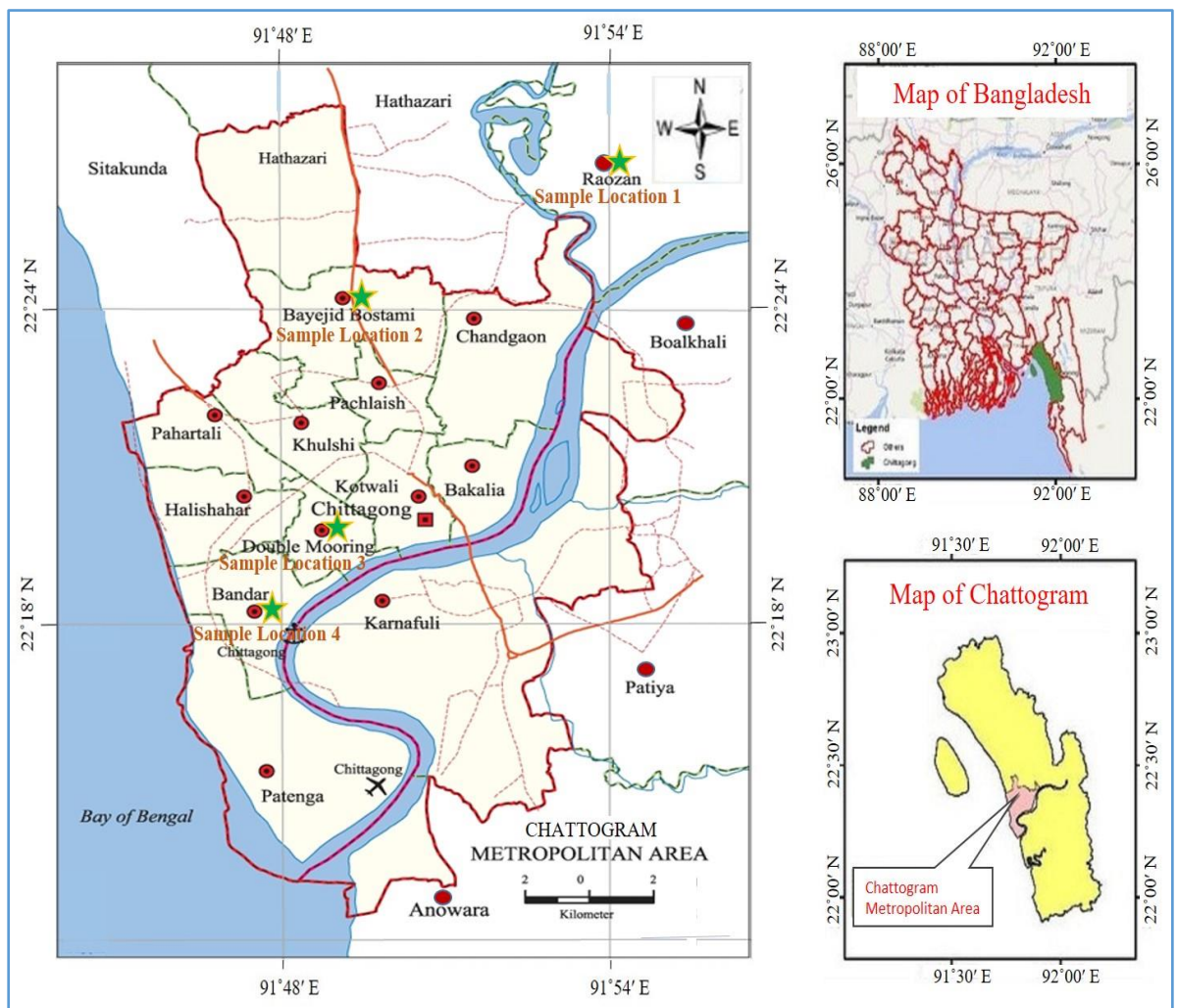


Fig. 3.1: The Sample collecting location of the study areas.

Due to the fact that of the recent decrease of rainfall, 84 per cent of Chattogram province

is facing heavy rain. Therefore, weather and climate information was collected from the latitude and longitude finder apps. Chattogram climate and weather tropical monsoon climate with significant rainfall during the monsoon with humid and hot weather in dry or summer.

In general, sunshine hours average 7.5-9 h, the daily temperature in average t is 31.9°C , the wind velocity is 11 km/h (which can increase during the monsoon season), the humidity is 80 % (at the time of the monsoon season (June to September)), and solar radiation is 5.0 kWh/m^2 as shown in Figure 3.2. Also, the daily average total worldwide and diffuse solar energy is 6.182 kWh/m^2 and 3.289 kWh/m^2 , respectively. Furthermore, a substantial increase in the region and the nation is evident when comparing the amount of dust generated recently with the long-term yearly average, highlighting the significance of this study. One of the main elements influencing the current study is the wind, which is created by a pressure differential and typically blows in a horizontal direction. Typically, air/winds are defined in terms of their orientation, velocity and degree of blowing. Long-term data indicates that the east and northeast are the test site's predominant airflow directions.

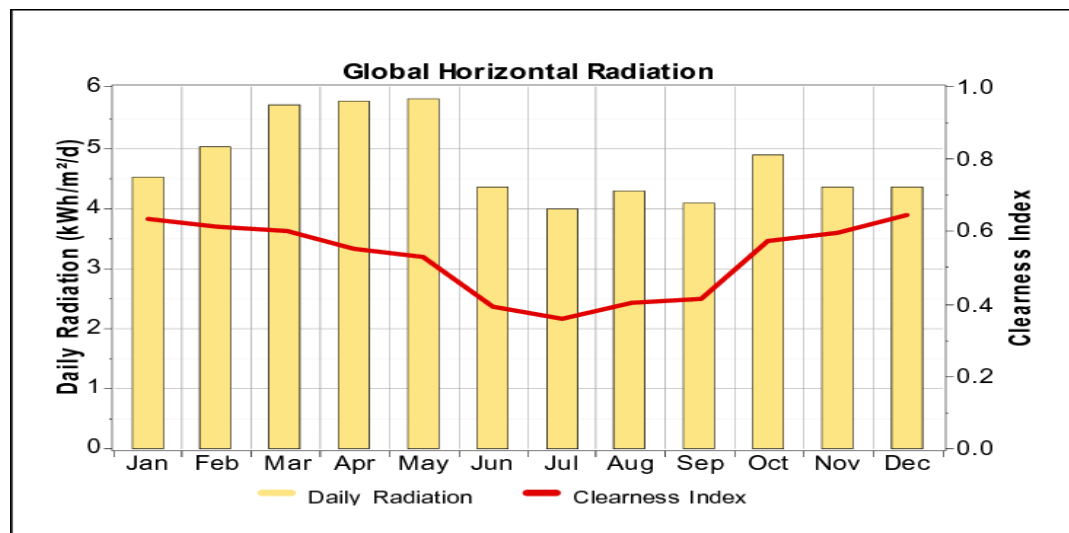


Fig. 3.2: Chattogram solar radiation profile.

3.5. Experimental Setup

3.5.1. Calculation of Site Area

The following formula has been used to determine the available space for the solar energy system installation: the amount of open space that is available for the solar system = (The area of stair room + machinery room + meeting place) + Void space + Parapet wall. Loss area = 5% of the remaining vacant space. So the area can be utilized for solar panel installation = Available unoccupied space-loss area.

3.5.2 Tilt Angle Calculation

The tilt angle β needs to be changed to guarantee that the maximum amount of radiation

is received for the purpose to optimize panel efficiency. Although the tilt angle of the panel can be changed seasonally, a fixed tilt angle has been utilized to minimize complexity and cost while achieving the maximum energy output throughout the year.

3.5.2.1 Latitude-Based formula:

Chattogram City is located at approximately 22.4° N latitude. The optimal fixed tilt angle is typically close to the latitude of the location, So the straightforward approach for a fixed tilt angle is to use this latitude: 22.4°.

3.5.2.2 Empirical Formula:

The tilt angle is determined using the following formula [79],

$$\beta = 0.76 \times \phi + 3.1^\circ \quad (3.1)$$

Where ϕ = geographic latitude. Thus, the most suitable tilt angle in this area is

$$\beta = 0.76 \times 22.4^\circ + 3.1^\circ \approx 20.1^\circ.$$

Practical installation may use an average annual angle of 20° to 24° to balance performance, structural considerations, and ease of maintenance.

3.5.3 Row Distance Calculation

The precise distance between two successive arrays must be established as one of the boundary criteria for PV module placement and performance. To prevent excessive shadowing, the arrays must be separated by a distance d , equal to the solar module width, a .

$$d/a = \cos \beta + \sin \beta / \tan \varepsilon \quad [80] \quad (3.2)$$

and

$$\varepsilon = 90^\circ - \delta - \phi \quad [80] \quad (3.3)$$

Where, ε = shadowing angle, and δ = ecliptic angle = 23.5

From (1), (2), and (3), $\varepsilon = 42.777^\circ$ and $d/a = 1.32$.

3.5.4 Dust Sample Collection

A horizontal glass panel collected dust from the mid of October 2023 to the mid of September 2024, representing the Chattogram's winter, spring, summer and rainy seasons. The dust samples were collected on the rooftop of each location building, one of them is adjacent to a refurbished residential (CUET campus) semi-urban area and also near from a thermal power plant, another one (AECC) is in a large industrial area, next one (BPDB) is in a commercial area and last one (NMI) is in near of EPZ area with heavy traffic from the east. Fig 3.3 shows the setup of the dust collection slides in four locations at the same tilt angle as the solar panel setup. A dust sample slide from each

location was collected every month throughout the year and handle the sample slide with wearing hand gloves and keep the sample slide a wax paper with proper numbering and then finally it kept in an air tide container for not to contaminated or loss.



Fig. 3.3: Dust collection slide set up in four locations.

3.5.5 Solar PV System Setup and Data Collection

Two cutting-edge mono-crystalline solar photovoltaic (PV) systems have been installed at the CUET campus to test the impact of dust deposition on energy output. Each system is made up of a 120 Ah battery, a 1250 VA inverter, and a solar panel with a maximum power capacity of 550 Wp. The gadgets are arranged at a deliberate 23-degree angle to optimize light exposure and reduce shadows. See Table 1 for detailed specifications of the solar panel, inverter, and battery. Figure 3.4 depicts the picture of installed solar panels.



Fig. 3.4: Set up of solar PV system

Throughout the month of March to September, data on energy output was continuously captured, providing real-time data on panel temperature, ambient temperature, and solar irradiation. In order to examine dust collection under regular seasonal conditions, this time frame was selected. To assess the efficiency loss resulting from dust deposition, panel conditions, both clean and dirty, were observed.

Table 3.1: Detail specifications of the solar panel, inverter, and battery.

SL No.	Name	Specification
01	Solar Panel	1. Model: LR5-72HPH-550M 2. Brand: Longi 3. Power Range: 540~550W 4. Material: Mono-crystalline Silicon 5. Maximum power Voltage: 41.64vmp 6. Short Circuit Current: 13.86Isc 7. Open Circuit Voltage (Voc): 49.60V 8. Maximum Power Current: 12.97Imp 9. Module Efficiency: 21.1 per cent 10. Panel Dimensions: 2274 x 1134 x 35mm 11. Weight: 27.5 Kg
02	Inverter	1. Model: PCU-1450 2. Brand: Microtek 3. Rated Power 1000W 4. Input voltage: 230VAC 5. AC voltage regulation: $\pm 5\%$ 6. Efficiency MPPT (peak) : 98% 7. Efficiency Inverter (peak): 94% 8. Transfer/ switching time: 10mS
03.	Battery	1. Model: Rahimafrooz 1TB 120 ah Tabular Battery. 2. Brand: Rahimafrooz 3. Volt: 12 V 4. Plate: 21 5. Amp-hour: 120ah

3.6 Dust Properties on PV

Dust consists of tiny particles made up of microscopic solid inorganic and organic materials, such as soil, ash (including pollutants from vehicles, factories, and firewood), bacteria, and more. These particles have a diameter smaller than 500–1000 μm , which is smaller than that of the air [68]. These particles vary in size, volume, shape, and chemical concentration [81]. The size, shape, and chemical makeup, including transmittance, thermal conductivity, absorption, reflectivity, and emissivity of dust can all have an effect on how photovoltaic systems behave thermally and electrically. It is significant to remember that the characteristics of dust might change based on the setting and location. Thus, it is essential to

comprehend these characteristics as well as the unique effects of dust in each area in order to establish cleaning and maintenance plans that effectively reduce the detrimental effects of dust on PV efficiency. It's important to understand that dust properties can be quite complex [82] . They can be divided into various categories, 1. The ability of dust particles to engage with light is referred to by their optical qualities, which include absorption and reflection. 2. Dust particles' capacity to transfer heat is correlated with their thermal characteristics, such as their thermal conductivity. 3. Particle characteristics, which include the dust particles' size, shape, and makeup. 4. Chemical properties incorporate organic chemicals, soot, and acid condensates, such as nitrates and sulfates, along with trace metals and other toxins substances [83]. It's fascinating to think about how these properties can affect our environment. Researchers must understand these dust features and how they impact PV performance in order to create effective investigation studies or dust mitigation approaches. Figure 3.5 illustrates the properties of dust on PV.

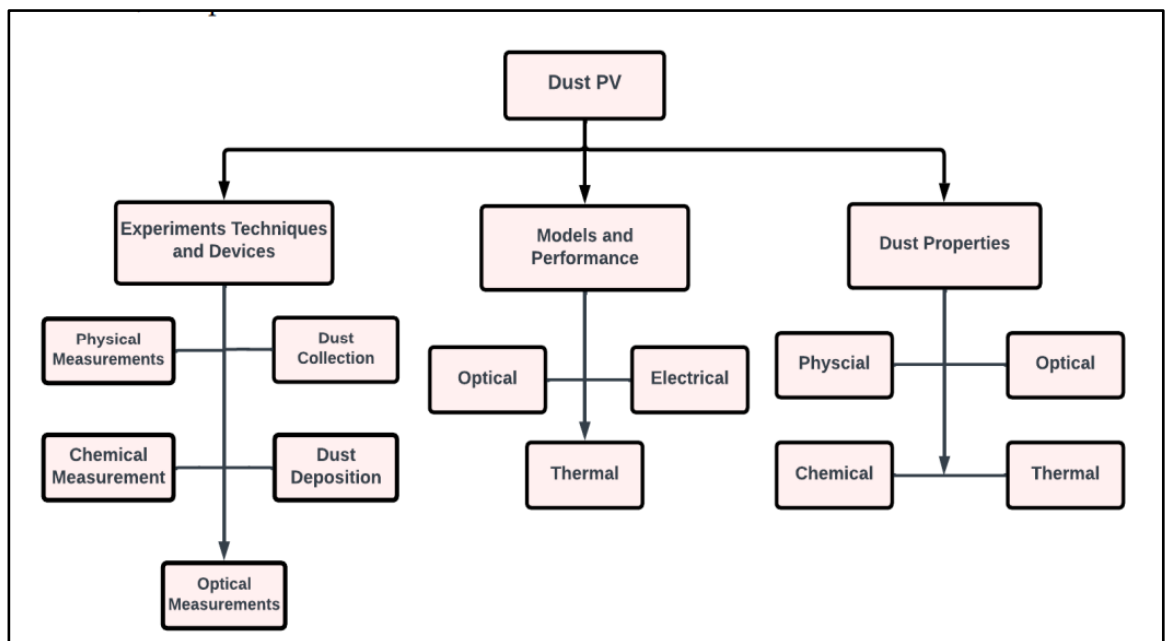


Fig. 3.5: The properties of dust on PV [83].

3.7 Influence principles

Once more, when dust falls on the surface of photovoltaic panels, three factors indicate the influence on Photovoltaic. The shielding effect is the first. Typically, the solar panel's upper structure consists of a toughened glass cover plate with a transmittance of more than 91%. When dust gathered on the glass cover plate, it blocked the light that was illuminating PV, weakening the glass cover plate's transmission and lowering the actual quantity of solar power that PV received. A portion of the solar light intensity (E1) is absorbed by the dust and converted to heat when it spreads to the PV-covered dust, while another portion (E2) is

dispersed across the dust's surface. Only a portion of the light intensity (E_3) is injected into the glass cover plate and received by PV. $\Delta E_1 + \Delta E_2 - \Delta E_3$ decreases the energy entering the glass cover plate, which is why the PV photoelectric effect is lessened. The temperature influence comes in at number two. Heat transfer is one modification that the dust on the PV may bring about. In the presence of dust, the PV modules' current heat balancing model is established. However, the dust affects the heat balance in the PV panels put into use. Because portion of the shielding cells are obstructed by the dust and cannot operate as planned, the electric current of the cells is reduced, as illustrated in Fig. 3.6. The cell voltage enters a reverse bias state when the operating current of the cell is less than the operating current of the photovoltaic array as a whole. After that, the cell loads additional PVs and uses energy to convert to heat energy, which causes the PV's temperature to steadily rise [84]. The reverse bias limit of a single photovoltaic cell is typically 25W; if this border is exceeded, hot spots are likely to appear. Hot spots will harm the entire photovoltaic system and result in irreversible damage, in addition to reducing the output efficiency of the system's power output.

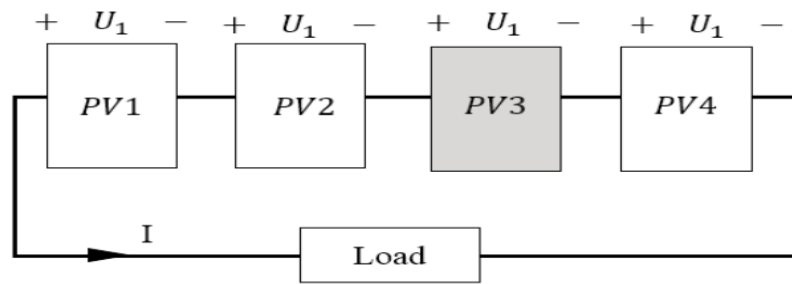


Fig. 3.6: The PV array's hot spot impact.

Finally, let's discuss the corrosion effect. Dust particles are extremely small, typically ranging from 0.001 to 0.01 mm. The primary chemical components found in environmental dust are oxides, including Fe_2O_3 , SiO_2 , Al_2O_3 , Na_2O , CaO , MgO , and TiO_2 . Among these, SiO_2 is the most prevalent, accounting for 68% to 76% of the composition [85]. Over time, the glass cover plate can react with alkalis or acids because it is primarily composed of silica. The glass cover plate's surface may become uneven as a result of this reaction, increasing diffuse reflection. The capacity for PV generation may be impacted as a result of the impaired symmetry of solar light propagation in the glass covering plate.

3.8 PV performance evaluation approach

Understanding the I-V and P-V characteristic curves is crucial for assessing the power production performance of PV modules, as they serve as key indicators of the PV power

generation status. It's important to note that the output characteristics of PV exhibit non-linear behavior, influenced by factors such as solar radiation, ambient temperature, and load. Optimizing the output power of the PV array requires identifying the specific output voltage value at which the maximum power can be achieved. As seen in Figure 3.7, this is demonstrated by the PV array's operational point hitting the output power voltage curve's peak (P_{max}). Dust accumulation on the PV surface causes the PV to operate outside of its maximum power point, which lowers output power efficiency and lowers the power generation system's revenue.

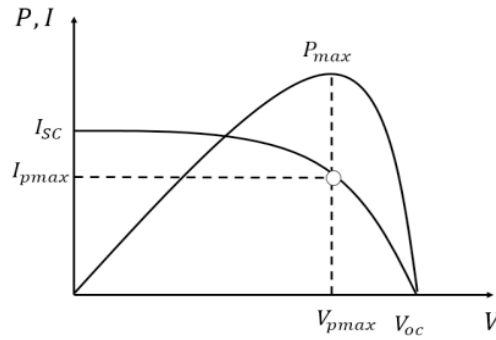


Fig. 3.7: Performance diagram of solar cells.

Fill factor (FF) and conversion efficiency are the final two crucial metrics for evaluating solar panel performance. A crucial part of evaluating the performance of solar cells is conversion efficiency, which gauges how well photovoltaic cells transform absorbed solar energy into electrical power. Several factors, such as the intensity of the sun, the type of battery, the temperature of the particles, the radiation environment, and the PV temperature, all affect conversion efficiency.

$$\eta = \frac{P_{max}}{P} \times 100\% \quad (3.4)$$

$$\eta = \frac{I_{mp} V_{mp}}{G \times A} \quad (3.5)$$

Where, A is the solar cell or module's area (m^2) and G is the incident radiation density (W/m^2).

The FF represents the relationship between the maximum power of the solar PV cell and the sum of the short circuit current and open circuit voltage. It is a crucial factor to consider while assessing the PV output characteristics. The photoelectric conversion efficiency increases with increasing value, and the output characteristics of the photovoltaic approach the rectangle more closely. Dust can have an impact on the PV surface's allowable light intensity, which in turn has an impact on the FF.

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} \quad (3.6)$$

3.9 Temperature effect on power:

The effectiveness of solar panels usually drops with increasing temperature. This is because as solar cells heat up, the semiconductor materials they use become less effective at transferring sunlight into electricity. The equation [79] can approximate the relationship between temperature and solar panel efficiency:

$$P_{eff} = P_{stc} \times \left(1 - \beta \frac{(T - T_{stc})}{100}\right) \quad (3.7)$$

Where,

P_{eff} = Effective power output of the solar panel

P_{stc} = Rated power output of the solar panel at standard test conditions (STC)

T = Operating temperature of the solar panel

T_{stc} = Standard test condition temperature (usually 25°C)

β = Temperature coefficient of the solar panel (-0.3% / °C to -0.5% / °C).

3.10 Environmental effect on power and efficiency:

Shading, dust, and debris can obstruct sunlight from reaching the solar panels, reducing efficiency. Partial shading on even a small portion of a solar panel can greatly impact overall efficiency, especially in interconnected systems.

Effective power output = Rated power output X Shading factor

$$\text{Shading factor} = 1 - A_{\text{shaded}} / A_{\text{total}} \quad (3.8)$$

Where, A = Area of the solar panel (in square metres).

Again, as we discussed before, the overall efficiency η of a PV panel can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (3.9)$$

P_{in} is the input power from sunlight (in watts). The input power P_{in} can be calculated as:

$$P_{in} = A \times I \quad (3.10)$$

Where I = solar irradiance (in watts per square metre)

Dust particles block sunlight, reducing the effective irradiance 'I' reaching solar cells. So, the new irradiance I' is:

$$I' = I \times \% \text{ of the irradiance reduced by dust.} \quad (3.11)$$

Furthermore, shadows from trees, buildings or other obstructions decrease the effective area A exposed to sunlight, reducing the overall power output. Shading can cause disproportionate losses due to potential mismatch losses in series-connected cells. So, the new area A' is:

$$A' = A \times \% \text{ of partial shading coverage area} \quad (3.12)$$

$$\text{So, } P'_{in} = A' \times I' \quad (3.13)$$

$$\eta = \frac{P_{out}}{P'_{in}} \times 100 \quad (3.14)$$

3.11 Measurement Parameters

The collected dust was checked using-

3.11.1 UV-Vis Spectroscopy

A transmission analysis using UV-visible spectroscopy was performed to measure the decrease in solar transmittance resulting from dust deposition on the solar panels. This investigation establishes a direct interrelation between the amount of dust and the reduction in light reaching the solar cells by calculating the proportion of light that travels through dust-covered slides relative to clean slides. UV-Vis spectroscopy is crucial to our work because it allows us to quantify dust's direct impact on the panels' energy conversion efficiency. The reduction in solar transmittance serves as a critical parameter for determining the severity of dust deposition and its effect on solar panel performance. The information gathered from this research is useful in measuring the efficiency losses caused by dust and emphasizes how crucial routine cleaning is to preserving optimal energy production.

3.11.1.1 Calculating the Average Transmittance

To determine the average transmittance reduction due to dust, follow these steps:

a. Integrate the Transmittance Data

Calculate the area under the transmittance curve for both the clean and dusty conditions: For simplicity, assuming equal spacing ($\Delta\lambda=25$ nm)

$$\text{Average Transmittance clean } \tau_{\text{clean}} = \frac{1}{800-350} \int_{350}^{800} \tau_{\text{clean}}(\lambda) d\lambda \approx \sum_{i=1}^N \tau_{\text{clean}}(\lambda_i) \Delta\lambda \quad (3.15)$$

$$\text{Average Transmittance dusty } \tau_{\text{dusty}} = \frac{1}{800-350} \int_{350}^{800} \tau_{\text{dusty}}(\lambda) d\lambda \approx \sum_{i=1}^N \tau_{\text{dusty}}(\lambda_i) \Delta\lambda \quad (3.16)$$

b. Compute the Transmittance Ratio

The ratio of the average transmittance with dust to the average transmittance without dust gives you the relative transmittance:

$$\text{Transmittance Ratio } \Delta\tau = \tau_{\text{clean}} - \tau_{\text{dusty}} \text{ ----- (14)}$$

c. Estimating Efficiency Degradation

The efficiency degradation rate can be estimated by considering how the reduction in transmittance affects the solar photovoltaic panel's power output. Since the power output is directly proportional to the incident light. So the formula is [86]:

$$\text{Efficiency Degradation} = 1 - \text{Transmittance Ratio} \text{ ----- (15)}$$

$$\eta_{\text{reduction}} = \frac{\eta_{\text{clean}} - \eta_{\text{dusty}}}{\eta_{\text{clean}}} \times 100\% \text{ ----- (16)}$$

3.11.2 Scanning Electron Microscopy (SEM)

To evaluate the morphology and surface structure of the dust particles extracted from the solar panels, **scanning electron microscopy (SEM)** analysis was carried out. Understanding the size, shape, and distribution of the particles—all of which are crucial for determining how various dust types stick to panel surfaces and impact solar transmittance—can be achieved by examining high-resolution SEM pictures. SEM is also useful for determining the physical compositions of the dust, such as irregular forms or agglomerations that could cast shadows on the panel and cause more substantial drops in energy production. The correlation between the physical features of dust and its impact on solar panel efficiency requires accurate surface topography, which can only be obtained using SEM.

To analyze the morphology and elemental composition of the dust samples, a Tescan VEGA Compact Scanning Electron Microscope (SEM) was used. The dust slide was cut into small pieces and carefully deposited onto an aluminium SEM stub using carbon adhesive tape. This ensured proper adherence of the particles for imaging. Since the dust particles were non-conductive, a thin layer (~10 nm) of gold was applied using a sputter coater to prevent charging effects and to enhance imaging resolution. The Tescan VEGA Compact SEM was operated at an accelerating voltage of 20 kV. The working distance was set between 8–10 mm to optimize focus and depth of field. The beam current was adjusted to minimize sample damage while ensuring clear imaging. Images were captured at magnifications ranging from 500× to 10,000× to observe both the overall morphology and finer structural details of the dust particles. The secondary electron (SE) imaging mode was utilized to capture surface morphology and texture.

3.11.3 X-ray with Dispersive Energy Spectroscopy (EDX)

X-ray with Dispersive Energy Spectroscopy (EDX) was employed to ascertain the elemental makeup of dust samples that were gathered from various sites. EDX offers both quantitative and qualitative information on the elements that were present in different amounts in the samples, such as silicon, aluminium, carbon, oxygen, and others. This research is important because the optical characteristics of the dust layer are affected differently by different constituents. For example, materials such as silicon and aluminium may make the dust layer more reflective, but carbon may improve absorption and decrease the total amount

of sunlight that enters the solar cells. Comprehending the elemental composition is essential for pinpointing the main causes of efficiency reductions and can also direct the creation of more specialized washing techniques tailored to the particular type of dust or dust composition.

The EDX detector integrated with the Tescan VEGA Compact was used to perform qualitative and semi-quantitative elemental analysis of the dust samples. Spectral data were collected from multiple regions of interest in the sample to ensure representative results. Elemental mapping was conducted to visualize the spatial distribution of key elements across the sample. Spot analysis was performed on individual particles to determine their specific elemental composition.

3.11.4 Solar PV System's Data Collection

To quantify the effect of dust accumulation on the energy yield of rooftop solar PV systems under different weather conditions. We installed two solar PV power systems and collected data for some specific months and matched it with the UV transmittance degradation rates. Furthermore, we created an experiment in which one solar panel was frequently cleaned while the other was left alone to investigate the effect of cleaning on solar panel efficiency. This study's finding is consistent with the observation that a great deal of residential rooftop solar panel installations need to be routinely cleaned. Our goal was to mimic the typical situation when homeowners fail to maintain their solar panels after installation because they are ignorant of the necessity. By doing so, we aimed to:

1. **Emphasize the Performance Benefit of Cleaning:** We predicted that the regularly cleaned panel would produce much more energy than the uncleansed panel because of less dust buildup, which would otherwise block sunlight and minimize efficiency.

2. **Highlighting the Value of Continual Upkeep:** We compared the energy production of the two panels to show the long-term advantages of routine cleaning. This would give people fact-based knowledge on why maintaining solar panels is essential to maximizing energy output.

Again, In this study, the longer time frame for data gathering enabled us to see how seasonal variations affected energy output, such as the effects of the monsoon, dust buildup, natural clean due to rainfall, increasing performance and less sunlight in some months. This provided information on how different times of the year (including monsoon effects, dust accumulation, and reduced sunlight during certain months) affect solar panel performance in

rooftop installations. This provides on how the performance of solar panels in rooftop installations varies with the season.

Chapter 4: Solar Panel Cleaning Methods

It is still anticipated that the use of solar PV will grow in the near future due to ongoing research and material selection, which may result in solar power plants producing enough electricity to meet local and regional requirements. For the purpose of capturing and reflecting solar energy, the solar PV panel's construction includes a transparent glass pane on top which mirrors the sun's radiation into the panel and traps it. Nonetheless, if physical factors alter glass transparency, the absorption rate decreases and the conversion efficiency is lowered. [87]. It is particularly difficult to clean solar panels after they are installed on the roof of a home, business, or store because dust particles prevent sunlight from entering the panel correctly, lowering the panel's conversion efficiency and lengthening the time it takes for batteries to charge. Due to the aforementioned effect, solar panels must have regular maintenance and cleaning to allow them to continue operating effectively. Because of their traditional installation and mechanics, solar panels are difficult and sometimes impossible to clean using standard techniques like vacuuming or hand wiping. Dust deposition creates a coating on the panel that prevents sunlight from entering the PV panel receiver properly, even when the panel is exposed to enough sunlight to provide an inefficient conversion. In this case, the accumulated dust particles can be eliminated by using an electrostatic precipitator (ESP) with fixed electrodes. For the most part, the cleaning method is ineffective in getting rid of tiny dust particles, or nanometers.

Additionally, because of the way they communicate with certain types of pollutants, some of these techniques might aid in hastening the corrosion of photovoltaic cells. Furthermore, because to the way that some of these techniques interact with specific kinds of contaminants, they might aid in quickening the corrosion process of PVs. Contemporary cleaning methods that have shown to be successful in cleaning photovoltaic cells include the use of highly reflective water cleaners and robots, as well as electrostatic and electrostatic power cleaning approaches. The most significant and modern techniques for PV cleaning will be covered in detail and discussed in the ensuing subsections.

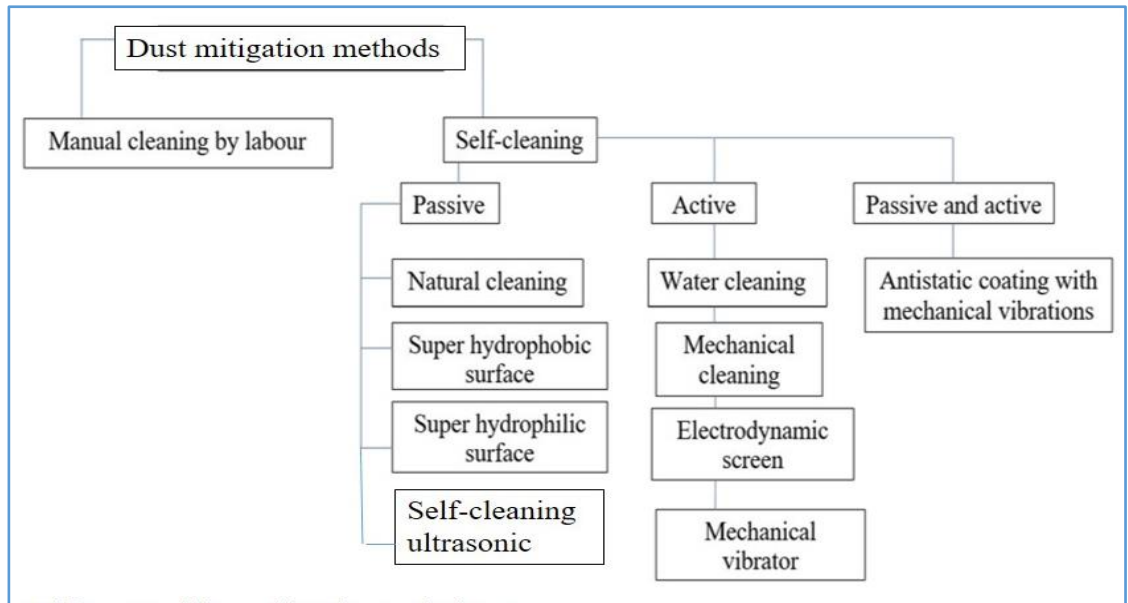


Fig. 4.1: Different dust mitigation techniques.

4.1 Manual Cleaning

As illustrated in Figure 4.2, the above method necessitates that the human operator do manual cleaning using a mop or any other wipers with appropriate support structures. The operator himself uses a visual approach to assess the cleaned surface's quality until the dust particles are totally removed, or to a suitable degree. Several panels are put at a height of 12 to 20 feet or more from the ground to create solar power plants, which makes the process highly difficult and time-consuming. Both the necessary amount of time and the person's and the panel's safety are in jeopardy. While it is possible to clean the panels manually, fluids such as solvents or gels must be employed. Improper cleaning will act on the panel and decrease its ability to reflect light. It is impossible to completely prevent the possibility of physical damage to the PV panels.



Fig. 4.2: Manual cleaning.



Fig. 4.3: Vacuum Suction Cleaning

4.1.1 Vacuum Suction Cleaner

An air pump is used by a vacuum suction cleaner to produce a partial vacuum, which is then used to shift dust and debris from top surfaces such as ventilator and floors. Typically, the electrical supply is received by the vacuum cleaner motor, which produces the suction pressure. The vacuum cleaner's power usage, expressed in watts, is insufficient to justify its effectiveness. At the conclusion, the power input is transformed into airflow and expressed in air watts. Only upper surfaces excluding corners may be effectively cleaned by the vacuum cleaner, so Figure 4.3 illustrates how this can only be done physically. As the physical actions on the cleaner panel are unavoidable, the operator must have the appropriate training. Sunlight insolation is not adequately absorbed over time because of blemishes and collected dust.

4.1.2 Automatic Wiper-Based Cleaning

A rubber wiper and a water pot are used in the automatic wiper-based cleaning system to spray water with additives and clean. The procedure is the same as washing the windows of a car, and it needs an automated system to work. Figure 4.4 illustrates a battery-operated device. This approach is comparable to the previous one and is automatically controlled by the appropriate mechanism, but it has an equivalent impact on the ones that came before.



Fig. 4.4: Battery-operated automatic wiper-based cleaning.

4.2 Natural cleaning using rain and wind

In natural cleaning, the falling rainwater on the surface of the tilted PV is used as the panels are usually fixed at a tilt angle to enable them to capture the optimal irradiation. This procedure leaves behind dust that has become adhered to the photovoltaic surface due to it interacts with the atmospheric moisture, which is one of its drawbacks: the PV is not entirely

cleaned. Typically, it takes a lot of rain to eliminate these adhesion molecules. This method is unreliable, especially in the presence of severe pollution and insufficient rainfall [53]. A discernible decrease in the quantity of power generated by the PV occurred after a small rain caused a coating of clay to form on the PV surface. PV surfaces exposing it can be naturally cleaned by wind motions, particularly if it is moving at a moderate speed and doesn't produce any dust. Rain can increase photovoltaic surface performance by preventing or reducing the accumulation of pollutants, despite the fact that it is impossible to accurately forecast the amounts and timing of precipitation. When setting up PV stations in distant locations where routine maintenance isn't always feasible, using specific surfaces like these will be the best option, even though it will raise the initial cost of the system.

4.3 Water cleaning

This procedure, which is seen in Figure 4.5, involves channelling a hose from the running water to the photovoltaic upper surface in order to remove the dust particles accumulated.. This method requires a large amount of water and the use of pumps for the reason to achieve the required high pressure. In modern methods, compressed water is sometimes mixed with a particular cleaning agent to remove dust more effectively. Water is also helpful for cooling photovoltaic cells, and it works similarly to rainwater for PV cleaning. The challenge of utilizing this strategy is its drawback.



Fig. 4.5: Automatic solar panel water cleaning system.

4.4 Mechanical cleaning

As seen in Figure 4.6, automation is used in cleaning with machine. An accurate controller is used to moving the system with the assistance of sensors. In the event that water

cleansing is not feasible, this approach might be regarded as being really helpful. Water can be used, but it can also cause the cleaned panels' surfaces to be scraped by the brushes' direct contact with the mechanical devices' weight. In places with limited water supplies, this approach uses more power than any other. Apart from the potential for chemical buildup on the PV edges, it also results in a significant water loss. High-pressure water pumps use a portion of the power produced by photovoltaic cells, which lowers their efficiency. They also run with the possibility of breaking or clogging water pipes, and when water falls, it could cause a thermal shock to the cells since it is undoubtedly colder than the plate surface. Solar panels are often cleaned at noon, following sunset. Since the most significant time for dust particle deposition and air stagnation occurs after sunset, Since the PV surface will be left wet to dry, there is a potential possibility that additional dust particles will stick to it. It is typically possible to prevent heat shocks by utilizing water that is heated by the sun in tanks that are heated near to the PV temperature. This approach can be highly costly for PV stations with larger spaces, and the cost goes up if the area experiences a water shortage. Additionally, the mechanical components requiring cleaning require upkeep. The complete efficiency of this approach for severe dust deposition has not yet been established.



Fig. 4.6: Automatic solar panel water cleaning system.

It is important to note that using automated cleaning technology involves significant upfront and ongoing costs. Additionally, the complicated mechanical and control designs of these devices—illustrated in Figure 4.7—are required.



Fig 4.7. Solar PV cleaning using automated brushes

4.5 Electrical screens (EDS)

A solar system's electro-dynamic display (EDS) can automatically and continuously remove collected dry dust without the need for water or any mechanical moving parts. This method of removal depends on converting dust into functional dust. By exposing a screen to a high-voltage electric field, it charges the dust particles and makes it possible to push them over the edge of the plate surface and remove them. After two minutes of system operation, 90% of the accumulated dust may be removed by using this strategy, according to the researchers. It has been applied in desert, arid, and dry regions. In Figure 4.8, a demonstration of a sophisticated EDS system.

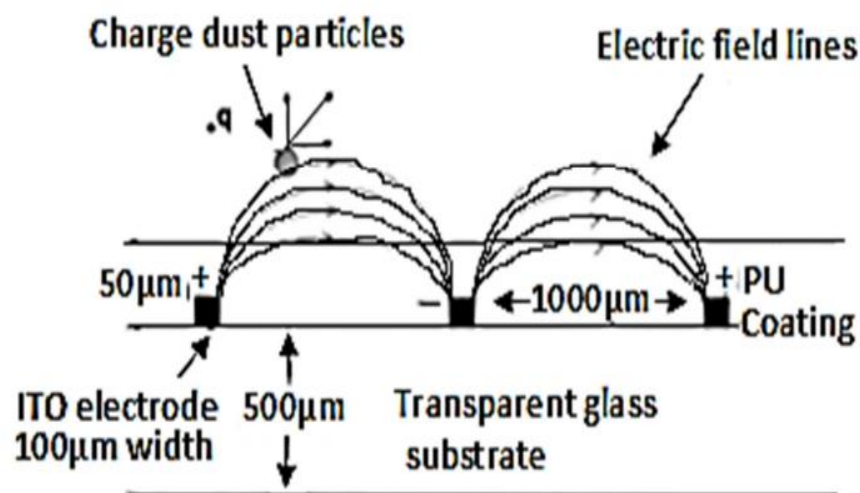


Fig. 4.8: Schematic of electro-dynamic screens.

4.6 Super-hydrophobic aircraft (SHOP)

This method cleans by using a porous surface on the outer layer. Applying a hydrophobic coating and a thin layer of barrier paint on the PV surface is the concept behind this technology. This keeps water from sticking to the panel's surface when it accumulates there.

As seen in Fig. 4.9, water droplets roll from the PV surface when it is tilted at an angle, much like a ball does on a slide. A super-hydrophobic surface has a minimal contact angle hysteresis, meaning that water droplets or rain can easily clean the surface, bounce off it, settle in down areas of the photovoltaic surface, and evaporate quickly, removing the accumulated dirt and waste that has been dissolved. [88].

This will increase the PV module's effective area to absorb the most solar irradiance and raise the likelihood that the surface cleaning conditions will be restored for the PV module. Some researchers [89] found that the cleaning impact of this technique could last for about 3 to 4 years. The hydrophobic upper surface is composed of polymer thin layers with a higher transmittance at first. Unfortunately, high surface energy is a characteristic of some of these layers, which may enhance the likelihood of dust collection. Additionally, these layers frequently deteriorate more quickly than glass when exposed to UV light regularly [42]. Moreover, exposure to specific chemical solvents present in rain of acidic and sea salt may cause significant corrosion and damage to this hydrophobic surface. It is still necessary to confirm whether this technology can be used and whether it is economically feasible in different types of weather and environmental circumstances.

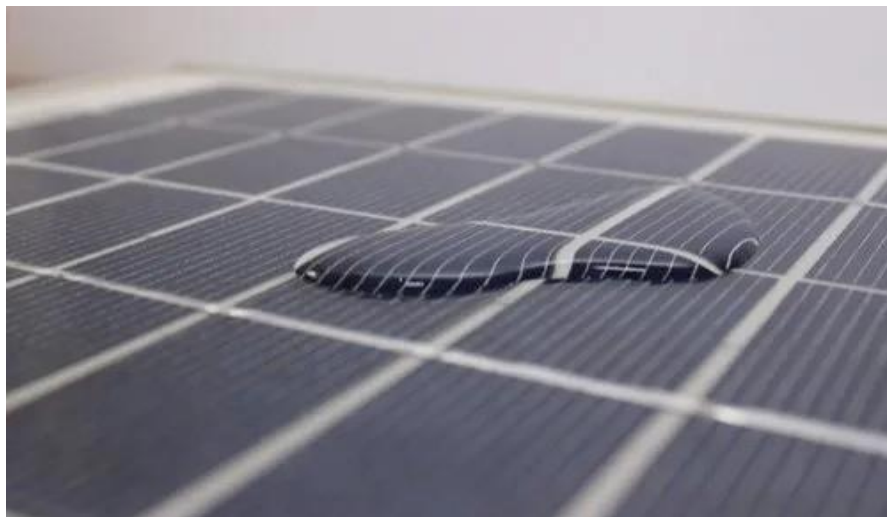


Fig. 4.9: Hydrophilic surface.

The whole dispersion of water or liquid on a substrate is referred to as hydrophilicity, Whereas a hydrophilic surface powerfully draws water droplets in, a hydrophobic

surface repels them. The antithesis of hydrophobicity, a hydrophilic surface exhibits the full dispersion of water on any surface and has a high wettability [90]. Since rain causes both hydrophilic and hydrophobic surfaces to become clean, they are similar to each other. This indicates that, in comparison to wet conditions, covering PV modules situated in arid and sunny environments with super-hydrophilic coatings that exhibit high hydrophilic characteristic ability is insufficient to eliminate the disintegrated dust particles [69]. The water drops on a super-hydrophilic layer form flattening globules that disperse and travel beneath the dirt particles and remove them [91], depicted in Fig. 4.10.

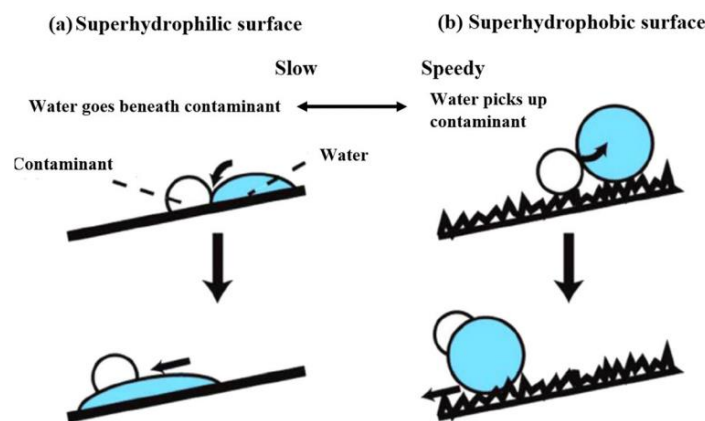


Fig. 4.10: Self-cleaning mechanism of the hydrophilic and hydrophobic surfaces (right).

4.7 Electrostatic Precipitator

Taking into account the effects of various cleaning techniques on solar PV panels, the electrostatic precipitator functions with a non-contact mechanism despite mechanical damages, scratches, and scars. Without coming into contact with the panel physically, it effectively cleans and shields its top surface. Using the power of an induced electrostatic charge, an electrostatic precipitator (ESP) is a filter that eliminates tiny dust particles from the top surface of solar PV panels. As soon as the Arduino controller receives the weight of the PV panel and compares it to a predetermined value, it signals the ESP electrodes, which then get power through a relay. A negative charge is applied to the dust particles on the panel's surface by the electrostatic precipitator's negative electrodes. Following their attraction, the dust particles gather at the positive electrode. The efficiency of solar PV panels is greatly increased by this non-contact method of dust removal. A weight sensor positioned on the sides of the photovoltaic panel measures weight changes to determine the dust layer on a regular basis. The Arduino microcontroller notifies the ESP to start dust separation and gather a positively charged electrode for disposal if the weight of the dust reaches the predetermined

value. As the dust particles approach and pick up a negative charge, to attract the negatively charged dust particles, the ESP's first electrode is charged to an exceptionally high negative voltage, and its second electrode is charged to an exceptionally strong positive voltage. When dust builds up at the positively charged electrode, it is removed manually, by the use of a brushing mechanism, or by vibrating the mechanism. Common cleaning methods include vacuum suction cleaning and hand wiping or cleaning, both of which can be laborious and ineffective at times. When the panel gets too much dust on it and needs to be cleaned more frequently, an Arduino-based electrostatic precipitation method takes intelligent periodic measurements and cleans the panel [92]. EPS is mostly utilized in dusty environments, such as those found in the ceramic, cement, and fertilizer powder industries, etc., where human operators are unable to clean for a variety of reasons. The gas fumes are released into the sky once the dust and smoke particles have been collected by the EPS. The idea of absorbing dirt particles can be utilized to eliminate the accumulated dust particles on the solar panel. The dust particles become charged as the precipitator electrodes create a field around them, and they gather at a positive electrode. [93].

4.8 Forced airflow of air conditioning systems

This technique has been applied in the United Arab Emirates and is applicable in numerous other industrialized nations with high air conditioning usage [94]. In order to forcefully remove the dust, air from fans in air conditioners is intended to flow swiftly onto the solar panels, as seen in Figure 4.11.

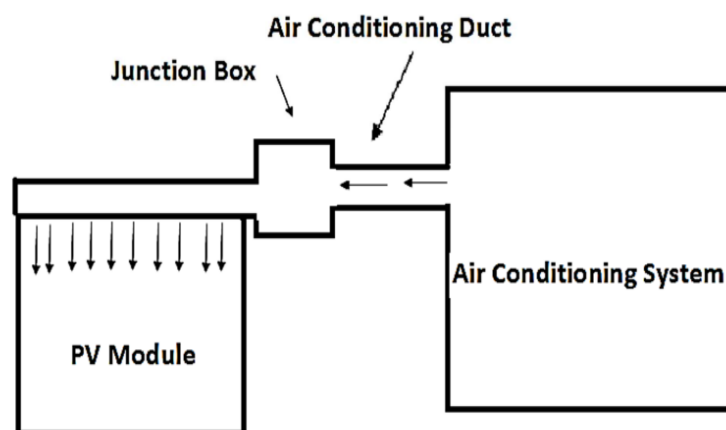


Fig. 4.11: Forced air flow-based cleaning concept diagram.

The method suggests using forced airflow from the air conditioning methods to transfer dust and cool the solar panels. The researchers found that this system of cleaning is suitable for areas with dust storms, strong levels of sunlight, and high environmental temperatures. By

decreasing the panels' temperature and maintaining their cleanliness, they found that the suggested approach might boost PV performance.

4.9 Self-cleaning ultrasonic

High-frequency standard ultrasound, which is above human hearing and can reach up to 20 kHz, is employed in this cleaning method. Part of the pollutants submerged in a water medium are eliminated with this approach. Oil, dirt, polishing compounds, mold-releasing agents, and grease are examples of these contaminants. Materials that can be cleaned with this technique include glass, metals, and ceramic materials, etc. Positive and negative pressure waves alternatively cause micron-sized bubbles to form and grow, forming the so-called cavity that is the process's means of formation. Large amounts of energy are stored in bubbles until they burst. Within the hollow bubble, pressures can reach 500 ATMs and temperatures can reach extremely high levels. The internal explosion happens in close proximity to the hard surface, causing the bubble to alter in shape and become a droplet around one to ten (1/10) the bubble's size. As they approach the hard surface, these droplets can travel up to 400 km/h. Contaminants that produce adherence to the surface are released from their bindings by the combination of fast speed, high temperature, and high pressure. Because the comparatively large droplets are modest in comparison to their size, the ultrasonic cleaning technique is able to successfully remove very fine dust particles from small gaps. Transducers operating between 20 and 80 kHz are utilized in the cleaning sector.

4.10 Sprinkler systems

In arid regions, sprinkler systems are frequently used to maintain clean panels. It may clean panels at a comparatively low cost and has the same cleaning effect as rainfall. Similar to most systems, the one on the Heliotex website is composed of a soap dispenser and a water filtering system. They also state that in places with water, it is optional to treat the water and that water hardness needs to be evaluated. There are certain disadvantages to this method, despite the fact that it frequently functions really well. While sand builds up quickly in certain situations, this method works well for it; nonetheless, it won't clean as thoroughly as a brush system. The distinction and classification of PV cleaning techniques are displayed in table 4.1, respectively.

Table 4.1: The comparison and classifications of PV cleaning methods.

No	Cleaning system	Advantages	Disadvantages
1	Forced airflow of air conditioning systems.	For dry cleaning, forced air is employed, and it works well. Since it utilizes the AC's rejected air, there is no power consumption.	It depends on how the AC operates. If the heat persists for an extended duration, solar panel efficiency may be reduced.
2	Natural cleaning using rain and wind.	No costs or resources.	It is weather-related technique.
3	Water cleaning	Dust particles are completely removed, and all PV panel components are covered. Water can be either hot or cold.	1) Needs a steady supply chain. 2) Water loss via splashing and evaporation. 3) Not appropriate for arid areas 4) Requires power for chemical concentration, tank refilling, and the use of pumps that lower system output. 5) Exorbitant labor expenses for manual systems, in addition to high water consumption costs 6) The potential for dirt to build up if the solar panel becomes washy from the bedew phenomenon 7) The possibility of thermal shocks
4	Manual cleaning	Eco-friendly and electricity-free	Water is needed, human interaction is necessary, and it is expensive.

5	Mechanical cleaning (blowing or brushing)	1) Aids in lowering the system's temperature without the need for water as a cleaning agent 2) Various sensors and controllers, including PLCs and microcontrollers, are used to trigger the cleaning system, which includes automatic brushes, wipers, etc. 3) Because of system independence, labor costs are decreased. 4) Quick reaction, excellent stability, and dependability	1) Dust buildup on the cleaning apparatus 2) Needs upkeep; 3) Expensive primary outlay and power usage 4) Abrasive damage brought on by coming into close touch with the surface of PV panels 5) Scratching occasionally occurs.
6	Electrical screens (EDS)	Dust particles may be removed effectively and efficiently without disturbing any elements.	1) The plastic screen's degradation as a result of UV light's ambiguous durability assessment. 2) A 15% elimination in the electricity production of the solar PV panels. 3) Requires a dry environment; not reliable in damp or sealed dust. 4) Ineffective on tiny dust particles ranging from 0 to 5 μm. 5) Has a high starting cost and requires a digital signal device, converter, and high voltage.

7	Super-hydrophobic surface	No parts that move. Natural dew or rain is helpful, though. No water or human involvement is required.	1) Due to the high surface energy of the polymer layers and the potential for degradation of the plastic screen from prolonged UV exposure, dirt can accumulate on the PV surface. 2) Layer degradation brought on by chemicals in acidic rain and salty air. 3) Additional dirt accumulation on the PV surface within time and anytime the coating deteriorates could be caused by the surrounding environment. 4) When compared to hydrophilic coatings, it degrades faster. 5) Requires precipitation 6) High upfront expenditures for PV systems installed on a wide scale. 7) Require additional research in an alternative setting.
8	Super hydrophilic surface	1) No need a separate power supply 2) Utilizing the photocatalytic effect to break down the organic dust. 3) Low adherence to particles of dirt. 4) Recently demonstrating superior performance compared to the super-hydrophobic surface	1) More dirt gathering whenever the coating deteriorates 2) Is reliant on precipitation 3) Large-scale photovoltaic systems have substantial upfront expenditures. 4) Lower screen efficiency as a result of coating
9	Self-cleaning ultrasonic	Utilize ultrasonic energy to reach the surface through the atmosphere. There is no need for people or water.	1) Ineffective in humid conditions. 2) Require a particular power source.
10	Heliotex's automatic cleaning	Water will reach all PV panel parts also it provides PV cooling	Water and a filter are necessary, and there is a little wastage.

11	Cleaning solutions	Various solutions of chemicals could be employed.	Cut down on surface tension. non-toxic and safe. Certain treatments are expensive and occasionally result in a coating that scatters sunlight.
12	Vibrating/rotating the PV panel	1) Effective in arid climates and hard settings, speeding up the PV surface's ability to clear dust particles. 2) Free of water	1) Automated technique Required power source, motor, and control circuit 2) Additional expense; the mechanical vibrator's initial cost is roughly 10% of the price of the PV panel. 3) Needs upkeep every six months 4) Loud

4.11 PV cleaning methodology

Drawing on the discourse as mentioned earlier, Figure 4.12 presents a proposed methodology that can be employed in research investigations to ascertain a suitable cleaning technique delineated in the flow chart [95]. The first stage is obtaining the required data, including PV and plant connections, the costs and details of any current cleaning schedule, infrastructure designs for the PV plant, etc. After this stage, the PV is evaluated for performance in order to determine how well the current cleaning approach is cleaning the area (if available). The first step is to examine the current cleaning plan's quality, method, speed, and cost-effectiveness. This will function as a starting point for the study of cleaning technique selection. The second phase evaluates the many approaches to solar panel cleaning that scientists, researchers, and other businesses have suggested. An assessment criterion is used to make the comparison to choose the best cleaning strategy. Though more precise and comprehensive, the comparison is comparable to Table 4.1. The best option will be selected in order to meet the study's objectives. The suggested remedy will be assessed financially to meet the cleaning cost per solar cell cost criterion and assess the other methods, which will be covered in stage 2. Following implementation, a second performance analysis will be conducted to gauge the suggested approach's attributes.

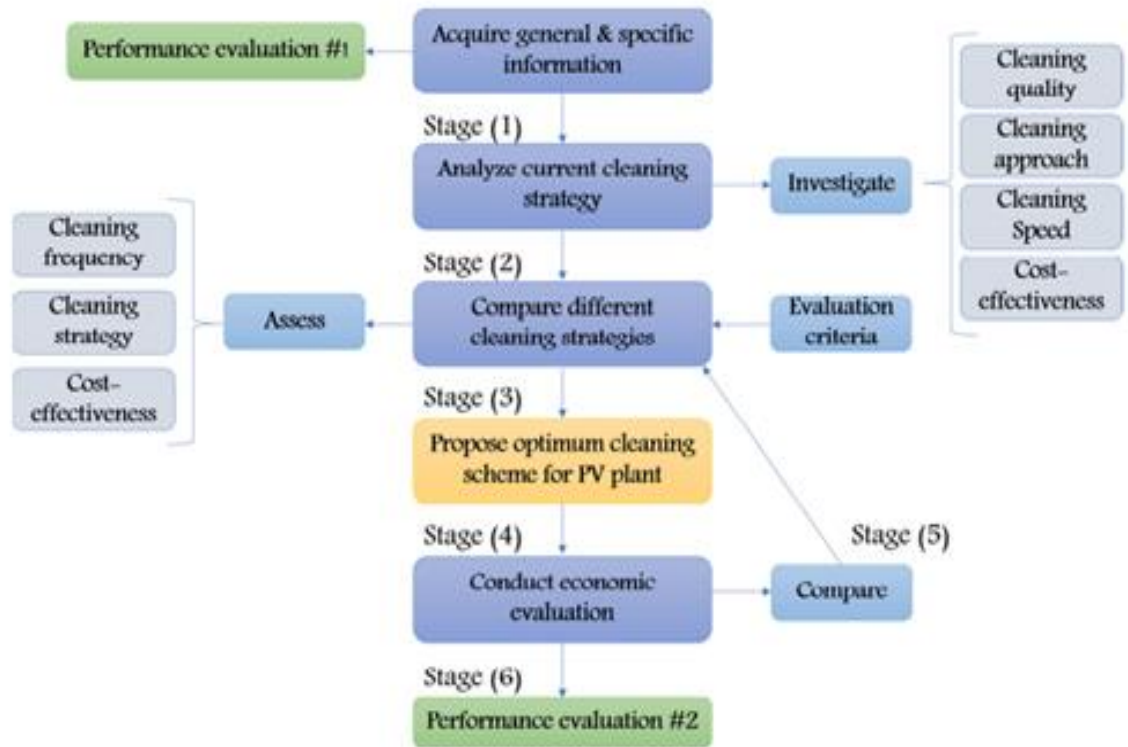


Fig 4.12: Methodology Flowchart

4.12 PV cleaning system of different countries

The efficacy and output efficiency of solar photovoltaic (PV) systems are influenced significantly by environmental factors and one of the primary reasons for declining energy output is dust collecting. Effective cleaning techniques are essential since solar energy is being used more and more globally, especially in dusty locations. Owing to the numerous environmental problems that various countries and areas face, specialized cleaning methods that take into account their unique needs have been created and implemented.

4.12.1. India:

1. Manual Cleaning: One of the most popular techniques in India is manual cleaning. To get rid of dust and grime, workers use water, soft brushes, and cloths. Although labour-intensive, this method works well, particularly in locations with considerable dust deposition [96].

2. Waterless Cleaning: Although less effective and potentially damaging to the panels, waterless cleaning techniques employing dry brushes or microfiber cloths are gaining popularity in areas with limited water supplies.

3. Robotic Cleaners: Large solar farms are progressively implementing automated robotic cleaners. These robots clean the panels with gentle brushes and either very little or no water at all.

4.12.2 Pakistan:

1. Manual Cleaning: Similar to India, manual cleaning is also prevalent in Pakistan. Workers commonly use brushes, detergents, and water hoses to clean the panels. After washing, the utilized water has been gathered and filtered using a Whatman filter, which is illustrated in Figure 4.13, which demonstrates the new technique. Since the filtered water is put back into the system's tank, this procedure enables an 85% water recovery efficiency. The process of recovery water characteristic of this technology makes it purely useful in places where water is scarce [97].

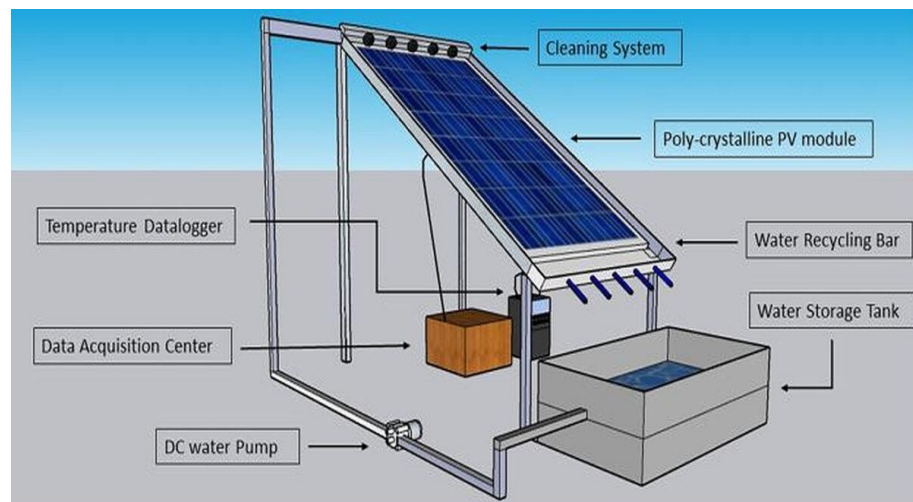


Fig. 4.13: Schematic of the cleaning system

2. Waterless Techniques: Waterless cleaning methods using soft brushes or air blowers are also used due to water scarcity in some regions,

3. Automated Cleaning Systems: Robotic cleaning systems are becoming more and more common in larger installations, especially in solar parks. These systems frequently clean the panels using brushes as well as air pressure. [96].

4.12.3 Middle East (MENA region) :

The MENA and Far East regions face challenges in water scarcity and balancing water supply availability with demand, making water-based dust mitigation techniques for PV panels unfeasible. Researchers are working to find new, non-water-dependent cleaning techniques with low initial and running costs. They aim to balance the primary and running costs of solar power systems with durability and performance, at now, robotic cleaning,

electrostatic cleaning and self-cleaning coating are used for the high levels of dust and sand removals.

4.12.4 USA:

1. Manual Cleaning: In residential and small-scale installations, manual cleaning using water and non-abrasive brushes or squeegees is common.

2. Automated Robotic Systems: Large solar farms in the USA often use automated robotic cleaners that work with or without water. These systems are especially popular in the Southwestern states where dust and bird droppings are frequent issues [42].

3. Advanced Waterless Systems: In areas where water conservation is a priority, such as California, advanced waterless cleaning systems using air blowers or vibrational cleaning techniques are being adopted.

4.12.5 Europe:

1. Manual Cleaning: In Europe, especially in residential areas, manual cleaning is still standard practice because dust levels are often lower than in arid regions. Water and gentle brushes or cloths are typically used for cleaning.

2. Robotic Cleaners: In large solar farms, particularly in countries like Germany, Spain and Italy where there is more sun exposure, robotic cleaning systems are used. These robots may use water or be entirely waterless, depending on the specific needs.

3. Rainwater Use: In regions with regular rainfall, natural rain is often relied upon to clean solar panels, supplemented by occasional manual or automated cleaning when necessary.

Chapter 5: Result and Discussion

In this chapter, the results of the investigation about the impact of dust accumulation on solar panel transmittance are explained in detail, along with a thorough discussion of the findings. The primary objectives of this investigation were to measure the amount of solar transmittance that is lost as a result of the accumulation of dust on solar panel upper surfaces and to examine the properties of the accumulated dust using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and ultraviolet (UV) transmittance tests. And also compare between regular cleaning and unclean solar system output power. Every approach offers a different perspective on the properties of dust and how it affects solar panels, resulting in a comprehensive knowledge of the problem.

Dust accumulation on solar PV panels greatly reduces the performance and effectiveness of photovoltaic systems, particularly in regions where air pollution is prevalent. A coating that blocks sunlight can form on the surface of solar panels due to dust deposition. This reduces the amount of solar radiation that reaches the photovoltaic cells and affects the system's overall energy output. To rectify this issue, we conducted an extensive compositional analysis of the dust samples and conducted experiments to measure the amount of transmittance reduction caused by dust.

To measure the impact of dust on light transmission through the solar panel surfaces, a UV transmittance analysis was carried out. This investigation establishes a direct correlation between the total volume of accumulated dirt and the gradual loss of solar panel efficiency over time by measuring the drop in UV light flowing through the dust-covered panels. The physical characteristic of the dirt particles, including their shape, size distribution, and surface unevenness, were further investigated using SEM analysis. Understanding how dust sticks to the panels, how it impacts light transmission, and how simple it is to remove during cleaning procedures all depend on these physical characteristics. Furthermore, an elemental composition analysis using EDX was conducted on the dust particles that were extracted from the panels. This method assists in determining the exact chemical components found in the dust, offer in understanding into the potential origins of pollution and the chemical reactions

that could affect the durability and effectiveness of the solar PV panels. Regular monitoring of the output was able to be aligned with realistic, practical circumstances according to the data-gathering approach, which also gave us important insights into the significance of routine solar panel maintenance. **This research shows how much energy will be gained by natural cleaning and the necessity of routine cleaning for rooftop** solar panels to function well. Ignoring this factor might result in a considerable decrease in energy production, which eventually impacts homeowners' return on investment.

The subsequent subsections will detail the experimental procedures, followed by a thorough analysis of the Solar light transmittance, SEM and EDX test results and solar output power analysis and also compare the performance between two cleaning methods- one is soapy water cleaning & another one is normal water cleaning. The discussion will interpret these findings in the context of their significance for maintaining and optimizing solar panel performance. Furthermore, potential approaches to lessen the damaging impacts of dust collection on solar panels will be investigated with the objective to improve the dependability and efficiency of solar power generation.

5.1 Variation of Weather Conditions at the Site

We choose three cloud conditions—blocky, thin, and thick—based on their various forms and thicknesses for the purpose to thoroughly examine the impact of the weather. The sky imager only begins to operate and record local sky field data when the sun rises to the minimal solar zenith angle that has been established. Datasets are collected between 7:00 and 17:00 in Figure 5.1. It is easy to see that the irradiance curve has a smooth, arching shape when there are no clouds in the sky, and this shape is solely connected to time delays. As is well known, ice crystals, super-cooled water droplets, and water droplets make up clouds under cloud-existing circumstances. Consequently, when clouds form and are thick enough to almost entirely cover the sky, a huge number of these particles may produce sunlight reflection, significantly lowering the amount of irradiance that hits the surface of the planet [98]. A cloud passing by the sun can cause irradiance oscillations and result in a significant value drop, as illustrated in Fig. 5.1 (a). In a clear sky, the irradiance value will increase to a normal value after passing across the sun. In thin cloud conditions, as shown in Fig. 5.1 (b), there is only a small change in the cloud-cover influence, not as much as in thick cloud. The sun irradiance values will be significantly reduced when there are dense clouds with strong light-resistance characteristics. Because sunlight can still penetrate the cloud layer, the irradiance curve's trend frequently matches that of a sky free of clouds. Yet, the degree of attenuation is more

noticeable than the latter. Because of the movement and distribution of clouds near the sun with varying thicknesses, the irradiance swings quickly and remains quite low most of the time.

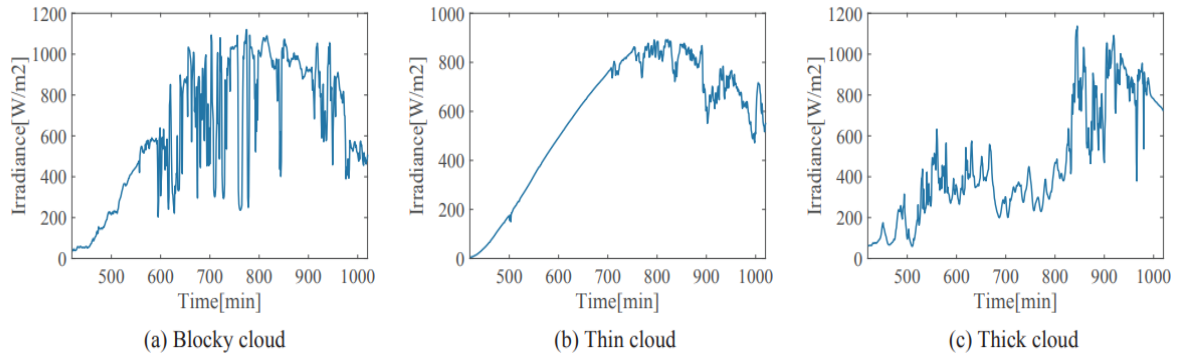


Figure 5.1: Irradiance curves in 3 weather conditions [98].

5.2. Optical Transmittance of Dust Layers

The optical transmittance tests were employed to quantify the impact of the dust layer on the penetration of solar radiation. These tests provided valuable insights into the optical properties of the dust and its effect on the efficiency of solar panels analysis was utilized to determine the elemental blending of the dust particles. This method enabled the identification of specific materials present in the dust, thereby offering a deeper understanding of the potential sources of contamination and their implications for solar energy systems.

Thirty microscopic slides were arranged horizontally on a broad metal grid measuring 0.5 m² in order to collect dust on the roofs of each of the four spots where the photovoltaic plant was constructed. One of the microscopy slides was taken out and placed in a box once a month. A Shimadzu UV1601 spectrophotometer was used to measure the photometric transmittance of dust formed on all of the microscope slides at various wavelengths (350–800 nm). Three slides' average transmittance was used as a reference point for measuring blank values. The lowest wavelength was set at 350 nm due to the sodium-calcium glass slides' significant absorptions below that wavelength. This choice was also made to prevent the photometer from adjusting the lamp, which happens at 366 nm. The machine will measure the fraction of light that passes through the dust sample at each wavelength. The result is typically presented in tables 5.1-5.4 as well as transmittance spectrums, a graph of transmittance (%) versus wavelength (nm).

Table 5.1: Monthly degradation of solar light transmittance for location BPDB.

Wavelength (nm)	Tclean λ (%)	Tdust λ (%)											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep
350	97.85	74.79	79.70	70.02	64.56	62.87	70.19	68.50	75.08	77	80.42	87.5	82.32
375	100.09	82.54	86.26	76.73	70.52	68.68	70.42	68.80	75.86	83.87	80.87	89.57	81.54
400	100.18	83.34	87.22	78.06	71.73	70.65	70.85	69.24	76.10	84.76	81.11	89.03	81.96
425	100.05	83.84	87.56	78.96	72.67	71.37	71.40	70.51	76.71	86.26	81.45	89.19	82.87
450	100.06	84.97	88.37	80.06	74.03	72.55	71.34	71.41	78.11	86.59	82.14	90.30	83.53
475	100.41	85.09	88.55	80.46	74.63	73.06	72.01	72.06	78.51	87.10	82.65	91.07	83.94
500	100.11	85.04	88.41	80.79	74.98	73.65	71.75	73.14	78.92	87.79	82.8	89.07	84.37
525	100	85.05	88.79	80.85	75.41	73.97	71.96	73.92	79.43	88.26	83.51	90.39	84.93
550	100.16	85.31	88.65	80.86	75.71	74.23	73.27	74.15	79.76	88.28	83.70	91.86	84.68
575	100.01	85.19	88.49	81.12	75.86	74.53	73.34	74.51	79.98	88.41	84.10	90.30	85.23
600	100.01	85.22	88.54	81.25	76.12	74.59	73.90	75.13	80.51	89.10	84.84	89.47	85.57
625	100.09	84.92	88.09	81.13	76.02	74.5	73.50	75.51	80.81	89.1	85.02	90.04	85.68
650	99.95	84.57	87.77	80.65	75.85	74.63	73.93	75.65	81.62	89.89	85.76	89.50	85.84
675	100.17	84.43	87.49	80.41	75.99	74.34	74.42	76.02	81.80	90.21	86.01	90.06	86.54
700	100.06	84.40	87.79	80.67	76.11	74.54	74.87	76.60	82.26	90.36	86.84	90.49	86.15
725	100.06	83.56	86.65	80.23	75.33	74.36	75.09	77.32	83.00	90.56	87.00	89.57	86.61
750	100.07	83.53	86.97	80.22	75.62	74.35	75.64	77.82	83.71	91.65	88.53	90.55	87.21
775	100.06	83.23	86.26	79.95	75.52	73.95	76.09	78.08	84.18	91.53	89.34	90.28	87.59
800	99.84	83.49	86.33	79.62	75.91	73.65	77	78.44	84.67	89.27	91.72	89.70	86.92
Average	100.04	83.82	87.26	79.58	74.35	72.87	73.21	74.04	80.05	87.89	84.62	89.89	84.96

Table 5.2: Monthly degradation of solar light transmittance for location AECC

Wavelength (nm)	Tclean λ (%)	Tdust λ (%)											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep
350	97.85	76.03	75.58	72.37	55.26	51.69	71.15	49.79	80.17	72.01	71.45	83.30	86.41
375	100.09	83.56	85.58	81.49	62.70	60.70	72.96	49.46	80.25	76.44	76.64	83.04	86.81
400	100.18	86.00	87.29	84.00	65.28	63.33	72.51	50.58	80.99	82.53	82.06	83.54	86.65
425	100.05	85.98	87.97	84.47	66.40	64.30	73.59	50.83	81.91	85.40	85.66	84.47	87.18
450	100.06	86.73	88.62	85.55	67.73	65.73	73.03	51.80	82.22	86.24	81.78	84.38	86.98
475	100.41	87.26	88.83	86.09	68.64	66.44	73.31	52.84	82.90	86.34	82.78	84.15	85.75
500	100.11	87.35	89.13	86.26	69.03	67.01	73.87	53.76	83.07	87	83.14	85.88	86.23
525	100	87.57	89.28	86.28	69.50	67.54	74.06	55.44	83.45	87.89	84.11	85.62	86.09
550	100.16	87.34	88.82	86.23	69.75	67.83	75.28	57.03	84.14	88.03	84.94	86.55	86.47
575	100.01	87.20	88.82	86.32	70.20	68.06	75.83	57.83	84.57	88.50	85.49	86.75	86.57
600	100.01	87.22	88.68	86.28	70.36	68.42	76.59	58.01	84.86	89.14	86.44	86.35	86.95
625	100.09	87.04	88.51	86.18	70.48	68.33	76.87	57.81	85.87	89.31	86.43	86.72	86.98
650	99.95	86.33	87.86	85.77	70.24	68.34	77.03	57.89	85.47	89.13	87.20	86.84	87.38
675	100.17	86.26	87.73	85.27	70.33	68.38	77.48	56.89	85.9	89.99	87.85	85.37	87.33
700	100.06	85.74	87.60	85.34	70.15	68.50	78.22	60.47	86.09	90.47	88.53	85.45	87.52
725	100.06	85.44	86.97	85.04	69.91	68.31	77.02	61.50	86.67	90.75	89.02	85.95	87.09
750	100.07	85.053	86.229	84.3	69.80	68.00	78.01	62.25	86.79	91.12	90.01	86.21	87.85
775	100.06	84.959	86.141	84.585	69.57	67.78	79.38	62.28	86.09	91.90	90.25	87.93	88.67
800	99.84	83.951	85.271	84.267	69.87	67.93	79.87	62.73	86.30	92.75	91.99	87.66	87.54
Average	100.04	85.636	87.104	84.535	68.17	66.14	75.58	56.27	84.09	87.10	85.04	85.59	87.03

Table 5.3: Monthly degradation of Solar light transmittance for location CUET.

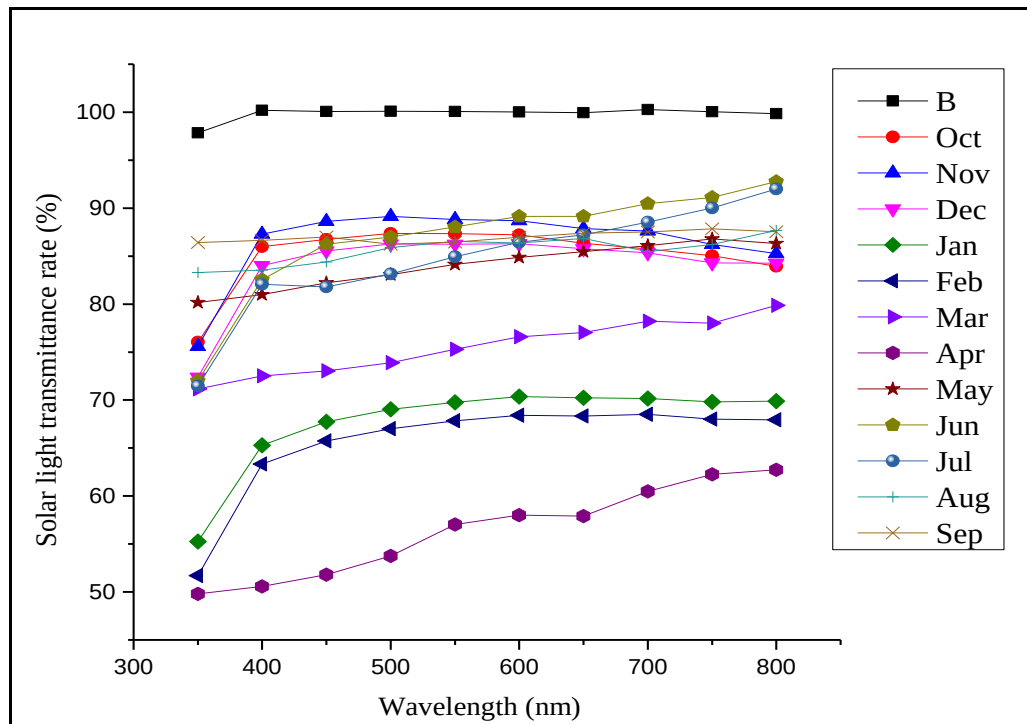
Wavelength (nm)	T _{clean} λ (%)	T _{dust} λ (%)											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep
350	97.859	82.22	76.28	76.80	73.30	74.09	87.16	80.56	95.15	98.14	97.68	89.28	90.82
375	100.092	89.61	87.34	87.19	82.39	83.71	89.19	80.88	94.93	99.79	97.58	90.52	91.72
400	100.088	90.63	88.81	89.23	84.96	85.75	90.83	80.34	94.94	99.07	97.55	91.91	91.80
425	100.059	90.74	89.17	89.49	85.57	86.27	91.16	81.41	95.71	99.98	98.55	91.48	92.50
450	100.067	91.20	90.04	90.14	86.56	87.31	92.14	81.97	95.40	99.58	98.39	91.90	92.98
475	100.419	91.80	90.55	90.55	87.13	87.80	92.50	82.14	95.62	99.58	98.53	90.39	94.65
500	100.11	91.71	90.34	90.34	87.20	87.71	92.35	82.09	96.30	98.15	98.81	91.71	93.93
525	100	91.47	90.55	90.55	87.47	87.92	92.65	82.58	95.82	99.89	98.71	92.11	94.29
550	100.166	91.40	90.10	90.26	87.20	87.94	92.77	81.77	95.96	99.59	98.50	91.78	94.14
575	100.01	91.48	89.98	90.08	87.25	87.71	92.99	81.97	95.98	99.47	98.50	90.15	94.21
600	100.019	91.1	89.93	90.02	87.19	87.66	93.39	82.36	96.47	99.70	98.97	91.27	94.93
625	100.094	90.82	89.51	89.59	86.92	87.51	93.42	82.65	96.44	99.59	98.87	91.55	94.94
650	99.955	90.30	89.23	89.32	86.71	87.36	93.55	82.84	96.83	98.04	98.50	91.63	95.57
675	100.179	89.66	88.96	89.12	86.48	87.16	93.73	82.87	97.56	97.35	97.93	92.86	96.41
700	100.062	89.53	88.93	88.77	86.41	86.69	94.49	82.16	97.09	97.44	97.63	93.19	96.71
725	100.065	89.01	88.47	88.52	85.97	86.35	94.64	82.84	97.84	97.34	98.08	93.60	96.84
750	100.437	88.36	87.89	87.91	85.59	85.60	94.53	83.19	98.15	98.32	97.31	95.64	95.03
775	100.296	87.62	87.51	87.77	85.04	86.18	93.73	83.61	97.60	99.58	98.06	95.43	95.58
800	99.844	87.64	87.06	86.44	84.37	85.22	94.20	83.40	97.50	98.18	98.59	96.01	95.33
Average	100.043	89.80	88.46	88.53	85.46	86.10	92.60	82.30	96.38	98.88	98.25	92.23	94.33

Table 5.4: Monthly degradation of solar light transmittance for location NMI

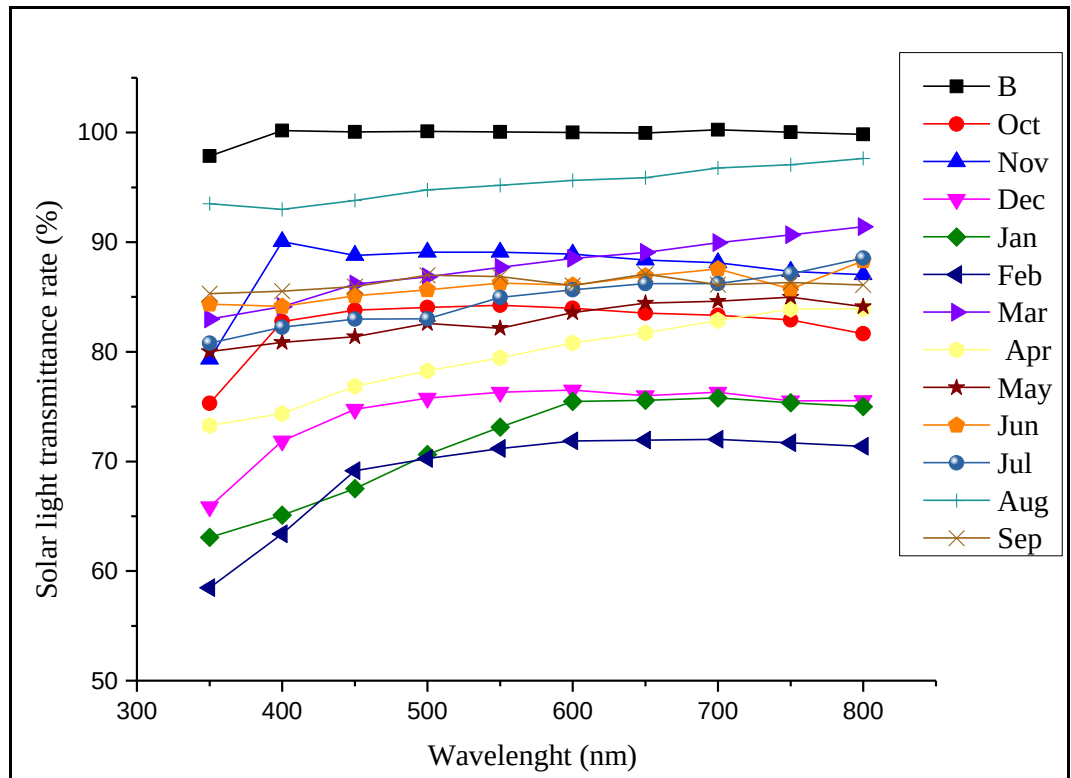
Wavelength (nm)	T _{clean} λ (%)	T _{dust} λ (%)											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep
350	97.85	75.30	79.32	65.86	63.059	58.474	82.98	73.26	80.01	84.34	80.78	93.50	85.31
375	100.29	81.47	85.20	71.23	69.705	64.649	83.83	73.78	80.52	84.01	81.99	92.50	85.83
400	100.18	82.77	90.04	71.87	69.094	69.385	84.12	74.35	80.86	84.13	82.25	92.99	85.53
425	100.05	83.28	87.73	73.88	72.43	67.724	85.36	75.68	81.02	84.84	82.59	93.70	85.85
450	100.06	83.80	88.79	74.76	73.513	69.137	86.17	76.86	81.38	85.09	82.99	93.79	85.95
475	100.41	84.24	88.88	75.34	74.113	69.7	86.54	77.75	81.97	85.22	83.34	94.57	86.03
500	100.11	84.05	89.08	75.77	74.632	70.258	86.83	78.26	82.58	85.64	83.01	94.76	86.97
525	100	84.09	89.40	76.08	74.989	71.103	87.22	79.05	82.62	85.03	84.76	95.13	86.63
550	100.16	84.23	89.09	76.31	75.118	71.173	87.71	79.45	82.14	86.26	84.95	95.19	86.86
575	100.01	84.05	89.15	76.52	75.348	71.547	87.87	80.06	83.35	86.49	85.01	95.27	86.65
600	100.01	83.96	88.91	76.52	75.463	71.876	88.51	80.80	83.57	86.06	85.65	95.64	86.03
625	100.09	83.88	88.77	76.35	75.674	71.866	88.67	81.17	83.81	86.34	85.98	95.99	86.62
650	99.95	83.53	88.36	75.99	75.568	71.949	89.07	81.71	84.43	86.92	86.23	95.89	87.08
675	100.17	83.47	88.27	76.47	75.501	71.643	89.21	82.47	84.91	87.40	86.87	96.95	87.13
700	100.26	83.34	88.11	76.30	75.79	72.003	89.96	82.85	84.62	87.56	86.23	96.76	86.12
725	100.06	82.83	87.578	76.011	75.562	71.706	90.50	83.46	84.91	87.83	86.51	97.48	86.36
750	100.43	82.9	87.32	75.52	75.35	71.68	90.67	83.90	84.994	85.72	87.11	97.06	86.32
775	100.29	82.09	87.13	75.36	75.30	72.01	90.82	83.66	84.61	87.6	87.56	97.68	86.33
800	99.84	81.64	87.03	75.54	75.01	71.37	91.42	83.93	84.129	88.30	88.54	97.64	86.09
Average	100.04	82.89	87.80	74.83	74.80	71.01	87.76	79.60	82.97	86.04	84.86	95.39	86.30

In an effort to gather information on exactly how dust on a surface prevents photons from moving freely, optical transmittance of the dust gathered on microscopic slides with varying exposure times was used in a UV-Vis Spectrometer. Figure 5.1 illustrates how transmittance decreases with exposure duration for wavelengths between 370 and 800 nm. First, the more exposure days, the greater the transmittance deterioration level. The reason for this is the persistent buildup of particles of dust on the photovoltaic surface. Second, deterioration continues because of longer exposure times since the semi-horizontal surfaces capture more coarse and fine particles, and smaller tilt degrees, such as the solar modules' 22° tilt angle in this instance. Light may be refracted, absorbed within the particle, reflected, or diffracted by particles when it travels through a dust-covered surface.

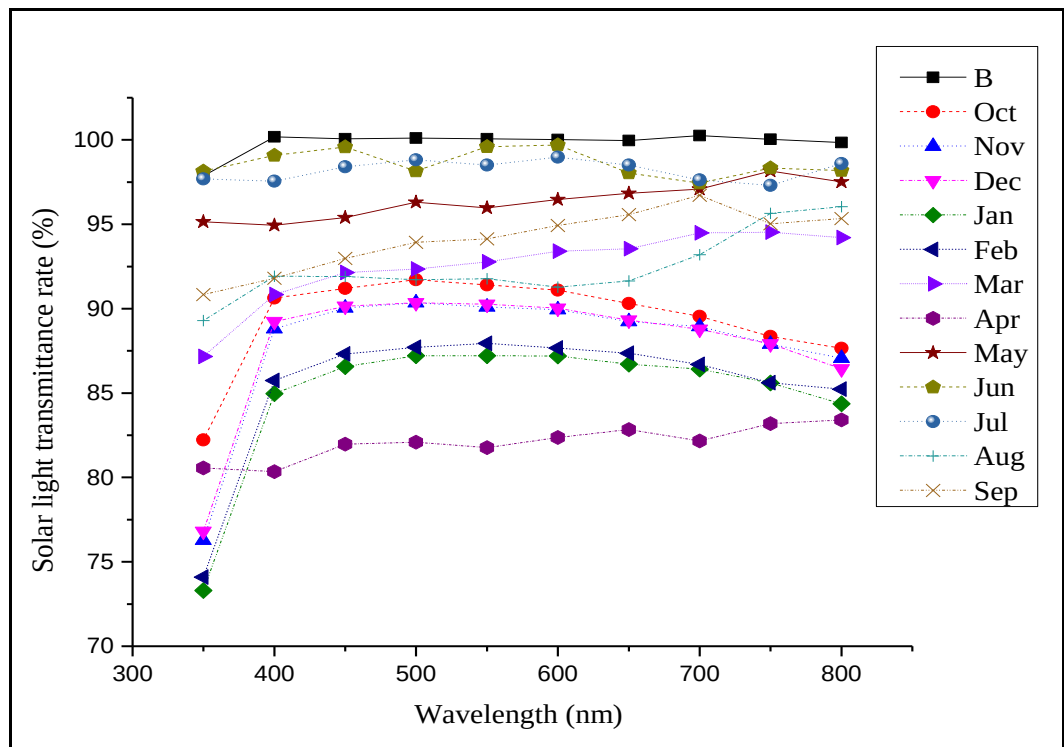
According to geometry evaluation, a larger area is occupied by the tiny fragments on the surface. On the other hand, scattering is controlled by a combination of particle size diameter and beam wavelength when the size of the particulate matter is near the wavelength. The function can be explained by Mie scattering when the ratio $\alpha = (\pi \cdot D)/\lambda$ is less than 12, and by Rayleigh scattering when the ratio $\alpha < 0.3$ [12]. In this instance, a beam's intensity decreases as the particle's diameter decreases. These effects are seen for particles less than 2 μm at the wavelengths of visible light [13]. In a consequence of their existence in deposits on microscopic slides, they are the cause of the wavelength dependence of transmittance reduction.



(a) AECC



(b) NMI



(c) CUET

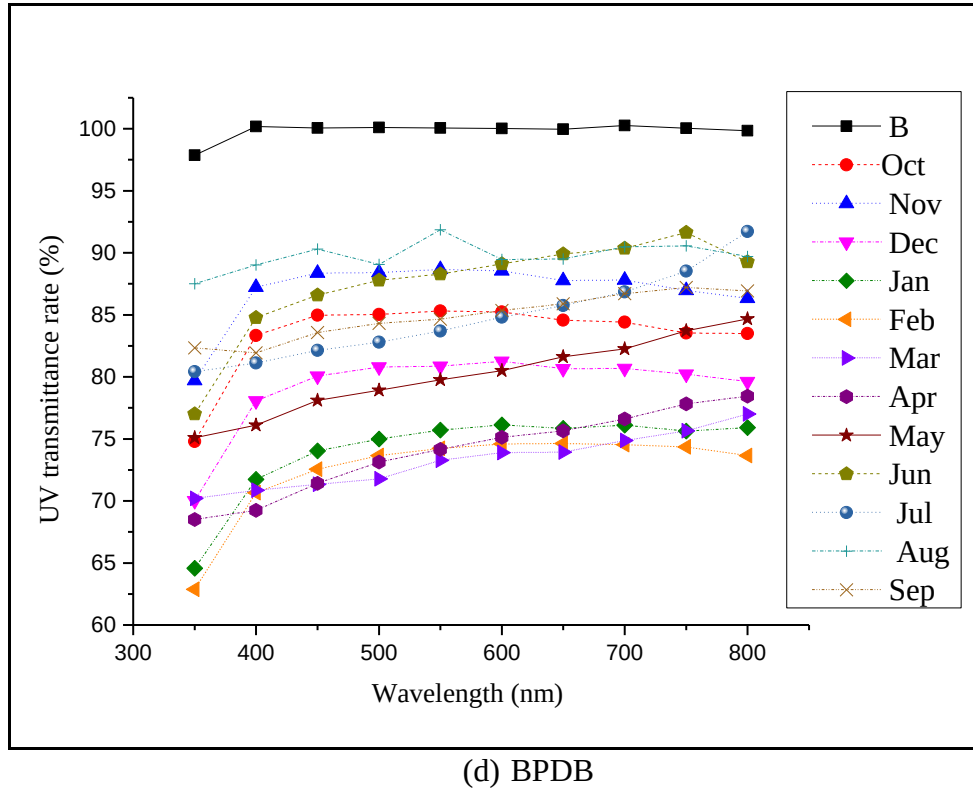


Fig. 5.2: Transmittance is reduced with exposition time for the 350-800 nm wavelengths (a) AECC, (b) NMI, (c) CUET (d) BPDB.

Figure 5.3 shows the average solar light transmittance rate over one year. From this data, we can see that CUET consistently demonstrates the highest average UV transmittance, maintaining values above 85% throughout the year, except in April. The transmittance peaks in May, June, and July, reaching up to 98% in June, indicating minimal dust accumulation and effective natural (rain) or manual cleaning.

BPDB exhibits more variability, with a significant drop in transmittance during the winter months. The lowest average transmittance is observed in February at 72.87%, reflecting higher dust accumulation and its impact on panel efficiency. Transmittance improves in the summer, peaking at 87.89% in June, likely due to natural cleaning from rainfall.

AECC shows the most significant fluctuations in transmittance, with steep drops and recoveries. The lowest transmittance is recorded in April at 56.27% and February at 66.14%, indicating severe dust accumulation. There is a strong recovery in transmittance in the summer months, with a peak of 87.10% in June, suggesting effective natural or manual cleaning.

NMI shows a moderate decrease in UV transmittance during winter, with the lowest point in February at 71.01%. The transmittance gradually increases from March onwards,

peaking at 92.25% in June, indicating effective dust removal during this period.

From the graph, we can divide the annual trend into two seasons: the dry season (November to April) and the wet season (May to October). During the dry season, the dust accumulation rate is typically higher due to reduced rainfall, resulting in lower solar light transmittance. However, in March (based on the graph), despite being part of the dry season, heavy rainfall occurred during the first half of the month in some locations, which effectively cleared dust from the sample glass in the AECC, NMI, and CUET locations. This unexpected weather event led to a sudden increase in solar light transmittance during March, deviating from the typical trend observed in the dry season.

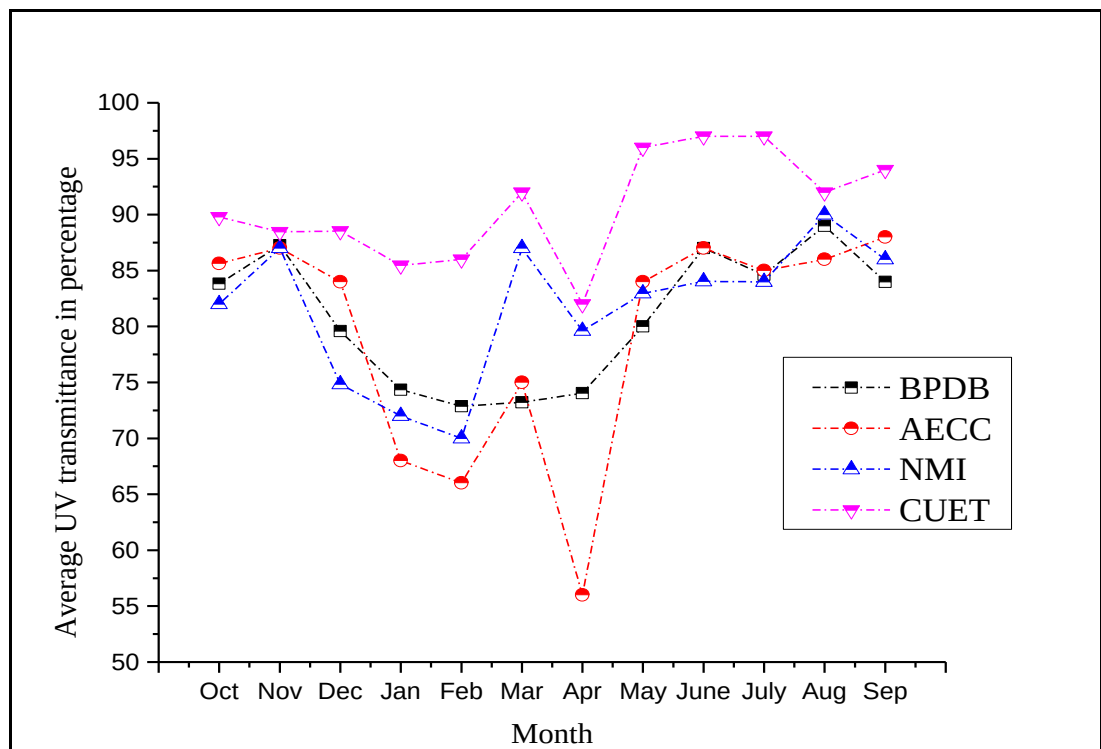


Fig. 5.3: Average transmittance of four locations in a year.

5.2.1 Efficiency Degradation

The efficiency degradation ratio, or EDR, shows the percentage decrease in solar panel efficiency brought on by dust buildup. The UV transmission through dust-covered panels is compared to that of clean panels in order to compute it. A greater EDR denotes a more notable loss in light transmission, which lowers the solar panels' energy production. The amount of dust deposition, the chemical makeup of the dust, and environmental factors like rainfall, which can naturally clean the panels, all have an impact on the EDR. Figure 5.3 shows the monthly efficiency degradation ratios (%) due to dust accumulation across four locations: CUET, AECC, BPDB, and NMI. The values represent the UV transmission reduction caused by solar panel dust from October to July.

$$\text{Efficiency Degradation} = 1 - \text{Transmittance Ratio}$$

5.2.1.1 Key Observations:

1. CUET:

The degradation ratio fluctuates, with the highest values observed in April (16.74%) and January (13.57%). May to July has the least amount of degradation (2%) average.

2. AECC:

This location shows significant variability, with a peak degradation in April (42.21%) and February (33.89%) respectively and a notable high in January (31.86%). May (14.95%) and June (11.94%) show lower degradation, indicating better transmission efficiency during these months.

3. BPDB:

The highest degradation is recorded in February (27.16%) and January (25.68%). Like CUET, June (11.15%) and July (14.5%) exhibit the lowest degradation, suggesting that dust accumulation had a lesser impact during these months.

4. NMI:

The highest degradation is seen in February (30.21%) and December (25.14%). Similar to the other locations, the lowest values occur in June (6.79%) and May (10.02%).

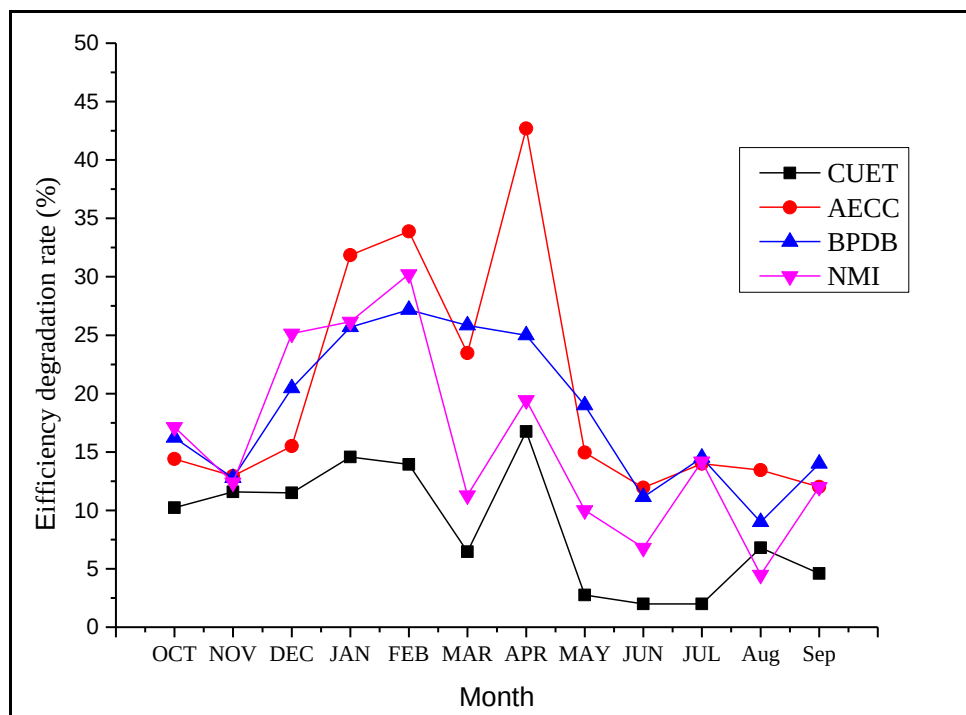


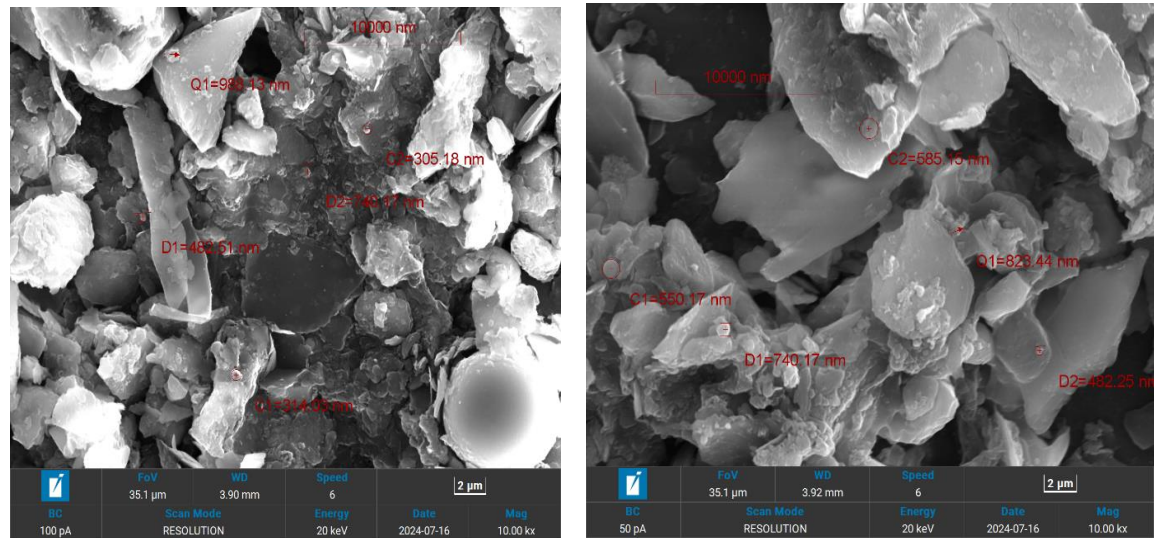
Fig. 5.4: Monthly ED ratio for four sampling locations for one year.

The data shows significant variation in EDR across the four locations over one year. The highest EDR values are generally observed in the dry seasons (November to April), indicating that these periods are particularly challenging for solar panel performance due to dust

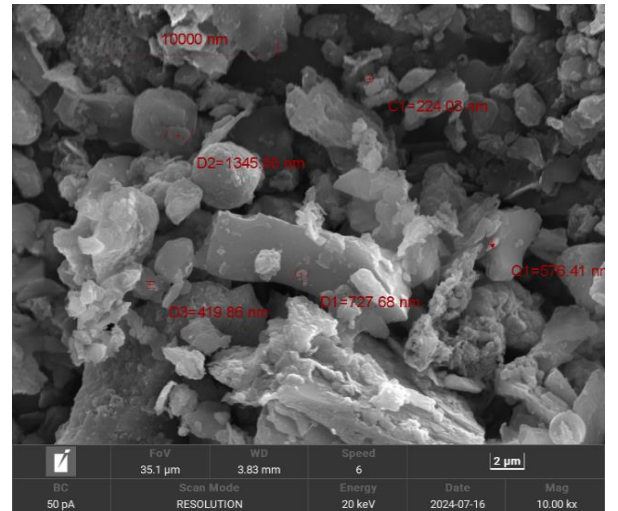
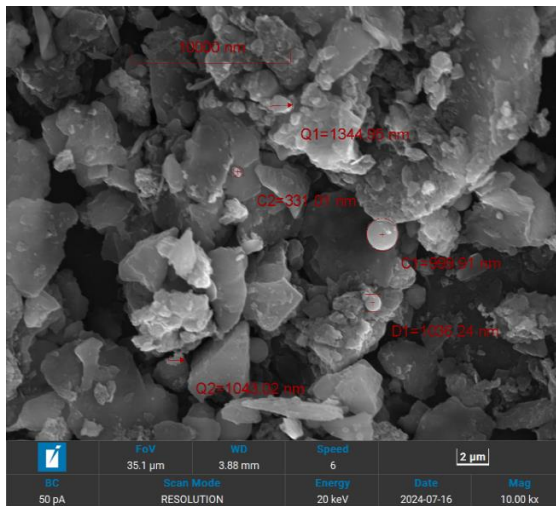
accumulation, except March. AECC consistently exhibits higher EDR values compared to the other locations, especially in January and February, suggesting more severe dust impacts in this area. In contrast, CUET generally shows lower EDR values, particularly during the summer months (June and July), which may be attributed to increased rainfall-reducing dust accumulation. BPDB and NMI also demonstrate seasonal variations in EDR, with notable peaks in the winter months and lower values in the summer, reflecting the broader trend of seasonal impacts on solar panel efficiency across different locations. This comparison highlights the need for tailored maintenance strategies to address the specific dust-related challenges in each location.

5.3 Scanning Electron Microscopy (SEM)

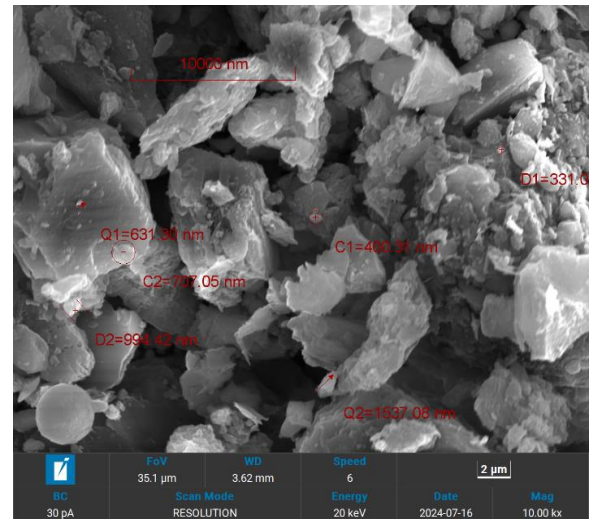
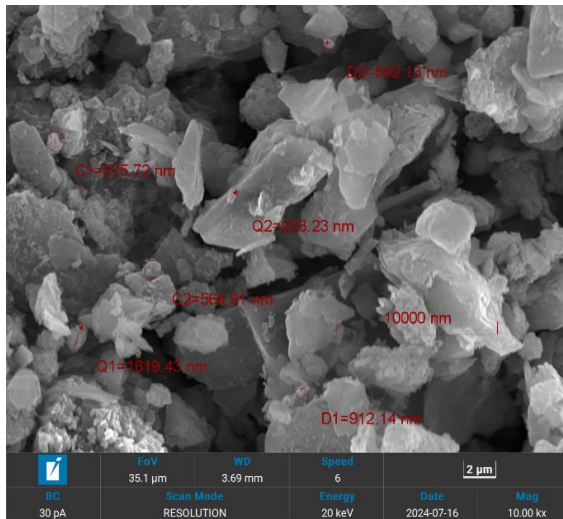
Using an electron beam to scan a sample's surface, SEM produces a high-resolution image that discloses the composition and structure of the material. Benefits of SEM include its high resolution, ability to test a wide range of components, and ability to provide incredibly detailed images of materials. Its sensitivity to light elements limits its ability to distinguish between comparable components. The electron beam can harm delicate materials; coating spreads the electrons and reduces localized heating and damage. Due to gold being a highly conductive metal that does not interfere with the electron beam used in the SEM, it is commonly utilized as a coating material. For this reason, a gold layer was used in this work to coat the dust layer. Additionally, gold is visible in the SEM due to its high atomic number, which simplifies the analysis and research of dust particles. This made it possible for the writers to investigate the dust particles' form and composition in great detail. [71].



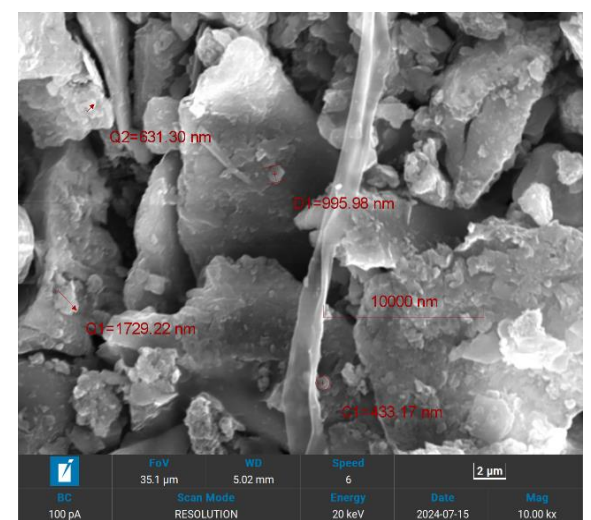
(a) CUET



(b) AECC



(c) BPDB



(d) NMI

Fig. 5.5: Scanning electron microscopy (SEM) image of dust samples from four locations—CUET, AECC, BPDB, and NMI.

5.3.1 Discussion (SEM analysis)

The scanning electron microscopy (SEM) analysis of dust samples from four locations reveals significant variations in particle size and distribution, which are critical factors affecting the efficiency of rooftop solar photovoltaic (PV) systems. The results underscore the complex relationship between dust deposition and solar panel performance, with implications for energy output and maintenance strategies.

At CUET, particle sizes range from 305.18 nm to 938.13 nm, indicating a heterogeneous dust composition. The broad size distribution of dust in solar panels suggests a heterogeneous composition, likely originating from multiple sources, such as building works and vehicular pollution. Larger particles, particularly those approaching 1 micron are large enough to cause significant light scattering and absorption, which can reduce sunlight reaching photovoltaic cells, affecting overall energy output. The non-uniformity in particle size also suggests irregular deposition, potentially causing uneven soiling on panels.

In contrast, AECC exhibited particles from 224.08 nm to 6.412 μm , with a noticeable outlier at the upper end of the scale. Large particles in solar panels may indicate coarser dust or aggregate formation, obstructing sunlight more effectively than finer particles. These larger particles reduce solar transmittance more than smaller ones, affecting panel efficiency. This variability in particle size distribution could be attributed to local environmental factors, such as construction activities or the proximity to dust-generating sources.

The dust sample from BPDB revealed particles ranging from 331.25 nm to 4.143 μm , with several particles near or exceeding 1 micron, posing a substantial risk to panel performance. The presence of multiple large particles in the BPDB sample suggests that the panels in this area are likely to experience greater efficiency losses compared to locations with finer dust particles. The varied particle sizes also indicate a mixed deposition pattern, possibly influenced by both local and distant sources of dust.

The NMI location had the largest particles among the four sites, with sizes ranging from 615.94 nm to 11.12 μm . The substantial presence of particles many particles sizes above 11 microns, is particularly concerning and overall suggests that environmental conditions here, such as proximity to heavy industrial activities or frequent construction, may promote the deposition of coarser dust.

Across all locations, NMI and BPDB show the greatest risk of efficiency loss due to larger particles, with AECC also at higher risk than CUET. The presence of large particles, particularly those over 1 micron, is a key factor in diminishing solar transmittance. The non-

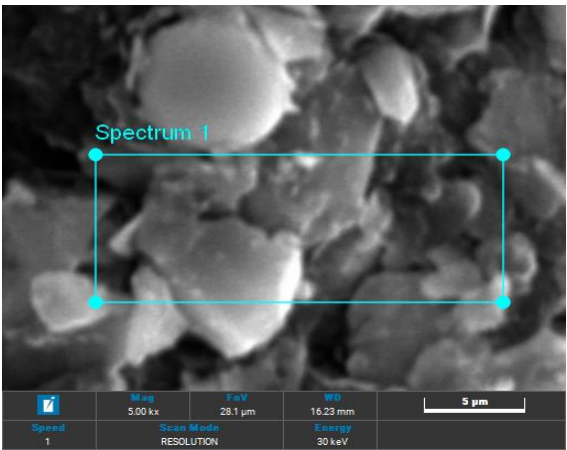
uniformity in particle size distribution highlights the need for location-specific maintenance strategies to mitigate dust accumulation and preserve solar panel efficiency. Regular cleaning and monitoring are essential to counteract the negative impact of dust deposition on energy output.

5.4 Energy Dispersive X-ray (EDX) Analysis

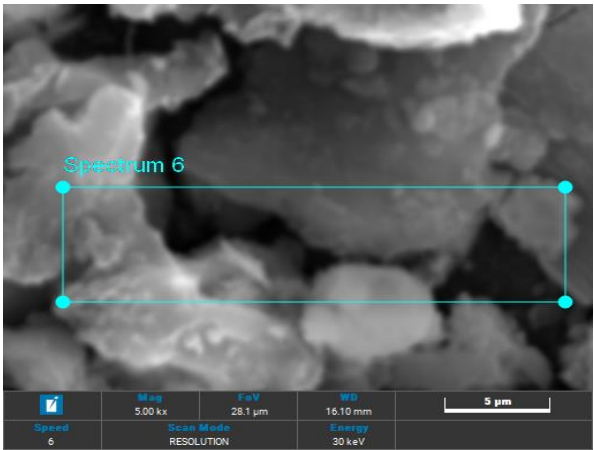
Environmental conditions have a considerable impact on the efficiency of solar photovoltaic (PV) systems, with dust deposition being a key worry. Although the impact of dust on solar panel efficiency through UV transmittance studies has been quantitatively explored in earlier sections, it is equally vital to comprehend the qualitative nature of the dust that settles on these panels. To pinpoint the precise origins and features of the dust influencing the solar panels, an in-depth elemental composition of the dust particles is provided using an energy-dispersive X-ray (EDX) study.

Chittagong City's fast urbanization and industrialization have resulted in a wide variety of airborne particulate pollution. Dust samples from the solar panels can be used to analyze the elemental composition of this particulate matter, which varies depending on the local environment. This allows insight into the types of particles that contribute to efficiency degradation and their respective sources. Residential areas, industrial zones, and regions with high vehicular traffic are some examples of these zones.

The purpose of the EDX analysis is to determine which major elements are contained in the dust, to compare the elemental compositions of the two sites, and to talk about how these elements affect the solar panels' efficiency. Comprehending the fundamental composition of the dust would facilitate the formulation of focused approaches to alleviate the detrimental consequences of dust buildup on photovoltaic systems, thereby augmenting their efficiency and durability. In Figure 5.6 indicates the image sections of the EDX have been conducted



(a) CUET



(b) AECC

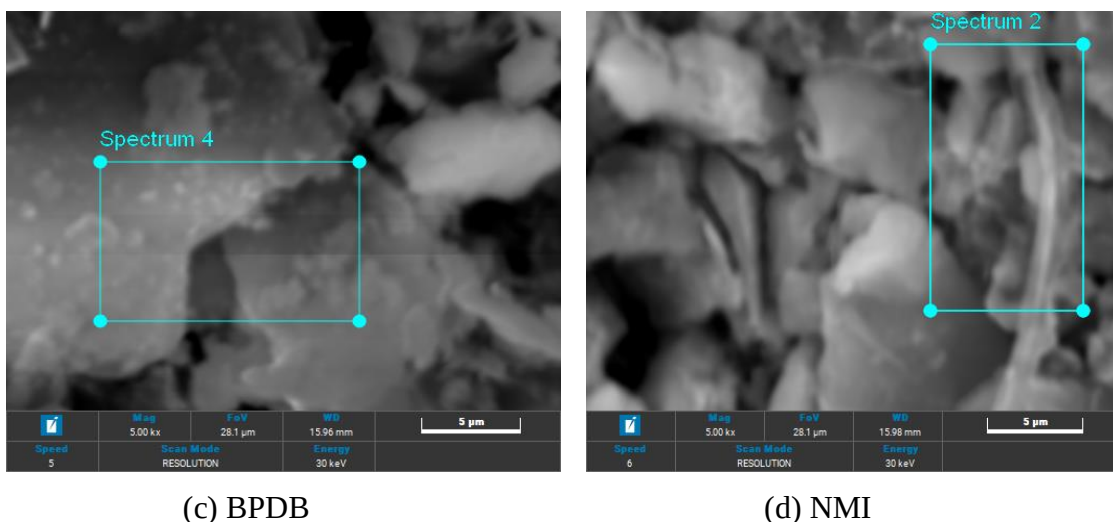


Fig. 5.6: The image sections of the dust slide sample for the EDX study.

5.4.1 Result of EDX Analysis of Dust Samples

The key elements identified across all samples include Carbon (C), Oxygen (O), Silicon (Si), Aluminum (Al), and smaller amounts of Potassium (K), Calcium (Ca), Iron (Fe), Nitrogen (N), Magnesium (Mg) and various metal oxides.

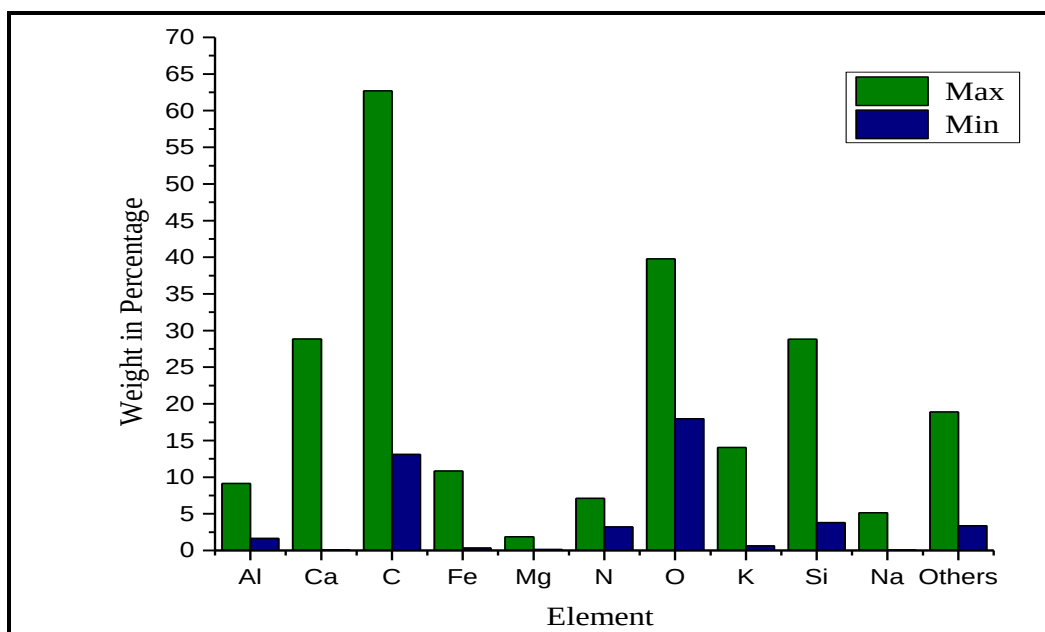


Fig. 5.7: Element weight in percentage found in CUET samples.

CUET Samples:

According to the elemental analysis, there is a notable amount of carbon (13.09% to 62.71%) and oxygen (17.98% to 39.11%) in the composition. With traces of aluminum (1.65–9.15%), iron (1.31–10.84%), nitrogen (3.2–7.1%), sodium (0.02–5.13%), and a negligible amount of magnesium (Mg), silicon was also substantial, ranging from 3.79% to

28.82%. Potassium and calcium achieved weight percentages of up to 14.06% and 28.86%, respectively, in one point and other elements (3.38-18.9%).

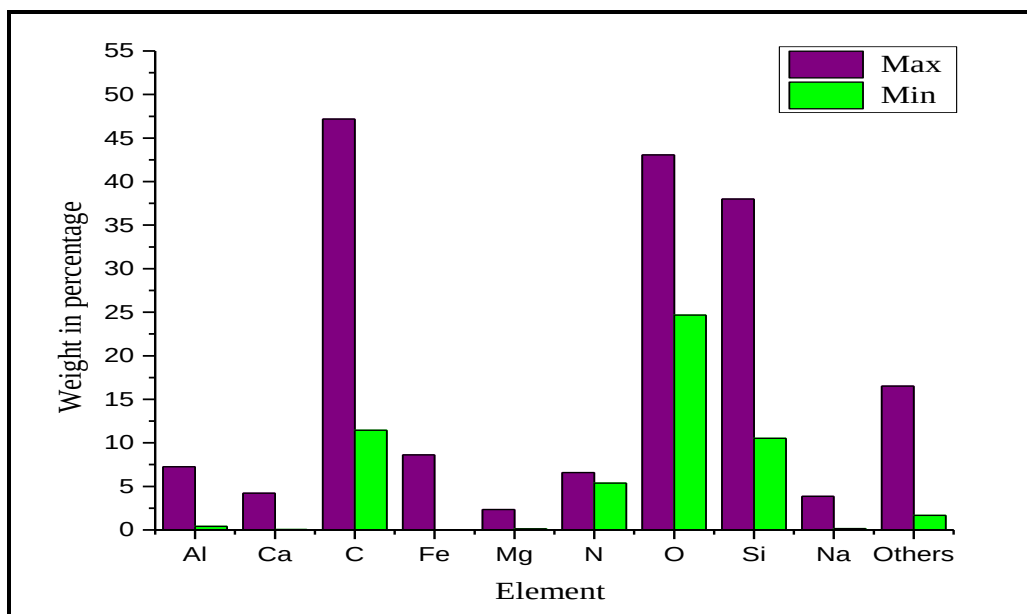


Fig 5.8: Element weight in percentage found in AECC samples.

AECC Location:

The AECC sample revealed higher percentages of silicon (10.52% to 38%) and carbon (11.44% to 47.17%), as well as significant amounts of oxygen (24.67% to 43.07%), aluminium (up to 5.77%), iron (0.01-10.62%), calcium (0.05-14.23%), sodium (0.16-3.87%), magnesium (Mg) (0.13 – 2.33%), and other elements (1.67-16.52%) by weight.

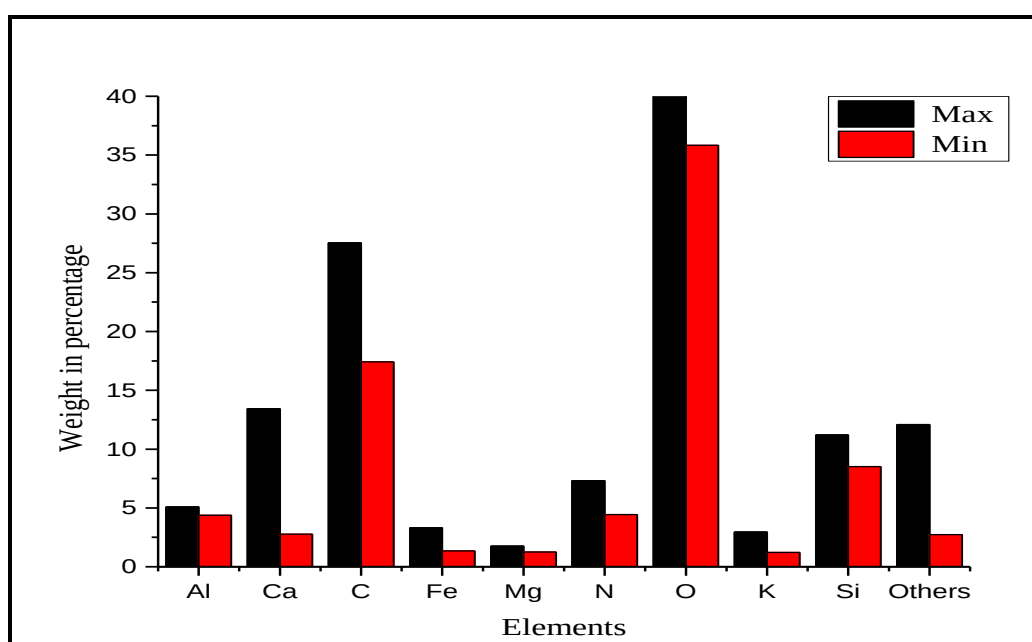


Fig. 5.9: Element weight in percentage found in BPDB samples

BPDB Samples:

The BPDB sample showed high levels of carbon (varying from 17.42 to 27.54%) and oxygen (42.83% to 35.02%), much like the CUET and AECC samples did. The sample had a modest amount of silicon (8.52–18.21%), and slightly more iron (1.34–3.31%), aluminum (4.37 -5.09%), nitrogen (4.44–7.32), and calcium (2.77-9.43%) were present by weight than the other elements (metal oxides) (2.73–12.09%). There were minuscule amounts of magnesium (up to 3.16%) and potassium (up to 2.96%).

NMI Location:

The NMI samples indicate that the presence of silicon (14.03-19.18%), carbon (17.33 – 18.82%), and oxygen (41.74 – 44.92%) is consistent with other places. Additional noteworthy elements included were nitrogen (6.07-6.29%), calcium (0.02-6.68%), and aluminum (2.65-4.94%). Additionally, trace levels of magnesium (0.53-2.62%), potassium (0.53-3.74%), iron (0.40-3.41%), and miscellaneous elements (including metal oxides) (3.45-12.62%) were found.

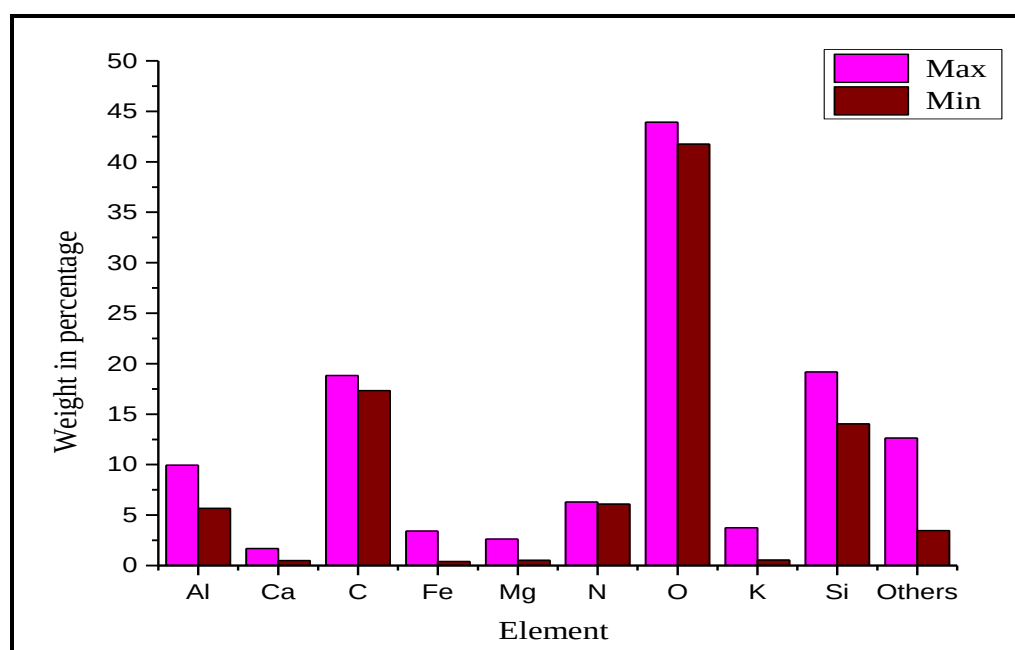


Fig. 5.10: Element weight in percentage found in NMI samples.

For better understanding, we took all the locations of sample elements in one graph (Figure 5.11). From that figure, we can easily compare the element with the location and trace the elements which one higher or lower in that location.

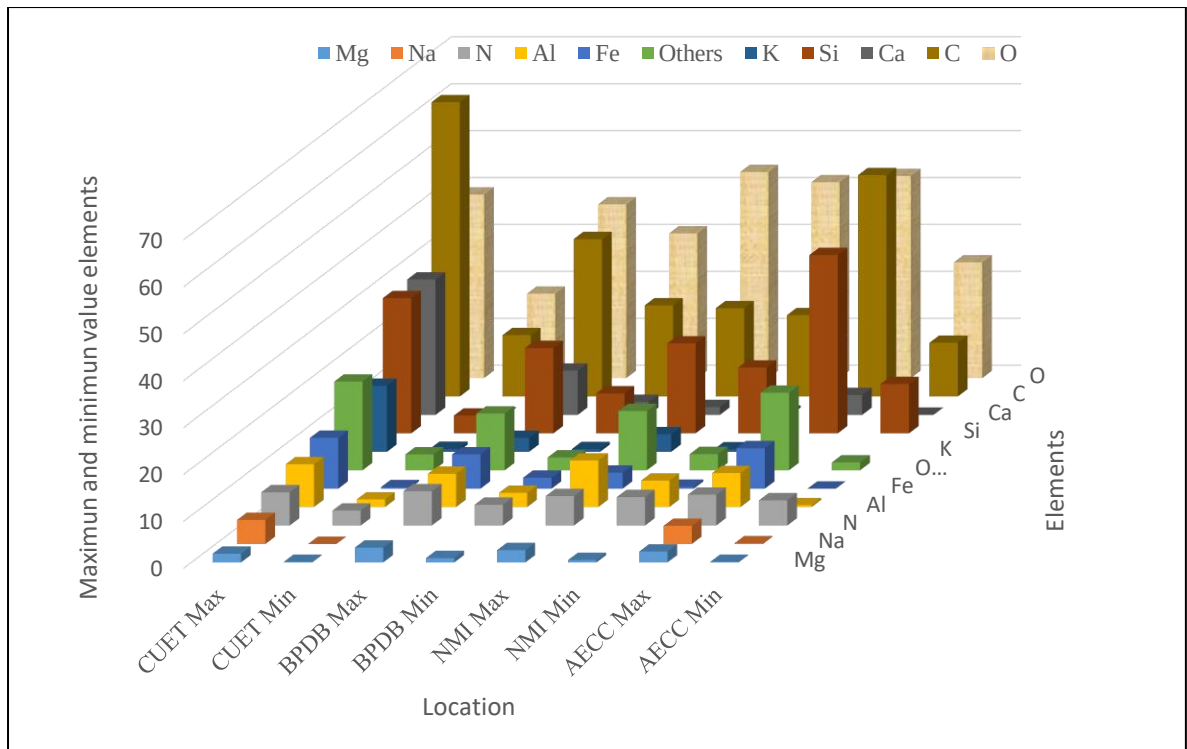


Fig. 5.11: The comparison of the elemental composition by EDX analysis of accumulated dust by location.

5.4.2 Discussion (EDX analysis)

1. Carbon: Carbon has high light-absorbing properties, which exacerbates the reduction in panel efficiency and it originates from organic materials such as plant matter, vehicle emissions, burning of fossil fuels, and industrial processes. Carbon was the dominant element in all locations, indicating significant organic material or soot deposition. CUET had the highest carbon content, possibly due to vegetation activities. AECC had a substantial carbon content, possibly from urban pollution and industrial emissions. NMI and BPDB had a moderate carbon range, suggesting a steady source of organic pollution, probably from industrial and vehicular emissions.

2. Oxygen: Oxygen content in various locations indicates the presence of oxides, silicates, and other oxygenated compounds. CUET had high carbon content, indicating organic oxides. AECC had higher oxygen levels, indicating silicates and oxygen-rich compounds. BPDB had substantial oxide formation, likely due to industrial processes. NMI had the highest oxygen content, indicating oxidized materials, which could be attributed to both industrial and urban sources.

3. Silicon: Silicon particles, due to their high density and adherence properties, significantly block sunlight when deposited on the solar panels. It was a significant component in all

samples, indicating mineral dust and possibly construction-related materials. Significant accumulation was observed in CUET, AECC, BPDB, and NMI, with higher levels indicating a strong influence of silicate materials from construction or industrial activities.

4. Aluminum and Iron: All samples showed aluminium, indicating aluminosilicate minerals and iron content. These elements are typically associated with industrial processes, emissions especially steel/coal plants, and vehicular wear and tear. CUET shows a significant range, AECC indicates mixed influences, BPDB shows a moderate range, and NMI shows lower levels. This is likely due to soil and industrial sources.

5. Calcium and Potassium: Calcium, found in lower concentrations, is usually derived from construction materials and natural dust. Although its impact is lesser compared to silicon and carbon, calcium deposits contribute to the overall reduction in light transmittance. Calcium and Potassium were more pronounced in certain locations. CUET had Calcium up to 28.86% and Potassium up to 14.06%, indicating significant contamination from cement or road dust. AECC and BPDB had moderate Calcium and Potassium levels than NMI had, reflecting a lower influence of construction dust or road salts.

6. Nitrogen, Magnesium, and Sodium: The samples showed varying amounts of elements, including Nitrogen, Sodium, and traces of Magnesium, indicating urban pollution and industrial activities. CUET, AECC, BPDB, and NMI showed consistent levels, indicating steady urban pollution sources.

7. Others (Metal Oxides): Various metal oxides indicate significant industrial pollution. These compounds can form a persistent, hard-to-remove layer on the solar panel surface causing long-term degradation in efficiency.

5.5 Dust Deposition Densities

An important determinant of solar panels' efficiency and energy output is the density of dust that has accumulated on them. The amount of sunlight that reaches the photovoltaic cells is decreased as dust density rises because more particles cover the solar panel's surface area. As a result, less energy is transformed into electrical power since the solar transmittance decreases. In this study, to measure the dust deposition rates, firstly cut the microscopic slides in an area of 3 cm × 2.5 cm and then weigh all of the locations slides and also a blank microscopic slide for subtracting the blank glass sample value from the other locations dust slide sample value to know the actual rate of dust deposition. Next, calculate the density of dust in different locations- such as in CUET 15.53 mg/cm², AECC 40.65 mg/cm², BPDB 27.32 mg/cm², and NMI 29.40 mg/cm², whose are the highest values in that location.

Higher dust density blocks more sunlight from reaching the solar panel, reducing the amount of solar radiation available for energy production. For example, AECC, with the highest dust deposition density (40.65 mg/cm²), would experience a more significant reduction in energy output compared to the rest of the location. Dust accumulation increases surface roughness, leading to higher reflection losses. While not always immediately apparent, high dust density can also cause long-term damage to the surface of the solar panels. Dust particles can act as abrasives, gradually scratching and degrading the surface, which can further reduce efficiency and lifespan.

In a nutshell, the performance of rooftop solar PV systems is significantly influenced by the density of dust. Energy yield may be significantly reduced in places with higher dust deposition, such as AECC, NMI and BPDB, than in places with lower dust levels, like CUET. This highlights how crucial it is to implement routine cleaning and maintenance procedures in order to lessen the negative effects of dust on solar panel performance and total energy generation.

5.6 Solar PV System Setup and Data Collection

To investigate the impact of dust deposition on energy output, two mono-crystalline solar photovoltaic (PV) systems with a peak power capacity of 550 Wp each were set up at the CUET campus. The devices were set up in a position that provided maximum sun exposure and little shade. Throughout March to August, data on energy output was continuously captured, providing real-time data on panel temperature, ambient temperature, and solar irradiation. To examine dust collection under regular seasonal conditions, this time frame was selected. To assess the efficiency gain by naturally clean and loss resulting from dust deposition, panel conditions, both clean and dirty, were observed. The cleaning process was normal water-based cleaning. Figure 5.12 illustrates the month-wise difference in output power production between the clean and dirty panels. Data shows a significant difference between the clean and dirty panels. For instance, the data reveals a consistent reduction in energy output for dirty panels compared to clean ones, emphasizing the impact of dust accumulation on solar panel efficiency. This effect becomes more pronounced over time. The highest power production was observed in March for both panels, with the clean panel producing 1.74 kW/day average and the dirty panel 1.43 kW/day average. Over the months, a declining trend in energy output is evident, likely due to seasonal variations such as reduced solar irradiation and possibly higher dust accumulation rates during specific months.

The difference between clean and dirty panels is most significant in March and April,

with efficiency losses of 0.25 kW and 0.43 kW, respectively. These months likely experienced higher dust deposition rates, significantly impacting the panels' performance. By contrast, the efficiency gap narrows in the later months (June to August), with the smallest difference (0.12 kW/day) recorded in August. This reduction could be attributed to seasonal rainfall acting as a natural cleaning mechanism. Those months (June to August) likely experienced higher humidity or cloud and sometimes heavy rain cover due to the monsoon season, resulting in reduced sunlight hours. Moreover, data shows that both dust accumulation and environmental factors (like temperature, shading, humidity, wind flow and seasonal variations) play significant roles in reducing the actual output compared to the data of solar light transmittance.

The Solar light transmittance data collected from CUET, with values ranging from 82.6% to 98% between March and August, shows a direct correlation with the solar power output from the panels. As transmittance decreases, so does the efficiency of solar panels, which is evident in the reduced energy output. For example, the lower transmittance in April (82.6%) aligns with a drop in power generation, while higher transmittance values in June and July (98%) correspond with relatively better performance but the overall output was decreased on those times because the rainy season and low sun hours. However, even with high transmittance, the recorded power output is still below theoretical expectations due to real-world factors such as dust accumulation and system losses. The theoretical output of 2.27 kWh/day (if sunlight averages 05 hours) was calculated under ideal conditions, and tested at 1 sun (1,000 W/m² of solar radiation) without environmental losses, highlighting the gap between lab-based predictions and real-world performance.

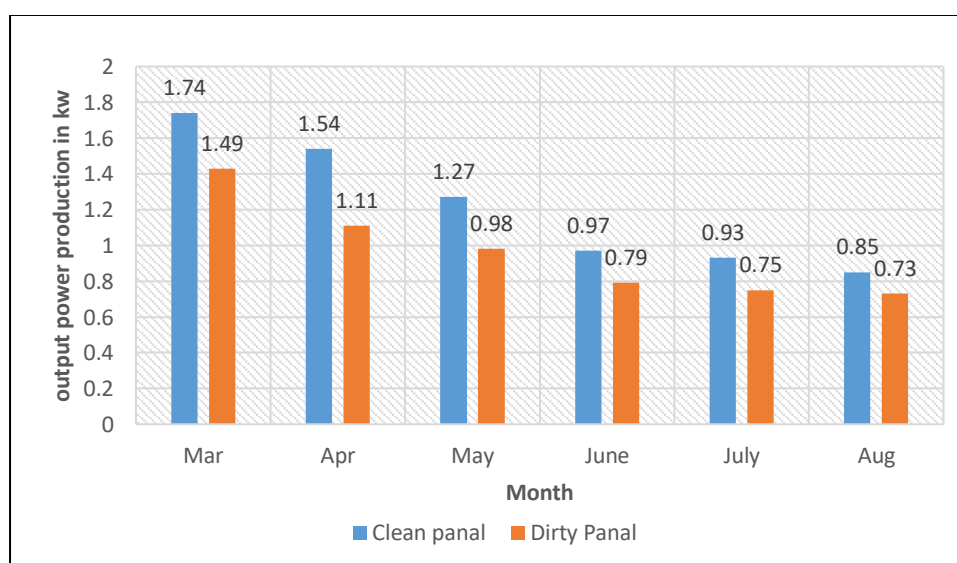


Fig. 5.12: Solar power output in kW for regularly clean and unclean panels month-wise.

There is a discernible difference between the clean and unclean solar panels, so for more visualization, we show the power generation data based on April. Throughout April, the energy output of the clean solar panel consistently outperformed the dusty panel, showing a clear decline in performance due to dust accumulation. The chart in figure 5.13 presents the power output data for clean and unclean solar panels throughout April, showing a significant performance gap caused by dust accumulation. The clean panel consistently delivered higher energy output, averaging around 1.5 kW, while the unclean panel averaged approximately 1.1 kW, reflecting a consistent efficiency loss of about 0.4 kW. Daily variations in power output are relatively minor for both panels, indicating stable weather and solar irradiation conditions during the month. The clean panel maintained a steady performance, with slight fluctuations likely influenced by day-to-day solar intensity changes. In contrast, the unclean panel exhibited consistently lower output, highlighting the adverse impact of dust deposition on energy generation efficiency. This visualization underscores the critical role of regular cleaning in maintaining optimal solar panel performance. The difference in output between clean and unclean panels reinforces the need for maintenance strategies, especially in dusty environments, to mitigate energy losses and ensure consistent power generation.

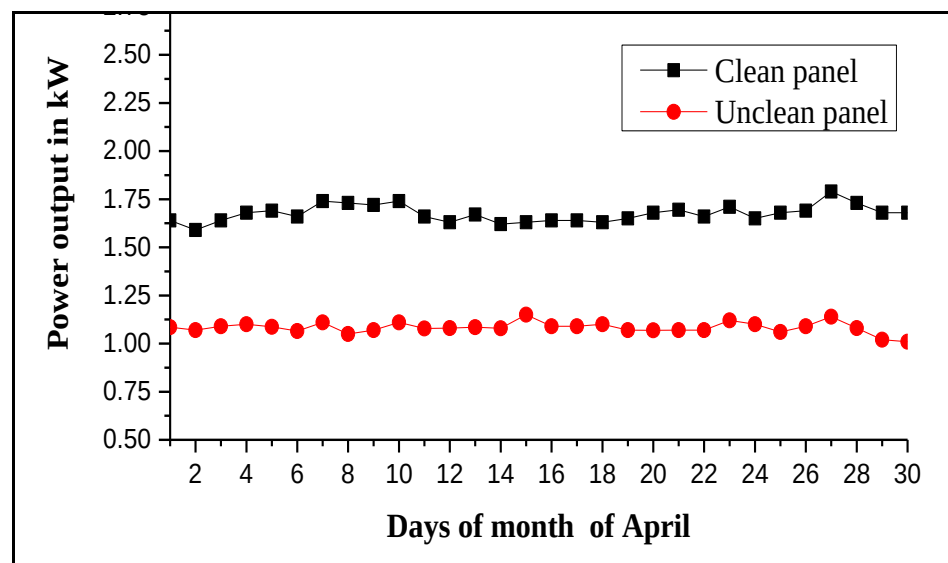


Fig. 5.13: Solar power output in kW for regularly clean and unclean panels in April.

5.7 I-V Characteristics of Monocrystalline Solar Cell

To investigate the performance of a monocrystalline solar cell, an outdoor experimental setup was employed to determine its current-voltage (IV) characteristics under real-world conditions. The key parameters measured included short-circuit current I_{sc} , and open-circuit voltage V_{oc} , which are critical indicators of the cell's efficiency and power output. These

measurements were conducted with the solar cell exposed to both clean and dust-deposited surfaces, enabling an evaluation of the impact of dust accumulation. Table 5.5 shows the details specifications of the 100 Wp solar panel.

Table 5.5: Monocrystalline Solar Panel Specification:

SL No.	Name	Specification
01	Solar Panel	1. Brand: Longi 2. Maximum Power (P_{max}): 95~100W 3. Voltage at Maximum Power (V_{mpp}): 17.5V 4. Current at Maximum Power (I_{mpp}): 5.80 A 5. Open Circuit Voltage (V_{oc}): 22A 6. Short Circuit Current (I_{sc}): 6.35 A 7. Module Efficiency: 22.8% 8. Panel Dimension (H/W/D): 990x660x35 mm 9. Material: Mono-crystalline Silicon 10. Cell Number: 36 11. Weight: 7.5 Kg

The IV data were collected using a digital multimeter and a variable resistor to measure current and voltage across a range of resistive loads. The setup was calibrated to capture data at different intervals of solar irradiance and temperature to ensure accurate readings. Measurements were taken both in a clean state (control) and after allowing dust deposition over an extended period to simulate typical environmental conditions in the region.

The short-circuit current was observed to decrease significantly when dust was present on the surface of the solar cell. For instance, a clean panel exhibited an I_{sc} 5.95 Amp at peak irradiance, while a dust-covered panel recorded a reduced value of 3.24 Amp under similar conditions. This reduction is attributed to the blockage of sunlight by dust particles, which limits the number of photons reaching the cell and thereby reduces the generation of charge carriers. While the open-circuit voltage showed less sensitivity to dust accumulation compared to the current, a slight reduction was noted. This is likely due to the temperature-dependent nature of V_{oc} and its lesser reliance on the intensity of incident sunlight compared to I_{sc} . The power output ($P = IV$) exhibited a notable decline in the presence of dust. Maximum power points (MPP) for the clean and dust-covered panels were calculated, revealing a decrease of approximately 10-15% in power output due to dust accumulation. The reduction in I_{sc} had a compounding effect on the overall energy yield, as power is directly proportional to the current under load conditions. Figure 5.14 shows the IV characteristic of Solar panels.

The test show that dust accumulation have a negative effect on I_{sc} and P_{out} but no effect

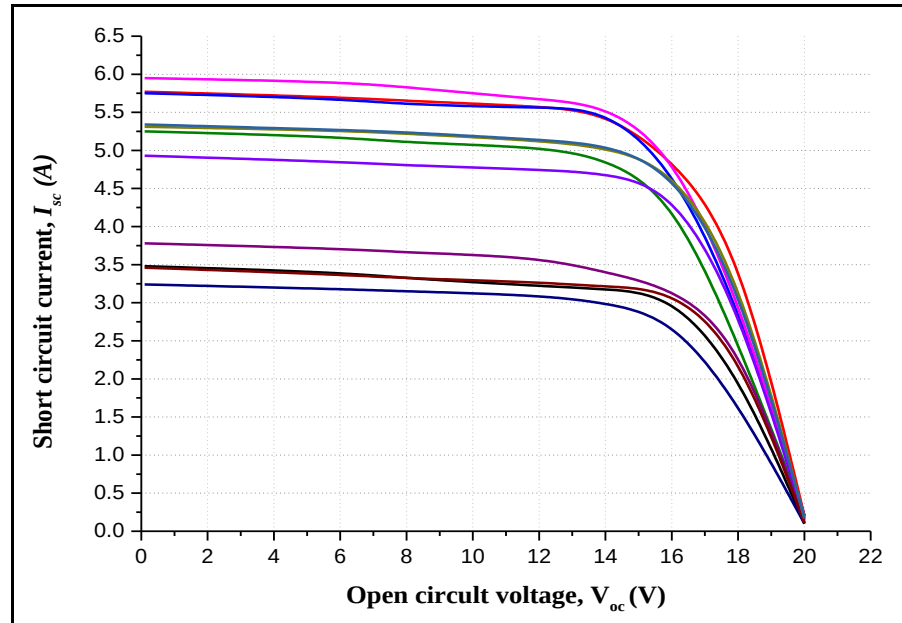


Fig. 5.14: I-V characteristics of 100Wp solar panel.

on V_{oc} . Moreover, the findings align with previous studies that highlight the relationship between dust particle size, composition, and their effect on solar panel efficiency. Smaller particles, such as silica and carbon, scatter light and create shading effects, while larger particles can contribute to hotspots due to uneven heating

5.8 Cleaning Methods (Suggested)

In many regions, dust deposition on solar photovoltaic (PV) panels is a common issue, especially in areas with high dust levels like in the dry season when infrequent rainfall or not. Here, figure 5.15 shows the rooftop solar system without cleaning and the rate of accumulation of dust. Such deposition significantly reduces the panels' efficiency by blocking sunlight from reaching the cells, thus lowering their energy output. Over time, if left unclean, this buildup can result in considerable losses in energy generation, maintenance costs, and potential damage to the panel surface.



Fig. 5.15: Dust accumulation on solar panel

Maintaining the efficiency and longevity of solar photovoltaic (PV) systems is heavily influenced by regular and effective cleaning, particularly in environments where dust accumulation can significantly reduce energy output. Different locations present unique challenges, such as varying dust composition and environmental conditions, necessitating tailored cleaning strategies to ensure optimal performance. This section discusses the recommended cleaning methods for four specific locations (CUET, AECC, BPDB, and NMI) based on detailed analysis of solar light transmittance, EDX data, and SEM images. The suggested cleaning techniques not only address the unique dust characteristics at each site but also offer cost-saving benefits and enhanced panel efficiency.

From the solar light transmittance data, we observe that from October to February, the dust accumulation rate was notably high in every location, significantly impacting the panels' efficiency. In this context, we found that in AECC, NMI and CUET the efficiency degradation ratio is high almost 34%, 30% and 27% respectively (in February) and CUET's highest rate is 14%. During this period, more frequent cleaning is essential, likely on a weekly or bi-weekly basis, depending on the specific conditions and dust levels at each site. Moreover, from March to July, the transmittance improved or increased significantly in all locations, partly due to occasional rainfall in summer and heavy rainfall in the rainy season that naturally washed away some of the dust. During these months, the need for cleaning may be reduced, with a monthly cleaning schedule possibly being sufficient to maintain efficiency. However, if extended dry periods occur, an additional cleaning session might be necessary to ensure optimal performance

5.6.1 CUET:

- **Method:** Regular water-based cleaning with a mild detergent is recommended. This approach effectively removes both organic and mineral dust, as the detergent breaks down organic particles while water flushes away the mineral dust without causing damage to the panels. This method preserves high efficiency by eliminating dust buildup that could lower energy output, and it is cost-effective because it uses easily obtained cleaning products.
- **Rationale:** The comparatively high values in the UV transmittance data for CUET suggest that the dust deposition is not very severe and consists of both organic and mineral dust. Significant amounts of silicon (up to 28.82%) and carbon (up to 62.71%) are shown in the EDX data, indicating that organic particles can be broken down with a mild detergent.

5.6.2 AECC:

- **Method:** For the AECC location, a more robust cleaning approach is essential due to the higher mineral dust content and variable organic material. Two times in a month in the dry season utilizing pressure washing will efficiently eliminate adhered particles, particularly the mineral and silicon & calcium-rich dust, without leaving any residues that could potentially hinder panel efficiency. This method is cost-effective over time by reducing the need for more frequent cleaning and preventing long-term damage to the panels.

- **Rationale:** The fluctuations in UV transmittance, with noticeable decreases in specific months, suggest times of substantial dust buildup. The AECC samples contain high levels of Silicon (up to 38%) and other minerals, necessitating a more thorough cleaning method. Using pressure washing will effectively eliminate these particles, thereby preserving panel efficiency.

5.6.3. BPDB:

- **Method:** The BPDB site contains both organic and inorganic dust, as confirmed by the EDX analysis. The variation in UV transmittance indicates that mineral deposits may develop if regular water is used. Therefore, it is recommended to use wet cleaning with deionized water to prevent mineral buildup. This method is effective for cleaning both organic and inorganic materials..

- **Rationale:** The presence of both organic and inorganic materials, with UV transmittance showing variability, indicates that deionized water is ideal for preventing mineral residue that could otherwise hinder panel efficiency.

5.6.4. NMI:

- **Method:** Gentle water rinsing is sufficient for NMI, where the dust composition includes moderate levels of Carbon and Silicon. This method effectively cleans the panels without the need for more aggressive cleaning techniques.

- **Rationale:** The mixed composition with moderate levels of Carbon (17.33% to 18.82%) and Silicon (14.03% to 19.18%) suggests that a gentle cleaning process will maintain panel efficiency while avoiding potential damage.

Here are two random sample slides that were washed with two distinct cleaning techniques—soapy water with a soft brush and regular water—were used to examine the light transmittance through solar panel surfaces. The outcomes demonstrate a considerable difference in the two approaches' performance between 350 and 800 nm in wavelength. Then, In Fig. 5.16, we present how much solar light transmission increased due to this work.

Throughout the spectrum, the panels that were washed with soapy water showed continuously high transmittance, with values beginning at 350 nm and staying above 98%. This demonstrates how well dust and other particles may be removed with soapy water, resulting in the least amount of light loss possible across the spectrum. With optimal light absorption guaranteed by soapy water, the high transmittance level indicates that solar panels can be made considerably more efficient overall. In contrast, the panels cleaned with normal water exhibited lower transmittance, starting at 81.857% at 350 nm and increasing to 86.245% at 800 nm. Although the transmittance improved at higher wavelengths, it remained consistently lower than that of the panels cleaned with soapy water using soft brush. This suggests that normal water may not be as effective in removing surface contaminants, leading to reduced light transmittance and potentially lower energy output from the solar panels.

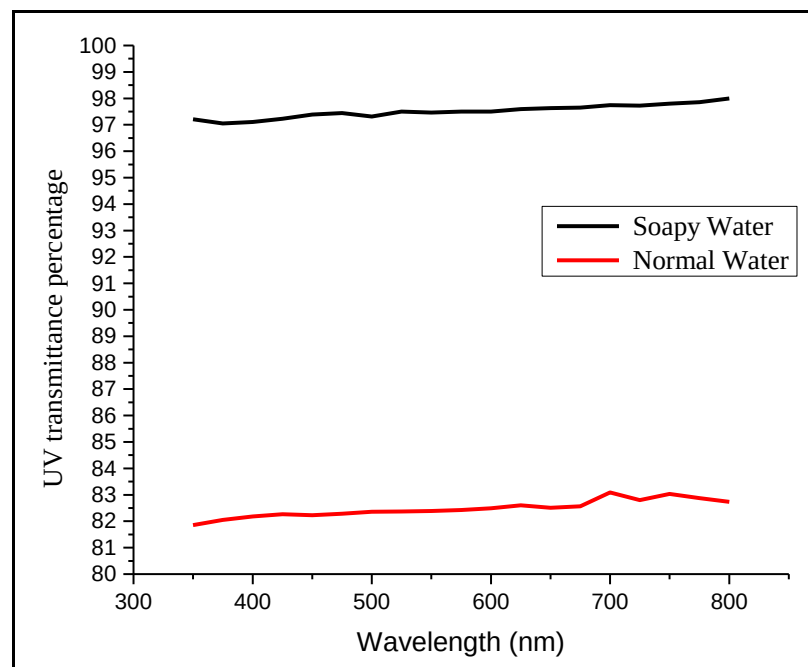


Figure 5.16: Transmittance is increased after cleaning with soapy water and normal water with exposition time for the 350-800 nm wavelengths.

Ultimately, the research emphasizes how crucial it is to properly clean solar panels to preserve their performance. Soapy water is a better option for preserving the efficiency of solar systems because it has been shown to maximize light transmittance more effectively than regular water. However, there is a risk that improper brushing or harsh brushing could cause a scratch at the top of the screen, which can limiting the amount of light that can escape.

Chapter 6: Conclusion

6.1 General Conclusion

The impact of dust deposition on solar panel efficiency was thoroughly investigated utilizing UV transmittance, SEM, and EDX studies in this work. The findings show that dust collection dramatically lowers solar panels' UV transmittance, which reduces the amount of light available for the conversion of energy. The efficiency of the solar panels decreases in direct proportion to this fall in transmittance, underscoring the significance of routine cleaning and maintenance.

Solar light transmittance results indicated that dust accumulation reduced solar radiation absorption and depended on the location's environment and weather conditions. This decrease contributed to the significant decline in energy output, particularly evident in the lower power generation during early April.

To further understand this impact, solar power output was collected from two 550wp systems between March and September. The data showed fluctuations in energy production, with the regularly cleaned panel consistently performing better than the uncleaned panel. This result underscores the importance of regular cleaning to maintain optimal energy generation, especially for rooftop solar panels in residential settings, where maintenance is often neglected.

SEM analysis revealed that the physical characteristics of the dust, including particle size and surface roughness, contribute to increased light scattering and absorption, further impairing the panels' performance. The EDX analysis provided insights into the elemental composition of the dust, highlighting the presence of elements like Carbon, Silicon, and Oxygen, which are known to impact light transmittance.

Overall, the study underscores the critical need for proactive dust management to ensure the sustained efficiency of solar panels, particularly in environments prone to high dust accumulation. Understanding the composition and sources of dust can guide and regular maintenance and tailored cleaning approaches are essential to mitigate the adverse effects of

dust and effective mitigation measures to enhance the long-term performance and reliability of solar PV systems in the urban and industrial environment.

6.2 Limitations of the Study

Despite the comprehensive nature of this study, several limitations must be acknowledged. One significant limitation is the variability in environmental conditions during the sample collection period. Dust samples were collected over a period of one year from four different locations within Chattogram city. However, the sample collection process was not without challenges. Notably, during the month designated for the initial sample collection, heavy rainfall occurred, which was an anomaly as the rest of the month experienced no precipitation. This unusual weather event may have influenced the characteristics of the dust collected during that period, potentially affecting the comparability of the samples across different months.

Additionally, the study's reliance on monthly dust sample collection may not fully capture the short-term variations in dust deposition rates and composition. Factors such as wind patterns, human activities, and seasonal changes can cause fluctuations in dust accumulation that are not adequately reflected in monthly sampling. This temporal limitation could impact the generalizability of the findings.

Moreover, even though the EDX analysis produced comprehensive compositional data, it is inherently incapable of distinguishing between elements with similar atomic numbers and identifying some light elements. As a result, it's possible that the study did not fully capture all of the components found in the dust samples.

The fact that the study's geographic reach was limited to Chattogram City presents another drawback. Although the results offer insightful information on the local conditions, they might not be readily transferable to other areas with dissimilar environmental and climatic variables. Expanding the research to encompass several cities or areas with distinct dust attributes would improve the resilience and relevance of the findings.

In light of these limitations, the results and interpretations presented in this section should be considered with an understanding of the contextual constraints. Future research addressing these limitations would contribute to a more comprehensive understanding of the impact of dust accumulation on solar panel performance.

References:

- [1] A. Shariah and E. A. Al-Ibrahim, “Impact of Dust and Shade on Solar Panel Efficiency and Development of a Simple Method for Measuring the Impact of Dust,” *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 11, no. 2, pp. 1–14, 2023, doi: 10.13044/j.sdewes.d11.0448.
- [2] “Global CO2 emissions rebounded to their highest level in history in 2021,” *UNFCCC*, 2022. [Online]. Available: <https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021>
- [3] “Causes of Climate Change.” [Online]. Available: https://climate.ec.europa.eu/climate-change/causes-climate-change_en
- [4] “Perspective Plan of Bangladesh 2021-2041,” 2021.
- [5] M. Larsson, *Global energy transformation: Four necessary steps to make clean energy the next success story*. 2009. doi: 10.1057/9780230244092.
- [6] L. Liu, “Comment on ‘recent progress in thermodynamics of radiation-exergy of radiation, effective temperature of photon and entropy constant of photon,’” *Sci. China, Ser. E Technol. Sci.*, vol. 52, no. 6, pp. 1809–1810, 2009, doi: 10.1007/s11431-009-0086-4.
- [7] A. S. B. M. Shah, H. Yokoyama, and N. Kakimoto, “High-Precision Forecasting Model of Solar Irradiance Based on Grid Point Value Data Analysis for an Efficient Photovoltaic System,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 474–481, 2015, doi: 10.1109/TSTE.2014.2383398.
- [8] “Technology Roadmap Solar photovoltaic energy.” [Online]. Available: <https://www.iea.org/reports/technology-roadmap-solar-photovoltaic-energy-2014>
- [9] V. Tachev, “Solar and Wind Power Potential in Bangladesh.” [Online]. Available: <https://energytracker.asia/solar-and-wind-power-potential-in-bangladesh/>
- [10] SREDA, “National Database of Renewable Energy Renewable Energy Installed Capacity,” p. 1, 2023.
- [11] A. Sayigh, “Mediterranean green buildings & renewable energy: Selected papers from the world renewable energy network’s med green forum,” *Mediterr. Green Build. Renew. Energy Sel. Pap. from World Renew. Energy Network’s Med Green Forum*, pp. 1–963, 2017, doi: 10.1007/978-3-319-30746-6.
- [12] H. A. Kazem, M. T. Chaichan, A. H. A. Al-Waeli, and K. Sopian, “A novel model and experimental validation of dust impact on grid-connected photovoltaic system

- performance in Northern Oman,” *Sol. Energy*, vol. 206, no. October 2021, pp. 564–578, 2020, doi: 10.1016/j.solener.2020.06.043.
- [13] M. M. Fouad, L. A. Shihata, and E. S. I. Morgan, “An integrated review of factors influencing the performance of photovoltaic panels,” *Renew. Sustain. Energy Rev.*, vol. 80, no. May, pp. 1499–1511, 2017, doi: 10.1016/j.rser.2017.05.141.
- [14] Z. Song, J. Liu, and H. Yang, “Air pollution and soiling implications for solar photovoltaic power generation: A comprehensive review,” *Appl. Energy*, vol. 298, no. March, pp. 117–247, 2021, doi: 10.1016/j.apenergy.2021.117247.
- [15] “Air quality in Chattogram,” IQAIR. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.iqair.com/bangladesh/chittagong>
- [16] “Indoor Air Hygiene Institute.” Accessed: Mar. 19, 2024. [Online]. Available: <https://www.indoorairhygiene.org/>
- [17] S. Akter, M. M. H. Shawon, M. K. Islam, S. Ahmed, and M. M. Rahman, “Degradation of PV Module Performance Due to Dust Accumulation on the High-rise Buildings,” *Proc. 2020 IEEE Int. Women Eng. Conf. Electr. Comput. Eng. WIECON-ECE 2020*, no. I, pp. 239–242, 2020, doi: 10.1109/WIECON-ECE52138.2020.9398017.
- [18] M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, “Power loss due to soiling on solar panel: A review,” *Renew. Sustain. Energy Rev.*, vol. 59, no. May 2023, pp. 1307–1316, 2016, doi: 10.1016/j.rser.2016.01.044.
- [19] O. A. Choobari and A. Zawar-Reza, P. Sturman, “The global distribution of mineral dust and its impacts on the climate system: A review”, doi: <https://doi.org/10.1016/j.atmosres.2013.11.007>.
- [20] H. Kutiel and H. Furman, “Dust Storms in the Middle East: Sources of Origin and their Temporal Characteristics,” *Indoor Built Environ.*, vol. 12, no. 6, pp. 419–426, 2003, doi: 10.1177/1420326X03037110.
- [21] WMO, *Establishing a WMO Sand and Dust Storm Warning Advisory and Assessment System Regional Node for West Asia: Current Capabilities and Needs*, no. 1121. 2013.
- [22] World Bank (WB), *SAND AND DUST STORMS (MENA) REGION AND NORTH AFRICA IN THE MIDDLE EAST*. World Bank, 2020. [Online]. Available: <https://library.unccd.int/Details/fullCatalogue/1609#:~:text=Displays-,Sand and Dust Storms in the Middle East and North,%3A Sources%2C Costs%2C and Solutions&text=Dust storms are capable of,the dustiest in the world>
- [23] Y. Shao, M. Klose, and K. H. Wyrwoll, “Recent global dust trend and connections to

- climate forcing,” *J. Geophys. Res. Atmos.*, vol. 118, no. 19, pp. 11,107–11,118, 2013, doi: 10.1002/jgrd.50836.
- [24] A. A. Babatunde, S. Abbasoglu, and M. Senol, “Analysis of the impact of dust, tilt angle and orientation on performance of PV Plants,” *Renew. Sustain. Energy Rev.*, vol. 90, no. October 2017, pp. 1017–1026, 2018, doi: 10.1016/j.rser.2018.03.102.
- [25] T. Alquthami and K. Menoufi, “Soiling of photovoltaic modules: Comparing between two distinct locations within the framework of developing the photovoltaic soiling index (PVSI),” *Sustain.*, vol. 11, no. 17, 2019, doi: 10.3390/su11174697.
- [26] T. Taniaesab, Julius. Parlevliet, David. Whale, Jonathan. Urmee, “The effect of dust with different morphologies on the performance degradation of PV modules”.
- [27] A. Sayyah, M. N. Horenstein, and M. K. Mazumder, “Energy yield loss caused by dust deposition on photovoltaic panels,” *Sol. Energy*, vol. 107, pp. 576–604, 2014, doi: 10.1016/j.solener.2014.05.030.
- [28] Zeki.A.darwish, Hussein.A.Kazim, K. Sopian, M.A.Alghoul, and M.Chaichan, “Impact of Some Environmental Variables with Dust on Solar Photovoltaic (PV) Performance: Review and Research Status,” *Researchgate.Net*, vol. 7, no. 4, pp. 152–159, 2013, [Online]. Available: [http://www.researchgate.net/publication/258051333_Impact_of_Some_Environmental_Variables_with_Dust_on_Solar_Photovoltaic_\(PV\)_Performance_Review_and_Research_Status/file/e0b49528126318a2ce.pdf](http://www.researchgate.net/publication/258051333_Impact_of_Some_Environmental_Variables_with_Dust_on_Solar_Photovoltaic_(PV)_Performance_Review_and_Research_Status/file/e0b49528126318a2ce.pdf)
- [29] J. Cano, J. J. John, S. Tatapudi, and G. Tamizhmani, “Effect of tilt angle on soiling of photovoltaic modules,” *2014 IEEE 40th Photovolt. Spec. Conf. PVSC 2014*, no. October, pp. 3174–3176, 2014, doi: 10.1109/PVSC.2014.6925610.
- [30] A. K. Kadhum and M. . Rasheed, “Some characteristics of sand and dust storm sources in Iraq,” *2nd Int. Conf. Eng. Technol. Sci. Al-Kitab, ICETS 2018*, no. May, pp. 11–15, 2018, doi: 10.1109/ICETS.2018.8724612.
- [31] M. Abdolzadeh and R. Nikkhah, “Experimental study of dust deposition settled over tilted PV modules fixed in different directions in the southeast of Iran,” *Environ. Sci. Pollut. Res.*, vol. 26, no. 30, pp. 31478–31490, 2019, doi: 10.1007/s11356-019-06246-z.
- [32] S. Pulipaka, F. Mani, and R. Kumar, “Modeling of soiled PV module with neural networks and regression using particle size composition,” *Sol. Energy*, vol. 123, pp. 116–126, 2016, doi: 10.1016/j.solener.2015.11.012.
- [33] A. H. Hassan, U. A. Rahoma, and H. K. Elminir, “Effect of Airborne Dust

- Concentration on the Performance of Pv Modules,” *J. Astron. Soc. Egypt*, no. January, pp. 24–38, 2005, [Online]. Available: https://www.researchgate.net/profile/Usama-Rahoma/publication/278386495_Effect_of_airborne_dust_concentration_on_the_performance_of_PV_modules/links/585af47d08ae6eb8719aaf0a/Effect-of-airborne-dust-concentration-on-the-performance-of-PV-modules.pdf
- [34] H. K. Elminir, A. E. Ghitas, R. H. Hamid, F. El-Hussainy, M. M. Beheary, and K. M. Abdel-Moneim, “Effect of dust on the transparent cover of solar collectors,” *Energy Convers. Manag.*, vol. 47, no. 18–19, pp. 3192–3203, 2006, doi: 10.1016/j.enconman.2006.02.014.
- [35] K. Menoufi, H. F. M. Mohamed, A. A. Farghali, and M. H. Khedr, “Dust accumulation on photovoltaic panels: A case study at the East Bank of the Nile (Beni-Suef, Egypt),” *Energy Procedia*, vol. 128, pp. 24–31, 2017, doi: 10.1016/j.egypro.2017.09.010.
- [36] K. P. Amber, I. Hussain, A. Kousar, M. A. Bashir, M. W. Aslam, and B. Akbar, “A self-cleaning device for pole mounted solar PV installations,” *Therm. Sci.*, vol. 23, no. 2, pp. 739–749, 2019, doi: 10.2298/TSCI170401065A.
- [37] Z. Abbas, K. Harijan, P. Hameed, and F. Bhayo, “Effect of Dust on the Performance of Photovoltaic System (A Case Study of Quaid-E-Azam Solar Park Bahawalpur ,” vol. 1, no. 6, pp. 73–79, 2017, [Online]. Available: <http://napublisher.org/?ic=journals&id=2%0AOpen>
- [38] Ahmed Al Mansur, J. Akhter, T. Rahman, M. I. Islam, and M. Sahin, “Optimizing PV Module Efficiency: Investigating the impact of Dry and Wet Dust on Solar Panel Output Power,” *GUB J. Sci. Eng.*, vol. 10, no. 1, pp. 68–74, 2024, doi: 10.3329/gubjse.v10i1.74947.
- [39] B. Weber, A. Quiñones, R. Almanza, and M. D. Duran, “Performance reduction of PV systems by dust deposition,” *Energy Procedia*, vol. 57, pp. 99–108, 2014, doi: 10.1016/j.egypro.2014.10.013.
- [40] A. A. Hachicha, I. Al-Sawafta, and D. Ben Hamadou, “Numerical and experimental investigations of dust effect on CSP performance under United Arab Emirates weather conditions,” *Renew. Energy*, vol. 143, pp. 263–276, 2019, doi: 10.1016/j.renene.2019.04.144.
- [41] S. Mekhilef, R. Saidur, and A. Safari, “A review on solar energy use in industries,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 4, pp. 1777–1790, 2011, doi: 10.1016/j.rser.2010.12.018.
- [42] T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, “A comprehensive review of the

- impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches,” *Renew. Sustain. Energy Rev.*, vol. 22, pp. 698–733, 2013, doi: 10.1016/j.rser.2012.12.065.
- [43] M. J. Adinoyi and S. A. M. Said, “Effect of dust accumulation on the power outputs of solar photovoltaic modules,” *Renew. Energy*, vol. 60, pp. 633–636, 2013, doi: 10.1016/j.renene.2013.06.014.
- [44] D. S. Rajput and K. Sudhakar, “Effect of dust on the performance of solar PV panel,” *Int. J. ChemTech Res.*, vol. 5, no. 2, pp. 1083–1086, 2013.
- [45] M. Mani and R. Pillai, “Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 3124–3131, 2010, doi: 10.1016/j.rser.2010.07.065.
- [46] J. K. Kaldellis and A. Kokala, “Quantifying the decrease of the photovoltaic panels’ energy yield due to phenomena of natural air pollution disposal,” *Energy*, vol. 35, no. 12, pp. 4862–4869, 2010, doi: 10.1016/j.energy.2010.09.002.
- [47] S. A. M. Said and H. M. Walwil, “Fundamental studies on dust fouling effects on PV module performance,” *Sol. Energy*, vol. 107, pp. 328–337, 2014, doi: 10.1016/j.solener.2014.05.048.
- [48] J. K. Kaldellis and M. Kapsali, “Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements,” *Energy*, vol. 36, no. 8, pp. 5154–5161, 2011, doi: 10.1016/j.energy.2011.06.018.
- [49] A. A. Hegazy, “Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors,” *Renew. energy*, vol. 22, no. 4, pp. 525–540, 2001, doi: 10.1016/S0960-1481(00)00093-8.
- [50] S. Darvekar, “Solar Photovoltaic Panels Cleaning Methods A Review Bhivarabai Sawant College of Engineering Photovoltaic panel is one which generates electricity from solar,” no. February, 2020.
- [51] M. Abderrezek and M. Fathi, “Experimental study of the dust effect on photovoltaic panels’ energy yield,” *Sol. Energy*, vol. 142, pp. 308–320, 2017, doi: 10.1016/j.solener.2016.12.040.
- [52] F. A. Mejia and J. Kleissl, “Soiling losses for solar photovoltaic systems in California,” *Sol. Energy*, vol. 95, pp. 357–363, 2013, doi: 10.1016/j.solener.2013.06.028.
- [53] A. Kimber, L. Mitchell, S. Nogradi, and H. Wenger, “The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest Region of the United States,” *Conf. Rec. 2006 IEEE 4th World Conf. Photovolt. Energy Conversion*,

- WCPEC-4, vol. 2, pp. 2391–2395, 2006, doi: 10.1109/WCPEC.2006.279690.
- [54] A. A. Hachicha¹ and E. M. Abo-Zahhad, “Dust Effect on Solar Energy Systems and Mitigation Methods,” *Int. J. Energy Prod. Manag.*, vol. 8, no. 2, pp. 97–105, 2023, doi: <https://doi.org/10.18280/ijepm.080206>.
- [55] M. Saidan, A. G. Albaali, E. Alasis, and J. K. Kaldellis, “Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment,” *Renew. Energy*, vol. 92, pp. 499–505, 2016, doi: 10.1016/j.renene.2016.02.031.
- [56] and K. M. Hussein A. Kazem, Miqdam T. Chaichan, Ali H. Alwaeli, *Effect of Shadows on the Performance of Solar Photovoltaic*, no. July 2018. 2017. doi: 10.1007/978-3-319-30746-6.
- [57] S. Mekhilef, R. Saidur, and M. Kamalisarvestani, “Effect of dust, humidity and air velocity on efficiency of photovoltaic cells,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 2920–2925, 2012, doi: 10.1016/j.rser.2012.02.012.
- [58] S. A. Sulaiman, A. K. Singh, M. M. M. Mokhtar, and M. A. Bou-Rabee, “Influence of dirt accumulation on performance of PV panels,” *Energy Procedia*, vol. 50, no. December, pp. 50–56, 2014, doi: 10.1016/j.egypro.2014.06.006.
- [59] M. Kumar Panjwani and G. Bukshsh Narejo, “Effect of Humidity on the Efficiency of Solar Cell (photovoltaic),” *Int. J. Eng. Res. Gen. Sci.*, vol. 2, no. 4, pp. 499–503, 2014, [Online]. Available: www.ijergs.org
- [60] M. J. Clifford and D. Eastwood, “Design of a novel passive solar tracker,” *Sol. Energy*, vol. 77, no. 3, pp. 269–280, 2004, doi: 10.1016/j.solener.2004.06.009.
- [61] C. S. Chin, “Model-Based Simulation of an Intelligent Microprocessor- Based Standalone Solar Tracking System,” *MATLAB - A Fundam. Tool Sci. Comput. Eng. Appl. - Vol. 3*, 2012, doi: 10.5772/46458.
- [62] C. S. Chin, A. Babu, and W. McBride, “Design, modeling and testing of a standalone single axis active solar tracker using MATLAB/Simulink,” *Renew. Energy*, vol. 36, no. 11, pp. 3075–3090, 2011, doi: 10.1016/j.renene.2011.03.026.
- [63] K. N. Shukla, S. Rangnekar, and K. Sudhakar, “A comparative study of exergetic performance of amorphous and polycrystalline solar PV modules,” *Int. J. Exergy*, vol. 17, no. 4, pp. 433–455, 2015, doi: 10.1504/IJEX.2015.071559.
- [64] K. Sudhakar and T. Srivastava, “Energy and exergy analysis of 36 W solar photovoltaic module,” *Int. J. Ambient Energy*, vol. 35, no. 1, pp. 51–57, 2014, doi: 10.1080/01430750.2013.770799.
- [65] A. K. Shukla, K. Sudhakar, and P. Baredar, “Exergetic assessment of BIPV module

- using parametric and photonic energy methods: A review,” *Energy Build.*, vol. 119, pp. 62–73, 2016, doi: 10.1016/j.enbuild.2016.03.022.
- [66] A. K. Shukla, K. Sudhakar, and P. Baredar, “Design, simulation and economic analysis of standalone roof top solar PV system in India,” *Sol. Energy*, vol. 136, pp. 437–449, 2016, doi: 10.1016/j.solener.2016.07.009.
- [67] A. Y. Al-Hasan and A. A. Ghoneim, “A NEW CORRELATION BETWEEN PHOTOVOLTAIC PANELS”, doi: 10.1080/14786450500291834.
- [68] Y. N. Chanchangi, A. Ghosh, S. Sundaram, and T. K. Mallick, “An analytical indoor experimental study on the effect of soiling on PV, focusing on dust properties and PV surface material,” *Sol. Energy*, vol. 203, no. April, pp. 46–68, 2020, doi: 10.1016/j.solener.2020.03.089.
- [69] G. He, C. Zhou, and Z. Li, “Review of self-cleaning method for solar cell array,” *Procedia Eng.*, vol. 16, pp. 640–645, 2011, doi: 10.1016/j.proeng.2011.08.1135.
- [70] X. Lu, Q. Zhang, and J. Hu, “A linear piezoelectric actuator based solar panel cleaning system,” *Energy*, vol. 60, no. January, pp. 401–406, 2013, doi: 10.1016/j.energy.2013.07.058.
- [71] A. Fernández-García, L. Álvarez-Rodrigo, L. Martínez-Arcos, R. Aguiar, and J. M. Márquez-Payés, “Study of different cleaning methods for solar reflectors used in CSP plants,” *Energy Procedia*, vol. 49, no. December, pp. 80–89, 2014, doi: 10.1016/j.egypro.2014.03.009.
- [72] H. Kawamoto and T. Shibata, “Electrostatic cleaning system for removal of sand from solar panels,” *J. Electrostat.*, vol. 73, pp. 65–70, 2015, doi: 10.1016/j.elstat.2014.10.011.
- [73] A. K. Mondal and K. Bansal, “Structural analysis of solar panel cleaning robotic arm,” *Curr. Sci.*, vol. 108, no. 6, pp. 1047–1052, 2015.
- [74] S. V.S and D. S.K, “Solar Photovoltaic Panels Cleaning Methods A Review,” *Int. J. Pure Appl. Math.*, vol. 118, no. 24, pp. 1–12, 2018.
- [75] K. Menoufi, “Dust accumulation on the surface of photovoltaic panels: Introducing the Photovoltaic Soiling Index (PVSI),” *Sustain.*, vol. 9, no. 6, 2017, doi: 10.3390/su9060963.
- [76] REN21, *Renewables 2016 Global Status Report*. 2016. doi: ISBN 978-3-9818107-0-7.
- [77] W. Huang, Jianping Wang, Tianhe Wang, Z. Li, and H. Yan, “Climate effects of dust aerosols over East Asian arid and semiarid regions,” *J. Geophys. Res. Atmos.*, vol.

- 119, pp. 1–12, 2017, doi: 10.1002/2014JD021796.Received.
- [78] Y. N. Chanchangi, A. Ghosh, S. Sundaram, and T. K. Mallick, “Dust and PV Performance in Nigeria: A review,” *Renew. Sustain. Energy Rev.*, vol. 121, no. January, p. 109704, 2020, doi: 10.1016/j.rser.2020.109704.
 - [79] J. A. D. Deceased and W. A. Beckman, *Solar engineering of thermal processes*, vol. 3, no. 3. 1982. doi: 10.1016/0142-694x(82)90016-3.
 - [80] P. Roy, Y. Arafat, M. B. Upama, and A. Hoque, “Technical and financial aspects of solar PV system for city dwellers of Bangladesh where green energy installation is mandatory to get utility power supply,” *2012 7th Int. Conf. Electr. Comput. Eng. ICECE 2012*, no. December, pp. 916–919, 2012, doi: 10.1109/ICECE.2012.6471700.
 - [81] R. Shenouda, M. S. Abd-Elhady, and H. A. Kandil, “A review of dust accumulation on PV panels in the MENA and the Far East regions,” *J. Eng. Appl. Sci.*, vol. 69, no. 1, pp. 1–29, 2022, doi: 10.1186/s44147-021-00052-6.
 - [82] W. J. Jamil, H. Abdul Rahman, S. Shaari, and Z. Salam, “Performance degradation of photovoltaic power system: Review on mitigation methods,” *Renew. Sustain. Energy Rev.*, vol. 67, pp. 876–891, 2017, doi: 10.1016/j.rser.2016.09.072.
 - [83] C. Xiong, Y. Zhang, and Q. Yuan, “Characterization of Dust on the Surface of Photovoltaic Panels in Low Latitude and High Altitude Plateau Areas,” *J. Phys. Conf. Ser.*, vol. 2356, no. 1, 2022, doi: 10.1088/1742-6596/2356/1/012007.
 - [84] S. Ben-Menahem and S. C. Yang, “Online photovoltaic array hot-spot Bayesian diagnostics from streaming string-level electric data,” *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 2432–2437, 2012, doi: 10.1109/PVSC.2012.6318087.
 - [85] L. L. Kazmerski *et al.*, “Fundamental studies of adhesion of dust to PV module surfaces: Chemical and physical relationships at the microscale,” *IEEE J. Photovoltaics*, vol. 6, no. 3, pp. 719–729, 2016, doi: 10.1109/JPHOTOV.2016.2528409.
 - [86] M. S. El-Shobokshy and F. M. Hussein, “Degradation of photovoltaic cell performance due to dust deposition on to its surface,” *Renew. Energy*, vol. 3, no. 6–7, pp. 585–590, 1993, doi: 10.1016/0960-1481(93)90064-N.
 - [87] H. H. H. N. S. H. N. L. and M. S. I. R. Shaharin A. Sulaiman, “Effects of Dust on the Performance of PV Panels,” *World Acad. Sci. Eng. Technol.*, pp. 588–593, 2011.
 - [88] X. Zhang, F. Shi, J. Niu, Y. Jiang, and Z. Wang, “Superhydrophobic surfaces: From structural control to functional application,” *J. Mater. Chem.*, vol. 18, no. 6, pp. 621–633, 2008, doi: 10.1039/b711226b.

- [89] K. Midtdal and B. P. Jelle, “Self-cleaning glazing products: A state-of-the-art review and future research pathways,” *Sol. Energy Mater. Sol. Cells*, vol. 109, no. 7465, pp. 126–141, 2013, doi: 10.1016/j.solmat.2012.09.034.
- [90] J. Drelich, E. Chibowski, D. D. Meng, and K. Terpilowski, “Hydrophilic and superhydrophilic surfaces and materials,” *Soft Matter*, vol. 7, no. 21, pp. 9804–9828, 2011, doi: 10.1039/c1sm05849e.
- [91] S. Nishimoto and B. Bhushan, “Bioinspired self-cleaning surfaces with superhydrophobicity, superoleophobicity, and superhydrophilicity,” *RSC Adv.*, vol. 3, no. 3, pp. 671–690, 2013, doi: 10.1039/c2ra21260a.
- [92] M. S. Sodha, “Electrostatic Precipitation,” *Springer Ser. At. Opt. Plasma Phys.*, vol. 81, no. 5, pp. 287–293, 2014, doi: 10.1007/978-81-322-1820-3_16.
- [93] G. B. Nichols and S. M. Qglesby Jr, “Electrostatic precipitator charging method,” no. 19, pp. 1–6, 1999.
- [94] A. Assi, A. Hassan, M. Al-Shamisi, and H. Hejase, “Removal of air blown dust from photovoltaic arrays using forced air flow of return air from air conditioning systems,” *2012 Int. Conf. Renew. Energies Dev. Countries, REDEC 2012*, no. November, 2012, doi: 10.1109/REDEC.2012.6416699.
- [95] H. A. Kazem, M. T. Chaichan, A. H. A. Al-Waeli, and K. Sopian, “A review of dust accumulation and cleaning methods for solar photovoltaic systems,” *J. Clean. Prod.*, vol. 276, 2020, doi: 10.1016/j.jclepro.2020.123187.
- [96] M. Mussard and M. Amara, “Performance of solar photovoltaic modules under arid climatic conditions : A review,” *Sol. Energy*, vol. 174, no. June, pp. 409–421, 2018, doi: 10.1016/j.solener.2018.08.071.
- [97] E. Bellini, “Water-based solar module cleaning tech for rooftop PV.” [Online]. Available: <https://www.pv-magazine.com/2023/08/29/water-based-solar-module-cleaning-tech-for-rooftop-pv/>
- [98] F. Wang *et al.*, “A minutely solar irradiance forecasting method based on real-time sky image-irradiance mapping model,” *Energy Convers. Manag.*, vol. 220, no. May, 2020, doi: 10.1016/j.enconman.2020.113075.