Experimental Investigations for Dust build-up on Low-Iron Glass exterior and its effects on the performance of Solar PV systems

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Abstract

The performance of solar photovoltaic (SPV) power plants is adversely affected by soiling losses caused by natural dust deposition on the module surface. The size and density of dust particles vary depending on the location. Thus, it is essential to investigate the impact of dust collection on SPV module performance. This work investigates the effect of dust build-up on the low-iron glass surface and the performance of SPV modules. To analyze the characteristics of these dust particles, low-iron glass samples have been chosen, which resemble a front glass surface of the SPV module. To study the holistic pattern of the natural dust accumulation of a particular area, low-iron glass samples have been placed with three different positions like vertical, horizontal, and local tilt angle for Building Integrated Photovoltaic Systems (BIPV) and rooftop PV power plant applications. The mineralogical study of dust particles provides insight in determining the transmittance loss from the glass surface of solar PV modules due to the local soiling loss. Furthermore, the electrical power output of the SPV modules has been monitored at various levels of dust accumulation. Moreover, these findings indicate that natural dust deposition at selected site locations significantly reduces energy generation from PV modules.

Keywords: Monocrystalline Solar PV; Polycrystalline Solar PV; Low iron glass; Transmittance; Soiling losses.

1. Introduction

The exploitation of fossil fuel resources emits greenhouse gasses, which have an adverse impact on the environment. Renewable energy sources are the alternative to fossil fuel resources, including solar, wind, tidal energy, and hydro. Benign power generation from photovoltaic technology is one of the most holistic approaches compared to other technology as they are simpler and easily accessible [1]. Globally installed PV capacity was 500 GW at the end of 2018, and an additional 500 GW installation is expected by 2022–2023, which will transform the global PV energy generation at the terawatt level [2]. However, power generation from PV technology depends on the climatic parameter (Solar intensity, ambient temperature, wind speed), tilt angle, and azimuthal orientation [3]. After solar insolation and temperature, dust is another factor that has an adverse impact on PV power generation[4]. Dust-covered PV restricts the incident solar radiation from reaching the PV cells[5,6]. Thus, PV power generation gets affected. Hence, evaluation of the soiling factor is also an indispensable criterion that needs to be understood before installing a PV system at a location [7]. Soiling, which occurs because of the dust accumulation on the PV system, is a location-dependent phenomenon. The site-specific soling factor depends on airborne dust concentration, rainfall frequency, PV module tilt angle, site specifications, wind speeds, relative humidity and dew formation, the top surface of the PV system [8,9].

Dust particles and liquid mixture suspended in air are known as particulate matter (PM). PM2.5 and PM10 represent the particulate matter of airborne dust particles having an aerodynamic diameter of 2.5μm and 10μm [10]. Get rid of PM2.5 is much more complicated than PM10. It was found that increased tilt angle of PV possess less accumulation of dust [11,12] while light rain helps to more dust settlement [13] and heavy rain tends to wipe out the surface [14]. Humid conditions enhance the adhesion between the PV surface and the dust particle [15]. Depending on the PV systems' top surface material, less or more dust can accumulate. Glass and acrylic sheets are the popular materials employed on the PV system. Glass promotes less dust accumulation than acrylic for a fixed tilt angle PV system [16]. PV power loss is linearly proportional to the amount of deposited dust [7,17]. However, the addition of power loss may not occur for extra dust deposition of a heavily soiled surface [18].

Two weeks of dust accumulation in Indonesia had reduced photovoltaic power generation by 10.8% [13]. In Saudi Arabia, after placing the photovoltaic modules at an angle of 26° for 45 days, the density of dust on the photovoltaic modules was 5 g/m^2, and the transmittance was reduced by 20% [19]. In Pakistan, soling losses can go up to 40% after 100 days of exposure [12], and the Middle East and North Africa (MENA - the Middle East and North Africa). In a desert climate, 1% power loss per day is possible because of the soiling [9,20]. In East China, 7.4% power reduction from PV system was observed in a week due to deposition of 0.644 g/m^2 dust [21]. Recently, relation between soiling losses and angular dependencies for photovoltaic system has been investigated in Nigeria [22][23].

The use of low iron coated Solar glass to understand the effect of dust accumulation on PV modules is an established approach [24]. To understand the composition of dust and the size distribution of deposited soil on PV modules, glass substrates were employed previously [15,25,26]. After exposure for several months in a desert region, the study of the dust accumulation on the glazing surface of the PV module at the local tilt angle of 32° decreases the Solar irradiance transmittance on an average between 0% and 8 % [27]. Employing low iron coated Solar glass substrate, experimental studies were carried out in various locations globally, which showed accumulated dust could lower up to 3% and 12% decrease in hemispherical and direct transmission loss on site-specific factors. Also, these losses are as high in the UV and portion of the Solar spectrum [28]. In recent work, optical characterization has been done for low-iron glass samples, which are commonly used on PV modules studied based on naturally occurring soiling losses at various locations worldwide. These studies show the importance of dust accumulation, which causes soiling loss and its effects on the glass surface, plays a significant role in the transmission of light for the performance of PV modules at specific site locations [29]. Indoor characterization of artificially deposited dust on glass and acrylic substrate revealed that soiling losses are more adverse for wet deposition than dry and acrylic substrate over the glass [16,30]. In Cairo's location, Hammy used glass instead of photovoltaic modules in Cairo in the experiments. When the tilt angle was from 0° to 90°, the density of the accumulated dust was from 15.84 g/m2 to 4.48 g/m2. When installed tilt angle was 45°, the output power is reduced by about 17.4% per month [31]. Recently soiling losses employing glass samples were evaluated in Morocco location, however, experiments were performed employing PV system[32].

India, which is the second large populated country globally, consumes a considerable amount of energy. Because of the growing urbanization, the power demand will increase more in the future. To deal with the environmental issue, India has set a plan to move 100 GW Solar power generation by 2022, where 40 GW from the rooftop [33] and 60 GW from the Solar park [34]. India annually receives 5.5 kWh/m^2/Day global average horizontal irradiance, while the average direct normal irradiance is 4.5–5.0 kWh/m^2/Day [35–37]. India also experiences about 300 sunny clear days in a year [38]. Accumulated dust on PV can reduce a considerable amount of generated power, which is a barrier for a country planning to become energy secured by generating power from PV [39][40]. However, the soiling study for the PV system in a different part of the Indian location is rare. Recently soiling analysis was estimated for the western part of India, where soiling rates were 0.37%/ day (equating to ~12 million US$ per year loss in Gujarat). Also, light rain and high humidity lead to 2 times higher the soiling rate over no rain condition. [41] collected dust from different Indian cities such as Mumbai, Jodhpur, Gurgaon, Hanle, Agra, and Pondicherry to conduct an indoor experiment artificially. However, this result does not reflect the natural soiling phenomenon. Cleaning technology is only feasible if the loss of PV power generation cost is higher than the cleaning cost [9].

The present work primarily focuses on long-term natural dust accumulation on low-iron glass surface with three different positions such as vertical, horizontal, and the local tilt angle for Building Integrated Photovoltaic Systems (BIPV) and rooftop or any type of PV power plant applications. Subsequently, various optical characterizations, like morphological studies, the size distribution of dust particles, and the transmittance losses over a period of time have also been accomplished. The obtained results can be very useful in determining the transmittance loss from the glass surface of commercial solar PV modules under the impact of natural dust deposition. Furthermore, the degradation in the amount of usable energy generated from the solar PV modules such as monocrystalline and polycrystalline due to natural dust deposition on the glass surface of PV modules has been examined. The rest of the paper is organized as; Section 2 describes the experimental setup of the work, and Section 3 comprises the analysis of the results. Finally, Section 4 includes the conclusion of the paper.

2. Experimental setup

The experimental work has been carried out at the Birla Institute of Science and Technology (BITS)-Pilani (17° 32' N, 78° 34' E), Hyderabad campus, Hyderabad, India. An experimental setup has been realized to analyze the effect of dust accumulation on the low-iron glass slides of 5 cm × 5 cm (length * breadth) with a 4 mm thickness obtained from the Renewable Energy Laboratory, University of Exeter, Penryn Campus, UK. These glass slides are generally used for the encapsulation of the top layer for SPV modules. Correspondingly, the effect of dust accumulation on the performance of the SPV modules has been studied.

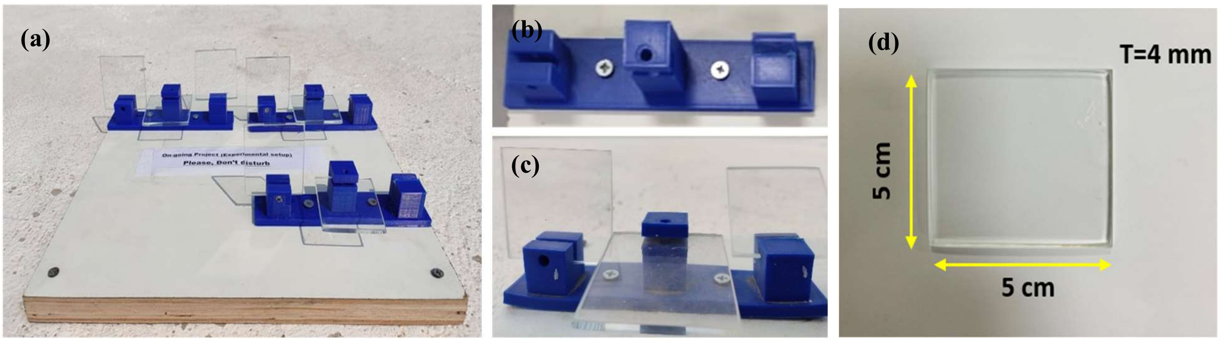


Fig.1 (a) Entire Experimental set up (b) 3D printed stand (c) Placing of Glass slides (d) Glass slide with dimensions (5 cm * 5 cm) with 4 mm thickness

Various suitable 3D printed jigs were designed and implemented to collect dust, as shown in Fig. 1. Accordingly, the glass slides were placed on these jigs with three different positions like horizontal, vertical, and local tilt angle. Further, monocrystalline and polycrystalline PV systems, each with a power rating of 50 Watts, have been installed according to the local tilt angle, as shown in Fig. 2.

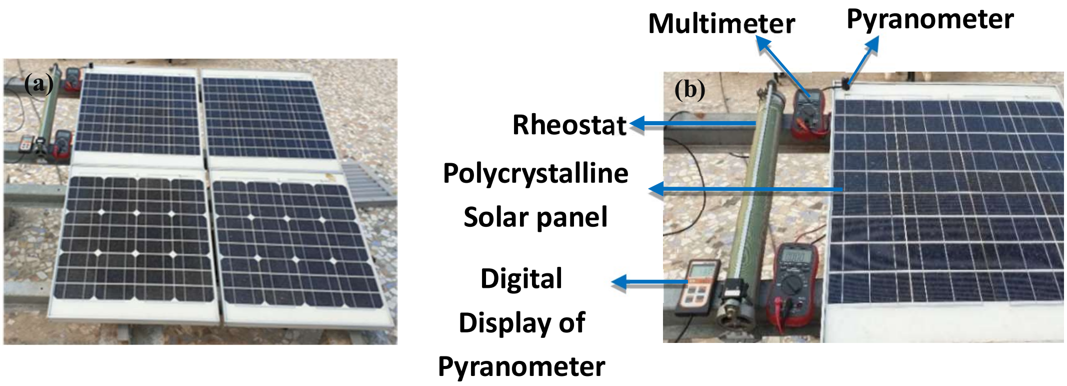


Fig. 2. (a) SPV installation set up and (b) Representation of the PV measurement system

UV-Vis's spectroscopy and optical microscopic studies were performed to analyze the transmittance, structure, and size of the dust particles. Also, the performance of monocrystalline and polycrystalline Solar panels has been studied after exposure to the natural deposition of dust without using any cleaning method. Initially, the solar radiation was measured using the pyranometer from Apogee instruments (MP-200: Pyranometer Separate Sensor with Handheld Meter). A rheostat of 65 Ω/4A was used as a resistive load for PV panels. Amprobe AM-220 Compact Digital Multimeter was used as the voltmeter and ammeter to measure the voltage and current from the PV modules. The specifications of electrical parameters for the Solar panels are shown in Table 1. Experiments for the Solar PV modules also were carried out from the Birla Institute of Science and Technology (BITS)-Pilani (17° 32' N, 78° 34' E), Hyderabad campus Hyderabad, India.

Table 1 Specifications of electrical parameters for Monocrystalline and Polycrystalline solar PV modules

Parameters	**Mono & Polycrystalline PV modules**
Maximum Power P_{max}	50 W_p
Voltage at maximum power V_{mp}	17.7 V
Current at maximum power I_{mp}	2.83 A
Open circuit voltage V_{oc}	21.6 V
Short circuit current I_{sc}	3.2 A
Tolerance	±2 %
Power measured at Standard Test Conditions (STC) 1000 W/m^2, AM 1.5, $25^{O}C$	

An optical microscope (Leica DM2000) was employed to study the structure of the dust accumulated on the glass slides. Also, the size of the dust particle and their distribution have been analyzed using the Image J software. The transmittance studies have been performed using a UV-Vis spectrometer from Ocean optics (Custom Configured Maya2000 Pro Series) of wavelength ranges from 300-1100 nm. All these measurements were captured regularly and analyzed with the natural build-up of dust particles on the glass slides without using any cleaning mechanism. The Scanning Electron Microscopy-Energy Dispersive X-rays Spectroscopy (SEM-EDX) was performed using ZEISS 1400, and the X-ray diffraction (XRD) of the dust sample was performed by Rigaku Ultima IV X-ray diffractometer (XRD) with Cu Kα radiation (λ = 1.5418 Å), and a scan rate of 1°/min with a step size of 0.02°.

3. Results and Discussion

3.1. Optical microscope studies

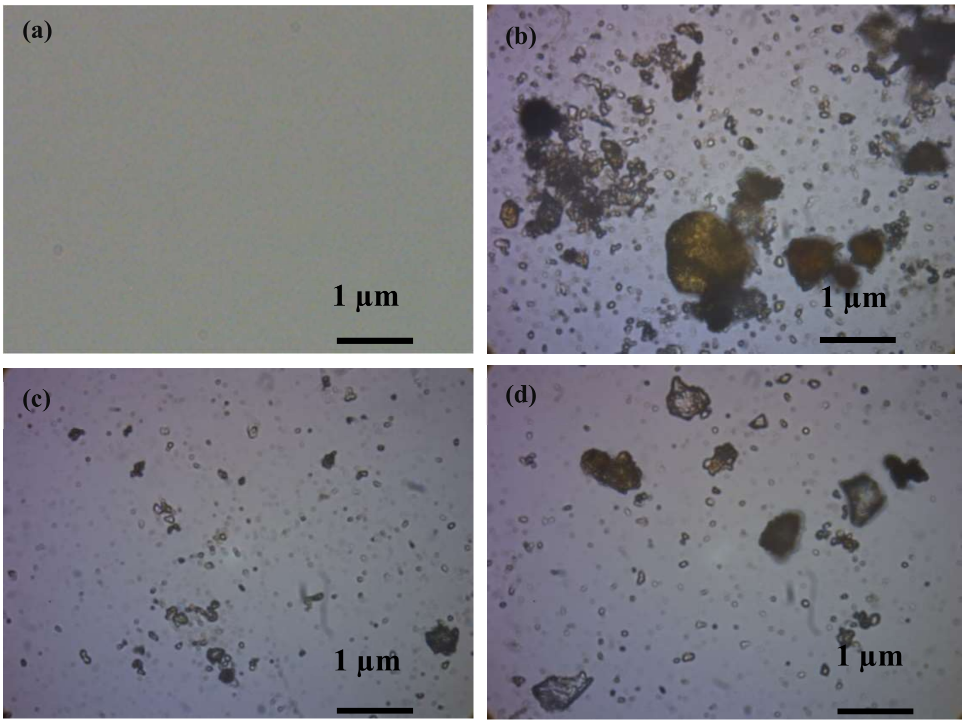


Fig. 3 Optical microscope images at 100x magnifications for (a) Bare glass, (b) Horizontal, (c) Vertical and (d) Local tilt angle

Fig. 3 shows images obtained from the optical microscope for the horizontal, vertical and the local tilt angle positioning of the Solar glass slides. It was found that the dust, with different sizes and random shapes, collected on the glass slides, was non-uniformly distributed. In the case of horizontal positioning, the accumulation of the dust was more, which formed like clusters at various places on the glass slide. Further, in a vertical position, the dust collection was much lower. Finally, at the local tilt angle, it was slightly higher than the vertical position but lower when compared to the horizontal position.

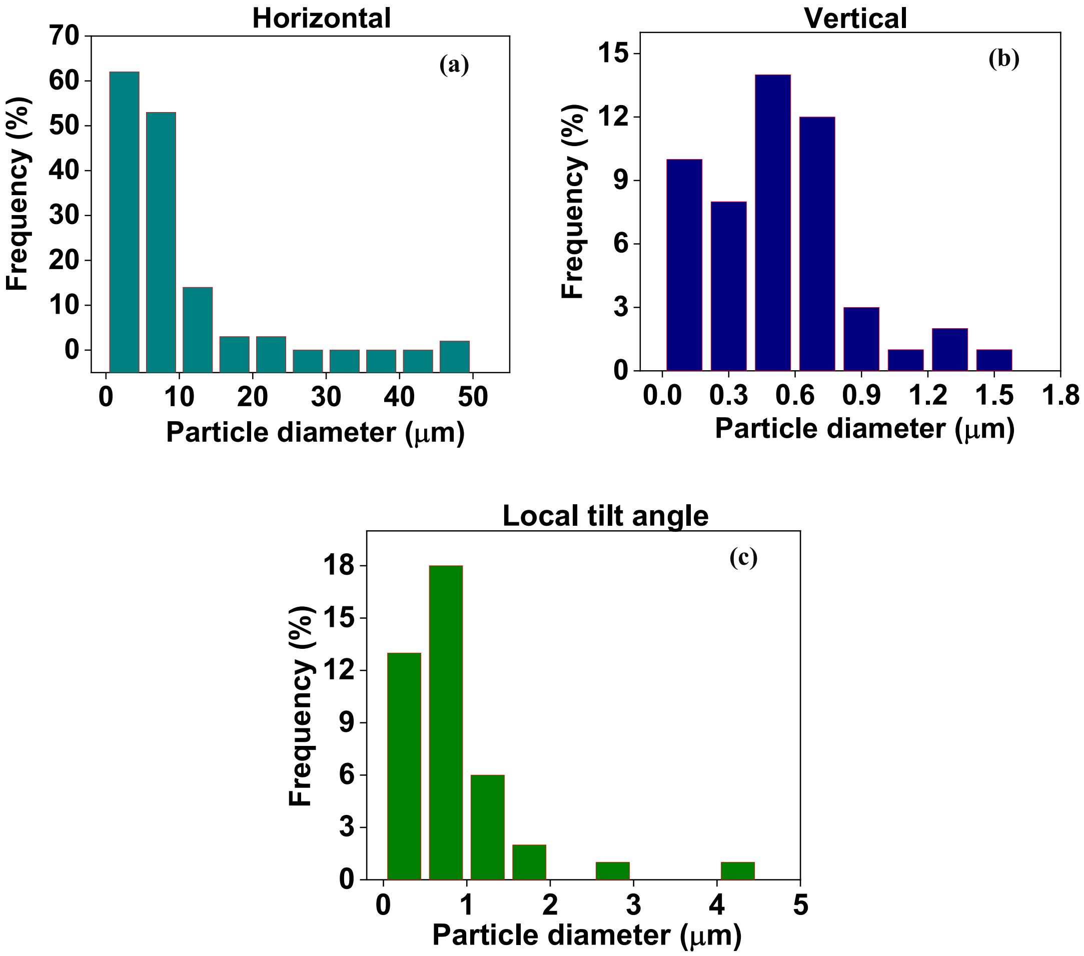


Fig. 4. Particle size distribution (a) Horizontal (b) Vertical and (c) Local tilt angle

Subsequently, the images obtained from the microscope were used to analyze further the size of the dust particles and their distribution on the glass slides. However, depending on the position of the glass slide, the size of the dust particle size and shapes was found to be varying, which was observed through the particle size distribution curve, as shown in Fig. 4. It is also cleared that particles having higher dimensions dropped due to gravity, while smaller ones had a tendency to remain attached to the glass surface. Between smaller particles and glass surfaces, Vander wall adhesive force dominates over gravity, which allows them to be attached to the surface [42]. The particle size analysis was made using the ImageJ software to identify the size of the dust particle on each glass slide. The obtained results were further used to estimate the particle diameter, D using the formula $(4A/\pi)^{1/2}$. It was identified that the grain size of the dust particles in horizontal placing is the range of 33.71 μm. For vertical and local tilt angle of PV module orientation, the grain sizes of the dust particle are found as 0.45 μm and 0.75 μm, respectively, and the accumulation of dust is more in horizontal placing. From the horizontal solar glass, it can be inferred that dust particles less than PM10 of that particular location are higher. Normally, the atmospheric dust particles can range from below 1 to 100 μm. However, the accumulation of dust and its properties may change with location and season throughout the world. As reported in the literature of Chaichan et al. [43], deposition of large grain size particles is caused by the atmospheric gravitational impacts and mass inertia. Furthermore, cleaning higher concentrations of micro-sized dust particles is much easier than lower nano-sized dust concentrations, especially silicon [44]. The dust particle size affects the reflection, dispersion, and absorption of the incoming light on the solar PV module surface from the PV systems. Hence it is also essential to investigate the grain size of dust particles to estimate the loss of energy output of the solar PV system.

3.1.3 Mineralogical analysis

The mineralogical analysis, such as the morphology of dust particles, elemental composition, and crystallinity, was identified using the Scanning Electron Microscopy (SEM), Scanning Electron Microscopy-Energy Dispersive X-rays Spectroscopy (SEM-EDX), and powder X-ray diffraction (XRPD) studies. The SEM images of the dust sample in different magnifications are shown in Fig. 5a-c. The micro-particles of dust are diverse in morphology. The SEM-EDX was executed to get better insight into the elemental composition of the dust sample on a large selective area, as shown in Fig. 5d. The SEM-EDX spectrum of the particular region is shown in Fig. 5e, and the corresponding atomic weight percentage distribution of the dust sample is given in Table 2.

From Table 2, it is envisaged that the dust sample contains the metallic elements Fe, Mg, Al, Ca, and Na, K, and non-metallic elements C and O along with the metalloid Si distributed in diverse weight ratio. Among the elements, Si, O, C, and Fe were the most abundant elements. The elements can be present as different minerals in the dust sample, which can be identified by the powder X-ray diffraction (XRPD) study of the dust sample.

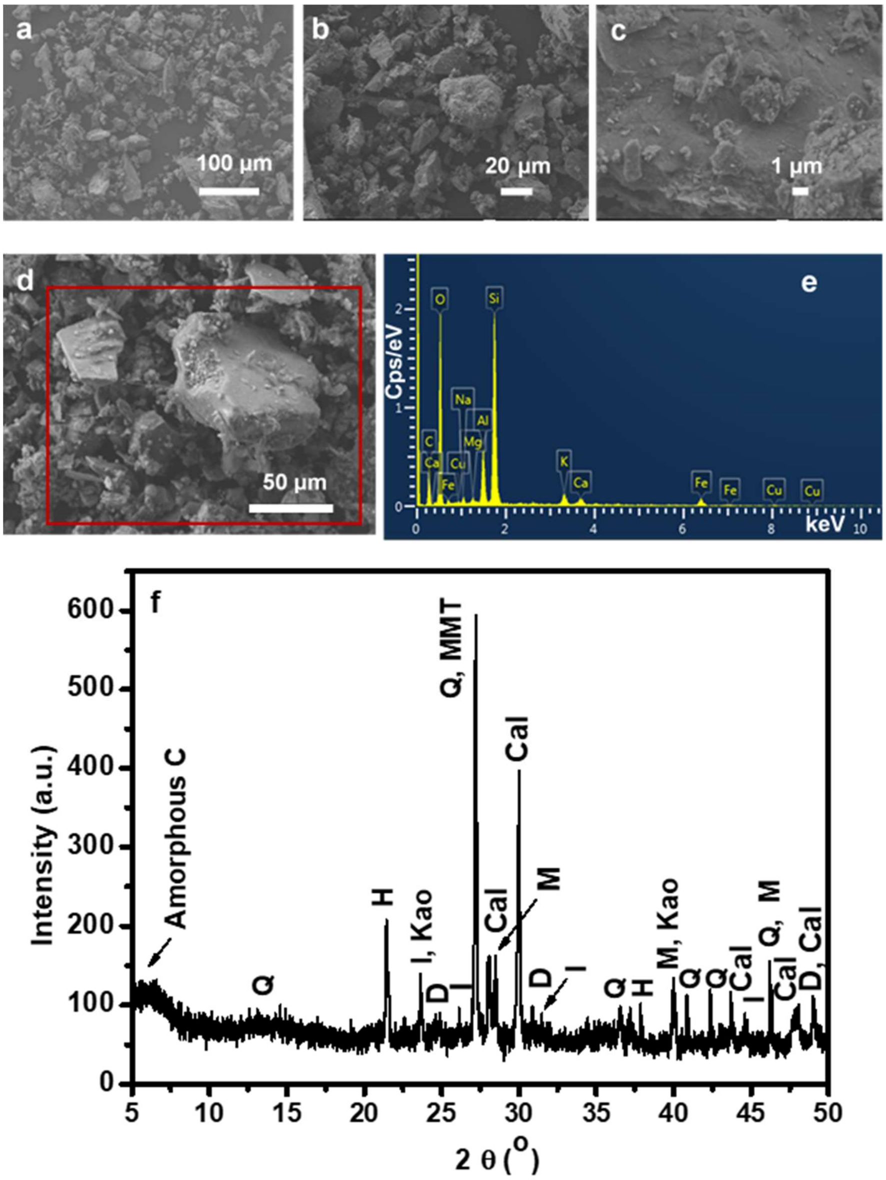


Fig. 5. (a-c) FESEM image study of the dust sample. (d) Selected area as marked by red square for SEM-EDX study and (f) the SEM-EDX study of the dust sample. (f) Wide angle powder XRD study of the dust sample. The peaks corresponding to different minerals are indicated by different letters. Q = quartz, H = hematite, I = Illite, D = dolomite, Kao = kaolinite, MMT = montmorillonite, Cal = calcite, and M = malachite.

Table 2. Summary of SEM-EDX study.

Sample	**Atomic weight percentage (%)**									
	C	**O**	**Si**	**Fe**	**Al**	**K**	**Ca**	**Na**	**Cu**	**Mg**
Dust Sample	27.7	40.7	17.0	5.1	4.6	1.8	1.3	0.7	0.5	0.4

The result of the XRPD study is shown in Fig. 5f. The experientially observed XRD peaks (2θ values), corresponding inter-planar spacing (d_{hkl}), and assignment for the minerals are provided in Table 3. We have also assigned the different XRD peaks in Fig. 5f with corresponding minerals with the help of the previous report [45]. The XRD pattern revealed the characteristic of illite, quartz, montmorillonite, kaolinite, hematite, dolomite, calcite, and a slight trace of malachite in the dust sample. The inference made here is very consistent with SEM-EDX analysis, as shown in Table 2. The majority of the intense peaks are either for Si-containing quartz, montmorillonite, etc., or carbonate-containing minerals. It is well-aligned with the higher atomic weight percentage for Si, O, and C in the dust sample. Alongside this, the broad peak around $2\theta = 6^{\circ}$ might be attributed to the amorphous C particles, which can be accumulated in the dust sample from the smoke in the environmental condition.

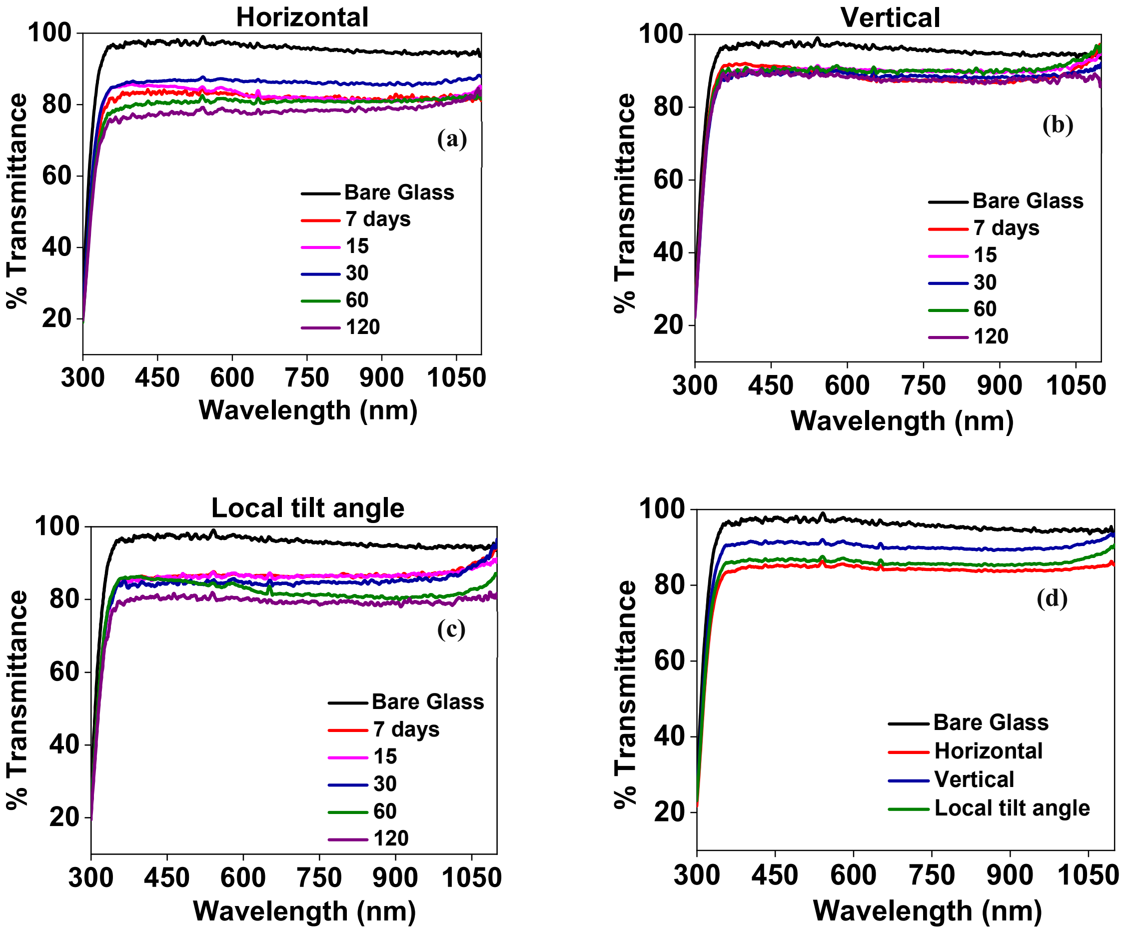
Table 3. Assignments of the different minerals in the dust sample were anticipated from the XRD study.

Minerals	**2θ (°)**	**d_{hkl} (Å)**
Illite	23.63, 26.12, 31.42, 44.69	3.76, 3.40, 2.84, 2.02
Quartz	12.91, 27.13, 36.53, 40.86, 42.41, 46.12	6.85, 3.28, 2.46, 2.20, 2.13, 1.96
Montmorillonite	27.13	3.28
Kaolinite	23.63, 40.01	3.76, 2.25
Hematite	21.44, 37.30, 37.97	4.14, 2.41, 2.37
Dolomite	24.81, 30.88, 49.00	3.58, 2.89, 1.86
Calcite	28.06, 30.03, 43.69, 47.90, 49.00	3.18, 2.97, 2.10, 1.90, 1.86
Malachite	28.54, 40.01, 46.20	3.12, 2.25, 1.96

In addition to the mineralogical analysis, the climatic conditions, which are essential elements for this study, such as the average temperature, sunshine hours, humidity, wind speed, and rainfall, indicate 34.8 °C, 8.6 hours, 41%, 6.2 km/h and 144.4 mm at 7° 32' N, 78° 34' E, Hyderabad, India has been considered for this work during January – May 2020 [46][47][48] .

3.1.3 Transmittance analysis

Fig. 6 shows the transmittance analysis for the horizontal, vertical, and local tilt angle positions. The transmission studies indicate that the change in the transmittance of light through the glass slides with the natural accumulation of dust over a period of time. The obtained results were analyzed in detail at regular intervals after exposing the glass slides for up to 120 days (mid-January 2020 to mid-May 2020). The transmittance at different tilt angles for each solar glass slide has also been analysed, and the average transmittance has been reported at regular intervals, as shown in Fig 6 (e). It has been found that with the increase in the exposure time, the overall transmittance decreased. Still, the rate of decrease in transmittance reduction was non-uniform because of the random climatic conditions.



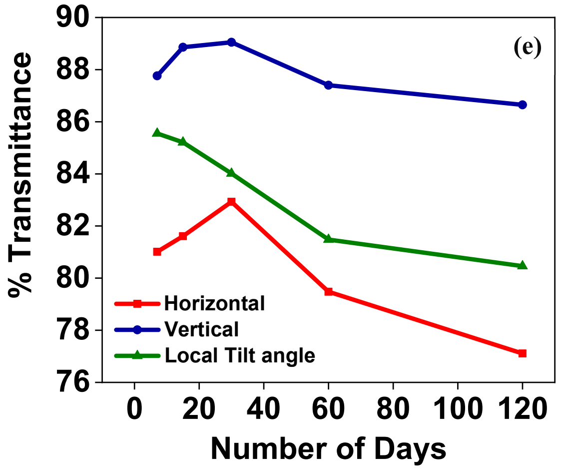


Fig. 6 Transmittance studies (a) Horizontal (b) Vertical (c) Local tilt angle (d) average transmittance after 120 days exposure to dust for horizontal, vertical, and local tilt angle and (e) % Transmittance with respect to the horizontal, vertical and local tilt angle up to 120 days

Table 4: % Transmittance with respect to the horizontal, vertical, and local tilt angle up to 120 days

#	**Number of days**	**Transmittance (%)**		
		Horizontal	**Vertical**	**Local tilt angle**
1	7	81.01	87.76	85.55
2	15	81.61	88.86	85.21
3	30	82.93	89.05	84.015
4	60	79.48	87.40	81.48
5	120	77.11	86.65	80.46

As identified with the microscopic studies and particle size distribution, the dust particles were more accumulated on the horizontal positioning as it reflected the light transmittance. Accordingly, the horizontal position showed less transmittance than the vertical and local tilt angle positioning, as shown in Table 4. The average transmittance of the bare glass slide was 94.59 % in the range of 300-110 nm wavelengths. However, after exposure for 120 days with the dust build-up without any cleaning system, the glass slides showed 77.11 %, 86.65 %, and 80.46 % in horizontal, vertical, and the local tilt angle positions, respectively. From Fig. 6e, as expected, the reduction nature of the transmission is revealed. However, for horizontal slides, an increased transmission was observed after 30 days. This was due to the rain, which cleaned the glass surface.

Table 5: Percentage (%) decrease in transmittance after 120 days of exposure to dust

#	**Position**	**% Decrease in Transmittance after 120 days**
1.	Horizontal	18.47
2.	Vertical	8.39
3.	Local tilt angle	14.93

Moreover, these results manifest the importance of the glass surface, which plays a significant role in the performance of the PV modules for longer periods. Table 5 shows that the percentage decrease in transmittance after 120 days, the horizontal positioning shows more loss compared to the vertical and local tilt angle.

3.1.4 Performance analysis of SPV modules

The performance of monocrystalline and polycrystalline Solar PV modules was studied based on the effect of natural dust accumulation after exposure to 120 days without any cleaning mechanism. The modules were cleaned naturally during this duration based on the climatic conditions, such as due to the rain and wind flow in the atmosphere.

Fig. 7 shows the IV and PV characteristics of monocrystalline and polycrystalline panels, the average of the measurements taken at regular intervals. The IV and PV characteristics change with respect to the time and the amount of solar radiation falling on them. Although generally, the performance of Solar panels mainly depends on the amount of solar radiation, it is essential to study the influence of the dust, which can block the incoming radiation on the glass surface, leading to a decrease in the performance of PV modules.

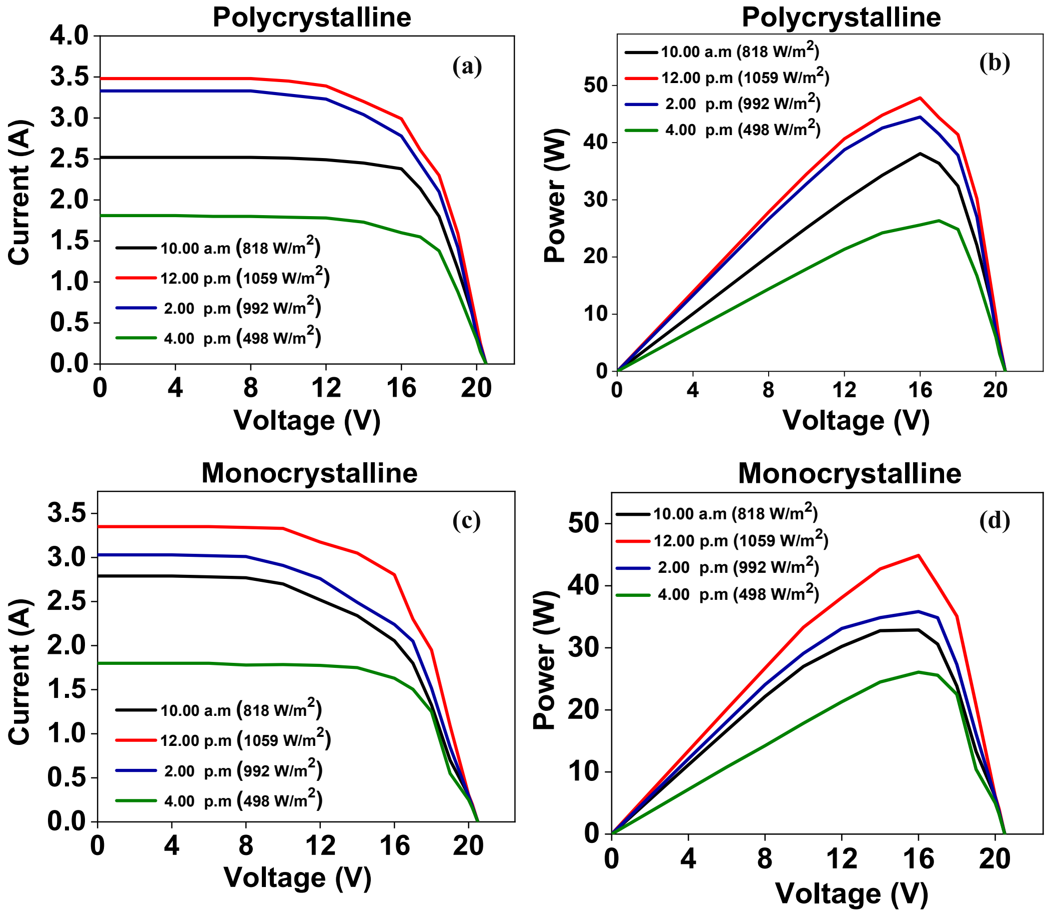


Fig.7. IV characteristics of Solar PV modules (a) polycrystalline, (c) monocrystalline and PV characteristics of Solar PV modules (b) polycrystalline (d) monocrystalline

As observed, the maximum power output (P_{max}) decreased to 44.88 W and 47.84 W for the monocrystalline and polycrystalline Solar panels, respectively, due to the accumulation of dust particles on the solar modules after exposure to 120 days, as shown in Fig.8. In contrast, at Standard Test Conditions (STC) with 1000 W/m^2, the P_{max} is 50 W. This drop-in P_{max} was 10.4 % and 4.32% for monocrystalline and polycrystalline Solar panels, respectively, after exposure to 120 days of natural dust accumulation. As the efficiency of the monocrystalline Solar cells (17.6%) was higher compared to polycrystalline Solar cells (15.2%), it has been observed that the polycrystalline solar panel showed a higher drop in P_{max} with the accumulation of dust. However, even though the solar radiation is slightly high after 120 days at noon, the Pmax still decreases due to the soiling losses. The soiling ratio has been plotted based on the ratio of the average short-circuit currents for the dust accumulated at regular intervals to that of without dust exposed (on the first day of experimentation) [10]

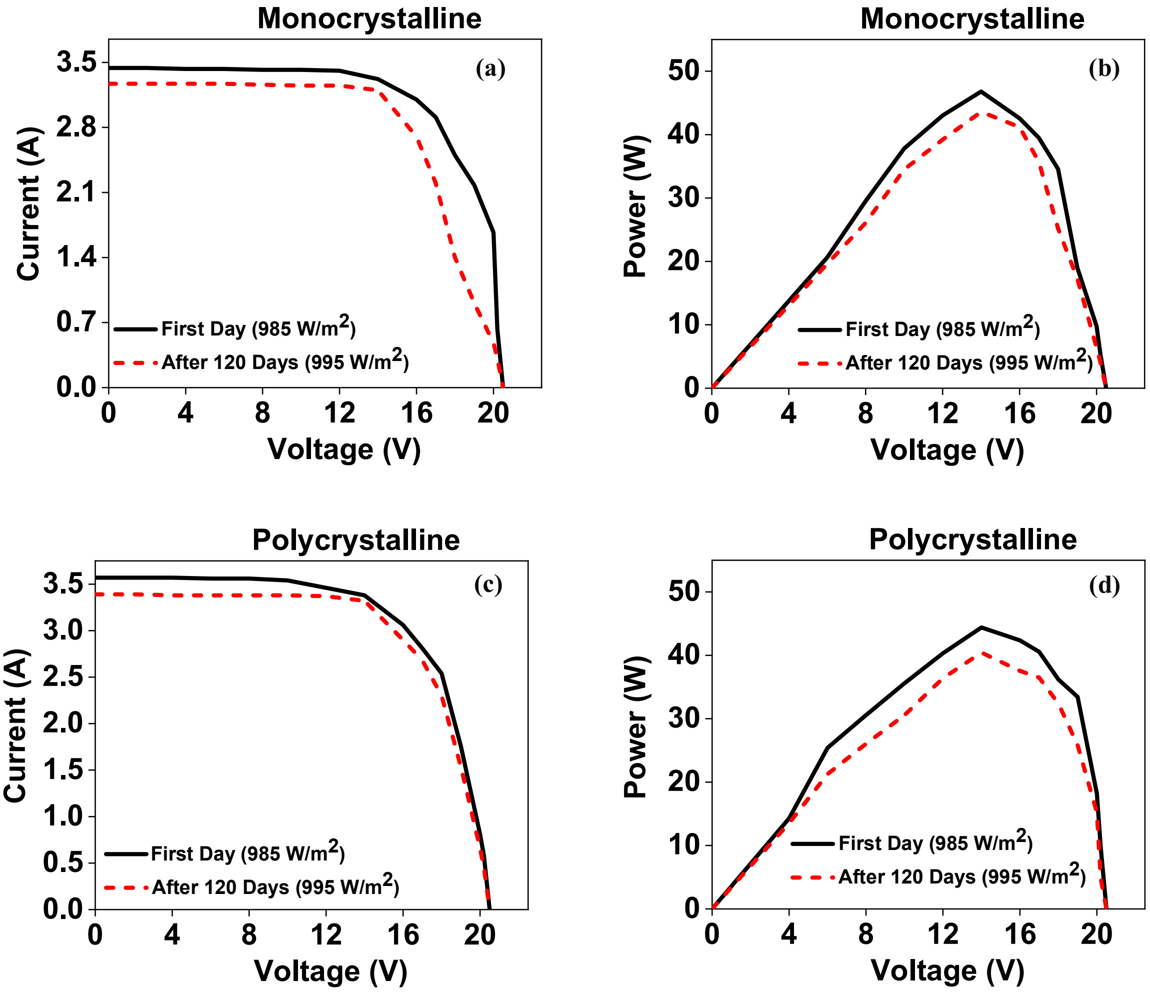


Fig.8 Comparison of IV characteristics (a) polycrystalline, (c) monocrystalline and PV characteristics (b) polycrystalline (d) monocrystalline Solar PV modules before and after exposure to 120 days

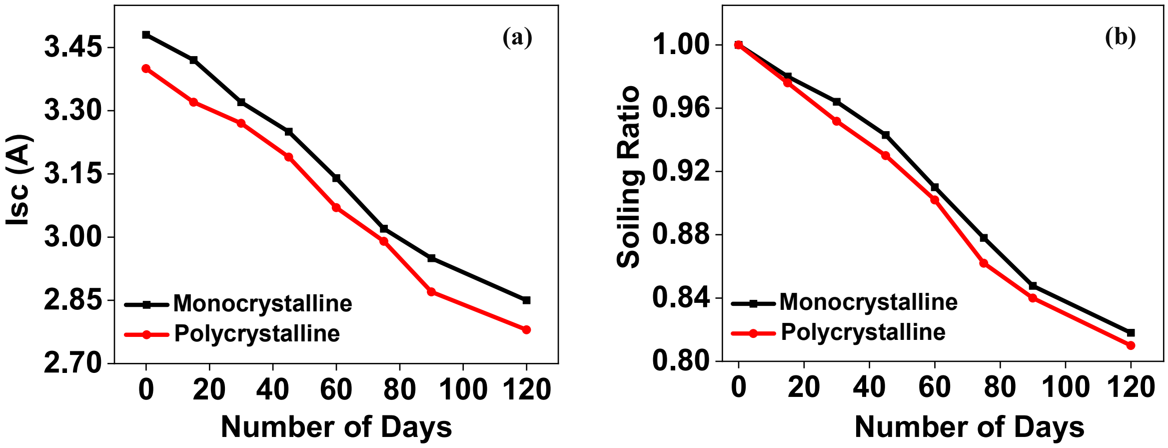


Fig. 9. (a) Isc of the Solar PV modules (Mono and Polycrystalline) over 120 days (b) Soiling ratio (Mono and Polycrystalline) over 120 days

Fig. 9(a) shows the short circuit current (I_{sc}) from the PV modules at regular intervals up to 120 days. Although the I_{sc} is always dependent upon the incoming Solar radiation falling on PV modules, it also varies depending upon the soiling losses because of the accumulation of the dust particles, which can block or lead to scattering the incoming Solar radiation on the glass slide of the PV modules. The decrease in I_{sc} is observed with an increase in the number of days of exposure to natural dust without using cleaning methods. Also, Fig 9 (b) shows the soiling ratio decreases with the increase in the days of exposure to dust. The rate of decrease in the soiling ratio after 120 days is more because all these studies have been performed mostly in summer, where the effect of rain is significantly less. This study of the soiling ratio is a generalized one and will be very useful for scalable Solar PV power plants.

Fig 10 shows the energy generation for monocrystalline and polycrystalline Solar PV modules with respect to the change in % transmittance for 120 days. Also, with respect to the transmittance, the change in solar radiation is essential because the power output of the solar photovoltaic modules always depends upon the incoming radiation falling on them. Table 4 shows the average solar radiation of 6 hours every day (10 a.m. - 4 p.m.). It also shows that the energy generation increases even though the transmittance decreases with an increase in the number of days of exposure to dust. Apparently, if we consider only the impact of dust accumulation on the Solar PV energy generation, it should have been decreased with days instead of increasing. Here, the typical feature in Fig 4 and Table 6 is the impact of Solar irradiance during seasonal variation (winter to summer, mid-January 2020 to mid-May 2020) in combination with dust accumulation. These obtained results manifest that the glass surface plays a significant role in the performance of the Solar PV modules.

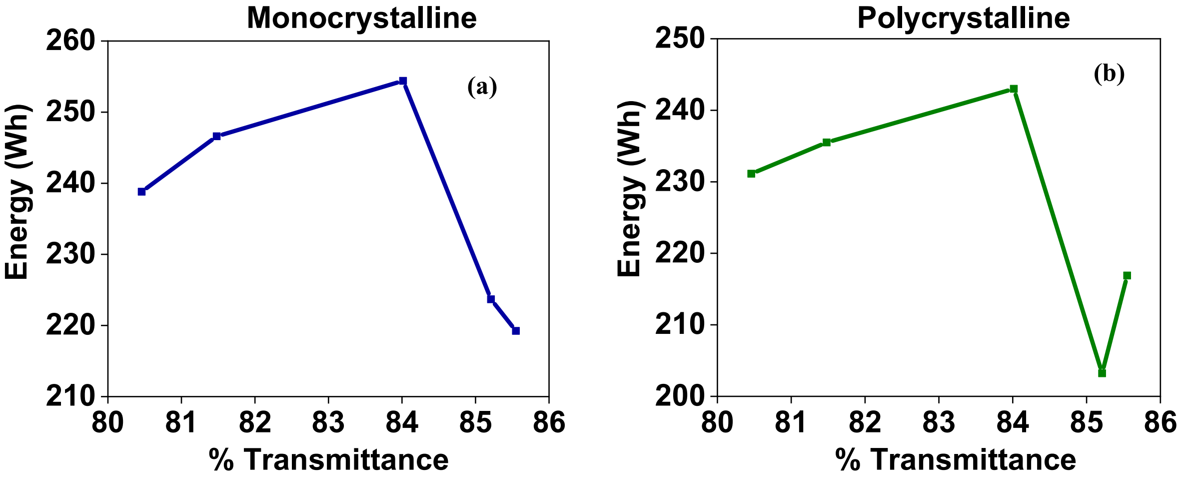


Fig. 10. Energy generation from the PV modules with respect to the transmittance of the glass samples for local tilt angle (a) monocrystalline (b) polycrystalline.

Table 6: % Transmittance and energy generation of monocrystalline and polycrystalline Solar PV modules at local tilt angle after 120 days exposure to dust

S.no	**No of days**	**Transmittance (%)**	**Energy (Wh)**		**Solar radiation (W/m^2) (10 a.m.- 4 p.m.)**
		Local tilt angle	**Monocrystalline**	**Polycrystalline**	
1	7	85.55	219.24	216.9	710.25
2	15	85.21	223.68	203.22	745.8
3	30	84.015	254.4	243	835.4
4	60	81.48	246.6	235.5	824.6
5	120	80.46	238.8	231.12	810.3

4. Conclusion

Herein, the impact of the natural dust accumulation for 120 days on the glass samples and its optical characteristics with three different positions like horizontal, vertical, and the local tilt angle has been studied. Also, in vertical positioning, the dust collection was much lower, whereas, in the local tilt angle, it is slightly higher than the vertical positioning but lower than the horizontal positioning. The mineralogical study of dust particles such as morphological, elemental composition, and crystallinity shown in this work would help in providing an insight to the local soiling problem. Also, the presence of PM10 is much higher in this location. After thorough experimentation, it was revealed that after allowing the dust to build up naturally for 120 days without using any cleaning system, the glass samples showed a 17.48 %, 7.94 %, and 14.13 % decrease in % transmittance for horizontal, vertical, and local tilt angle positions respectively. The transmittance loss was significantly less in vertical positioning, which can be helpful for BIPV systems. Still, in real-time conditions, the Solar PV modules are installed according to the local tilt angle to obtain maximum solar radiation for the rooftop applications. However, the local tilt angle shows 14.13 % transmission loss after exposure to 120 days without using any cleaning system. Also, the degradation of energy generation from the monocrystalline and polycrystalline SPV modules based on naturally accumulated dust on the glass surface of PV modules showed 20.4 % and 22.96 %, respectively, because of the soiling losses on the glass surface. These preliminary results suggest that the degradation of energy generation from PV modules was very high due to the impact of natural dust deposition.

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