Self-cleaning of glass surface to maximize the PV cell efficiency

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Abstract. Photovoltaic (PV) modules are widely used for harnessing solar energy which ensure maximum output when their glass surface is clean. However, PV modules are open to dust, grime and other contaminations which get deposited on their surface causing reduction in transmittance and hence their efficiency reduces. It is therefore required to clean the glass surface of PV modules time to time either manually by labor or using some special arrangements such as automated systems. However, these techniques are either laborious or require extra energy. Therefore, another solution to offset such complications is to use chemical coatings which ensure self-cleaning of glass surface by increasing water contact angle. In the present study, two types of water repellent chemicals (such as trimethylchlorosilane and hexamethyldisilazane) have been used to coat the glass surface using dip coating technique. The performance of such coated glass slides has been investigated using some important characterization techniques, such as finding transmittance by spectrophotometer and measuring water contact angle using a high resolution camera. Moreover, the self-cleaning effect has been observed using a microbalance to measure dust on coated glass exposed to open atmosphere and compared with uncoated glass. The results revealed that these coatings have increased the water contact angle up to 149% which reduces friction between the glass surface and water droplets. Moreover, the friction reduction helps in mobility of water droplets which in turn can easily carry out dust along with them, thus improving the efficiency of PV module.

Keywords: Solar energy, photovoltaic, dust accumulation, chemical coating, water contact angle.

1. Introduction
Solar energy is a major source of renewable energy that is abundant in nature and free of cost, providing heat and electricity to many places across the globe. Being an important source of renewable energy, solar energy can be harnessed using a wide range of technologies such as solar architecture, photovoltaic, artificial photosynthesis, solar thermal energy, molten salt power plants and solar heating. Although solar thermal conversion provides a lot of benefits in term of heating in commercial applications, electricity generation from photovoltaic (PV) modules is attracting the focus of commercial, industrial and domestic users each passing day due to the higher grade of harvested energy. Its applications are becoming wide and wide starting from home applications to large industrial solar power plants.

1.1. Photovoltaic (PV) modules
Photovoltaic (PV) modules are used for harnessing solar energy and converting it to electrical energy. Due to its ability of harvesting both direct and diffuse sunlight, it can operate in both hazy and cloudy
conditions. PV modules are made up of solar cells which generate electricity working on the principle that light energy strikes the solar cell knocks electrons from atoms in semiconductor material thus producing electric current. Solar cells individually have low voltage and are combined into solar modules which are further combined to make solar panel and then a PV system. To meet the demand of specific power requirements, several panels are connected together to make a PV system as shown in Figure 1.

1.2. Photovoltaic phenomena
The PN-Junction solar cells use a semiconductor such as silicon which has four electrons in its valence shell. The conductance of pure silicon crystal lies in between that of pure conductors and pure insulators. Impurity atoms can be added to increase its conduction by a process called doping. Negative charges called electrons are introduced by doping with atoms containing more electrons than silicon. Being extra, these electrons are not tied up in chemical bonds and so are free to move around. Likewise, freely moving positive charges called holes are introduced by doping with atoms containing fewer electrons than silicon. Since these charges are mobile, they can carry an electric current. When an n-type and a p-type semiconductor come together, they form a PN-junction. Electrons can wander across the junction leaving behind static positive charges on the atoms in the solid. On the other side, they join with the holes and neutralize them. At the same time, holes can wander across the junction, leaving behind the static negative charges on the atoms in the solid. Near the PN-junction, the region where there are no charge carriers is called Depletion Zone. The separated positive and negative charges create an electric field across the depletion zone. When energy from the light is incident on the PN-junction, it dislodges an electron, creating a mobile electron and an extra mobile hole. The electric field makes the electron flow to n-type material and hole flow to p-type material as shown in Figure 2.

The resulting separation of positive and negative charges across the junction is called junction potential. Connecting the solar cell to an external circuit allows the electrons and holes to travel around and recombine returning the system to its starting condition. The charges driven around the circuit forms an electric current and does useful work such as lighting etc.

1.3. Factors affecting the performance of PV module
PV modules are installed in open atmosphere where its performance is influenced by outdoor conditions such as ambient temperature, irradiance level, dust accumulation, wind speed, and humidity etc. which have been addressed by a lot of researchers [3-7]. The performance of PV modules can be assessed by a lot of parameters in which efficiency is a prime factor. PV modules have generally low energy efficiencies; however, they ensure maximum achievable efficiency when its top surface is clean enough. The modules are generally mounted on ground and rooftop, deriving energy from solar radiations and are exposed to sunlight in open atmosphere thus eventually dust, grime and other
contaminations get adhered to its surface which degrade its performance. Previous researchers proposed that dust is one of the most important factors that should be considered before installing a PV system.

1.4. Effect of dust on the performance of PV module

Dust accumulation is one of the major problems facing by PV modules to degrade its performance and life [8]. The reduction in efficiency of PV module due to dust accumulation depends on the size and mass of dust. It has been observed by Sarver et al. [9] that increase in mass of dust has a direct impact on efficiency degradation while size of dust has inverse impact on it. Darwish [10] investigated the effect of dust deposition on daily energy loss of PV module for one year. He examined that deposition of dust can cause 4.4% loss in mean of daily energy. He also proposed that this loss can be higher than 20% when there is no rain for a long period. Similarly, Said and Walwil [11] carried out some experiments to find out the effects of dust fouling on glass cover of PV module. They examined 35% reduction in spectral transmittance and 20% in overall transmittance. Furthermore, Kumar and Chaurasia [12] conducted research to investigate the effect of dust on PV module's efficiency in India and they examined the accumulation of dust can degrade the efficiency of PV module up to 40% in desert area.

![Figure 2. Photovoltaic phenomena](image)

Some researchers tried to generalize the effect of dust on performance of PV system and proposed some correlations between dust accumulation and efficiency of PV systems. For instance, Mekhilef et al. [3] carried out some experimental studies and found a correlation between the efficiency of PV module and thickness of the dust accumulated over its surface in a composite climate. They revealed that the accumulation of heavy layers of dust have a significant reduction of 10-20% in output of PV module while small amount of dust has a negligible effect on it. Similarly, Al-Hasan and Ghoneim [13] performed experimental and theoretical studies to correlate the efficiency of PV system with the quantity of dust accumulated. They measured and compared the I-V characteristics for both dusty and clean PV systems and proposed a linear correlation between the PV system's efficiency and dust accumulated on its surface. Moreover, they observed that the maximum output power and short circuit current decreases as the concentration of dust increases up to 1 g/m² but the rate of reduction decreases beyond this value. Furthermore, they concluded that there is no significant effect of dust accumulation on open circuit voltage of the PV system.

Different researchers attempted to prove that the effect of dust on PV system is different for different samples at different parts of the world. For example, Hussain et al. [14] carried out a detailed investigation of PV module subjected to different dust samples by analyzing its electrical performance such as output power, current and voltage. They observed that a minimum value of power was 3.88W when the PV module was accumulated by particles of rice husk. A similar type of research has been conducted by Kaldellis and Kokala [15] which concluded that the effect of dust on PV module performance varies from site to site. In this regard, Appels et al. [16] conducted research and proved that the problem of dust settlement in Belgium is not severe as compared to Middle East. Besides this, a very detailed review of dust soiling effects on solar panels has been done by Sayyah et al. [17]. They
compared the effect of dust on solar panels for different parts of the world and concluded that the minimum power loss due to dust accumulation occurs in Cyprus while maximum occurs in Saudi Arabia.

Apart from investigating the effect of dust on PV module, some work has been dedicated to analyze its effect on transparent glass. For example, the effect of dust on transparent cover of solar collector has been discussed by Elminir et al. [18]. They observed that the transmittance of glass is greatly dependent on the deposition density of dust and tilt angle of solar collector. Moreover, they examined that the best tilt angle to reduce a maximum reduction of 17.4% in output power per month was 45° facing towards south.

1.5. Dust cleaning methods for solar panels

As discussed above, the accumulation of dust particles on the surface of PV module degrade its performance in terms of efficiency, output power and short circuit current etc. Therefore, proper functioning of PV module demands for some special arrangements that should be done to maintain its efficiency. In this regard, some techniques for cleaning PV modules has been summarized by He et al. [19] which include manual cleaning, natural cleaning, self-cleaning by coating with nano-films, electrostatic cleaning and mechanical dust cleaning methods etc.

Mostly, solar panels are cleaned manually using clean water and a little scrubbing with coarse cloth, covered sponge or soft brush to remove the most stubborn grime adhered to glass surface. However, this practice is very laborious and should be repeated time after time depending on the dust accumulation probability in that area where solar panel is installed. Similarly, dust can also be removed by natural process [20, 21] with the aid of heavy rains or strong winds. However, in the desert regions the winds will have an adverse effect in the form of increase in dust accumulation. Moreover, heavy rain will lead to non-uniform cleaning which leave permanent scratches on the surface of solar panel thus decreasing the power output. Another important method for solar panel cleaning is the use of automated system like Robots [22, 23]. The input to these systems can be given by making the use of a part of energy generated by PV system. Furthermore, the use of electrostatics force to remove sand from the surface of solar panels is currently in use in NASA’s hover to Mars. A single-phase high voltage is applied to parallel wire electrodes embedded in the cover glass plate of a solar panel. More than 90% of the adhering sand is repelled from the surface with virtually zero power consumption [24, 25]. However, this method uses a lot of energy and can't be recommended for normal routines but rather they are used for special missions.

Apart from the above mentioned techniques, one of most promising technique is the use of self-cleaning nano-films which can be made by coating chemicals on the surface of glass of PV module. Chemicals possessing the property of self-cleaning have been under investigation for a long time because they can clean solar panel surfaces with minimum possible amount of water while keeping in view the importance of maintaining the transmittance of the glass.

1.6. Self-cleaning

The idea of self-cleaning of surface due to higher water contact angle was first discovered in lotus leaf known as lotus effect. Lotus leaf in order to wash out dust particles from its surface possesses the quality of super hydrophobicity which results in repulsion of water droplets when falls on its surface. It has a water contact angle of more than 160° making its surface super hydrophobic [26]. Dirt particles are picked up by water droplets and hence results in self-cleaning. The image of water droplet on lotus leaf is shown in Figure 3. Inspired from the phenomenon of natural self-cleaning, many researchers have tried and developed artificial self-cleaning surfaces by applying certain chemical coatings.

1.7. Use of chemical coatings for self-cleaning

Chemicals are found in three states i.e. solid, liquid and gas and a variety of chemicals are available today. However, more research studies are being carried out and new chemicals are being introduced day by day because they play a vital role in modern engineering studies and engineers can't deny the importance of chemicals in modern applications. Various industries use chemicals for various applications such as foods, Beverages, paints and varnishes etc.
Apart from daily life items, chemicals are used for different purposes in different industries. For example, in glass industries chemicals are coated on the glass surface to change its properties like transmittance, reflection and to decrease the roughness of glass surface and sometimes used to make glass surface attractive or repellent for water. Depending on the later applications, chemicals can be classified into following categories:

1.7.1. Hydrophobic chemicals
Hydrophobic means “water-hating”. Sometimes water spreads evenly when it hits a surface; sometimes it beads into tiny droplets. Materials that naturally repel water, causing droplets to form, are known as hydrophobic. If the droplet forms a sphere that barely touches the surface like drops of water on a hot griddle, the contact angle is more than 90 degrees and the surface is hydrophobic, or water-fearing. Chemicals which are used to make any surface hydrophobic are called hydrophobic chemicals. Special techniques are applied while coating chemicals on substrate. When hydrophobic chemicals are coated on a surface and water comes in contact with that surface, droplets of water becomes spherical and tend to slip on the surface as shown in Figure 4. This property of surface refers to hydrophobicity and has been used by a lot of researchers to increase the efficiency of PV system [27-33].

1.7.2 Hydrophilic chemicals:
Hydrophilic means “water-loving”. Materials with a special affinity for water — those it spreads across, maximizing contact are known as hydrophilic. Hydrophilic and hydrophobic materials are defined by the geometry of water on a flat surface specifically the angle between droplet’s edge and the surface underneath it which is called the contact angle. If the droplet spreads, wetting a large area of the surface, then the contact angle is less than 90 degrees and that surface is considered as hydrophilic surface. Chemicals coated to make any surface hydrophilic are called hydrophilic chemicals. When hydrophilic chemicals are coated over a surface and water comes in contact with that surface, it spreads over surface and tends to increase wettability as shown in Figure 5. This property of surface refers to hydrophilicity which has been used in a lot of studies to improve the performance of solar panels by preventing it from dust accumulation [34-40].
2. Materials and methods

2.1. Selection of chemicals and coatings

There are different kinds of chemicals available for different applications. Hydrophobic and hydrophilic chemicals are being used by different industries for various sorts of items requiring certain hydrophobic or hydrophilic characteristics. Glass industry is one of the major users of these chemicals. Different types of hydrophobic and hydrophilic chemicals are available in the market today. In the present study, Trimethylchlorosilane (TMCS) and Hexamethyldisilazane (HMDS) were used to be coated on the glass surface whose thermo physical properties are given in Table 1.

| Properties          | TMCS     | HMDS     |
|---------------------|----------|----------|
| Form                | Liquid   | Liquid   |
| Odor                | Pungent  | Ammonia like |
| Freezing point      | -58 °C   | -78 °C   |
| Boiling point       | 56 °C    | 125 °C   |
| Flash point         | -27 °C   | 25 °C    |
| Density at 20 °C    | 0.856 g/cm³ | 0.774 g/cm³ |
| Molecular weight    | 108.64 g/mol | 161.39 g/mol |

TMCS is also known as Chlorotrimethylsilane which is a colorless fuming liquid with a pungent odor. Its molecular formula is \( (CH_3)_3SiCl \) which reacts vigorously and exothermically with water. It is highly flammable and produces fumes in air. The vapor and liquid may cause burns. Hexamethyldisilazane is found in liquid form whose molecular formula is \( C_6H_{19}NSi_2 \). It is flammable and is miscible with acetone, ethyl ether and benzene. It is stable under normal temperatures and pressures but may decompose on exposure to moist air or water. It is very harmful if swallowed, inhaled or absorbed through skin.

A lot of techniques are available for chemical coatings such as chemical vapor deposition, physical vapor deposition, dip coating, spin coating and spraying etc. Although every technique has its own merits but dip coating was used in the present study because of its simple approach. Two separate dry and clean beakers were taken and labeled before making solution. Fairly cleaned glass specimens were labeled and made ready for coating. Both the chemicals (TMCS and HMDS) were used as solute and solution was prepared in the separate beakers by constant stirring for fifteen minutes with the help of a stirrer as shown in Figure 6. Benzene was used as solvent for TMCS and the ratio of solute to solvent was 1:5. Similarly, ethyl alcohol was used as solvent for HMDS in the ratio of 1:13. After making...
solutions, different glass samples were dipped with uniform speed and kept in the solution for thirty minutes. After thirty minutes glass samples were taken out of the beakers and were allowed to drain off excess amount of solution. Samples were exposed to dry environment and placed for some time to dry. Coating was carried out in this way and samples were made available for further testing.

2.2. Characterization techniques
The aim of characterization techniques is to forecast the behavior of solar panel when it is operational and exposed to dust, grime and other contaminants. Following techniques were selected for testing the effects of coating.

![Figure 6. Preparation of solution for coating](image)

2.2.1. Measurement of water contact angle (WCA)
Contact angle is an angle that a liquid creates with the solid surface when it is deposited on it. The contact angle depends upon both the properties of the solid as well as the liquid and the attractive and repulsive forces between liquid and solid. These interactions between solid and liquid are referred as the phenomena of cohesion and adhesion forces. Figure 7 shows the contact angle formed by a water droplet with the surface of a solid 2-D.

Contact angle defines the wettability of the surface. For example, the smaller contact angle means that cohesive forces are weaker than adhesive forces and molecules of liquid tend to interact more with solid molecules than liquid molecules and result in complete wettability of the surface. Generally such surfaces are known as hydrophilic surfaces with contact angle less than 90°. In other words these surfaces are the ones which attract water. There are some surfaces which exhibit extremely low contact angle approaching 0° are called super hydrophilic surfaces. Moreover, the larger contact angle means that cohesive forces are stronger than adhesive forces and the molecules of liquid tend to interact more with each other than with the solid molecules and result in poor wettability of the surface. Generally such surfaces are known as hydrophobic surfaces with contact angle greater than 90°. In other words these surfaces are the ones which repel water. There are some surfaces which exhibit extremely high contact angle approaching 180° are called super hydrophobic surfaces.

![Figure 7. Measurement of WCA](image)
The apparatus used for measuring WCA is Goniometer which consists of high resolution camera and a stand with adjustable height on which glass slide is placed. Droplet of water is poured on the surface and high resolution pictures are taken and analyzed in software. Since goniometer was not available in Pakistan so, a new apparatus was formulated for WCA measurements which is similar to goniometer as shown in Figure 8. High quality pictures were taken and converted into grey scales which are then analyzed by the online available software “image j”.

![Figure 8. Apparatus for measuring WCA](image)

2.2.2. UV-Vis-NIR Spectroscopy

Ultraviolet visible near-infra red (UV-Vis-NIR) spectroscopy is a useful technique to characterize the absorption, transmission and reflection properties of a variety of technologically important materials, such as pigments, coatings, windows, and filters. This more qualitative application usually requires recording of at least a portion of the spectrum for characterization of the optical or electronic properties of materials. After chemical coating of glass slides by HMDS and TMCS, spectrometry of glass slides was conducted to found its transmittance. Two samples each of TMCS and HMDS and one uncoated glass slides were tested in Physics department at Material Research Lab. University of Peshawar, KPK, Pakistan.

2.2.3. Dust measurement

After coating samples with TMCS and HMDS, glass slides were kept for drying at room temperature. The weight of each glass slide was measured by microbalance (KERN, ALS 220-4) as shown in Figure 9. The sensitivity of microbalance was in range of 0.0001 g to 220g. Small plastic bags were weighted before use to carry glass slides. The glass slides were kept in open atmosphere under a controlled environment so that self-cleaning can only occurs by means of natural wind. Total of 30 glass slides (10 sets, each containing 1 TMCS, 1 HMDS and 1 uncoated glass sample) were placed for dust measurement test. Glass samples were numbered as shown in Figure 10 where any number without alphabet represents uncoated sample, alphabet A represents sample coated with TMCS and B represents sample coated with HMDS.

![Figure 9. Microbalance (KERN, ALS 220-4)](image)
After 15 days, 5 sets of samples were selected to measure the total weight of the glass slide. Then the weight of the dust was calculated by subtracting the initial weight (weight of glass slide + weight of plastic packets) from the final weight.

2.2.4. Self-cleaning with the aid of water
Although the main purpose of such coatings is to achieve self-cleaning of dust particles in the presence of natural wind but sometimes it may not work well in some areas where wind velocity is very slow like plain areas of Khyber Pakhtunkhwa, Pakistan. Therefore, to evaluate and proof the possibility of self-cleaning, another test can be performed which is to analyze the self-cleaning phenomenon under the action of water. The weight of dust sprinkled on each sample was measured by means of microbalance which was around 0.4506 grams and the particle size was 74 microns which was measured with the help of a sieve. The samples were placed with 20° angle of tilt so that water droplets can easily roll over its surface under the action of gravity as shown in Figure 11. Then same amount of water (5 drops per sample=1ml) was poured by means of a dropper and self-cleaning was observed with naked eye.

3. Results and discussion

3.1. Comparison of water contact angle
Water contact angle predicts the behavior of water droplet on a solid surface. Total of 30 glass slides (10 sets, each containing 1 TMCS, 1 HMDS and 1 uncoated glass sample) were taken and their water contact angles were measure and compared. Images taken for 1 set of glass slides are shown in Figure 12. For each category, an average value of 10 sets has been taken and compared with each other as shown in Table 2. It is clearly shown that TMCS sample has achieved the maximum average WCA followed by HMDS and uncoated sample. The high WCA of 68.96° is because of high non-polar nature of TMCS as compared to HMDS. The percent increase in WCA for TMCS was 149% while in case of HMDS, it was 48%. Although the WCA for both coatings was less than 90° showing that the surfaces are still hydrophilic but the increase in WCA means that it has increased the hydrophobicity of the glass
surface. On the basis of such results, it can be concluded that TMCS can be used to enhance the hydrophobic behavior of any solid surface especially for those surfaces having the WCA greater than 90°. Moreover, the maximum WCA in case of TMCS coating witnessed that it has better hydrophobic behavior than HMDS and uncoated sample.

![Figure 12. Water contact angles of (a) uncoated sample, (b) HMDS sample, (c) TMCS sample](image)

| Table 2. Comparison of water contact angle (degrees) |
|-------------------------------------------------------|
| Sample No. | WCA for Uncoated sample | WCA for HMDS | WCA for TMCS |
|------------|--------------------------|--------------|--------------|
| 1          | 30.75                    | 38.26        | 65.46        |
| 2          | 25.88                    | 38.50        | 65.96        |
| 3          | 32.87                    | 38.75        | 66.12        |
| 4          | 23.98                    | 40.78        | 67.20        |
| 5          | 29.99                    | 40.90        | 69.19        |
| 6          | 28.32                    | 41.41        | 69.51        |
| 7          | 26.52                    | 41.97        | 70.53        |
| 8          | 27.02                    | 42.34        | 71.03        |
| 9          | 24.22                    | 42.50        | 71.10        |
| 10         | 26.77                    | 43.34        | 73.51        |
| Mean       | 27.63                    | 40.87        | 68.96        |

3.2. Spectrometry
The chemical coating over a glass surface may affect its transmittance characteristics. In this regard, UV-Vis-NIR spectrometry was utilized to investigate the effect of TMCS and HMDS coating on the transmittance of glass slides in electromagnetic spectrum having wavelength range of 250-900nm which is the working range of PV modules. Figure 13 shows the variation of percent transmittance and solar intensity with wavelength for uncoated, HMDS and TMCS coated samples. It can be noticed that percent transmittance increases when the wavelength increases from 250nm to 320nm. Moreover, the percent transmittance becomes almost constant when wavelength further increases from 320nm. It is also obvious that maximum transmittance has been observed for uncoated glass slides i.e. up to 90%.
Furthermore, it has been observed that the transmittance of coated glass slides starts later than uncoated glass slides in the UV region which improves the efficiency of PV module. It is due to the fact that UV light heats up solar cells, which causes reduction in the performance of PV module. In the visible region, the transmittance of coated samples is relatively less than that of uncoated sample. This reduction in transmittance can be compensated by the increase in WCA of coated samples.

3.3. Dust measurement

The main aim of this study was self-cleaning of dust with the aid of natural wind but it was examined that there was no significant effect of self-cleaning through wind in open atmosphere. To investigate this effect, 10 sets of glass slides were divided into two groups and both were placed at the rooftop of University of Engineering and Technology (UET) Peshawar, KPK, Pakistan. For the first 5 sets of glass slides, the amount of dust accumulated was measured after 15 days and compared with each other as given in Table 3. Although there was no significant difference between the dust accumulated on coated and uncoated samples; however, the maximum dust was accumulated over HMDS samples followed by TMCS and uncoated samples. Moreover, it was observed that the coated sample accumulates more dust over its surface as compared to uncoated sample after 15 days.

Table 3. Comparison of dust accumulation after 15 days

| Sample No. | Dust on Uncoated sample (g) | Dust on HMDS sample (g) | Dust on TMCS sample (g) |
|------------|-----------------------------|-------------------------|-------------------------|
| 1          | 0.4625                      | 0.4587                  | 0.4652                  |
| 2          | 0.4271                      | 0.4787                  | 0.4486                  |
| 3          | 0.4440                      | 0.4700                  | 0.4680                  |
| 4          | 0.4476                      | 0.4350                  | 0.4502                  |
| 5          | 0.4582                      | 0.4834                  | 0.4498                  |
| Mean       | 0.4479                      | 0.4652                  | 0.4564                  |
Similarly, for next five sets of glass slides, the amount of dust accumulated was measured after 30 days and compared with each other as given in Table 4. It is clear that the maximum dust was accumulated on uncoated sample followed by HMDS and TMCS after 30 days which means that coatings helped to prevent some amount of dust accumulation which was not so after 15 days reading.

Table 4. Comparison of dust accumulation after 30 days

| Sample No. | Dust on Uncoated sample (g) | Dust on HMDS sample (g) | Dust on TMCS sample (g) |
|------------|-----------------------------|------------------------|------------------------|
| 1          | 0.5555                      | 0.6315                 | 0.6745                 |
| 2          | 0.5979                      | 0.6941                 | 0.5831                 |
| 3          | 0.6666                      | 0.7050                 | 0.6318                 |
| 4          | 0.7161                      | 0.5655                 | 0.6302                 |
| 5          | 0.6873                      | 0.6042                 | 0.6735                 |
| Mean       | 0.6445                      | 0.6400                 | 0.6386                 |

Although self-cleaning through wind is not significant in the present study but the comparison of Table 3 and Table 4 shows that the effect of self-cleaning increases as the time span increases. Therefore, it can be concluded that TMCS and HMDS coating take some time to show their effects of self-cleaning through natural wind.

3.4. Self-cleaning with water

Although the main purpose of this study was to achieve self-cleaning of dust particles in the presence of natural wind but the results obtained was not significant. Therefore, another procedure was performed to examine the effect of coating on self-cleaning with the aid of water. In this regard, specific amount of water was sprinkled on each glass slides and the then water droplets were poured on them and self-cleaning was observed as shown in Figure 14.

Self-cleaning with the aid of water clearly shows that TMCS sample ensures maximum cleaning of dust as compared to HMDS and Uncoated glass. Moreover, no trail of water was left in the case of TMCS while mud is formed on uncoated and HMDS samples. Therefore, it can be concluded that TMCS is a promising candidate for self-cleaning under the action of water. This is probably due to high water contact angle for TMCS sample which reduces the friction for same amount of water droplet as on HMDS and uncoated surface. This reduction in friction will result in ease of mobility of water droplet which in turn can easily carry out dust along with it.

4. Conclusions

In the present study, an attempt has been made to prevent the surface of PV module from dust accumulation by use of chemical coatings. The chemicals used in this study were trimethylchlorosilane (TMCS) and heaxmethyldisilazane (HMDS) and tests were performed using glass slides for coating. The performance of glass slides coated with TMCS and HMDS was compared with each other and with uncoated glass slides. For this comparison, some important characterization techniques were used such as measurement of water contact angle (WCA), spectrometry, dust measurement, and self-cleaning with water. Some important conclusions that have been drawn from this study are:
Figure 14. Comparison of self-cleaning effect for (a, b) uncoated sample, (c, d) TMCS sample, (e, f) HMDS sample

- The maximum WCA has been achieved by samples coated with TMCS followed by HMDS and uncoated sample. The high WCA of 68.96° is because of high non-polar nature of TMCS as compared to HMDS. Moreover, the percent increase in WCA for TMCS was 149% while in case of HMDS, it was 48%

- Although the WCA for both coatings (TMCS and HMDS) was less than 90° showing that the surfaces are still hydrophilic but the increase in WCA means that it has improved the hydrophobicity of the glass surface. On the basis of such results, it can be concluded that TMCS can be used to enhance the hydrophobic behavior of any solid surface especially for those surfaces having the WCA greater than 90°

- It has been observed that the transmittance of coated glass slides starts later than uncoated glass slides in the UV region which improves the efficiency of PV module. It is due to the fact that UV light heats up solar cells, which causes reduction in the performance of PV module

- The percent transmittance of TMCS and HMDS sample is slightly less than uncoated sample which is due to coating layer that has been deposited over glass slides during coating. However,
this reduction in transmittance is not so damaging as compared to the expected reduction in transmittance of solar panel with the passage of time when exposed to dust in atmosphere without coating.

- Although self-cleaning through wind is not significant in the present study but the comparison of data for 15 days and 30 days shows that the effect of self-cleaning increases as the time span increases. Therefore, it can be concluded that TMCS and HMDS coating take some time to show their effects of self-cleaning through natural wind.

- The increase in WCA causes reduction in friction that result in ease of mobility of water droplet which in turn can easily carry out dust along with it. Self-cleaning with the aid of water clearly shows that TMCS sample ensures maximum cleaning of dust as compared to HMDS and Uncoated glass. Moreover, no trail of water was left in the case of TMCS while mud is formed on uncoated and HMDS samples.

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