

Green-precursor sol-gel synthesis of transparent hydrophobic silica coatings with improved self-cleaning durability

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ABSTRACT

Solar energy has become a prominent source of renewable energy; nevertheless, the dust accumulation on solar glass has been a significant contributing factor in the reduction of light transmission and power output. In this research, a green precursor sol-gel process is proposed for the fabrication of transparent hydrophobic silica coatings with enhanced self-cleaning durability for solar glass. The application of environmentally friendly precursors allowed for the fabrication of a hybrid silica matrix with low-surface-energy functional groups, which exhibited high optical transmittance (>90%) and long-lasting hydrophobicity. The effect of modifying agents such as phenyltriethoxysilane (PTES) and trimethoxyoctylsilane (TMOS) was examined for different molar ratios, as well as the incorporation of silica particles (0.04-0.063 μm). The optimal composition, obtained at a TEOS/TMOS ratio of 1:4 with the incorporation of silica particles, exhibited a water contact angle of 107.54° and a self-cleaning efficiency of 94.45% using the blade-coating technique. The durability test revealed minimal degradation in hydrophobicity after repeated washing cycles, which was attributed to the enhanced cross-linking and surface morphology introduced by the green sol-gel process. When tested on solar panels, the coating demonstrated an enhancement in current and power output of up to 43.75% compared to the uncoated solar panels under dusty conditions. In conclusion, this research work presents a green and efficient sol-gel process for the fabrication of transparent, hydrophobic, and self-cleaning silica coatings for solar glass.

Keyword: *Green sol-gel synthesis, Hydrophobic silica coatings, Self-cleaning durability, Silane modification*

1. INTRODUCTION

Solar energy is a renewable energy source that best demonstrates the advantages of sustainability, cost-effectiveness, environmental friendliness, noiseless operation, space efficiency, and improved energy security and independence [1]. Currently, solar panels have gained widespread acceptance because of their capacity to harness sunlight to produce electricity. Recently, solar panels have been identified as the most cost-effective solution to produce new electricity in different parts of the world, which is expected to trigger more investment in the coming years. As a result, they have become relatively cheaper and more accessible to both households and industries. However, the dust accumulation on solar panels affects the efficiency of solar energy absorption. Therefore, different studies have been performed to overcome this problem.

One of the natural self-cleaning mechanisms that can be emulated is the phenomenon observed in lotus leaves, which exhibit inherent self-cleansing properties due to their unique surface structure. Self-cleaning surfaces have several advantages in terms of cost efficiency and the conservation of clean water resources compared to energy-consuming surface cleaning. The water-repellent nature of

self-cleaning surfaces minimizes the adhesion of dust particles. Consequently, most solid contaminants are weakly attached and can be effectively removed through the rolling action of rain droplets [2]. To achieve hydrophobic surface characteristics, various methods have been employed to modify surface texture. These methods include prototyping, phase separation, electrochemical deposition, plasma processing, electrospinning, sol-gel processing, plasma spraying, and lithography [3,4]. Among these techniques, the sol-gel process is frequently used for the fabrication of hydrophobic coatings due to its advantages, which include higher homogeneity, improved consistency of raw materials, low processing temperatures, and the ability to produce a range of products from thin films to composites [5].

The sol-gel process is the synthesis of small silica molecules to produce transparent glass materials, which involves the formation of a colloidal suspension solution (sol) to form a homogeneous network (gel) under mild conditions. The process steps begin with a series of hydrolysis reactions (water reacts with metal alkoxide precursors) followed by condensation of sodium silicate to form metal-oxygen-metal [6]. This silica network formation reaction will only occur in the presence of a catalyst such as an acid (HCl) or

base (NH_3). During this process, the metal alkoxide group such as TEOS is hydrolyzed to produce silanol. Then, the silanol and ethoxy groups undergo polymerization through a condensation process resulting in the formation of a siloxane network (Si-O-Si), which forms the overall structure of the silica [4,5]. The hydrophobicity alone is insufficient for long-term self-cleaning performance thus, systematic investigations and optimization silane ratio that combine green sol-gel precursors with silane modifiers and silica particle reinforcement remain limited.

The preparation of various silane-functionalized groups as modifying agents is essential for achieving effective hydrophobicity during the sol-gel process. The hydrophobic properties of a modifying agent can be attributed to non-polar substituents, such as fluorinated hydrocarbons or aliphatic hydrocarbons. However, the use of a fluorinated modifying agent is not economically viable due to its high cost and environmental toxicity [7,8]. Thus, non-fluorinated modifying agents have been selected as alternatives. Additionally, researchers have modified the formulation by incorporating fillers or reinforcement agents during the process to enhance efficiency comparable to that of fluorinated alkyl silane. The wettability of the coating improved while maintaining transparency at 89% through the incorporation of silica particles as fillers [9].

In this research, green superhydrophobic coatings were developed through the sol-gel method due to its simplicity, lower chemical consumption, minimal waste generation, and suitability for scalable industrial applications, thereby supporting the development of environmentally friendly hydrophobic coatings. Previously, conventional hydrophobic coating techniques often involve the use of fluorinated compounds, hazardous solvents, and energy-intensive processing methods, which may raise environmental and sustainability concerns. In contrast this study, used different type greener organosilanes precursors agent namely trimethoxyoctylsilane (TMOS) and phenyltriethoxysilane (PTES), molar ratio between agents and amount of silica filler on the overall performance of the sol-gel coating have been investigated. Since conventional laboratory coating are not appropriate for industrial-scale applications, new simple techniques such as brush coating, bar rolling, and blade coating have been proposed. The hydrophobic self-cleaning coated surfaces was assessed, and the coating liquid was then applied to real solar panels, with the outcomes monitored and regulated via Internet of Things (IoT) technology. This study offers a promising technology for the application of self-cleaning hydrophobic coatings on solar panels, which has the potential to improve performance, extend lifespan, advance sustainability, and optimize the cost-effectiveness of solar panels.

2. EXPERIMENTAL

2.1. Materials

The components of the sol-gel method for preparing the coating solution are: TEOS as the aggregating agent, and TMOS and PTES as the modifying agents, which were purchased from Merck, Germany. The silica particles with sizes of 0.04-0.063 mm, 0.063-0.2 mm, and 1-5 μm were

purchased from Sigma-Aldrich, Germany. The other chemicals, such as hydrochloric acid (HCl), sodium chloride, methanol (MeOH), nanoclay, and graphite, were purchased from Sigma-Aldrich, United States.

2.2. Coating Solution Preparation

Two modifying agents, trimethoxyoctylsilane (TMOS) and phenyltriethoxysilane (PTES), were employed in the sol-gel solution preparation. In this mixture, TEOS was the main network-forming (aggregating) component, and it was mixed with methanol and water in a fixed molar ratio of (TEOS:TMOS/PTES):MeOH:H₂O = 1:5:4. Amounts of TEOS, methanol, and water were kept constant, the type of modifying agent and ratio was varied (refer Table 1) to evaluate its influence on hydrophobic performance. Initially, 4.05 mL of methanol was mixed with 4.43 mL of TEOS in a 50 mL beaker, and the solution was sonicated for 10 minutes at room temperature to ensure homogeneous mixing.

The ratios of TEOS/PTES and TEOS/TMOS (1:4 and 1:6) were varied to study the effect of different ratios of modifying agents, whereby, a total of 4.8 mL of PTES or 10 mL of TMOS were mixed into the mixture of TEOS and methanol solution. The mixture was mixed for 30 minutes using a sonicator to facilitate binding and achieve perfect mixing. Then, 0.1 M HCl (0.1 mL) was added slowly using a micropipette, followed by the addition of 2.2 mL of distilled water. The mixture was further modified by incorporating silica particles of varying sizes (0.04–0.063 mm and 0.063–0.2 mm). The resulting mixture was then agitated using a shaker for 2 h (250 rpm) at 25 °C. The solution mixing was stopped after 2 hours of continuous stirring and a transparent solution was obtained.

2.3. Preparation of Coating Techniques

Microscope glass slides measuring 75 mm × 25 mm were used in this study. Before use, the glass was cleaned using a mixture of 5% sulfuric acid and 5% methanol with distilled water. Then, the glass soaked in this mixture sonicator for 5 minutes. Later, the cleaned glass slides underwent a sol-gel solution coating process using the micropipette droplet delivery system with a volume of 1 mL. The micropipette and glass slide were positioned at a fixed distance of 1 cm. Next, three different coating methods were used and modified according on previous work. In the brush method, the dropped solution was deposited on the glass slide using a soft brush at 25 °C, followed by drying in an oven at 70 °C for 30 min to remove any residual solvent before the polymerization step [10]. In the bar rolling method, the applicator was moved slowly to ensure uniform distribution of the coating material on the glass slide [11]. In the blade method, 1 mL of the coating material was placed in front of the blade, which moved parallel to the surface of the glass slide, resulting in the formation of a wet film [12]. The glass slides coated with the sol-gel solution were then placed in an oven at 100°C for 2 hours to facilitate the polymerization process. After heating, the samples were cooled and stored at room temperature before the contact angle measurement process.

2.4. Characterization of the Coating Samples

The Water Contact Angle (WCA) images of the coated glass were captured using a camera phone equipped with a macro lens. Subsequently, the images were transferred to a computer for analysis using ImageJ software. A water droplet with a volume of 1 μL was used for WCA measurement.

The surface morphology of the coated glass was analyzed using a scanning electron microscope (Zeiss/EVO-MA10, Germany). Before scanning, the samples were coated with a thin platinum layer for 5 minutes to improve image clarity and surface reflectivity.

Fourier transform infrared (FTIR) spectroscopy was conducted using Perkin-Elmer Spectrum (version 10.03.06). Both uncoated and coated glass samples were cut into 1 cm $\times$ 1 cm pieces and analyzed using the attenuated total reflectance (ATR) technique over a wavelength range of 500–4,000 nm to identify the functional groups present on the coated surfaces.

The transparency of the samples was determined using an ultraviolet-visible (UV-vis) instrument (model UV-1900, Shimadzu, Japan) to measure the transmittance and reflectance of light through the coated glass samples across a wavelength range of 300–800 nm. The sample was positioned in the sample holder, while a clean, uncoated glass sample was placed on the blank holder, both on the UV-vis instrument.

2.5. Evaluation of Dirt Accumulation and Self-Cleaning Efficiency

The glass surface was sprayed with a prepared artificial dirt solution. The artificial dirt was formulated by mixing 0.85 g of nanoclay with 0.1 g of silica nanoparticles, followed by the addition of approximately 0.02 g of oil, 0.18 g of graphite, and 0.02 g of salt. The mixture was then stirred thoroughly to obtain a homogeneous, cloudy suspension. Next, the dirt mixture was dispersed in water at a concentration of 10 g/500 mL. The resulting artificial dirt solution was sprayed on the glass-coated materials and allowed to dry overnight before being heated at 60 $^{\circ}\text{C}$ for 1 h. A spectrophotometer was used to monitor changes in lightness (L) values to evaluate the accumulated dirt and self-cleaning efficiency of the coated glass. The L value was then measured using the spectrophotometer. The percentage of accumulated dirt and self-cleaning efficiency were calculated using Eq. 1 and Eq. 2, respectively [13].

Percentage of dirt accumulation

$$= \frac{L_1 - L_2}{L_1} \times 100\% \quad (1)$$

Self-cleaning efficiency

$$= 100 - \left(\frac{L_1 - L_3}{L_1} \right) \times 100\% \quad (2)$$

where the L value for the coated glass sample in the absence of accumulated dirt is denoted as L_1 , while L_2 represents the L value measured after the dirt solution was sprayed onto the sample (12 pumps, approximately 10 mL) and allowed to dry. The L value was evaluated again as L_3 for the coated glass sample following clean water (12 pumps, approximately 10 mL).

2.6. Durability

During the abrasion process, the sandpaper (320 Cw) was in constant contact with the coated glass surface in a back-and-forth motion for a period of 10–20 abrasion cycles. This process was carried out on all glass coating samples prepared using different methods. The strength of the glass coating was determined using UV-vis spectroscopy and scanning electron microscopy (SEM), which gave an estimate of the light transmittance and surface topography, respectively.

2.7. Application of Hydrophobic Coatings on Solar Panels

The hydrophobic coating solution was applied to the surface of a solar panel with a size of 275 $\times$ 180 mm². The coating solution was applied at an angle of 45 $^{\circ}$ to the top surface of the solar panel. Later, a glass wiper, which acts as a blade, was used to distribute the solution evenly across the surface of the solar panel. The performance of the solar panel was measured using a voltage sensor, which relayed the voltage output to an ESP32 microcontroller for processing. The IoT system was developed using an ESP8266 Wi-Fi module, which enabled the real-time display of voltage values from the solar panels on a cloud-based system, hence enabling remote monitoring by the user. The data was collected over a period of 7 days and averaged to provide the current and power voltage values.

3. RESULTS AND DISCUSSION

3.1. Synthesis and Characterization of Glass Coating Materials

3.1.1. Water Contact Angle (WCA)

Figure 1 illustrates the water droplets and their corresponding contact angles on the different coated surfaces. Among the samples, the TEOS/TMOS-coated surface exhibited the highest contact angle (93.41 $^{\circ}$), followed by TEOS/PTES (89.88 $^{\circ}$) and TEOS alone (76.48 $^{\circ}$). In contrast, the uncoated glass showed the lowest WCA (42.49 $^{\circ}$). The water droplets on the uncoated glass and TEOS surfaces appeared relatively flat compared to those on the TEOS/PTES and TEOS/TMOS coated system. This behavior can be attributed to the hydrophilic nature of the glass and TEOS surfaces, which contain hydrolyzable silanol groups that promote stronger interaction with water.

The hydrophilic nature of silica films is mainly due to the presence of surface silicon dioxide (SiO₂) groups, which enhance water adsorption through their strong affinity for

water molecules. Terminal SiO₂ groups that interact with water can result in the degradation of siloxane bond network. Consequently, both clear glass and TEOS coating exhibit hydrophilic characteristics. Meanwhile, the WCA enhancement can be seen with the integration of hydrophobic groups of the modifying agents (i.e., PTES and TMOS). A similar observation was reported by Raditoiu and co-workers in their study on the fabrication of anti-reflective coatings using hydrophobic silica coating produced through the sol-gel process [14].

Replacing the ethoxy groups in the TEOS molecule with hydrophobic silane groups enhances the water-repellent nature of the surface. When organic groups such as phenyl group and octyl alkyl chain are introduced, they substitute the hydrogen atoms of the surface hydroxyl (–OH) groups, forming a more stable, non-hydrolyzable layer on the glass surface. As a result, the original silanol groups are replaced by alkyl-silyl groups, lowering the surface energy and producing a hydrophobic coating. [14].

The higher WCA observed for TEOS/TMOS (93.41°) compared to TEOS/PTES (89.88°) is mainly due to the long chain octyl groups in TMOS, which impart greater hydrophobicity than phenyl groups, along with its lower molecular weight that promotes improved surface modification. This observation aligns with the findings reported by Kumar and co-workers in their study on the effect of functional groups on hybrid sol-gel silica coatings [15]. Furthermore, the longer carbon chains on the glass surface of TMOS, as opposed to those of PTES, lead to the formation of the most hydrophobic surface [16].

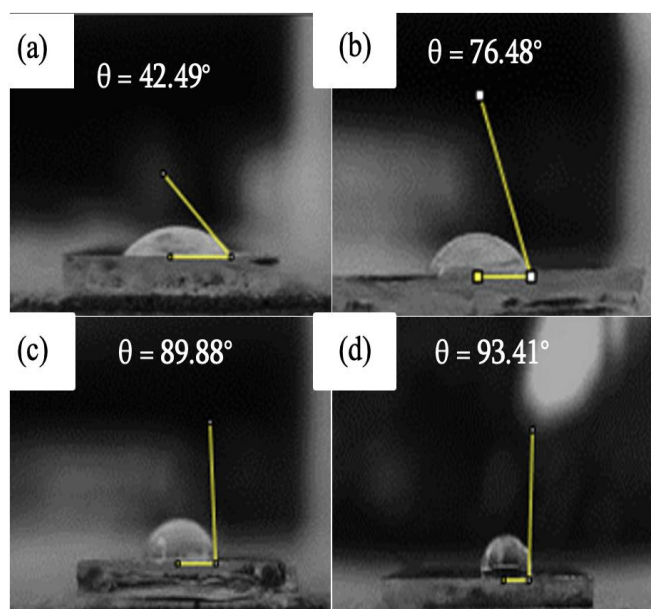


Figure 1. Water contact angles with different modifying agent: (a) glass only, (b) TEOS only, (c) TEOS/PTES, and (d) TEOS/TMOS

3.1.2. Fourier Transform Infrared Spectroscopy Analysis

The FTIR spectra shown in Figure 2 display the functional groups detected on the coated glass surfaces. The uncoated glass is indicated by the green line, whereas the TEOS,

TEOS/TMOS, and TEOS/PTES coatings are represented by the red, blue, and black lines, respectively. This analysis allows for a clear comparison of the chemical structures present in each sample. As seen in Figure 2, the peaks found between 1230 and 1000 cm⁻¹ are assigned to the bending modes of Si-O-Si bonds, and these peaks are found in all the coated glass samples. For the uncoated glass and the glass coated with TEOS alone, the peaks are found at 1223 cm⁻¹ and 1210.4 cm⁻¹, respectively.

For TEOS modified with TMOS and PTES, the peaks become sharper and stronger at 1056.8 cm⁻¹ (TEOS/TMOS) and 1049.9 cm⁻¹ (TEOS/PTES). In both instances, the peaks have shifted to lower wavenumbers. This indicates a reduction in the Si-O bond force constant, and this can be attributed to the presence of alkylsilane groups within the silica matrix. The appearance of these distinct peaks indicates the successful creation of a cross-linked silica layer on the glass surface.

Notably, the peak observed in the TMOS-containing coating is sharper and more prominent than that of the PTES-modified sample. This trend can be attributed to the higher affinity between the inorganic silica network and the organic functional groups in the TMOS system. The trend suggests that TMOS has a higher affinity to facilitate hydrophobic interactions, allowing it to form an independent structure without relying much on other alkoxysilane agents. This trend is consistent with the WCA measurement values, which indicate that TMOS is a low polarity compound than PTES.

Moreover, an absorption bands corresponding to the C-H stretching vibrations were found in the range of 3000-2800 cm⁻¹. These bands are typical for the C-H stretching vibrations in -CH₃ and -CH₂ groups. For the TMOS-modified coating, the absorption bands were found at 2920.0 and 2847.7 cm⁻¹, which indicate more intensive C-H stretching vibrations compared to the PTES-modified coating, which showed absorption bands at 2932.2 and 2854.0 cm⁻¹. This indicates that the octyl group in TMOS enhances more hydrophobic interactions because of the higher hydrocarbon content. This result is in agreement with the previous studies that used octyltriethoxysilane (OTES) as a modifying agent in sol-gel coatings, where the enhanced hydrophobic properties were explained by the presence of long-chain alkyl groups [17].

Furthermore, additional absorption bands detected at 895.58 cm⁻¹ and 892.43 cm⁻¹ are assigned to the stretching vibrations of Si-C bonds associated with the octyl and phenyl functional groups. Similar spectral features were reported by Lin *et al.* in their characterization of PTES-based sol-gel coatings [18], confirming the successful incorporation of PTES as an organic modifier on the glass surface.

Overall, these results indicate that the organosilicon groups in both TEOS/TMOS and TEOS/PTES systems effectively substitute the hydrogen ions of surface Si-OH groups, leading to the formation of hydrophobic surface functionalities on the coated glass

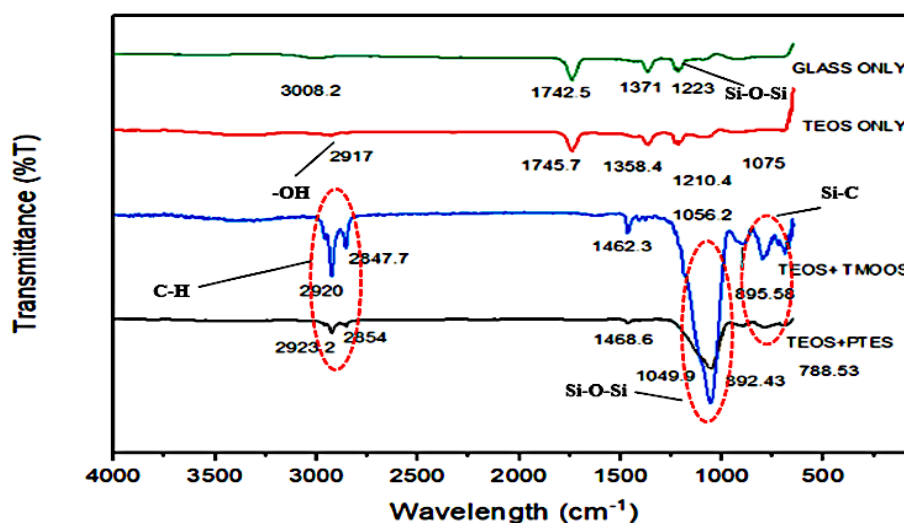


Figure 2. Fourier transform infrared spectra of the glass-coated surfaces

3.2. Optimization of Synthesis Parameters for Enhanced Hydrophobicity, Dust Accumulation Reduction, and Improved Self-Cleaning Efficiency

3.2.1. Different Ratios of Modifying Agents

A comparable trend was observed in the TEOS/PTES system, where the water contact angle (WCA) increased from 89.87° to 91.20° as the molar ratio was adjusted from 1:4 to 1:6. This improvement in hydrophobicity can be attributed to the greater presence and surface coverage of phenyl groups, which enhance the adhesion of hydrophobic functionalities onto the glass substrate. Such behavior agrees with earlier studies reporting that variations in the proportion of modifying agents significantly influence the surface properties of sol-gel derived glass coatings [18].

In contrast, a different pattern was observed for the TEOS/TMOS system. Increasing the molar ratio to 1:6 resulted in a decrease in WCA to 81.42°, compared to 93.41° at the 1:4 ratio. This reduction in hydrophobic performance may be associated with excessive incorporation of non-polar octyl groups, leading to near-complete substitution of surface hydroxyl (Si-OH) hydrogen ions. At higher concentrations, the system may approach a saturation threshold, beyond which further addition of TMOS does not enhance and may even hinder the formation of an optimally structured hydrophobic layer. Consequently, the 1:6 ratio appears to exceed the effective limit for improving surface hydrophobicity in this formulation.

3.2.2. Incorporation of Silica Particles

The effect of adding silica particles as fillers to the TEOS/modifying agent system was also investigated. In this experiment, two ranges of particle sizes were used, namely 0.04-0.063 mm and 0.063-0.2 mm. As shown in Table 1, the results of the water contact angle measurements indicate that the maximum hydrophobicity of 99.28° was achieved using the smaller silica particles with a size range of 0.04-0.063 mm and a TEOS/TMOS ratio of 1:4. However, when the ratio was increased to 1:6, a decrease in hydrophobicity was noted. This is in line with the previous discussion that showed a high TMOS content could cause surface saturation, thus preventing further improvements in hydrophobicity [19].

In the TEOS/PTES system, the maximum WCA of 96.33° was achieved when the smaller silica particles (0.04-0.063 mm) were added with a TEOS/PTES molar ratio of 1:6. This finding clearly shows that smaller particle sizes are important factors in improving the hydrophobicity of the surface. This can be attributed to the better dispersion of the smaller silica particles in the coating matrix, which results in higher surface roughness and, hence, better water repellency [20].

Apart from the effect on surface wettability, the addition of silica fillers also enhances the mechanical properties of the coating. The addition of the fillers increases the surface hardness of the coating, thus offering a higher degree of

protection to the glass substrate. The combined effect of the factors not only enhances the durability of the coating but also helps in the creation of stable hydrophobic properties [21].

3.2.3. Accumulated Dirt Reduction and Improved Self-Cleaning Efficiency

Environmental dust accumulation on solar panel surfaces can significantly impair their self-cleaning functionality, leading to reduced light transmission and overall efficiency [20]. The situation becomes more critical when rainwater

interacts with deposited dust, forming adhered dirt layers on the glass surface that are more difficult to remove.

To evaluate this effect under controlled conditions, artificial dirt was sprayed onto the glass coating surfaces, and its impact on optical transmittance as well as self-cleaning efficiency was assessed. Table 1 summarizes the hydrophobicity (WCA), optical transparency, percentage of dirt accumulated and corresponding self-cleaning efficiency for all coated glass samples prepared under different formulation parameters.

Table 1. Optimization of accumulated dirt and self-cleaning efficiency of different hydrophobic coatings

TEOS/ Modifying Agent	Ratio/Silica range	WCA (°)	Transparency (%)	Accumulated Dirt (%)	Self-Cleaning Efficiency (%)
TEOS/PTES	1:4	89.87	76.3	29.94	76.93
	1:6	91.20	78.7	26.43	79.92
TEOS/TMOS	1:4	93.41	86.6	12.82	89.38
	1:6	81.41	85.2	15.02	86.97
TEOS/PTES	1:4/0.04–0.063 mm	93.56	85.7	18.32	93.47
	1:4/0.063–0.2 mm	92.49	84.5	19.29	89.11
	1:6/0.04–0.063 mm	96.32	78.4	20.92	97.92
	1:6/0.063–0.2 mm	93.59	86.6	15.36	97.22
TEOS/TMOS	1:4/0.04–0.063 mm	99.28	87.3	7.30	98.17
	1:4/0.063–0.2 mm	96.62	86.1	15.80	81.65
	1:6/0.04–0.063 mm	84.38	94.4	5.51	94.5
	1:6/0.063–0.2 mm	82.67	92.3	45.29	92.52

The experimental findings are discussed in two main aspects: (i) the influence of modifying agents in the absence of silica fillers and (ii) the effect of varying silica particle sizes within the TEOS/modifying agent system. For coatings without silica incorporation, the TEOS/TMOS system at both evaluated ratios demonstrated superior overall performance compared to the TEOS/PTES system. Specifically, TEOS/TMOS (1:4) exhibited higher optical transparency, lower dirt accumulation, and enhanced self-cleaning efficiency. Nevertheless, a slight change in trend was observed when the TEOS/TMOS molar ratio was increased to 1:6. At this ratio, reductions in WCA, transparency, and self-cleaning performance were recorded, which may be attributed to surface saturation or excessive incorporation of the modifying agent. In contrast, the TEOS/PTES system showed comparatively more stable behavior at the higher ratio, as previously discussed. Overall, among the non-filled coatings, the TEOS/TMOS formulation at a 1:4 ratio provides the most balanced combination of surface wettability and anti-dirt performance.

The incorporation of silica particles into both TEOS/modifying agent systems significantly enhanced the hydrophobic and self-cleaning properties of the coatings. In the TEOS/PTES (1:4) formulation, the addition of fine silica particles (0.04–0.063 mm) increased the water contact angle from 89.87° to 93.56° and improved the self-cleaning efficiency from 76.93% to 93.47%. This enhancement

indicates that finer particles promote the formation of a larger effective surface area and increased micro-scale roughness, which in turn strengthens the water-repellent behavior of the coating. Furthermore, when the TEOS/PTES ratio was increased to 1:6 in the presence of fine silica particles, the WCA further increased to 96.32°, and the self-cleaning efficiency reached 97.92%, representing one of the best performances observed within the PTES-based system.

A similar trend was noticed in the TEOS/TMOS system, which showed the maximum enhancement in the presence of fine silica particles. With a molar ratio of 1:4 and particle sizes of 0.04–0.063 mm, the coating showed the highest water contact angle of 99.28°, along with the highest transparency of 87.3%, lowest dirt accumulation of 7.30%, and highest self-cleaning efficiency of 98.17%. This composition is found to be the best among all the samples tested. However, with larger silica particles of 0.063–0.2 mm and a molar ratio of 1:4, the dirt accumulation was found to increase to 15.80%, while the self-cleaning efficiency dropped to 81.65%, which is a drastic decrease.

Notably, an increase in the TEOS/TMOS ratio to 1:6 with fine particles led to an increased transparency of 94.4% and lower dirt accumulation of 5.51%, with a high self-cleaning efficiency of 94.5%, despite the lower WCA of 84.38°. This indicates that the efficiency of self-cleaning is not solely dependent on the WCA, but also on other factors such as surface homogeneity, integrity, and microstructure. On the contrary, the 1:6 mixture with large particles showed a

significantly higher dirt accumulation of 45.29%. In general, the experimental results show that the chemical composition of the coating and the surface microstructure are both essential factors in determining their performance. The addition of more modifying agent does not always result in better hydrophobicity performance; rather, it can cause saturation or even instability beyond a certain optimal point. The addition of fine silica particles (0.04–0.063 μm) is always beneficial in improving the surface properties by increasing the WCA, reducing accumulated dirt and improving the efficiency of self-cleaning. Among all the formulations studied, the TEOS/TMOS ratio of 1:4 with fine silica particles (0.04–0.063 μm) showed the best overall performance. This formulation showed the highest efficiency of self-cleaning (98.17%), the highest hydrophobicity (99.28°), and the lowest dirt accumulation (7.3%).

3.3. Effect of Different Coating Techniques on the Performance of Hydrophobic Silica Coatings

3.3.1. Effect of Different Coating Techniques

The fabrication and characterization of the surface coatings were carried out using clear glass slides as the substrate material. The coating solution consisted of a TEOS/TMOS mixture at a molar ratio of 1:4, with the incorporation of fine silica particles in the size range of 0.04–0.063 μm to enhance surface properties. The previous coating method employed the dropping technique. However, this technique is not feasible for industrial applications. Various simple and cost-effective coating techniques have been developed.

This study focused on three different coating methods: brush, bar rolling, and knife (or blade) coating. Cleaned glass slides served as the control for this study. Table 2 shows the WCA values for different coating techniques: bar rolling coating (106.57°), brush coating (106.86°), and blade coating (107.54°), which attained the highest WCA. Nevertheless, all three coating techniques showed insignificant WCA values.

Table 2. Performance efficiency of different coating techniques

Coating Techniques	WCA (°)	Transparency (%)	Dirt Accumulation (%)	Self-Cleaning Efficiency (%)
Glass	42.49	89.09	67.70	63.3
Drop	99.28	87.3	7.30	98.17
Brush	106.86	68.39	15.98	88.66
Bar Rolling	106.57	59.42	18.35	81.67
Blade	107.54	71.74	4.44	94.45

As presented in Table 2, the uncoated and cleaned glass exhibited the highest transparency (89.09%) among all samples evaluated. This can be attributed to its inherently smooth and uniform surface, which does not contain additional layers or particulates that may interfere with light transmission. In contrast, the application of a hydrophobic coating introduces a material with a refractive index different from that of the glass substrate. This mismatch can promote light scattering and partial reflection at the interface, thereby reducing the overall transparency of the coated glass.

The lowest transparency was obtained by the bar rolled-coated glass slide (59.42%), followed by the brush-coated glass slide (68.39%), and the blade-coated glass slide (71.74%). Meanwhile, the drop-coated glass slide recorded the highest transparency (87.3%), which is nearly equivalent to the light transparency of native glass and superior to that of other coating techniques. The significant light transparency achieved through the drop coating technique is believed to result from most of the silica not adhering to the glass slide; instead, it rolls down to the edges of the glass slide during coating application. This results in only a minimal amount of silica adhering to the surface of the glass slide, thereby explaining the high light transmittance values associated with the drop coating technique, despite its low WCA. The transparency is influenced by several factors, including the thickness, surface roughness, uniformity, and density of silica particles

across the glass surface area [22]. The blade coating enables better control of the coating surface, improves the regularity of silica particle dispersion, and provides a smoother surface, which reduces irregularities that might otherwise influence transparency, as seen in the SEM image. The blade provides a more even application, which reduces the possibility of light scattering and ensures higher transparency. On the other hand, bar rolling provides irregular coating thickness and surface irregularities. The force used in the rolling process might cause waves or stripes on the coating surface, which may result in light scattering as it travels through the material, hence reducing transparency. Brush coating, which involves coating with a brush, faces difficulties in ensuring a smooth and even coating. The brush coating might provide irregular layers, and the brush surface might cause irregularities on the coated surface, hence resulting in light scattering and reduced transparency. The surface roughness, uniformity, and flatness of the silica particles have been observed and proved through SEM imaging.

In general, blade coating showed better transparency, less dirt accumulation, and optimal self-cleaning ability compared to brush coating and bar rolling coating methods. This can be attributed to the ability of the blade coating method to offer a more uniform and controlled application of the coating material. The blade coats the material evenly on the substrate, and this results in a smoother and more transparent coating. The smoother surface promotes

transparency and prevents dirt accumulation. Additionally, the motion of the blade assists in agitating and removing particles, which results in a cleaner surface. The brushes or bars encountering the substrate might cause irregularities on the surface, which could influence transparency and potentially result in areas where dirt can accumulate, leading to increased dirt accumulation over time and potentially allowing more particles to be left on the surface [23].

3.3.2. Durability of Different Coating Techniques

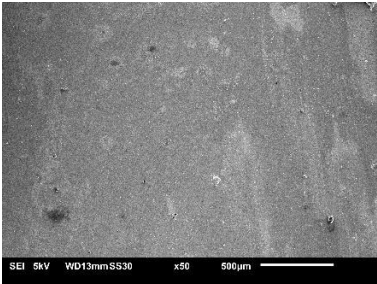
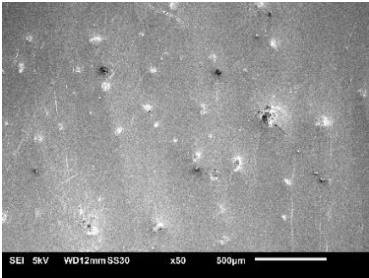
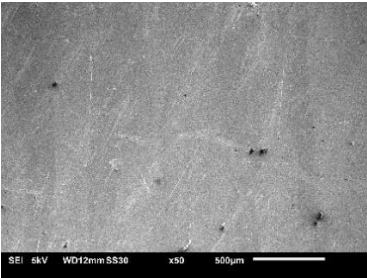
The data of the WCA and transparency before and after abrasion for various coating techniques on glass slides are shown in Table 3. Among the three coating techniques, the blade coating showed the highest value of WCA and transparency, followed by brush coating and bar rolling coating. The better results of the blade coating technique can be ascribed to the fact that it provides a smoother surface with less dust contamination. It is worth mentioning that even after the abrasion test, the blade coating

technique continues to prove its effectiveness as a hydrophobic surface with a high percentage of transparency.

As shown in Table 3, among the three coating techniques, the bar rolling coating technique showed a considerable decrease in transparency (4.5%) compared to the brush and blade coating techniques after abrasion. On the other hand, the variation in the WCA value of the bar rolling coating technique was relatively small, with a difference of only 0.224°. The difference in variations of transparency and WCA values of the bar rolling coating technique can be attributed to the complicated interactions of various parameters, such as coating uniformity, surface roughness, optical properties, material properties, substrate interactions, and microstructural changes. For instance, the bar rolling coating technique may cause microstructural changes in the coating, which may influence the transparency. The transparency values may not necessarily show direct correlation with the WCA values [24].

Table 3. Durability test of WCA and transparency for different coating techniques

Coating Techniques	Before Abrasion		After Abrasion		Differences (Before Abrasion – After Abrasion)	
	WCA (°)	Transparency (%)	WCA (°)	Transparency (%)	WCA (°)	Transparency (%)
Brush	106.858	68.39	106.382	65.41	0.476	2.98
Bar Rolling	106.566	59.42	106.342	54.92	0.224	4.50
Blade	107.538	71.74	106.470	69.71	1.068	2.03

Coating Techniques	Before Abrasion	After Abrasion
None coating	Clean glass (control) 	
Brush	(a) Brush coating 	(b) Brush coating 

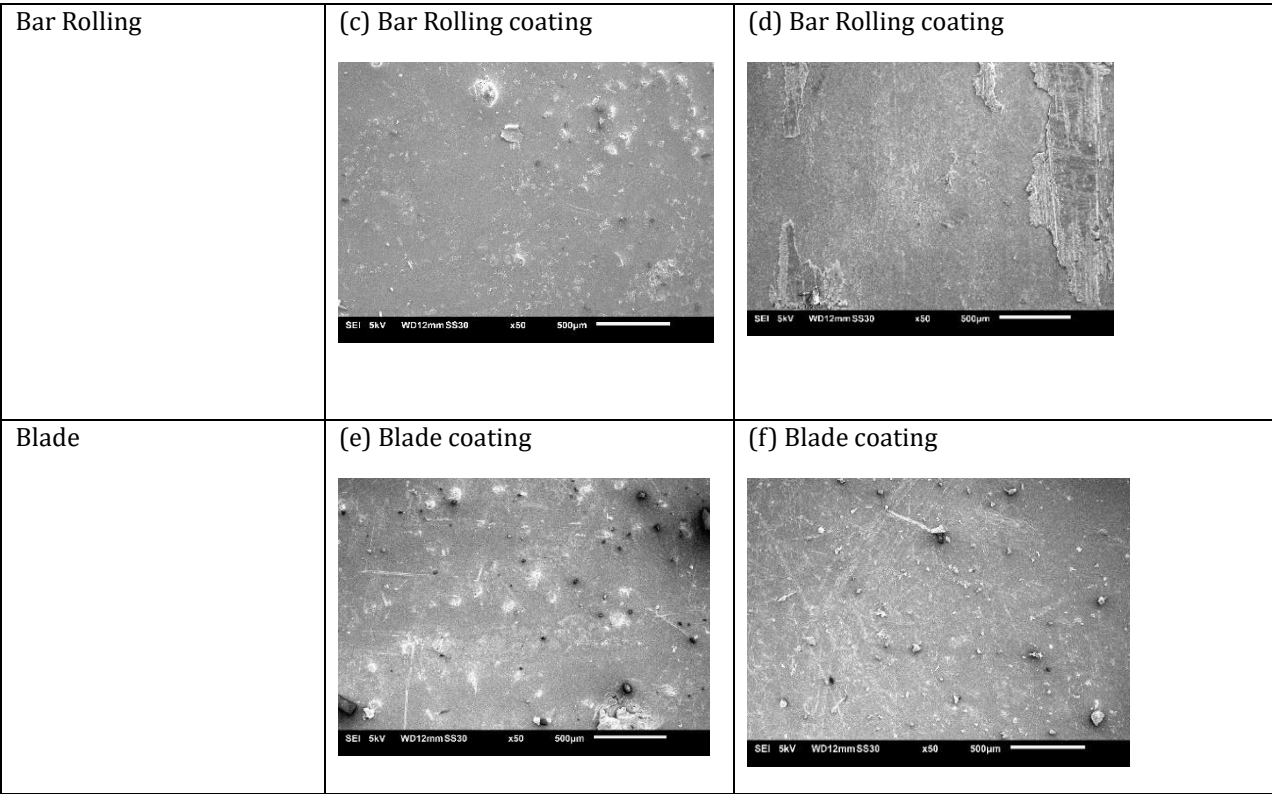


Figure 4. Scanning electron microscopy characterization of different coating techniques before and after abrasion at 50× magnification. Glass slides coating method before abrasion using brush (a), bar rolling (c), and blade (e). While surface morphology of glass slide coating method after abrasion using brush (b), bar rolling (d), and blade (f).

Figure 4 shows the SEM images of various coating methods applied to the top surface of glass slides, both before and after abrasion. The cleaned glass slide is used as a standard reference for the various coating methods applied. Figures 4(a), (c), and (e) illustrate the surface morphology of glass slides coated with brush, bar rolling, and blade coating methods, respectively, before abrasion, while Figures 4(b), (d), and (f) illustrate the surface morphology after abrasion.

It is observed that the uncoated cleaned glass slide had a surface morphology with oily spots, which can be considered as the result of improper cleaning in the initial stages, resulting in the presence of contaminants or residues on the glass surface. Various coating methods were applied to the glass slides with a fixed volume of 1 mL and a uniform composition of the sol-gel solution. Before the application of the abrasive, the surface morphology of all three coated glass slides had a smooth surface with evenly dispersed silica particles.

In Figures 4(b), (d), and (f), each coating method exhibited scratches or grooves on the surface, as the SEM images captured these irregularities and highlighted the damage caused by the sandpaper abrasion test. The surface morphology after abrasion shows that the silica particles experienced fragmentation or breakage due to the abrasive action. This behavior can be explained by the inherent brittleness of silica particles. When exposed to mechanical stress during abrasion, the particles may crack, fragment, or even break completely into smaller pieces. In addition, the abrasive grains in the sandpaper are typically harder than

silica, which further accelerates physical wear and contributes to the degradation of the silicate-based coating. However, the blade coating technique demonstrated substantially higher retention of silica particles compared to brush and bar coating methods, indicating improved particle adhesion and coating stability.

The SEM image obtained from the blade coating method revealed a very flat surface with a uniform distribution of silica particles across the glass slide. This observation is supported by the fact that the blade coating technique achieved the highest WCA and transparency compared to the bar rolling and brush coating methods. In contrast, the SEM image of the bar rolling coating technique showed noticeable surface imperfections, which aligns with its lower WCA and transparency values. This difference may be due to the presence of residual moisture or a partially dried coating layer on the glass slide prepared by the bar rolling method. Such conditions can cause charge accumulation during SEM analysis, potentially leading to issues such as image distortion, blurring, or drifting [25].

3.3.3. Effect of Recycling on Dust Accumulation and Self-Cleaning Performance

The blade coating method shows satisfactory results in terms of WCA, characterization, durability, and self-cleaning ability; therefore, this coating technique was further evaluated for recyclability. In this study, five cycles were conducted, during which the self-cleaning performance and dirt accumulation were assessed, as illustrated in Figure 5.

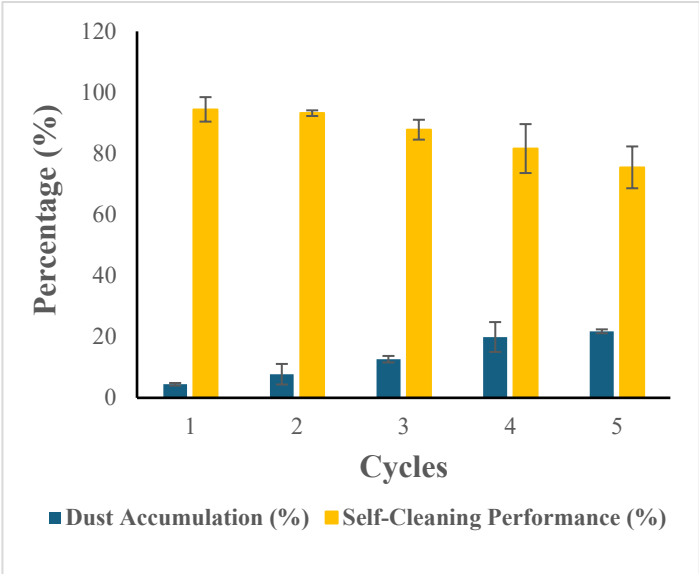


Figure 5. Effect of recycling on dust accumulation and self-cleaning performance for the blade coating technique

The glass prepared using the blade coating method was found to exhibit the most effective self-cleaning performance, and five cycles were carried out to evaluate its recyclability. As shown in Figure 5, dirt accumulation on the glass slides gradually increased with each cycle, while the self-cleaning efficiency showed a slight decline as the number of cycles progressed. From the first to the fifth cycle, the self-cleaning performance decreased by approximately 20%, whereas dirt accumulation increased by about 15%.

Although the surface retained its self-cleaning capability, some contaminants likely remained on the glass after each cycle. Over time, these residual particles can build up, leading to a gradual increase in overall dirt accumulation. Repeated cycling may also cause minor surface changes or degradation, potentially reducing the coating’s ability to repel contaminants or maintain effective cleaning performance [26]. It is also important to consider that the relatively high self-cleaning percentages observed in this study may be influenced using concentrated artificial dirt, which may not fully represent real-world conditions involving natural dust and environmental contaminants.

3.4. Performance Analysis of Hydrophobic Coatings on Solar Panels

Figure 6 illustrates the current-voltage (I-V) and power-voltage (P-V) characteristics of both the hydrophobic-coated and uncoated solar panels. These curves allow for a clear comparison of their electrical performance and highlight the impact of the hydrophobic coating on overall efficiency and power generation.

According to the results, the coated solar panel achieved a 43.75% increase in efficiency compared to the uncoated panel. Based on economic perspective, this efficiency improvement may increase the return of investment (ROI) by 21.88% and shorten the payback period to apporimately 4.57 years. The improvement can be attributed to the enhanced light transmission, reduced dust accumulation, self-cleaning capability, and potential anti-reflective properties provided by the hydrophobic coating, all of which contribute to better energy conversion performance [27].

Graph	Before Coating	After Coating
I-V Curve		

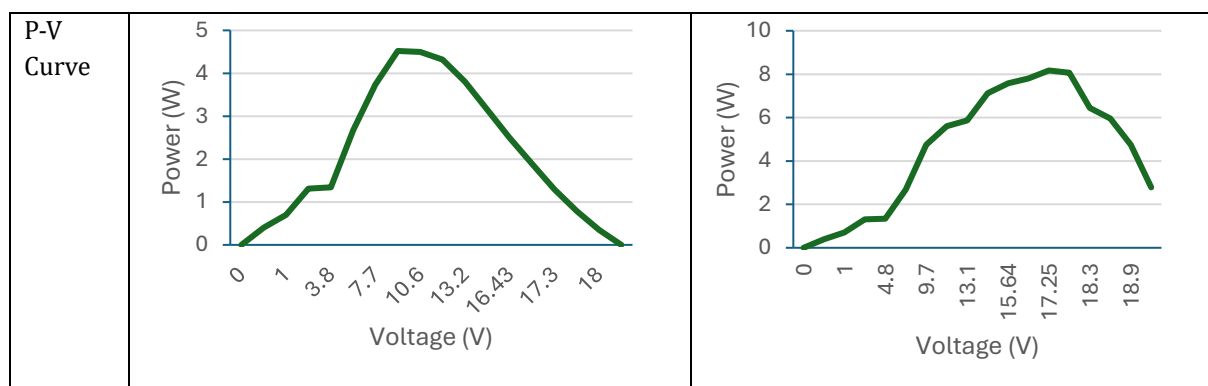


Figure 6. Comparative analysis of I-V and P-V characteristics before and after application of hydrophobic coating

4. CONCLUSION

In summary, an environmentally friendly hydrophobic coating was successfully synthesized using a simple sol-gel method, with TEOS serving as the primary backbone of the silica network. Among the formulations evaluated, the TEOS/TMOS system at a molar ratio of 1:4 exhibited the best hydrophobic performance, achieving a water contact angle (WCA) of 93.41°. While the incorporation of fine silica particles (0.04–0.063 nm) as fillers further enhanced the surface characteristics, increasing the WCA to 99.28° and improving the self-cleaning efficiency to 98.17%. These enhancements are linked to increased surface roughness and improved water-repellent behavior introduced by the fine silica particles. Notably, the blade coating technique led to an even higher WCA of 107.54%, while maintaining high transparency, durability, and self-cleaning efficiency, as well as reducing fouling accumulation.

Importantly, when applied to real solar panels, the optimized hydrophobic coating resulted in a 43.75% increase in power current and voltage compared to uncoated panels. Overall, these findings demonstrate that hydrophobic silica coatings prepared via the blade coating technique offer a practical and scalable strategy for improving solar panel performance, highlighting their strong potential for large-scale industrial implementation.

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