

Development and Performance Evaluation of Silicone-Based Hydrophobic Coatings for Anti-Soiling Applications on Solar PV Glass

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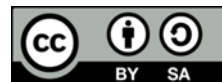
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ABSTRACT

Soiling is a major cause of performance degradation in solar photovoltaic (PV) systems, particularly in tropical environments characterized by high humidity and persistent dust accumulation. This study presents the development and experimental evaluation of silicone-based hydrophobic coatings designed to enhance the anti-soiling and water-repellent properties of PV glass substrates. Three coating formulations with varying silicon dioxide (SiO₂) nanoparticle contents, 2.03 wt% (HC1), 3.34 wt% (HC2), and 0 wt% (HC3), were prepared and systematically characterized. Coating performance was assessed using water droplet mobility tests, static water contact angle (WCA) measurements, and controlled dust-accumulation experiments. Among the formulations, HC2 exhibited the best overall performance, achieving the highest average WCA (94.3°), fastest droplet runoff time (0.8 s), and lowest dust accumulation (4.4 mg). The results confirm that increasing SiO₂ nanoparticle concentration enhances surface hydrophobicity and reduces dust adhesion by modifying surface roughness. These findings highlight the potential of optimized silicone-SiO₂ coatings as a cost-effective, passive anti-soiling solution for improving the operational efficiency of solar PV systems, particularly in dust-prone environments.

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1. INTRODUCTION

The global energy landscape is shifting towards reducing dependence on fossil fuels and embracing cleaner energy solutions to mitigate climate change [1], [2]. Solar energy is an increasingly important renewable energy source, offering a sustainable means of electricity generation [3], [4]. Solar photovoltaic (PV) systems are recognized for their potential to contribute substantially to achieving net-zero emissions targets [5], [6]. However, the operational performance of PV systems is often degraded by surface soiling, particularly dust accumulation and deposition of airborne particulates [7], [8]. In certain regions, soiling can cause energy losses of up to 80%, especially in tropical climates characterized by high humidity and intermittent rainfall [9], [10]. These environmental conditions promote strong adhesion of contaminants to glass surfaces, reducing the effectiveness of natural cleaning mechanisms such as wind and light rain [11].

To address this issue, hydrophobic surface coatings have been widely investigated as a passive anti-soiling strategy. By reducing surface wettability and contaminant adhesion, hydrophobic coatings can enhance self-cleaning behavior, thereby reducing maintenance requirements and performance degradation [12], [13]. Silicone-based coatings are particularly attractive due to their chemical stability, low surface energy, and compatibility with transparent substrates [14], [15]. However, developing such coatings requires a careful balance of material components and formulation ratios to achieve optimal water repellence and anti-soiling performance [16].

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Despite extensive research on hydrophobic and superhydrophobic coatings, many reported solutions rely on complex fabrication methods and high-cost materials, or exhibit limited durability and transparency, thereby restricting their large-scale adoption in PV systems [17], [18]. Therefore, there remains a need for cost-effective, easily deployable coating solutions that provide sufficient hydrophobicity while maintaining optical transparency [19].

The present work focuses on the preparation and experimental evaluation of silicone-based hydrophobic coatings with varying SiO₂ content, with emphasis on anti-soiling performance. The successful development of such a coating could significantly reduce the need for frequent cleaning and improve the durability of solar panels, thereby promoting a more sustainable and cost-effective approach to solar energy production, particularly in challenging tropical climates. In addition, this study evaluates the applicability of these coatings across different environmental conditions and their long-term stability.

2. METHOD

The methodology employed in this study comprised three primary stages: the preparation of hydrophobic coatings, their application to substrates, and subsequent characterization. The experiments were performed under varying environmental conditions, simulating tropical and desert-like climates to better evaluate their practicality across diverse settings. In addition, long-term stability and durability were assessed through accelerated UV aging. A statistical analysis framework was incorporated to evaluate the reliability and significance of the experimental results.

2.1 Preparation of Hydrophobic Coating Solutions

Silicone-based hydrophobic coatings were developed by carefully mixing silicone oil, toluene, and silicon dioxide (SiO₂) nanoparticles to create a stable formulation. Formulations were adjusted to evaluate a range of SiO₂ concentrations to achieve optimal performance across different climatic regions. Multiple formulations were prepared by adjusting the proportions of the components, as shown in Table 1, to optimize both water repellence and anti-soiling performance. The mixing process was performed at room temperature with continuous stirring at 500 rpm for 30 minutes to ensure uniform dispersion. After preparation, the coating solutions were allowed to stabilize for 24 hours before being applied to the test samples.

Table 1. Hydrophobic Coating Formulations

Coating	Silicone Oil (vol%)	Toluene (vol%)	SiO ₂ (wt%)
HC-1	37.5	62.5	2.03
HC-2	37.5	62.5	3.34
HC-3	37.5	62.5	0

Three formulations of hydrophobic coatings (HC) were studied in this work. Each coating comprised silicone oil (37.5 vol%) and toluene (62.5 vol%). They differed in SiO₂ nanoparticle concentration: 2.03 wt% (HC1), 3.34 wt% (HC2), and 0 wt% (HC3). These formulations were characterized to understand their physical properties and to correlate their results with their anti-soiling performance.

2.2 Application of Hydrophobic Coating

The silicone-based hydrophobic coatings were applied to clean glass substrates by spray deposition, as shown in Figure 1. Prior to application, the substrates were thoroughly cleaned with ethanol and rinsed with deionized water to remove contaminants. They were then air-dried to ensure a clean surface for adhesion of the coating. The hydrophobic solutions were applied using a spray applicator held 20 cm from the substrate. The spray speed was set to 3 cm/s, and the flow rate was 2 mL/min. The coating was applied in three passes to ensure uniform coverage, with the spray traversing the surface at 5 cm/s. This method was carried out at room temperature (25°C) to ensure consistency in application. After spraying, the coated substrates were either air-dried at room temperature for 24 hours or oven-cured at 60°C for 2 hours to promote the formation of a stable, solid coating layer. This combination of methods ensured uniform application and solidification of the hydrophobic coatings, preparing them for subsequent testing.

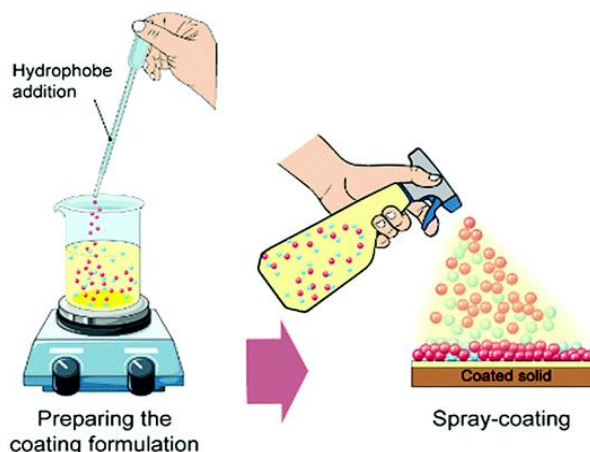


Figure 1. Hydrophobic solution preparation method

2.3 Characterization of Coatings

Water Droplet Mobility Test: This test was designed to assess the dynamic water repellence of the coated surfaces. The movement of water droplets across a tilted surface was observed to determine the speed of water runoff, an essential property for applications requiring rapid water shedding [20]. Coated samples were placed at a 30° angle, and water droplets were applied to the surface. The time taken for the droplets to travel across the surface was recorded. Each measurement was repeated three times per sample, and the average time was calculated to ensure consistency. The test was performed in ambient conditions (25°C) to simulate real-world environments.

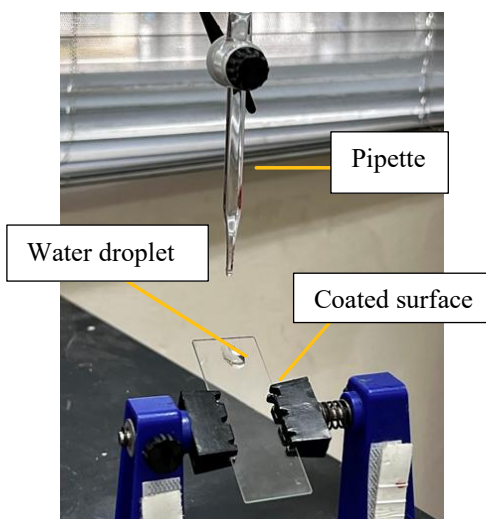


Figure 2. Experimental results for the droplet mobility test at 30°

Dust Accumulation Test: This test evaluated the coatings' anti-soiling properties by simulating dust buildup [21]. Coated samples with an area of 25 cm² were placed in a dust chamber containing 0.5 g of artificial dust. The dust was subjected to airflow from a fan motor running for 3 minutes to simulate wind-blown dust. After 24 hours, the amount of dust accumulated on the surface was measured using a digital balance. The dust used had an average particle size of 50 microns (standard dust size for such tests). Rainfly, a commercially available hydrophobic coating, was used as a benchmark for comparative performance evaluation of the developed coatings. This method was repeated three times per coating formulation, and the results were averaged to minimize variability.

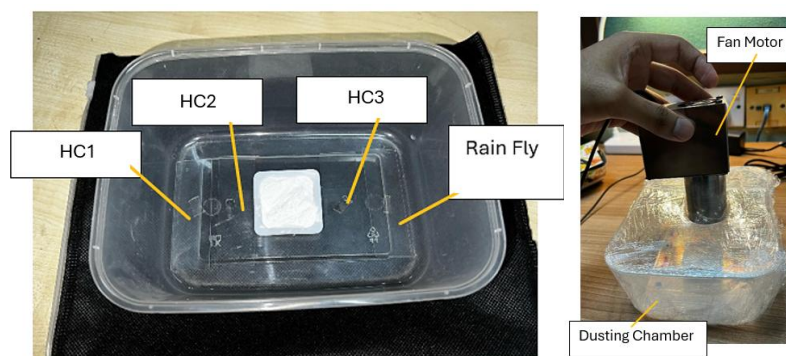


Figure 3. Dusting chamber with coated samples for dust adhesion evaluation

Water Contact Angle (WCA) Measurement: The WCA was used to quantify the static hydrophobicity of the coated surfaces [22]. A higher WCA value indicates better water repellence. The WCA was measured using a goniometer (see Figure 4) to determine the contact angle between a water droplet and the coated surface. Five independent measurements were taken for each sample, and the average WCA value was calculated. The goniometer precision was $\pm 0.5^\circ$, and each measurement was repeated at three locations per sample to ensure consistent hydrophobic properties across the surface.

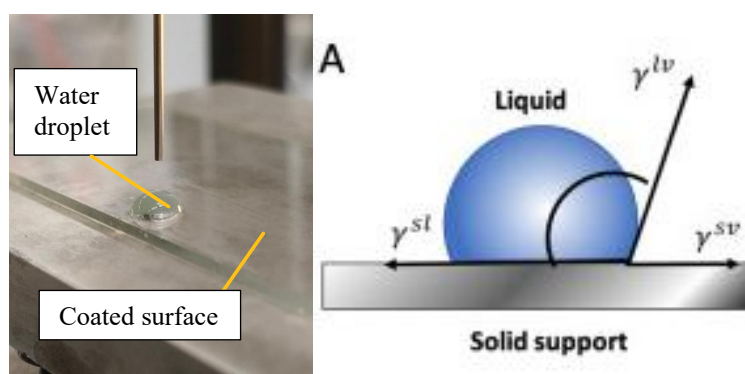


Figure 4. Water contact angle (WCA) measurement using a goniometer

Optical Transmittance and Ultraviolet Durability Assessment: The optical transmittance of coated and uncoated glass samples was measured using a UV-Visible spectrophotometer over the 400-700 nm range to assess transparency in the visible solar spectrum [23]. The average transmittance was calculated over this range to assess overall optical losses, which were mainly attributed to light scattering caused by surface roughness and SiO_2 nanoparticle incorporation.

Ultraviolet stability was evaluated through accelerated aging in a UV weathering chamber operating at 340 nm for 120 hours under controlled conditions. Hydrophobic performance after exposure was assessed by measuring changes in water contact angle and by visual inspection for surface degradation. This test provides a preliminary indication of the coatings' short-term UV durability.

Economic Feasibility Evaluation: An economic assessment was conducted to assess the practical viability of the developed coating system for large-scale solar PV applications. The analysis considered material costs, application costs per square meter, estimated coating lifetime, and the cost of conventional manual cleaning. The payback period was calculated by comparing the coating cost with annual cleaning expenses avoided due to reduced soiling. This simplified economic model provides insight into the cost-benefit balance of implementing hydrophobic coatings in real PV installations.

Statistical Analysis: To assess the statistical significance of differences among coating formulations, a one-way analysis of variance (ANOVA) was used to analyze key performance parameters, including water contact angle, droplet runoff time, and dust accumulation. A confidence level of 95% ($p < 0.05$) was used as the criterion for statistical significance. All experimental data are presented as mean \pm standard deviation, ensuring transparency and reproducibility of the results.

3. RESULTS AND DISCUSSION

The characterization of the hydrophobic coatings revealed clear differences in water repellence, anti-soiling behavior, optical transparency, UV durability, and economic viability, primarily due to variations in the concentration of silicon dioxide (SiO₂) nanoparticles.

3.1 Water Droplet Mobility and Water Contact Angle (WCA)

The water droplet mobility test demonstrated differences in water-repellent properties among the coatings. As shown in Figure 5, HC2 exhibited the fastest droplet movement (0.8 seconds), indicating superior water shedding compared to the other coatings. This observation was supported by the WCA measurements (Figure 6), which showed that HC2 had the highest average WCA of 94.276°, confirming enhanced hydrophobicity. The WCA values for all coatings are summarized in Table 2, with five measurements taken per sample and the standard deviation reported.

Statistical analysis (one-way ANOVA, $p < 0.05$) confirmed that the differences in WCA and droplet runoff time among the coating formulations are statistically significant, indicating that the observed performance trends are not attributable to experimental variability. The results suggest that the inclusion of SiO₂ nanoparticles improves water repellence, likely due to increased nanoscale surface roughness.

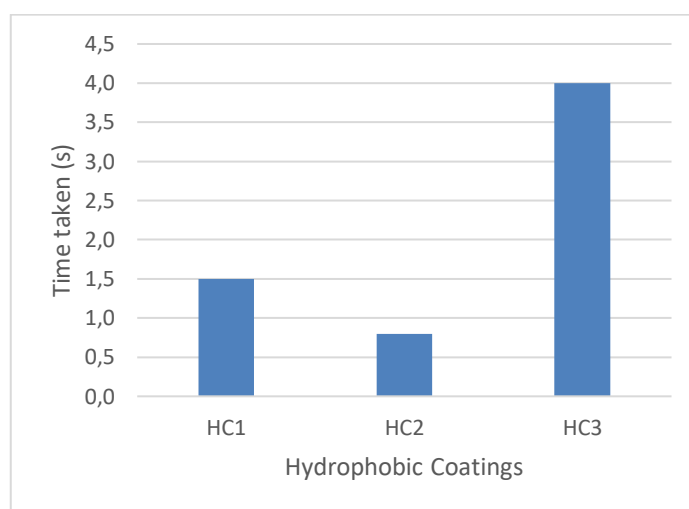


Figure 5. Experimental results for the droplet mobility test at 30°

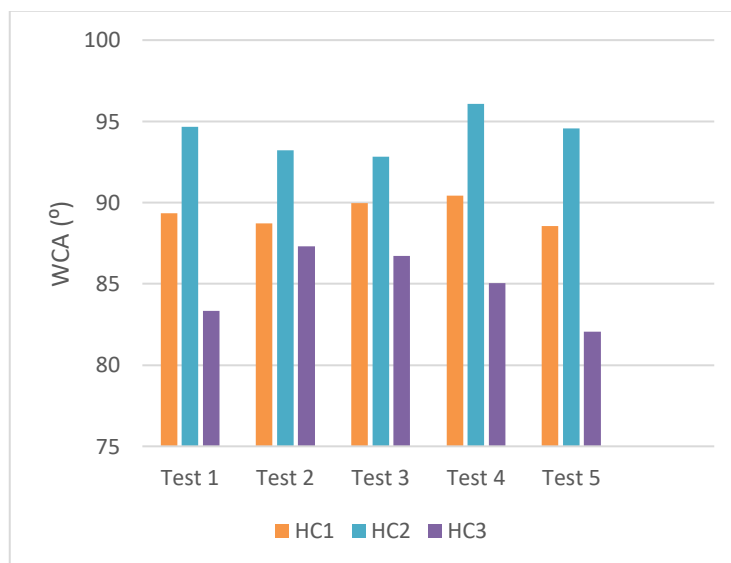


Figure 6. Experimental results for goniometer WCA (°) testing

Table 2. Average and standard deviation results for goniometer WCA (°) testing

Coating	HC1	HC2	HC3
Average	89.804	94.276	84.894
Standard Deviation	0.794	1.296	2.225

3.2 Dust Accumulation

The dust accumulation test further confirmed HC2's superior anti-soiling performance, with the least dust accumulation (4.4 mg) under controlled conditions. Figure 7 shows the comparative dust deposition for all coatings. These results are consistent with HC2's enhanced hydrophobicity and indicate improved resistance to dust adhesion compared with HC1 and HC3.

One-way ANOVA analysis revealed a statistically significant reduction in dust accumulation for HC2 compared to the other coatings ($p < 0.05$), further validating the effectiveness of increased SiO₂ nanoparticle content in improving anti-soiling performance.

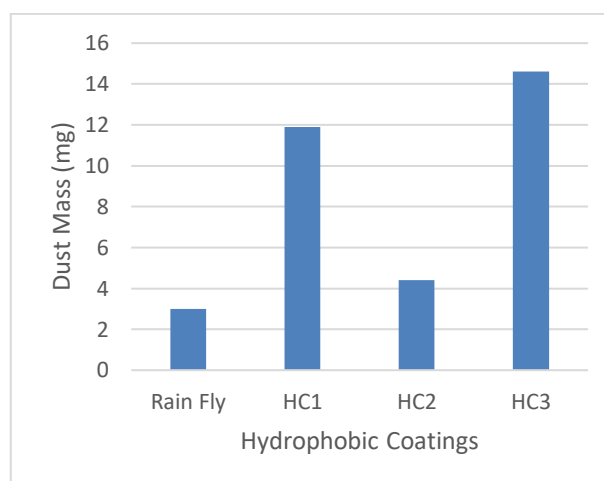


Figure 7. Experimental results for dust adhesion on coated samples

3.3 Optical Transmittance Analysis

All coatings preserved high optical transparency, with only minor reductions due to the presence of SiO₂ nanoparticles. HC2, which had the highest nanoparticle concentration, showed slightly lower transmittance (91.6%) than uncoated glass (92.8%), indicating that the trade-off between enhanced hydrophobicity and optical performance is minimal, as shown in Table 3.

The observed reduction in transmittance for HC2 is attributed to increased light scattering caused by nanoscale surface roughness, yet it remains within acceptable limits for solar PV applications. These results confirm that the coatings can maintain efficient light transmission while providing anti-soiling functionality.

Table 3. Visible-light transmittance (400-700 nm)

Sample	Transmittance (%)
Uncoated glass	92.8 ± 0.4
HC-1	92.2 ± 0.5
HC-2	91.6 ± 0.6
HC-3	92.5 ± 0.4

3.4 Ultraviolet Aging and Durability Assessment

All coatings retained their hydrophobic properties, with only minor reductions in WCA. HC2 exhibited the smallest change (-2.6%), suggesting that the combination of silicone and SiO₂ nanoparticles provides effective short-term UV resistance. The relatively low Δ WCA values across all samples indicate good resistance to UV-induced degradation under accelerated aging conditions. No visual signs of cracking, delamination, or discoloration were observed, supporting the coatings' suitability for outdoor PV applications, as shown in Table 4.

Table 4. UV durability assessment

Coating	Initial WCA (°)	Initial WCA (°)	Δ WCA (%)
HC-1	89.8	86.9	-3.2
HC-2	94.3	91.8	-2.6
HC-3	84.9	80.7	-4.9

3.5 Economic Feasibility Analysis

A preliminary economic evaluation was conducted to assess the practical benefits of implementing the coatings in solar PV installations. The analysis considered material and application costs per square meter, expected coating lifetime, and the cost savings from reduced manual cleaning, presented in Table 5.

HC2, despite a slightly higher material cost due to its higher SiO₂ content, offered the most favorable payback period thanks to its superior anti-soiling performance. The estimated coating lifetime of 12-18 months and payback period of 7-9 months indicate that the coating becomes economically advantageous within the first year of operation, particularly in dust-prone regions.

Table 5. Economic comparison

Parameter	Value
Coating material + application cost	USD 2.5 / m ²
Annual manual cleaning cost	USD 4.0 / m ²
Estimated coating lifetime	12–18 months
Payback period	7–9 months

4. INTEGRATED DISCUSSION OF COATING PERFORMANCE

The results demonstrate that SiO₂ nanoparticle concentration plays a decisive role in governing the hydrophobic and anti-soiling performance of silicone-based coatings. Among the formulations studied, HC2 (3.34 wt% SiO₂) consistently exhibited superior performance, indicating an optimized balance between surface roughness and low surface energy.

HC2 showed the fastest water droplet runoff time (0.8 s) and the highest average water contact angle (94.276°), confirming enhanced hydrophobicity compared to HC1 and HC3. This improvement is attributed to the introduction of SiO₂ nanoparticles, which increase nanoscale surface roughness and reduce effective solid-liquid contact, thereby promoting efficient water shedding. In contrast, the lower hydrophobic response of HC3 highlights that silicone oil alone is insufficient to achieve optimal water repellence without nanoparticle-induced surface texturing.

The accumulation of dust further validates this trend. HC2 exhibited the lowest dust deposition (4.4 mg), demonstrating improved resistance to particle adhesion. Enhanced hydrophobicity reduces capillary and adhesion forces between dust particles and the surface, enabling passive self-cleaning behavior. The higher dust retention observed for HC1 and HC3 underscores the importance of optimizing SiO₂ loading to minimize soiling losses in PV applications, particularly in dust-prone environments.

Although increasing SiO₂ content slightly reduced optical transmittance, the reduction for HC2 remained minimal (91.6%) and within acceptable limits for solar PV operation. This indicates that the trade-off between enhanced anti-soiling performance and optical transparency is well balanced. Additionally, HC2 exhibited the smallest reduction in WCA after UV aging (-2.6%), suggesting good short-term UV stability and coating integrity.

In summary, HC2 emerged as the most effective formulation, offering enhanced hydrophobicity, reduced dust adhesion, acceptable optical transparency, and promising durability. These findings confirm that controlled incorporation of SiO₂ nanoparticles is critical for developing efficient, low-cost, and practical anti-soiling coatings for solar PV glass.

5. CONCLUSION

This study highlights a significant enhancement in hydrophobicity and anti-soiling performance of silicone-based coatings for solar PV glass through the incorporation of SiO₂ nanoparticles, specifically tailored for tropical environments. Among the formulations tested, HC2 (3.34 wt% SiO₂) demonstrated the most impressive overall performance, achieving a water contact angle of 94.3°, the fastest droplet runoff (0.8 s), and the lowest dust accumulation (4.4 mg). These improvements are attributed to the synergistic effect of nanoparticle-induced nanoscale surface roughness and silicone's inherently low surface energy, which together promote efficient water shedding and minimize dust adhesion. While hydrophobic coatings are widely

acknowledged in the literature, this research provides novel, application-driven insights into how optimized SiO₂ loading can directly impact the anti-soiling behavior, optical transparency, and UV stability of PV glass under the harsh conditions of tropical climates. HC2 not only retained high optical transparency (91.6%) but also exhibited commendable resistance to UV degradation, confirming its suitability for long-term outdoor PV applications. The applicability of this study lies in its performance-driven approach, focusing on practical, low-cost solutions to the real-world challenges faced by solar energy systems in dust-prone, humid climates. These findings establish the potential of silicone-SiO₂ coatings as a scalable, passive solution for enhancing PV system efficiency, reducing maintenance requirements, and lowering cleaning costs, making them a viable option for widespread implementation in tropical regions.

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