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Experimental Examination of Enhanced Nanoceramic-Based Self-Cleaning Sprays for High-Efficiency Hydrophobic Photovoltaic Panels

Merna Abdrabo [1], Ahmed Elkaseer [1,2], Engy Elshazly [1], Mohamed S. El-Deab [3,4] and Iman El-Mahallawi [1,5,*]

[1] Department of Mechanical Engineering, The British University in Egypt, Cairo 11837, Egypt; merna.ibrahim@bue.edu.eg (M.A.); ahmed.elkaseer@bue.edu.eg (A.E.); engy.samy@bue.edu.eg (E.E.)
[2] Department of Production Engineering and Mechanical Design, Faculty of Engineering, Port Said University, Port Fuad 42526, Egypt
[3] Department of Chemistry, Faculty of Science, Cairo University, Giza 12613, Egypt; msaada@sci.cu.edu.eg
[4] Department of Biochemical Engineering, Faculty of Energy and Environmental Engineering, The British University in Egypt, Cairo 11837, Egypt
[5] Department of Metallurgical Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt
* Correspondence: ielmahallawi@bue.edu.eg

Abstract: Dust deposition poses a significant challenge in the implementation of photovoltaic panels (PV) especially in hot and dusty environments, such as the Middle East and North Africa (MENA) region. This issue leads to progressive degradation of PV efficiency and output power. In this context, this research work aims to improve PV performance by developing self-cleaning sprays as a preventative solution. Different concentrations of SnO_2 and TiO_2 nanoceramics were dispersed in isopropyl alcohol solvent to reduce the mixture's viscosity and facilitate smooth spraying on solar panels, whose efficiency was continually assessed in outdoor conditions. Although less commonly used for this application, the nano-SnO_2 was selected for the purpose of enhancing the surface hydrophobicity, whereas nano-TiO_2 was included for its favorable photocatalytic properties. Polydimethylsiloxane (PDMS) oil, known for its self-cleaning characteristic, was served as the base material in the developed sprays. The described blend of materials represents a novel combination. The results indicated that 2.5% nano-SnO_2 and 2.5% nano-TiO_2 in PDMS oil enhanced efficiency by 5.4% compared to a non-sprayed panel after five weeks of outdoor exposure. This efficiency gain was experimentally justified and attributed to the spray's ability to achieve a water contact angle (WCA) of 100.6°, forming a hydrophobic surface conducive to self-cleaning. Further characterization results, including photocatalysis and zeta potential have been gathered and analyzed.

Keywords: solar photovoltaic (PV) cells; self-cleaning coatings; anti-soiling; hydrophobic surfaces; polydimethylsiloxane (PDMS)

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1. Introduction

The Middle East and North Africa (MENA) region holds a substantial amount of solar potential with average radiation of 2000–3200 KWh/m^2 of solar irradiance per year and daily sunlight hours in the range 9–11 h [1–6]. Because of that, the utilization of solar photovoltaic (PV) systems has been recently increasing. However, soiling, high ambient temperatures, and shading act as factors that can adversely influence PV power output and hence, efficiency [7,8]. Soiling refers to the accumulation of particles such as dust and dirt. While the MENA region is the most prone to soiling and high temperatures due to the presence of vast desert areas and arid climates [8], the likelihood of shading does not necessarily depend on the geography of the location and it may result in mismatching, preventing the operation of one or more cells of the module. Consequently, these cells behave as a load, destroying the module [7].

Soiling hinders the transmission of solar radiation through PV glass [7]. This happens due to the ability of the dirt particles to scatter, absorb, or reflect incoming solar rays [9]. A study focusing on type of dust has shown that dust particles of lower size have greater capability of PV performance degradation and that dust particles produced from cement sources caused the largest power depletion relative to various investigated dust types [10]. For instance, Egypt among other countries was found to have cement dust as the most common dust in its atmosphere [11]. Besides, it has been proven that PV efficiency reduction due to dust can reach up to 17.4% per month for panels installed in Egypt at 45° tilt angle [12]. Furthermore, it was concluded that PV power could be reduced by 1.7% per g/m^2 increase of dust accumulation on PV panels under the weather conditions of the UAE [6]. Moreover, in Adrar, Algeria, solar cells lost 29 to 32% of their efficiency after 6 months of outdoor exposure [13]. European cities could be prone to PV dust accumulation as well. For example, a study conducted in Kraków, Poland concluded that dust accumulation could reach 277.0 mg/m^2 on PV panels after a week of exposure [14]. In East China, a total of 0.644 g/m^2 was accumulated on PV modules within a week, resulting in 7.4% of weekly power degradation [15].

High ambient temperatures, which is the second major problem facing PV performance in North Africa and MENA region, it was discovered that each degree Celsius rise in PV surface temperature reduces efficiency initially by 0.4%–0.5%, with an increasing exponential rate with greater temperature rises [12]. Also, it was proven that there is a direct correlation between the quantity of dust deposition to the rise in PV surface temperature [16]. This also extends to a possibility of surface damage, if not appropriately dealt with [17].

PV cleaning approaches can be classified into manual, mechanical and chemical [18]. Mostly, these approaches, except the chemical method, implement the application of brushes, which puts the panel glass health under potential risk [19]. Manual cleaning is the most widespread, due to its simplicity and cost effectiveness [7]. Unfortunately, it is labor intensive, time consuming and consumes significant amounts of water, which is not environmentally friendly, contradicting the main objective of using solar panels [20]. Mechanical cleaning commonly involves wipers or brushes attached to a rod. Other forms of mechanical cleaning may involve mechanical blowers that force dust away off surfaces [21]. Mechanical cleaning systems could be robotic [22], the employed robots may have built-in water tanks for more efficient water utilization [7,20]. However, in all cases water cleaning utilizes energy and could negatively affect the surface quality of the panel surfaces if brushes are used.

Chemical cleaning methods differ from other techniques by being preventative. Typically, the process mainly involves applying a self- cleaning coating on clean panel glass before exposure to outdoor dust to influence its surface properties [23]. This method is advantageous relative to the other specified ones in terms of water consumption, mechanical and/or electrical power requirements [24]. It relies on the physical and chemical properties of material constituents involved in the prepared coating [22] and the function of the coating ranges from being self- cleaning by collecting dust in forms easy to wash off, minimizing dust accumulation through anti-static effect, promoting antireflection performance and increasing photocatalytic effect, etc., with a number of commercial cleaning regenerating sprays available in the market [9]. Often, nanoceramics are integrated to aid in attaining the required self-cleaning effect [25].

Chemical self-cleaning coatings are categorized into hydrophobic and hydrophilic coatings, depending upon their surface wettability [24,26]. Surface wettability describes the tendency of a liquid to spread over a surface and is indicated by water contact angle (WCA) [27]. If the resulting angle between the resting surface of a water droplet and its tangent is less than 90°, the water tends to spread on the surface, and it is classified as hydrophilic. Whereas, when the WCA is greater than 90°, the droplet tends to roll over and the surface is known as hydrophobic [24,26]. This is due to the extremely low adhesive properties of hydrophobic surfaces [22,28]. Therefore, liquid droplets tend to form spherical shapes, which provide them the capability to carry impurities along the way as they leave tilted surfaces [21]. On the other hand, hydrophilic surfaces have lower self-cleaning effectiveness, as water droplets do not have the strong tendency to slide away with dust particles, but rather spread between them, resulting in a greater need for water quantity and pressure to rinse impurities away [21,29]. The application of suitable coatings has the ability to significantly decrease the cleaning frequency needed by solar cells [30]. In this context the arid and dry weather of North Africa and MENA region creates additional challenges resulting from rare rains and very limited raining periods.

Numerous researchers attempted to develop hydrophilic self-cleaning coatings for solar PV applications. The larger body of the reported literature attempted to incorporate nano-TiO_2 for its photocatalytic action through solgel preparation procedure. An experimental investigation was conducted to achieve antifogging and antimicrobial features along with self-cleaning for the glass surfaces of solar panels to enhance their efficiency [31]. The final coating material involved nano-SiO_2 & nano-TiO_2 that achieved a marginal increase in PV efficiency. Justifications include the coating being too thin or low outdoor exposure. Coating characterization was performed by photocatalysis test, contact angle measurement, SEM, FT-IR & UV-Vis spectroscopies. Another study attempted to dope nitrogen into nano-TiO_2, obtaining an increase in voltage up to 0.788 V after exposure to dust, noting that the improvement increased with nitrogen concentration [32]. Moreover, doping other materials, such as nickel, cadmium, molybdenum, bismuth, and strontium, in nano-TiO_2 had resulted in superhydrophilic coating of WCA below 5° [33].

As for reported investigations on hydrophobic coatings, SiO_2 nanoparticles were the most prominent. A thin film coating based on ammonia, as a catalyst, showed significant increase in WCA [34]. The thin film was capable of increasing PV voltage by 20% when uncatalyzed and by 40% when catalyzed. Under Middle Eastern/Egyptian climatic conditions, Alamri et al. measured the performance of a 160 W PV panel covered with a commercial hydrophobic coating constituting of SiO_2 nanoparticles for 45 days and it resulted in a 15% efficiency increase compared to an uncoated panel [25]. Nano-SnO_2, although uncommon, was used with silicone oil and successfully increased the WCA of glass surface and its self-cleaning behavior [35]. This coating maintained the surface hydrophobicity despite being subjected to repetitive peeling cycles. The development of superhydrophobic coatings which are significant by larger WCA, as well as their inclusion of hybrid nanoceramics usually of SiO_2 and TiO_2 resulted transparent anti-reflective self-cleaning coatings characterized by high water contact angles greater than 150 and a sliding angle of less than 10 with a micro-/nano-hierarchical structure that prevents water and other dust particles from reaching the substrate [36], resulting from both the superhydrophobic surface roughness and surface chemistry. The significant role of WCA larger than 150 with approximate spherical shapes enables effective capture and removal of dust [37].

Recently, polydimethylsiloxane (PDMS) oil was employed in several studies to assess its self-cleaning ability. Syafiq et al. discovered a covalent bond between PDMS, nano-calcium carbonate ($CaCO_3$) and nano-TiO_2 that resulted in a significant increase in WCA [38]. In addition, the study assessed and validated the self-cleaning ability of the coating by investigating the adherence of Methylene Blue (MB) solution to a coated substrate, which was almost non-existent. Furthermore, McShea et al. attempted doping various nanoceramics, each individually, in PDMS for medical hygienic applications [39]. and the results have revealed that all coatings exhibited satisfactory hydrophobicity with SiO_2-PDMS being the most hydrophobic and it was concluded that PDMS-doped TiO_2 showed the highest self-cleaning behavior. Our team's previous study [8] reported an increase in PV efficiency by 14%–15%, as well as improvements in surface temperature and the reported results obtained through different solar panels' coating attempts included coatings based on PDMS, which showed significant promising results [8]. The previous study [8] focused on concept proving of the utilization of PDMS as the carrier fluid for the coating, since the application of PDMS for solar coating was not reported before. However, the study lacked characterization of the prepared coating, therefore the current study aims at further exploring the characteristics of PDMS- based coating, as well as the effect of incorporating various nanoceramic particles in the self-cleaning sprays. This research extends previous work with a more systematic approach in examining the development of nanoparticle-based coatings to enhance the surface properties of solar panels. Several previous studies have utilized nanoparticles to enhance the surface properties of solar panels for self-cleaning, but most of them focused on nano-TiO_2 and nano-SiO_2.

This study employs advanced techniques and methodologies to explore the potential benefits of nanoparticle-enhanced PDMS coatings. In this context, this research aims to investigate the effects of materials like nano-SnO_2 dispersed in PDMS, with and without nano-TiO_2, on the efficiency of PV solar panels. Additionally, the study examines the performance of nano-TiO_2 as the sole nanoparticle to determine whether it would be outperformed by the presence of nano-SnO_2. These materials were chosen for their promising self-cleaning capabilities, as reported in previous literature. Sprays were developed instead of conventional coatings to provide a user-friendly approach and pave the way for future commercialization.

2. Materials and Methods

2.1. Materials

All materials were delivered by Nano Gate (Cairo, Egypt) and used without further purification. The available SnO_2 and TiO_2 nanoceramic particles had spherical-like shapes of an average size lower than 20 nm and 10 nm, respectively. Nano-SnO_2 was selected for its ability to enhance self-cleaning by increasing the surface roughness and thus, WCA [35]. In addition, it is chemically and thermally stable in outdoor environments and has adequate optical transmission [40]. Nano-TiO_2, although usually used for hydrophilic surfaces, was included to benefit from its photocatalytic effect [41]. The utilized PDMS oil was of brand LANXESS (Cologne, Germany). It is a viscous transparent fluid of 0.965 g/cm^3 density at 20 °C. PDMS is hydrophobic by nature and has a viscosity of 350 cSt. The purchased isopropyl alcohol (2-Propanol) was of brand Sigma Aldrich (MO, St. Louis, MI, USA), and 99.99% purity. It is a colorless and volatile liquid of a molecular weight of 60.10 g/mol and 0.785 g/cm^3 density at 20 °C. Its melting and boiling points are −89 °C and 82.6 °C, respectively. Moreover, PDMS is considered a superior candidate for this application due to other economic and performance benefits [38–42]. Methylene Blue (MB) powder of 82% concentration was employed in this study. It has a dark green appearance and a molecular weight of 319.86 g/mol. The brand name was LOBA CHEMIE (Mumbai, India). The bulk density of the powder ranges between 400–600 kg/m^3 and it has a 50 g/L solubility. The melting point of the powder pigment is 180 °C. This pigment was chosen in order to validate the photocatalysis of the employed nanoparticles by studying their ability to degrade it. For sterilization purposes, ethyl alcohol (Sigma Aldrich) of 100% concentration and 46.07 g/mol molecular weight was used when necessary.

2.2. Preparation of Spray Material and Samples

In this study, four spray materials consisting mainly of PDMS solution, three of which mixed with dispersed nanoceramics, were developed. Specifically, Spray 1 contained 5% nano-SnO_2, while Spray 2 contained 2.5% SnO_2 and 2.5% TiO_2, and Spray 3 had 5% TiO_2. While Spray 4 is the spray that did not include any nanoparticle with the PDMS solution. For each of Sprays 1, 2 & 3, a beaker was rinsed with distilled water and disinfected. The equivalent of the recorded weight percentage(s) of each spray was transferred to the beaker, where 50 mL of isopropyl alcohol were added. Then, the described mixtures were exposed for 20 min to probe sonication (brand sonics, one of VCX models, Newtown, CT, USA) at room temperature and 5 min of ultrasonication (brand Jeio Tech, model UCP 10, Daejeon, Republic of Korea) for additional homogenization. Next, PDMS oil was magnetically stirred for 20 min with the obtained mixture on a 1:1 ratio. To form Spray 4, magnetic stirring of isopropyl alcohol and PDMS was also conducted in a similar manner at a 1:1 ratio.

10 mL of each produced spray material was sprayed homogeneously on a polycrystalline 5 W panel (ReneSola RS-SL5TU-18P-polycrystalline-260 mm × 220 mm × 18 mm) of 0.0572 m^2 area with maximum power 5 W with open circuit voltage of 22 V and max current power of 0.27 A) and left for 24 h to dry. An unsprayed panel was included in the experiment to aid in comparison. Also, three spray shots were applied on sterilized 76.2 × 24.4 mm^2 glass substrates for characterization purposes.

2.3. Characterization

To investigate the surface wettability of the produced samples, the setup in Figure 1 was formed. A dropper was positioned above the substrate by a holder and two cameras recording the front and top views of the released droplets. The holder was moved such that several droplets hits different spots on the substrate to provide several readings for average calculation.

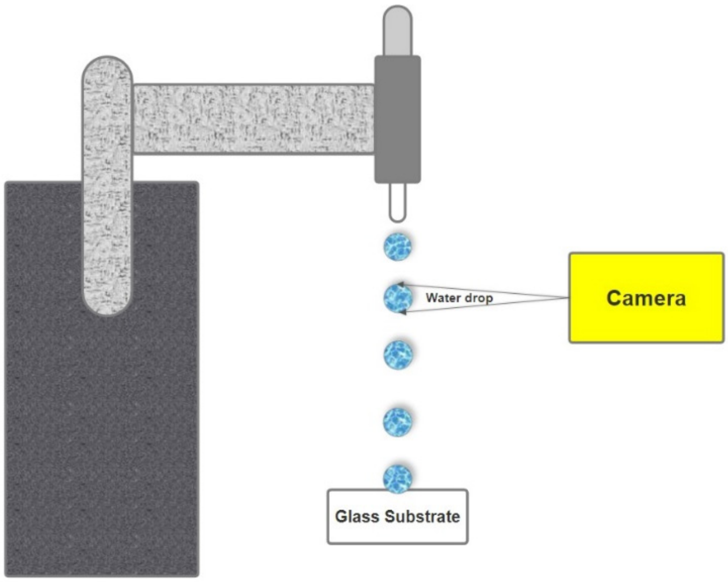

Figure 1. A schematic of the WCA measurement setup, where a dropper release drops at different positions on the sprayed substrates and a camera captures a picture of the droplet before it hits the substrate for initial diameter measurement.

The readings were collected by measuring the size of the droplet before hitting and immediately after hitting the substrate surface to be substituted in Equation (1) [43] to obtain the value of the contact angle.

$$d_f = d_i \times \sqrt[3]{\frac{8}{\left(\tan\frac{\theta}{2}\right) \times \left(3 + \tan^2\frac{\theta}{2}\right)}} \tag{1}$$

where d_f is the droplet diameter after it hits the surface, d_i is the droplet diameter before hitting the surface and θ is the contact angle.

Furthermore, to investigate the photocatalysis of the employed nanomaterials, 10^{-5} moles of MB powder were mixed with 1 L of water for the photocatalysis test. 100 mL of the aqueous MB solution was magnetically stirred with 0.1 g of each nanoceramic for 2 h. Another mixture was made but with both nanoceramics combined, specifically, 0.05 g each. The three samples were left in a dark compartment overnight, after which they were exposed to UV radiation (350 nm–800 nm) in a photoreactor (Horus company). Samples were withdrawn from the reactor according to pre-decided intervals, which were 0 min, 10 min, 30 min, 1 h, 2 h, 3 h, and 4 h. Finally, all the samples were tested for absorbance using the spectrophotometer (accuracy **+/−0.0015**) to correlate the results to photocatalytic activity. It was noticed that the more degraded MB concentrations exhibited less absorbance and greater photocatalytic effect.

Finally, Malvern nano series zeta sizer (Worcestershire, UK) was used to conduct the zetapotential test for the purpose of determining the stability of the nanoparticles in the samples.

2.4. Experimental Setup and Procedure

Individually, each panel was vertically placed facing a 400 V lab light source at a fixed distance. The light source consisted of twenty-one tungsten halogen lamps of 400 W that provided light of wavelength range 350 nm–2500 nm. PROVA 1011 PV system analyzer (New Taipei City, Taiwan) was connected to the panel through cables. The readings of the PV parameters from the analyzer were gathered directly after 2 min of light exposure to ensure power generation. After collecting the first set of readings, the panels were placed outdoors under real operating Egyptian conditions at 30° tilt angle. The second set of readings were gathered after dust accumulation through the described experimental setup over a course of about a month. The panel energy efficiency was calculated using Equation (2).

$$\eta = \frac{P_{max}}{A \times I} \times 100 \tag{2}$$

where η is the electrical energy efficiency, P_{max} is the maximum power in watt, A is the solar panel area and I is the irradiance in w/m^2.

3. Results and Discussion

3.1. Apperance of PDMS-Based Coatings

After the sprayed substrates were left to dry, the appearance of the coatings was observed. The substrates covered with PDMS-SnO_2 coating exhibited a brownish-appearance due to the brown color of the SnO_2 nanoparticles. The substrates coated with both SnO_2 and TiO_2 nanoparticles had a light brown surface, as half the nanoparticle concentration was SnO_2 and the other half was white TiO_2, resulting in a lighter mix of colors and more transparency. The spray with TiO_2 as the sole nanoparticle resulted in a whitish-semi-transparent surface. As expected, spraying PDMS without nanoparticles gave the substrate a shiny transparent look. The substrates with nanomaterials induced a slightly rough shape.

3.2. Water Contact Angle (WCA)

Table 1 lists the calculated WCAs using the measured droplet diameters. As expected, all WCAs of substrates covered with nanoceramic-based sprays are categorized as hydrophobic. Typically, the bare glass showed a hydrophilic surface of a 15.26° WCA. Despite being known as a hydrophobic oil, PDMS (without nanoparticles), resulted in a WCA of 80.82°. This is due to being stirred with isopropyl alcohol solvent prior spraying. However, the WCA was improved to 115.9° by the addition of 5% nano-SnO_2. This is attributed to the ability of nano-SnO_2 to increase surface roughness and hence, reduce wettability [35]. On the other hand, the presence of 5% nano-TiO_2 caused a WCA of 94.23°. This increase is justified by the roughness added by the nanoparticles, however, it is not as high as the value resulting from the addition of nano-SnO_2, because TiO_2 is known to photo-induce hydrophilicity [31]. A reasonable WCA of 100.6° was achieved when both nanoceramics were involved, each contributing to its effect on surface properties. Each reported WCA value is the average of at least three droplets' measurements.

Table 1. Measured droplet diameters and calculated contact angles.

Substrate No.	Materials in Spray	Initial Diameter (mm)	Equilibrium Diameter (mm)	Calculated Contact Angle (°)
1	PDMS + SnO_2	4.44	4.29	115.9
2	PDMS + SnO_2 + TiO_2	4.5	5.14	100.6
3	PDMS + TiO_2	4.36	5.29	94.23
4	PDMS	4.29	5.81	81.45
5	None	4.67	12.63	15.26

3.3. Photocatalysis

Absorbance tests by UV-Vis-NIR spectrophotometer were applied on the extracted MB samples to easily indicate the level of degradation experienced by the dye. The lower the absorbance value, the less presence of MB, meaning that degradation had occurred, and the utilized nanomaterial is photocatalytic. The employed nano-TiO_2 showed high photocatalytic behavior, as the longer the MB solution samples were exposed to UV radiation, the greater the experienced degradation by MB. This is revealed by the chart in Figure 2, as the absorption values continued to decrease, the longer the samples were exposed to UV radiation. For instance, the MB solution sample that was exposed to UV radiation for 4 h showed the lowest absorbance values by being at the bottom of all curves. On the other hand, the MB samples mixed with nano-SnO_2 (see Figure 3) showed very slight change in absorbance values in the wavelength range 580–675 nm, indicating little photocatalytic effect.

When both nano-TiO_2 & nano-SnO_2 were mixed with MB, a photocatalytic behavior, as displayed by Figure 4, had resulted but not to the significant extent as when only the nano-TiO_2 was present. This is owed to reducing the amount of nano-TiO_2 to half the amount relative to the first situation, and replacing it by nano-SnO_2. Thus, a moderate photocatalytic effect had resulted. As evidenced by Figure 4, the peak absorbance of this sample after 4 h was 0.255, whereas, when TiO_2 was the only present nanoceramic, no peak was identified, as the absorbance value approached 0, as shown by Figure 2.

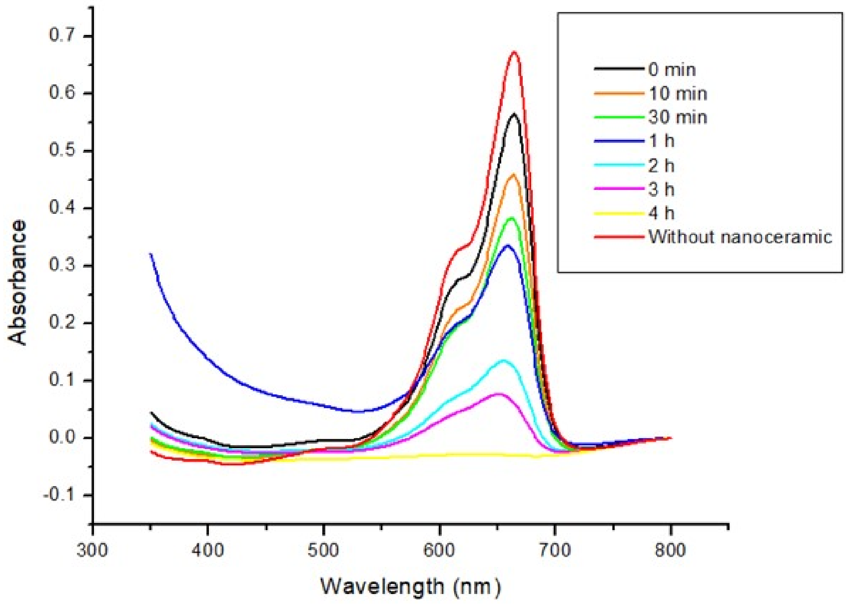

Figure 2. Absorbance plots of MB samples with nano-TiO_2 exposed to different durations of UV radiation against light wavelength.

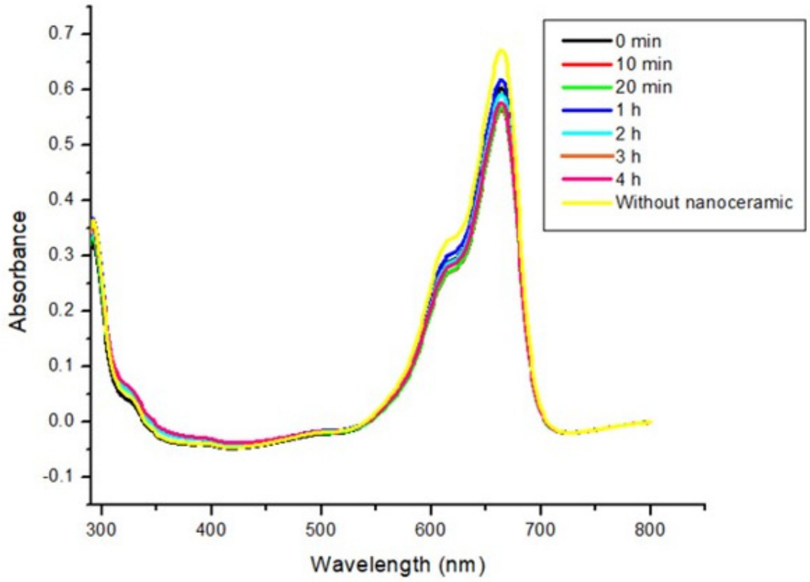

Figure 3. Absorbance plots of MB samples with nano-SnO_2 exposed to different durations of UV radiation against light wavelength.

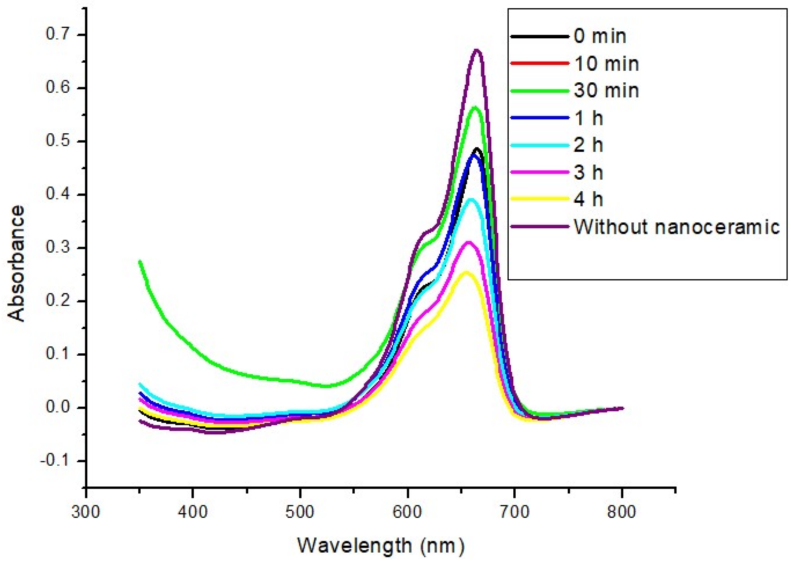

Figure 4. Absorbance plots of MB samples with nano-TiO_2 and nano-SnO_2 exposed to different durations of UV radiation against light wavelength.

3.4. Zeta Potential

Table 2 records the mean zeta potential values of the dispersed nanoceramics in each of the three sprays that contained nanomaterial(s). Note that all values are under −20 mV, namely: 0.626, 0.366 and 1.62 mV, respectively, for SnO_2, SnO_2 + TiO_2 and TiO_2 containing PDMS + isopropane solutions. These values (close to zero) suggest that the particles are prone to aggregation [44], as a stable and homogenous mixture of suspended particles would have a minimum zeta potential value of ±30 mV [45,46]. However, this opens the doors to investigate whether the stability levels would be improved if lower concentrations of nanoparticles were dispersed in the mixture, or if a pretreatment process to the nanoparticles would be beneficial, etc. Besides, attempting to enhance the homogenization of these particles through altering the preparation process may provide more satisfactory zeta potential values [46].

Table 2. Zeta potential test results of the various nanoparticles solutions containing PDMS + isopropane.

Type of Nanoceramic in Sample	Zeta Potential Value (mV)
5% SnO_2	+0.626
2.5% SnO_2 + 2.5% TiO_2	+0.366
5% TiO_2	+1.62

3.5. PV Efficiency

Figure 5 exhibits the electrical energy efficiency curves of the test panels. Overall, the electrical energy efficiencies of the panels decline with time, probably due to the accumulated dust, during the experiment's timeframe. The role of dust on impairing light rays from being received by the solar cells and rise in surface temperature have been shown [8]. The panels sprayed with PDMS & nano-SnO_2 and with PDMS & TiO_2 interchange between the 2nd and 3rd highest achieved electrical energy efficiency level. As indicated by the discussed characterization results, spray 1 (PDMS + SnO_2) results in greater WCA than that of Spray 3 (PDMS + TiO_2), therefore, it is expected to be more likely to slide deposited dirt or dust than panel 3. However, Spray 3 has shown a significantly greater photocatalytic behavior and hence, it is the most capable of degrading dirt. It is believed that the described superiority of each of the two sprays has caused results that are close to each other. Combining both nanomaterials to simultaneously make use of their advantageous features resulted in the overall greatest efficiency level, such that the surface is both sufficiently hydrophobic and photocatalytic. From previously obtained data, this panel has a WCA of 100.6°, allowing a satisfactory slippage of dust and dirt, as well as its degradation. On the other hand, during approximately half the experimental period, the panel sprayed with only PDMS showed the lowest efficiency values and then crossed with the efficiency curve of the non-sprayed panel to become the second lowest curve. This implies that the spray may have to carry a nanoceramic to positively impact PV efficiency. The non-sprayed panel produced the lowest efficiency, probably because it accumulated more dust over time relative to the rest of the panels that were under the effects of the investigated surface-enhancing materials [41,47–49].

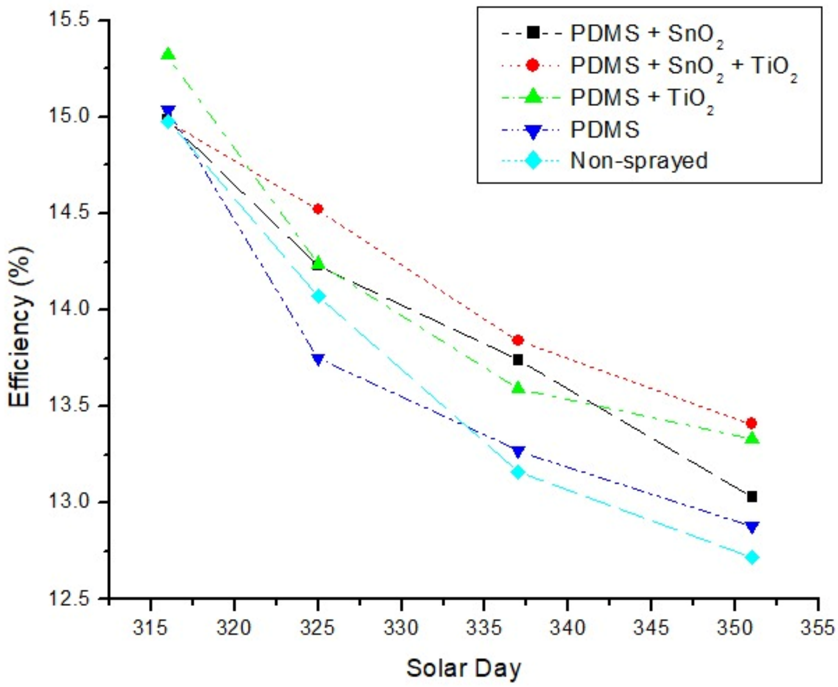

Figure 5. Energy Efficiency plots of sprayed and unsprayed panels against solar day (day of the year).

Finally, this work has reported new findings regarding the application of transparent PDMS- based nanoceramic composite coating. The aim of the work was to investigate the role of using PDMS as the main fluid carrier for producing superhydrophobic self-cleaning coating for solar cells. Previous work [41,47–49] has emphasized the significance of using transparent self-cleaning coatings in the glass panel application especially for the photovoltaic (PV) panel industry. This work has investigated the application of PDMS with and without SnO_2 and/or TiO_2 nanoparticles to examine their self-cleaning behavior on the performance of PV panels. This was achieved by sonicating the mentioned nanoparticles in a solvent to be magnetically stirred with PDMS oil. The mixture was sprayed onto solar cells that were exposed to outdoor conditions. Efficiencies of the employed solar cells were observed several times during the experiment. For interpretational reasons, the WCA of the sprays, photocatalysis and zeta potential of the nanomaterials were studied. The superior performance of the nanoparticles-based sprays when compared with sprays without nanoparticles indicated that the presence of the utilized nanoparticles in the spray is essential for the providence of an instant positive effect [41,47–49]. The spray that includes a mixture of both nano-TiO_2 and nano-SnO_2 was found to be highly beneficial, achieving higher performance compared to sprays with individual types of nanoparticles. This was particularly evident for solar panels installed in highly dust-prone regions. The obtained results suggest that the nanoparticles-based sprays are expected to reduce the need for cleaning solar PV panels for over a month while maintaining higher performance levels compared to those without sprays.

At this stage it is worth mentioning that the use of PDMS for PV self-cleaning coating applications has only been explored recently. While a significant number of publications of PDMS applications for coating surfaces for biomedical applications appear in literature, few research articles focus on PV applications [8,38,39,41,42,47–52]. Since the most significant characteristics defining superhydrophobic coatings are their water contact angles greater than 150 and a sliding angle of less than 10 [36], this work paid special attention to the WCA measurement relevant to other reported work. The developed transparent coating material (in this work) exhibited WCAs in the range 94–116°, with electrical energy efficiency in the range of 12.75%–15.3%. It was shown by previous work that WCA around 155.1° [47] and 103.9° [48] were verified for superhydrophobic self-cleaning PDMS-based coatings, 123° for PDMS/SiO_2 nanocoating [49], while others [41] reported WCAs around 154°, from 74.8° to 135.58° [50], 144.15° by using ZnO as the ceramic additive [51] and 158.41 $\pm$ 1.58° with 4° sliding angle [52]. Using hexamethyldisilazane-modified silica [47] antireflective buffer layer and an epoxy modified silicone/fumed silica superhydrophobic surface layer exhibited a coating with a transmittance 4.3% higher than the bare glass and achieving a static water contact angle of 155.1° and a sliding angle of 0.1°. Electrical energy efficiency (13.7%) was reported for nano PDMS-coated panels with an increase mounting to 30.7% higher than the reference panel was reported [49]. Thus, it is shown that the developed transparent coating material (in this work) has WCAs values within the range of values reported in literature.

This work opens the door for further research on some important topics aiming at optimizing the spray composition. The selection of the polymeric- based fluid carrier for manufacturing the self- cleaning coatings has been investigated by researchers and recently, the application of PDMS has been explored, based on its superior surface properties in other applications [8]. However, modifying the PDMS structure to integrate anti-reflection, antistatic, photocatalytic, etc. properties is still open for investigations. Also, in this work since the simultaneous presence of nano-SnO_2 and nano-TiO_2 in PDMS exhibited the best efficiency relative to the rest of the applied sprays, it is worth investigating the optimal concentrations for each of them. This could be accomplished by varying the concentration percentage of each and determining which results in the most desirable PV efficiency. Furthermore, it would be beneficial to observe the PV efficiency for longer than 5 weeks to specify the time at which the panels should be cleaned and resprayed. Also, some reported results from a study that simulated the thermal behavior of PV systems showing that the adoption of PDMS and PET coatings with 200 µm film thickness coatings slightly improve the temperature reductions by up to 1.15 °C in the case of PET and 1.35 °C in the case of PDMS [53] calls for designing some tests including temperature measurements. Finally, real- life implementation in urban and rural areas need more emphasis in future studies [54,55].

4. Conclusions

The following conclusions present the main findings of this work:

(1) The addition of SnO_2 and/or TiO_2 nanoparticles to PDMS oil- spray increase the hydrophobicity of the sprayed surfaces, as evidenced by the increased (94–116) contact angles obtained. The spray with a mixture of both nano-TiO_2 and nano-SnO_2 resulted the highest energy efficiency and performance compared to sprays with individual types of nanoparticles. This contributes to the self-cleaning effect of the nanoparticle-based sprays, especially in highly dust-prone regions.

(2) However, mixtures or dispersions of either nano-TiO_2 or nano-SnO_2 alone could be sufficient, providing acceptable performance and thus can be utilized in less dusty environments.

(3) The strong photocatalytic characteristics of TiO_2 played a significant role in achieving a self-cleaning effect, as observed from the energy efficiency results, thereby reducing PV efficiency degradation.

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