JOURNAL OF
EMERGING INVESTIGATORS

Article

Nanotexturing as a method to reduce dust accumulation on solar panels

Sooa Choi[1], Thomas J. Webster[2]

[1] International School of Dakar, Dakar, Senegal

[2] Division of Pre-College and Undergraduate Studies, Brown University, Providence, RI, USA

SUMMARY

Many countries experience dusty weather year-round. This type of weather is a major challenge for collecting solar energy. Specifically, dust buildup reduces solar panel electricity output by 20 to 50%. Rather than changing the fundamentals of how solar panels are made, an easier way to modify the surface energy of solar panels could be to create nanotextures on the solar panel itself. As water and dust are both polar substances, we hypothesized that a hydrophobic solar panel surface would repel not only water, but dust and dirt as well, to increase solar energy capture. For this study, we first used a mathematical equation to predict the optimal surface nano-roughness on solar panels to reduce dirt accumulation by creating a hydrophobic surface. We found that a surface roughness of 205 and 445 nm for model solar panel silicone and glass surfaces, respectively, would decrease dirt accumulation. Our results further showed the least amount of dirt accumulation when soaking glass and silicone in potassium hydroxide (KOH, a base which creates a nanotexture and changes the energy of surfaces) for 13 and 10 minutes, respectively. Although requiring more studies to determine the specifics of which basic chemical is optimal and the best treatment time with that chemical to create hydrophobic surfaces on different solar panel chemistries, our study suggests that solar panels can be easily treated with KOH to create a nanotextured surface decreasing dirt and dust accumulation to optimize the adsorption of light by photovoltaic cells for greater solar energy.

INTRODUCTION

A commonly occurring problem for solar panels is the buildup of dust, sand, dirt, and other debris, which causes a reduction of power output by 20 to 50% (1). Cleaning solar panels is a time-consuming, frequent, and an expensive process that involves a great amount of fresh water and other materials, which is an inconvenience for users. Countries that are prone to dusty weather, such as those in Africa and the Middle East due to their proximity to the Sahara Desert, experience more intense dust buildup compared to other regions of the world, particularly in rural and extremely sandy and dusty areas (2). Such areas also tend to lack electricity and the continuous access to fresh water to clean dirty solar panels (3, 4). There has been progress made in terms of creating coatings for solar panels to reduce dirt accumulation, however, most of these approaches are costly and more challenging than using simple bases such as potassium hydroxide (KOH) since KOH does not create a coating but rather quickly etches the surface whenever needed (5). Additionally, in the long run, solar panel coatings will wear off and need to be reapplied.

Tempered glass is usually the outermost layer of solar panels, while silicone is often used for placement (6). Nanotexturing is a well-known process that can increase the surface area of a material and, thus, change its surface energetics (7). Nanotexturing of solar panels can occur through a top-down method which is defined as an approach taken when parts of a material are removed from the larger material to develop nanotextures. This can be accomplished chemically by using a strong base (such as KOH) to etch the glass surface (8).

In this study, we aimed to develop a simple nanotexturing method that can alter the surface energetics of solar panels to decrease charged dirt accumulation and maximize the power output of solar panels. This study also used contact angles to confirm if the surface energy of glass was changed through a base (KOH or NaOH) treatment. If the contact angles of water and a surface are acute (<90˚), the surface is considered to be hydrophilic or of high surface energy, and if they are obtuse (>90˚), the surface is considered to be hydrophobic or of low surface energy.

The contact angle between a liquid and a solid can be used in the well-established Young's equation to determine the surface tension or surface energy of silicone and glass (model solar panel chemistries) which can then be used in the Webster's equation to determine the effective roughness on silicone and glass needed to achieve a hydrophobic surface to reduce charged dirt accumulation (9, 10). We used contact angles to determine how the hydrophobicity of model glass or silicone solar panel samples changed with various KOH or NaOH treatment times. Moreover, the contact angle before treatment was used to determine the desired surface energy of a control model solar panel surface. These equations help explain that small contact angles result from high surface energy and hydrophilic solar panels that would promote dirt accumulation, while large contact angles result from low surface energy and hydrophobic solar panels that would inhibit dirt accumulation. Water and charged dust likely behave similarly in a typical state. Specifically, water molecules are polar due to their uneven sharing of bonded electron pairs and dust as well as dirt have either a positive or a negative charge due to interactions with different objects and particles (11). Thus, a change in contact angles would provide evidence of a change in surface energy of the silicone or glass solar panel surface to interpret different dirt accumulation.

Ultimately, in this study, we tested the hypothesis that

https://doi.org/10.59720/23-318

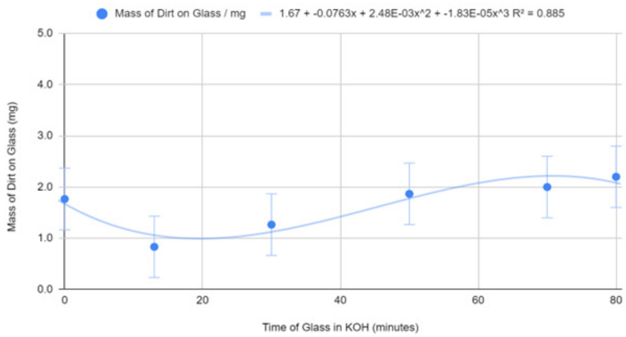

Figure 1: The relationship between the KOH treatment time of glass and the weight of dirt-settlement. Average of n=3 glass samples are shown per timepoint. The average of all the SD of the mass of dirt was ±0.6 mg which was used to graph the error bars. The sample that accumulated the smallest mass of dirt was the 13 minute treated sample. The trend is a cubic trend as the best-fit polynomial function passes through all of the error bars. The optimal treatment time to decrease dirt accumulation using the cubic trend was around 20 minutes.

Time of Glass in KOH (minutes)	Mass of Dirt on Glass (±0.000.1g)			Mean Mass of Dirt on Glass (mg)
	Trial 1	Trial 2	Trial 3	
0	0.0012	0.0018	0.0023	1.8
13	0.0002	0.0010	0.0013	0.8
30	0.0009	0.0009	0.0020	1.3
50	0.0015	0.0013	0.0028	1.9
70	0.0014	0.0025	0.0020	2.0
80	0.0017	0.0027	0.0022	2.2

Table 1: The effect of KOH treatment time of glass on the weight of dirt that settled on glass. n=3 glass per timepoint. The mass of the dirt that was accumulated on the surface of the glass samples as recorded by trial and the mean in mg.

glass and silicone (key components of solar panels) could be modified with KOH or NaOH to possess nanotextures to increase their hydrophobicity, reducing dirt accumulation and increasing solar power output. For this, we measured contact angles with a liquid and determined dust accumulation where the change in mass of a glass or silicone sample was measured when fine dirt was blown onto its surface. Results showed that a model solar panel glass sample treated for 13 minutes in KOH accumulated the least amount of dust and dirt by 0.8 mg suggesting the value of using this simple method to improve solar panel performance. This approach was further confirmed by showing that treating silicone surfaces in 10 minutes of KOH reduced dirt accumulation by 3 mg.

RESULTS

The aim of this study was to determine the optimum treatment time for model solar panel chemistries of glass and silicone in basic solutions (KOH or NaOH) to minimize dust and dirt accumulation. After we treated the samples in the basic solutions for various times, we determined contact angles on each sample converting such values to surface energy using the Young's equation. For glass, we used honey as the contact angle liquid because even with an extremely small drop of only water, the contact angles were too small and there were no measurable differences. Therefore, a more viscous liquid with honey was used so that the measured contact angles were larger leading to smaller uncertainties. The surface energy of honey is 55 mJ m^{-2} (12). For silicone, we used water contact angles since silicone is more hydrophobic so the contact angles were easier to determine with pure water. Then, to calculate the predicted effective roughness for a surface to repel dirt, we used the Webster equation and then completed dirt accumulation studies.

Using the Young's equation and the Webster equation, we determined $E_s(r_{eff})$ by calculating the nearest whole number greater than σ_s that would provide an idea for the minimum positive value for the effective roughness. If $E_s(r_{eff}) < \sigma_s$, the effective roughness was a negative number, indicating a smoother surface would be more ideal and polar water molecules would remain attached more easily. See the Appendix for the calculations. Results from these equations showed that the predicted effective roughness for solar panels to reduce dirt accumulation was between 205 nm to 455 nm. Next, we determined the effective basic solution treatment times to create the surface energy needed to reduce dirt accumulation. For glass, we found that the sample that was left in KOH for 13 minutes accumulated the smallest mass of dirt (**Figure 1, Table 1**). We further fit the data to a cubic equation where the cubic equation showed an optimal KOH treatment time to reduce dirt accumulation was 20 minutes. However, these results did not correspond with the sample that had the largest contact angle or was the most hydrophobic (**Figure 2**) which was the sample that was not treated in KOH. This would require more investigation as it was expected that the most hydrophobic surface would decrease dirt accumulation the most, thus, suggesting that other factors for controlling dirt accumulation are coming into play (such as the surface features for the most hydrophobic surface may have had the most crevices or defects to physically trap dirt confounding trends).

For silicone, similar to glass, the least amount of dirt accumulation occurred by soaking silicone in KOH for 10 minutes (**Figure 3**). The greatest hydrophobicity was observed after soaking silicone in KOH for 30 minutes (**Figure 4**). For

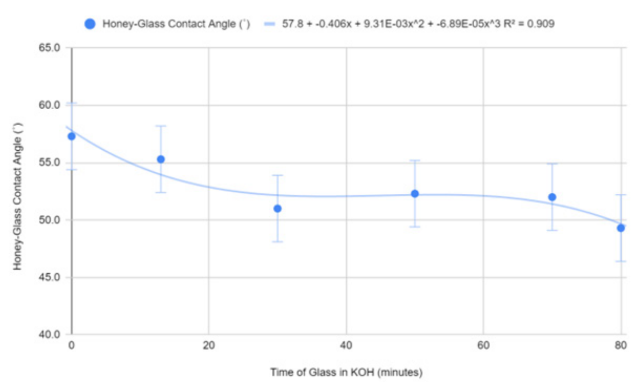

Figure 2: The relationship between the KOH treatment time of glass in minutes and the contact angle between honey and glass. Average of n=3 glass samples are shown per timepoint. The trend is cubic which corresponds to the cubic trend observed with the dirt accumulation experiment (Figure 1) and the function passes through all of the error bars. The magnitude of the error bars was calculated by finding the average of all SD of all of the contact angles (±2.9°). The 0-minute treated sample had the highest contact angle.

https://doi.org/10.59720/23-318

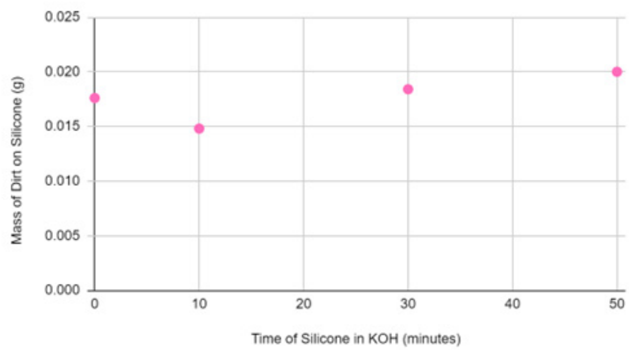

Figure 3: The effect of KOH treatment time on the mass of dirt on silicone. n=1 silicone per timepoint. The least amount of dirt accumulation was achieved at 10 minutes of KOH treatment time or when the contact angle showed increased hydrophobicity.

NaOH, the greatest hydrophobicity was found for soaking silicone for 50 minutes (**Figure 5**). All the angles were obtuse, meaning that the surface was hydrophobic. By comparing the results from using NaOH and KOH, the main difference was that the contact angles from soaking in NaOH produced an increasing trend while the silicone samples treated in KOH showed that the angles first increased, reached a maximum, and then decreased. Again, such results may be confounding in terms of interpreting dirt accumulation due to simultaneous changes in roughness (which can independently inhibit water from spreading on a surface) and surface energy.

Nonetheless, the least amount of dirt accumulation was found when soaking glass and silicone in KOH for 13 and 10 minutes, respectively.

DISCUSSION

As a reminder, the central question of this paper lies around the problem of dust accumulation hindering the performance of solar panels. This study used materials from two solar panel types: silicone and glass. First, we calculated an optimal surface roughness to reduce dirt accumulation using well established mathematical equations. Then, we nanotextured silicone and glass by soaking them in bases (KOH and NaOH) for various amounts of time, determined contact angles, and the mass of dirt they accumulated. Results showed that contact angles increased (surfaces became more hydrophobic) as the treatment time increased, except for the 50-minute silicone KOH sample. Additionally, we discovered that on silicone, there was less dirt buildup on a more hydrophilic surface, created by a shorter treatment time of about 10 minutes. Glass exhibited similar behavior: as treatment time increased, contact angles increased (became more hydrophobic) and there was less dirt buildup on the hydrophilic surfaces. Dirt accumulation showed an initial decrease on both materials at the short treatment times. Overall, while we were successful in reducing dirt accumulation and thus improving solar panel efficiency, correlating this change to changes in surface energy (or contact angles) can be difficult due to the confounding effects of roughness and surface energy on dirt accumulation. For example, due to the type of roughness, it can be envisioned that a more hydrophobic surface could have crevices and defects that physically trap dirt more than a hydrophilic surface.

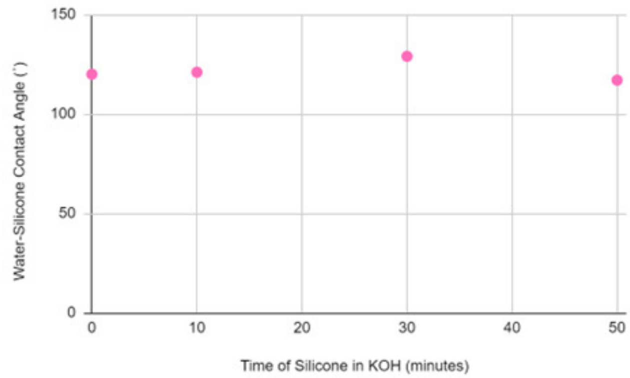

Figure 4: The effect of KOH treatment time on the water-silicone contact angle. n=1 silicone per timepoint. The most hydrophobic silicone surface was made after 30 minutes of KOH treatment.

In this project, KOH and NaOH were used to etch the samples. However, seeing these effects with different bases or even acids may be interesting as well to determine which one is most economically viable, safe, or efficient. Further, instead of soaking glass in these solutions, future studies should consider a spraying method for ease of use. Questions like these must be posed for the real-life application of nanotexturing solar panels for harnessing energy. Finally, finding the surface energy of dirt should be further investigated, as it would be another method for determining the effective roughness and energy of dirt-resistant solar panel surfaces.

A point of weakness from the methods used here was that the initial basic (NaOH versus KOH) treatment for silicone was different as they were applied using different methods. The NaOH treatment involved allowing the silicone to sit on a glass surface then removed, whereas the KOH treatment was from letting silicone dry on parafilm then peeled off. They most likely molded to the different underlying surfaces resulting in contrasting initial contact angles. This may have affected the rate of change of contact angles, therefore, an improvement to this method should be implemented and could use a consistent silicone surface for treatment.

Another limitation in this study is that the type of dirt, dust, and other particles should be formulated differently depending on the target location of the solar panels, as there are distinct

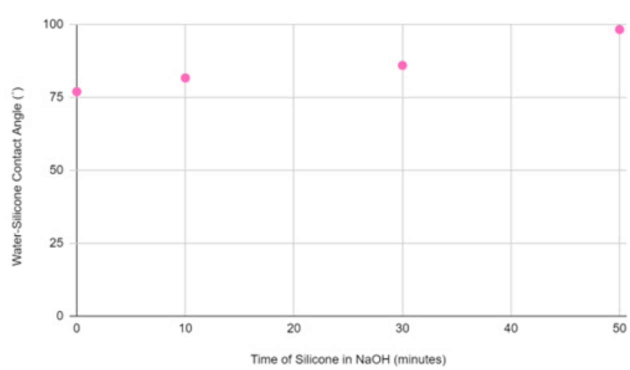

Figure 5: The effect of NaOH treatment on the water-silicone contact angle. n=1 silicone per timepoint. The contact angles made when a small drop of water was placed onto a 1.5x1.5 cm piece of silicone treated in NaOH for various length of time. The most hydrophobic silicone surface was made after 50 minutes of NaOH treatment.

https://doi.org/10.59720/23-318

types of airborne particles found in select regions that may adsorb in alternative ways chemically to a solar panel due to various charges (14). This study was focused on producing more efficient solar panels to be used in Middle Eastern, North African (MENA), and West African countries, and as the dirt that was experimented with was found in Providence, RI (USA), the composition of dirt likely does not represent the soil and dust found in MENA and West African regions. Therefore, experiments completed in different locations will improve the validity of this research.

Results from this study could be directly used in the solar panel industry, with further research for greater certainty, to improve the ability of solar panels to collect sunlight and convert that sunlight into energy. This study shows that treating solar panels with a strong base for just a few minutes can achieve such an important goal. Or, one could apply such a base as that used in this study after solar panels are installed to reduce dirt accumulation which inhibits solar light accumulation. Nanotexturing the glass or silicone surface of solar panels will be vital for regions that have dusty weather so that they can begin using solar energy, a renewable energy, more effectively.

It is important to place the results of this study into context with other studies. For example, one study found that NaOH smooths glass at a faster rate than KOH (15). In this present study, this finding was not demonstrated, as the comparison between KOH and NaOH was done solely through silicone samples and therefore was not verified. However, using KOH for glass may have allowed for results that provided a more complete picture. As the treatment times were kept the same here, the behavior of NaOH and KOH interacting with glass are likely to be very similar, as the only difference is the metal ion in the base. However, because KOH reacts with glass at a slower rate, the contact angle trend may be more accurate than the one found for NaOH.

Further, a study published in 2015 by Yilbas et al. investigated a similar issue regarding the effect of dust and mud accumulation on solar panels (16). Whereas the present study utilized a more affordable and easier method and materials to find a solution to this problem, the aforementioned study looked into the problem of dust altering the properties of solar panel surfaces. They found that KOH present in mud causes etching of glass so this raises the question of how long the treated, nanotextured glass will last if or when put into use if placed in locations where KOH and other bases naturally occur.

In regards to the results, the behavior of contact angles increasing then decreasing requires further study, this could be due to KOH being a stronger base which increased the etching reaction, perhaps first forming nanotextures but then smoothing the surface when treated too long. The KOH-treated samples reached a maximum contact angle before the NaOH samples did, essentially allowing us to view the potential results if the samples treated in NaOH were to be treated for longer periods of time. Additionally, both silicone and glass with short treatment times support the hypothesis that as the surface became hydrophobic, it became more dust-resistant.

There are many areas to be considered to further research this topic. A crucial point to consider is the reflectiveness of the glass. Reflecting light away from the solar panels is the last thing that is desired as the purpose of solar panels is to harness or collect energy. Therefore, ensuring that the glass (and resulting nanotexture) is not reflective is also important, which leads to another idea for future research that could be done to minimize the reflectiveness of glass on solar panels so that increased quantities of energy can be absorbed by the PV cells. Specifically, the reflectiveness of the nanotextures created from this study could be tested as a future experiment. Moreover, the type of glass used in this study was borosilicate. However, solar panels are made with tempered glass, which may have different properties than the microscope slides; therefore, such differences in chemistry must also be investigated.

It is clear that the process developed here to reduce dirt accumulation is easy, inexpensive, and effective. However, similar to existing solutions which use coatings that may need to be reapplied frequently, nanotexturing glass may need to be replaced or chemically treated again and again. If research on this topic continues, it is clear that large-scale solar farms could use this approach as an economic and effective solution in the long-term. This method does not yet permit zero dust accumulation, however, even around 10 minutes of treatment time could reduce the frequency that solar panels have to be cleaned. In regions where dust is a major barrier to switching to solar energy for electricity, this is a breakthrough that could reduce inequalities of resources and opportunities, thus, also having significant social impact.

MATERIALS AND METHODS

Nanotexturing

Silicone, used as a model solar panel surface, was poured onto a flat piece of parafilm and was left to dry overnight. It was then cut into six pieces 1.5 cm long × 1.5 cm wide. KOH was poured into a wide-base beaker/container up to a height of around 1 cm. Pieces of silicone were added to the KOH solution and then removed after 0, 10, 30 and 50 minutes and fully dried with a paper towel. Glass was added then removed from the KOH solution at 0, 13, 30, 50, 70, and 80 minutes and then dried with a paper towel. There was one set of silicone samples tested in this study and three sets of glass samples, making a total of 18 glass samples and four samples of silicone.

The main component of glass consists of silicon dioxide/ silica (SiO_2). The chemical reaction between KOH(aq) and SiO_2(s) predicts that the surface of glass will corrode after exposure to KOH (Equation 1), leaving behind an altered surface of glass which has varying roughness, thus, affecting the adsorption of water, dust, and other substances:

$$2KOH(aq) + SiO_2(s) \rightarrow K_2SiO_3(aq) + H_2O(l) \quad \text{(Equation 1)}$$

Contact Angles of Water/Honey on Silicone/Glass

The silicone/glass samples were placed on flat surfaces with the nanotextured surface facing up and placed in order from shortest to longest treatment time. A three-mL syringe was filled with regular tap water for silicone samples and honey for glass samples. It was closely held above a silicone/ glass sample and a drop of water/honey was placed on it, ensuring it was as even as possible. Similarly sized water/ honey droplets were placed onto each silicone/glass sample. A side-view picture of the droplets was taken. The contact angles were manually measured with a protractor by estimating the tangential line where the droplet meets the silicone/glass surface.

https://doi.org/10.59720/23-318

Testing for Dust Resistance

A flat surface that was long enough to hold all the microscope slides and silicone samples, and large enough so that no samples overlapped each other, was made from cardboard. It was made to form an angle of between 30˚ and 45˚. A small lip was added to the bottom of the device so that the content stayed in place. An electronic balance (± 0.0001 g) was used to measure the weight of the silicone and glass samples. The apparatus was set up outside with a small fan and a bag of around 100 g of fine, dry dirt on standby. The fan was moved back and forth parallel to the surface of the cardboard while taking a small handful of dirt in hand. The dirt was slowly released in increments, making sure that it flew towards the silicone and glass and landed on their surfaces. This process was continued while ensuring that the dirt was blowing on the silicone and glass surfaces as evenly as possible until there was no more dirt. The weights of the silicone and glass samples were carefully measured and recorded again, making sure not to add or remove dirt particles from them in the process. The silicone and glass samples were rinsed with water and paper towels to repeat this process two more times for a total of three trials, but only for the glass samples. One silicone was used for each experimental condition.

Calculations

The Young's equation (Equation 2) shown below can be used to determine the surface tension of silicone and glass: where σ_s is the surface tension of the solid, σ_{sl} is the interfacial tension (which is 0 J as it is in equilibrium), σ_l is the surface

$$\sigma_s = \sigma_{sl} + \sigma_l \times cos\theta \qquad \text{(Equation 2)}$$

tension of the liquid, and θ is the contact angle. As the contact angle gets closer to 0˚, σ_s gets larger. Increasing the contact angle to 90˚ decreases the surface tension value as cosθ approaches 0.

The Webster equation (Equation 3) can then be used to determine the effective roughness desired $E_s(r_{eff})$. The equation is as follows:
where $E_s(r_{eff})$ is the desired surface energy of a substance, $E_{0,s}$ is the initial surface tension, ρ is a constant of 1.4 mJ m^2

$$E_s(r_{eff}) = E_{0,s} + \rho \times r_{eff} \qquad \text{(Equation 3)}$$

$(100\ nm)^{-1}$, and r_{eff} is the predicted effective roughness for that surface to possess the desired surface energy.

ACKNOWLEDGMENTS

We would like to thank the Division of Pre-College and Undergraduate Studies at Brown University for financial support.

Received: October 30, 2023
Accepted: April 1, 2024
Published: January 30, 2025

REFERENCES

1. "Say Goodbye To Solar Panel Cleaning | Ultimate Efficiency." Solar Sharc®, solarsharc.com. Accessed 13 July 2023.
2. Middleton, N. J., and A. S. Goudie. "Saharan Dust: Sources and Trajectories." *Transactions of the Institute of British Geographers*, vol. 26, no. 2, 2001, pp. 165–81, https://doi.org/10.1111/1475-5661.00013.
3. Blimpo, Moussa P., et al. "Why Is Household Electricity Uptake Low in Sub-Saharan Africa?" *World Development*, vol. 133, Sept. 2020, p. 105002, https://doi.org/10.1016/j.worlddev.2020.105002.
4. Falk, Joern, et al. "Drinking Water Supply in Rural Africa Based on a Mini-Grid Energy System—A Socio-Economic Case Study for Rural Development." *Sustainability*, vol. 14, no. 15, Jan. 2022, p. 9458, https://doi.org/10.3390/su14159458.
5. Mozumder, Mohammad Sayem, et al. "Recent Developments in Multifunctional Coatings for Solar Panel Applications: A Review." *Solar Energy Materials and Solar Cells*, vol. 189, Jan. 2019, pp. 75–102, https://doi.org/10.1016/j.solmat.2018.09.015.
6. Svarc, Jason. "Solar Panel Construction." *Clean Energy Reviews*, 20 Mar. 2020, www.cleanenergyreviews.info/blog/solar-panel-components-construction.
7. Heckenthaler, Tabea, et al. "Self-Cleaning Mechanism: Why Nanotexture and Hydrophobicity Matter." *Langmuir*, vol. 35, no. 48, Dec. 2019, pp. 15526–34, https://doi.org/10.1021/acs.langmuir.9b01874.
8. Tournié, A., et al. "Glass Corrosion Mechanisms: A Multiscale Analysis." *Solid State Ionics*, vol. 179, no. 38, Nov. 2008, pp. 2142–54, https://doi.org/10.1016/j.ssi.2008.07.019.
9. Owens, Wendt, Rabel and Kaelble (OWRK) Method. www.kruss-scientific.com/en-US/know-how/glossary/owens-wendt-rabel-and-kaelble-owrk-method. Accessed 20 Jul. 2023.
10. Webster, Thomas J. Thomas J. Webster's Nano-Optimized Predictive Equation. 2023, www.youtube.com/watch?v=mq1HOYkTbBY.
11. Bowling, R. Allen. "A Theoretical Review of Particle Adhesion." *Particles on Surfaces 1: Detection, Adhesion, and Removal*, edited by Kashmiri Lal Mittal, Springer US, 1988, pp. 129–42, https://doi.org/10.1007/978-1-4615-9531-1_10.
12. Bormashenko, Edward Yu.. "Wetting of Real Surfaces." *Studies In Mathematical Physics*, 2019, https://doi.org/10.1515/9783110583144.
13. Baloš, Milica Živkov, et al. "COMPARATIVE STUDY OF WATER CONTENT IN HONEY PRODUCED IN DIFFERENT YEARS." *Archives of Veterinary Medicine*, vol. 12, no. 1, Sept. 2019, pp. 43–53, https://doi.org/10.46784/e-avm.v12i1.42.
14. Krueger, B. J., et al. "Heterogeneous Chemistry of Individual Mineral Dust Particles from Different Dust Source Regions: The Importance of Particle Mineralogy." *Atmospheric Environment*, vol. 38, no. 36, Nov. 2004, pp. 6253–61, https://doi.org/10.1016/j.atmosenv.2004.07.010.
15. Bashir, S. T., et al. "A Simple Chemical Approach to Regenerating the Strength of Thermally Damaged Glass Fibre." *Composites Part A: Applied Science and Manufacturing*, vol. 102, Nov. 2017, pp. 76–87, https://doi.org/10.1016/j.compositesa.2017.07.023.
16. Yilbas, Bekir Sami, et al. "Influence of Dust and Mud on the Optical, Chemical and Mechanical Properties of a Pv Protective Glass." *Scientific Reports*, vol. 5, no. 1, Oct. 2015, p. 15833, https://doi.org/10.1038/srep15833.

https://doi.org/10.59720/23-318