Smart Engineering Systems: Design and Applications

ARTIFICIAL INTELLIGENCE, INTERNET OF THINGS (IOT) AND SMART MATERIALS FOR ENERGY APPLICATIONS

Edited by
Mohan Lal Kolhe, Kailash J. Karande
and Sampat G. Deshmukh

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Artificial Intelligence, Internet of Things (IoT) and Smart Materials for Energy Applications

This reference text offers the reader a comprehensive insight into recent research breakthroughs in blockchain, the Internet of Things (IoT), artificial intelligence and material structure and hybrid technologies in their integrated platform, while also emphasizing their sustainability aspects.

The text begins by discussing recent advances in energy materials, energy conversion materials using machine learning and recent advances in optoelectronic materials for solar energy applications. It covers important topics including advancements in electrolyte materials for solid oxide fuel cells, advancements in composite materials for Li-ion batteries, progression of materials for supercapacitor applications, and materials progression for thermochemical storage of low-temperature solar thermal energy systems.

This book:

- Discusses advances in blockchain, Internet of Things, artificial intelligence, material structure and hybrid technologies
- Covers intelligent techniques in materials progression for sensor development and energy materials characterization using signal processing
- Examines the integration of phase change materials in construction for thermal energy regulation in new buildings
- Explores the current happenings in technology in conjunction with basic laws and mathematical models

Connecting advances in engineering materials with the use of smart techniques including artificial intelligence, machine learning and Internet of Things (IoT) in a single volume, this text will be especially useful for graduate students, academic researchers and professionals in the fields of electrical engineering, electronics engineering, materials science, mechanical engineering and computer science.

Smart Engineering Systems: Design and Applications

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Preface

In the past decade, significant developments have taken place in computing techniques and materials development. There is a global trend to use artificial intelligence techniques for processing and analysing complex data for specific applications in decision-making. Also, Internet of Things (IoT) technology is widely used in developing integrated cyber-physical systems that have machine-to-machine networking for automation and system monitoring. Applications of computing techniques and perceptible advancements in material developments have emerged over the past few years. Recent technological advancements in materials significantly contribute to the development of sustainable technologies.

This monograph presents applications of artificial intelligence techniques in the context of opportunities for applications in selected cases using collected complex data for a meaningful purpose. Specific examples of IoT technologies are discussed to collect and process complex data to perform meaningful operations and take appropriate actions. Also, chapters on energy materials cover some aspects of fundamental and applied research on design/developments of materials for specific applications spanning metallurgy and energy conversion. The authors have attempted to present individual chapters as research manuscripts. However, the authors of respective chapters remain accountable for all enduring inaccuracies.

Finally, the editors wish to express their sincere gratitude to the authors and peer reviewers who have significantly contributed to the preparation of this book. We are also very grateful to our publisher CRC Press of Taylor and Francis Group, for providing an opportunity to publish a monograph on emerging topics of artificial intelligence, the Internet of Things and smart materials for energy applications.

Editors

Prof. (Dr.) Mohan Lal Kolhe is a full-time professor at the University of Agder, Norway. He is a leading renewable energy technologist with three decades of academic experience at the international level and previously held academic positions at the world's prestigious universities such as University College London (UK/Australia), University of Dundee (UK), University of Jyvaskyla (Finland) and Hydrogen Research Institute, QC (Canada). In addition, he was a member of the Government of South Australia's first Renewable Energy Board (2009–2011) and worked on developing renewable energy policies. He received the offer of a full professorship in smart grid from the Norwegian University of Science and Technology (NTNU). He won competitive research funding from the prestigious research councils (e.g. Norwegian Research Council, EU, EPSRC, BBSRC, and NRP) for his work on sustainable energy systems. He has published extensively in the Energy Systems Engineering. He has been invited by many international organizations for delivering expert lectures/keynote addresses. His research works in Energy Systems have been recognized within the top 2% of scientists globally by Stanford University's 2020 and 2021 matrices. He is working as editor for various journals published by Springer, Elsevier, AIP Publishing, and MDPI. He is an internationally recognized pioneer in his field, whose top 10 published works have an average of over 175 citations each.

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14 Superhydrophobic Coatings of Silica NPs on Cover Glass of Solar Cells for Self-Cleaning Applications

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14.1 INTRODUCTION

Solar cell is a promising and widely used energy device due to its environment-friendly and renewability characteristics. Such energy devices absorb incident sunlight and convert it into electric energy. However, the solar cell is contaminated due to the accumulation of organic and inorganic dust particles over a long period. These dust particles prevent incident light to reach the solar cell panels, consequently, the output efficiency gets decreased [1,2]. Paudyal and Shakya [3] have studied the effect of dust deposition density ranging from 0.1047 to 9.6711 g m^{-2} on output efficiency of solar modules during a period of 148 days in outdoor exposure. The 9.6711 g m^{-2} dust deposition has reduced the efficiency of the solar panel up to 29.76% with respect to the module that is cleaned on daily basis. Adinoyi et al. [4] have experienced 50% decrease in output power of photovoltaic (PV) module, when it was kept without cleaning for a period of 6 months in outdoor conditions. Results of this literature confirm that dust accumulation could significantly affect the output power of solar modules. Therefore, it is a challenging task to keep the output efficiency of the solar panels at maximum for a long period without frequent cleaning of the surface.

A lotus leaf grabbed the attention of scientists and inspired them to develop a self-cleaning surface, which exhibits a highly nonwetting property with a water contact angle of nearly 160° and a sliding angle of less than 5° [5,6]. Currently, many efforts have been taken to develop lotus leaf–like self-cleaning superhydrophobic coating to protect the surface of windshields of vehicles, the entire body of vehicles, window and door glasses, skyscrapers, solar cell panels, fabrics, sports shoes, and so on [7–10]. When the suspension of SiO_2 nanomaterial in alcohol was sprayed on paper at room temperature and atmospheric pressure, the hydrophobicity of the coatings was found dependent on the size of nanoparticles (NPs) as well as the aggregation of NPs, which again depends on the type of alcohol used in the coating solution [11]. Datta et al. [12] have fabricated self-cleaning superhydrophobic coating on solar cell cover glass by depositing sol–gel processed silica NPs coating and grafting a monolayer of fluoroalkylsilane on it. Almari et al. [13] have investigated the efficiency of solar PV panels after coating with hydrophobic SiO_2 nanomaterial. This investigation concludes that output power was increased by 15% more than the dusty panels and 5% more than the uncoated panels, which were cleaned manually every day. Zhi et al. [14] have prepared antireflective, transparent, and self-cleaning superhydrophobic surface through dipping in silica NP solution. Such coating showed static water contact angle of 157.9° and contact angle hysteresis of 1.2°. Wang et al. [15] have sprayed the paint-like suspension of silica NPs and 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (FAS) onto the polydimethylsiloxane (PDMS) coated glass substrate to obtain robust self-cleaning superhydrophobic coating. Zhang et al. [16] have prepared superhydrophobic surface on glass substrate by spraying the suspension of hydrophobic silica NPs and curing at room temperature without any modification or surface treatment. The damaged superhydrophobicity of coating was recovered by simply respraying the suspension. Lazauskas et al. [17] have fabricated a transparent, self-cleaning superhydrophobic surface by dropping the dispersion of hexamethyldisilazane (HMDS) and SiO_2 NPs in ethanol on microscopic glass slides and dried at room temperature to evaporate ethanol.

Herein, we have prepared a superhydrophobic coating on the glass slide and covered the glass of solar cell panel by spraying the suspension of hydrophobic SiO_2 NPs. The aggregated SiO_2 NPs on the glass surface formed a hierarchical dual scale rough structure, which is responsible for the high water contact angle $160 \pm 2°$ and low sliding angle 6°. The prepared superhydrophobic coating was sustained for water jet impact test and mechanical durability test. The rolling water droplets cleaned the contaminated solar cell panel, which confirmed that the prepared superhydrophobic coating exhibits self-cleaning ability.

14.2 EXPERIMENTAL SECTION

14.2.1 Materials

Hydrophobic silica NPs (surface area $210\,m^2g^{-1}$) were purchased from AEROSIL Company, RX 300-5, Japan. Hexane (puriss for synthesis) was bought from Spectrochem, Mumbai, India. Micro glass slides (Blue Star, India) and solar cell panels (local market) were procured.

14.2.2 Preparation of Superhydrophobic

The glass slide and cover glass of the solar cell panel were cleaned with the laboratory detergent (Molyclean 02 Neutral, from Molychem, India) to eliminate surface contaminants. The suspension of hydrophobic silica NPs was prepared by dispersing it in hexane ($5\,mg\,mL^{-1}$) using ultrasonication for 20 minutes. The prepared suspension was applied on a glass slide and cover glass of solar cell panel using a spray coating method. The successive ten layers of SiO_2 NPs were applied from 10 cm with a time interval of 1 minute between each layer. Then, the coatings were kept in air at room temperature to evaporate hexane. The process of deposition of suspension of SiO_2 NPs on the substrate is shown in Figure 14.1.

14.2.3 Characterization

The surface microstructure of the coated substrate was observed by scanning electron microscope (SEM, JEOL, JSM-7600F). The water contact angles and sliding angles were measured three times at various locations, and the mean value was noted as final value using a contact angle meter (HO-IAD-CAM-01, Holmarch Opto-Mechatronics Pvt. Ltd., India). The self-cleaning property of the coating was investigated by spreading the fine chalk particles as dust on the coating. The mechanical stability of coating was evaluated by adhesive tape peeling, sandpaper abrasion, and water jet impact test.

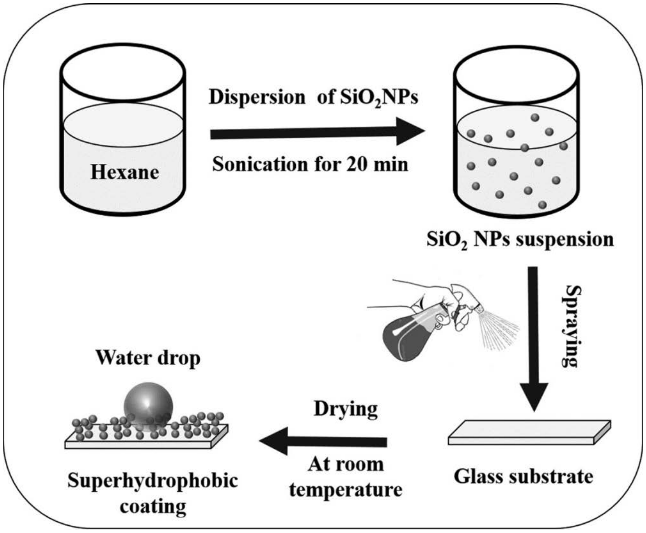

FIGURE 14.1 Schematic of experimental procedure for the preparation of superhydrophobic coating on the substrate.

14.3 RESULT AND DISCUSSION

14.3.1 Surface Structure and Wettability

In the beginning, the primary coatings were done at a laboratory scale on micro glass slide. Figure 14.2a reveals color-dyed water drops on a coated glass slide. The water drop attains a spherical shape with a water contact angle of $160 \pm 2°$ on prepared superhydrophobic coating and a sliding angle of less than 6°. The optical image of water drop on the superhydrophobic coating received from the contact angle meter is shown in Figure 14.2b.

The SEM image confirms the suspension of SiO_2 NPs was uniformly covered on the surface of the glass slide. The rough porous microstructure was attained from aggregated SiO_2 NPs (Figure 14.2c). Numerous nanovoids were observed on the coating, which is evidence of nanoscale roughness. However, in high-magnification SEM image (Figure 14.2d), it is clearly observed that the rough and porous microstructure of the superhydrophobic coating is a result of aggregated SiO_2 NPs. Low surface energy of hydrophobic NPs and micro/nanostructure of coating are two important key factors of the superhydrophobic coating. Zhang et al. [16] have observed a similar surface structure in the spray deposited coating of hydrophobic silica NPs. Such micro-/nanoscale hierarchical rough surface allows more air to be trapped underneath the water drop, and hence the solid–liquid contact area will be effectively minimized.

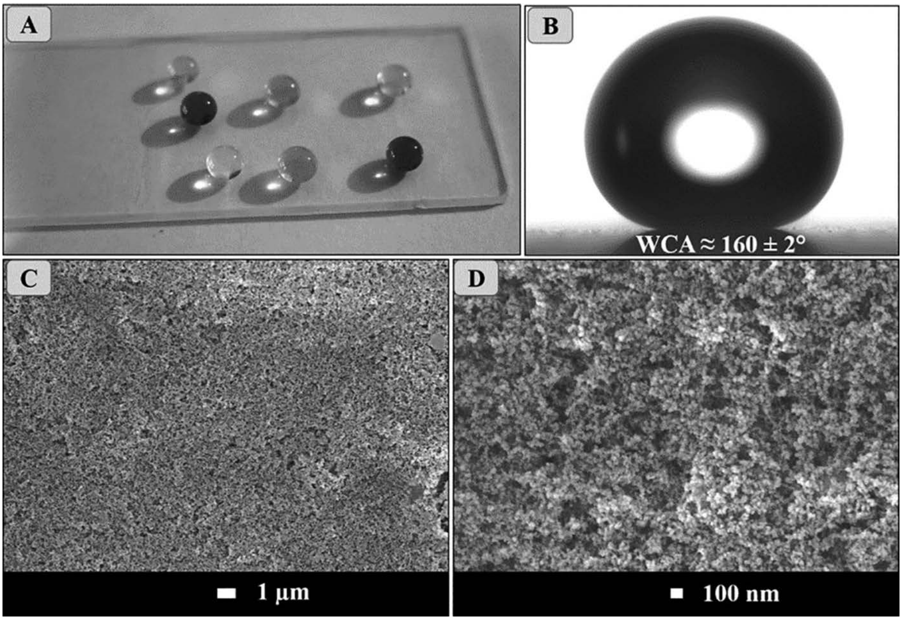

FIGURE 14.2 (a) The photograph of color-dyed water drops on coated micro glass slide, (b) the optical image of a water drop on the superhydrophobic coating, and (c) low- and (d) high-magnification SEM images of superhydrophobic coating.

14.3.2 Durability of Superhydrophobic Coating

The mechanical durability of the superhydrophobic coatings is essential key factor for its commercial applications. However, the fragile hierarchical structure of superhydrophobic coatings can be easily destroyed by mechanical rubbing and hence gives poor durability. In the literature, the adhesive tape peeling and sandpaper abrasion tests are mostly used to determine the durability of the prepared coatings. The adhesive tape with adhesion strength of 4 N m^{-1} was gently applied on the prepared superhydrophobic coating. A 50 g metal disk was rolled on it to ensure good contact between tape and coating. The adhesive tape was slowly peeled off and quickly water contact angle and sliding angle were measured on the coating. The coating exhibited superhydrophobicity even after four times of the tape peeling test was carried out. This adhesive tape peeling test confirmed that the silica NPs are firmly adhered to the glass substrate. In recent work, Dessouky et al. [18] have observed that the hydrophobic silica NPs–coated metals lost their superhydrophobicity after single adhesive tape test and the water contact angle reduced from 155° to 118°. For further evaluation of the mechanical stability of the coating, a 50 g weight-loaded superhydrophobic glass slide was placed on sandpaper (600 grit) and dragged linearly with a speed of 5 mm s^{-1} for 30 cm [15]. We observed that the superhydrophobic coating was completely scratched and lost superhydrophobicity. The continuous water jet

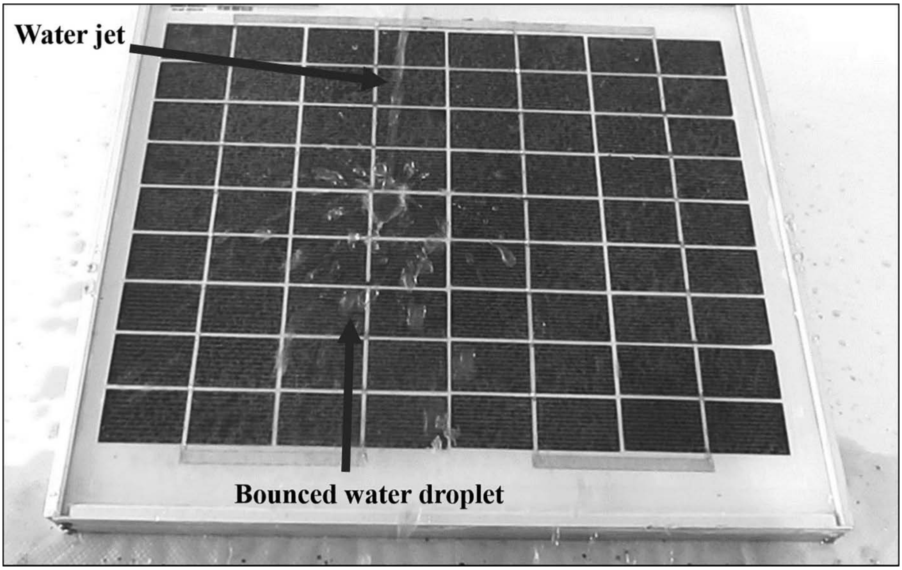

FIGURE 14.3 The water jet bouncing on coated solar cell panel.

was applied on coated solar cell panel from the height of 10 cm to demonstrate the remarkable water resistance [19]. The water jet bounces up when it falls on a coated solar cell panel (Figure 14.3). The air trapped in a rough structure of the coating could not allow the water to enter inside it. However, after 5 minutes of water jet impacting, water drops stuck on the coating, which confirms that the coating material got removed from the cover glass due to water jet impact.

14.3.3 Self-Cleaning Property

Self-cleaning is one of the most important properties of superhydrophobic surface in practical applications, which can automatically clean the surface through rolling water drops. Mostly solar cell panels are installed in large areas for the generation of electric power. They can be covered by various types of contaminants, subsequently reducing the output power of solar cell panels. The frequent cleaning of solar panels serves challenging problem in the whole world. The mechanical/chemical methods of cleaning are time-consuming and cost-effective. The superhydrophobic coating on the cover glass of the solar cell panel can be a solution and water drops on the coated cover glass can eventually roll off by collecting the water drops; hence, the solar cell panels are self-cleaned. Fine particles of chalk dust were spread randomly on coated solar cell panel to investigate self-cleaning behavior (Figure 14.4a). Dust contaminated solar cell panel kept at an inclination of 30° from the horizontal plane and water droplets poured on it [20]. The dust particles cannot be removed from the uncoated solar panel with a water droplet. However, on superhydrophobic coated solar panel, the rolling water drops take off the dust particles on their way and eventually cleaned the surface of the solar panel. Figure 14.4b reveals a dust contaminated solar panel

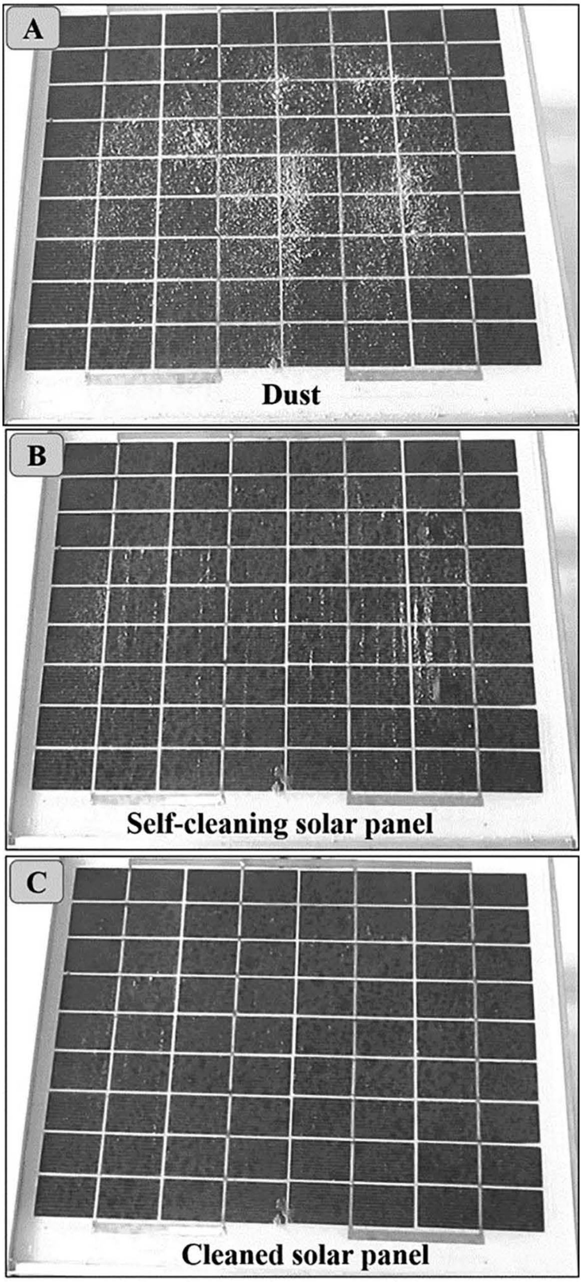

FIGURE 14.4 (a) Randomly spread dust particles on superhydrophobic cover glass of solar panel, (b) self-cleaning behavior, and (c) cleaned solar panel.

cleaned by the rolling action of water drops. When water was continuously poured on contaminated solar panel, almost all dust particles are removed from the solar panel without contact cleaning (Figure 14.4c).

Literature confirms that the SiO_2 particle–based superhydrophobic coatings are more efficient in the self-cleaning phenomenon. Due to high bonding energy, SiO_2

TABLE 14.1
Summary of a Literature Review on the Self-Cleaning Property of SiO_2 NPs–Based Superhydrophobic Coatings

Materials	WCA/SA (°)	Self-Cleaning Performance Carried by Considering	References
PDMS/SiO_2	156.4/5	Sand particles as dust	[21]
Linear low density polyethylene (LLDPE)/ SiO_2	170/3.8	Charcoal powder as dust	[22]
Polystyrene/SiO_2	158/9	Charcoal powder as dust	[23]
Hydroxy acrylic resin/ Hexamethyl disilazane (HMDS) SiO_2	170/2	Hydrophilic fly-ash and hydrophobic carbon nanotube particles as dust	[24]
Polybenzoxazine/SiO_2	167/5	Graphite powders as dust	[25]
Polyvinyl chloride/SiO_2	169/6	Soil-based muddy water as dust	[26]
Poly(methyl methacrylate) (PMMA)/SiO_2	165/4	Soil, muddy water and chalk particles as dust	[27]
SiO_2/ methyltrichlorosilane (TMCS)	153/8	Carbon particles as dust	[28]
SiO_2	162/5	Chalk dust as dust	[29]
SiO_2/epoxy resin	155/5	Sand and muddy water as dust	[30]
SiO_2 and Fluorinated Epoxy	158.6/10	Carbon black powder and $CuSO_4$ powder as dust	[31]
Polyethylene wax/SiO_2	163/9	Hydrophobic solvent (MnO powder partially wetted by oil) as dust	[32]
PDMS/SiO_2	152/10	Carbon-powder as dust	[33]
Poly(methyl methacrylate)/SiO_2	159/1<0	Oil Red O powder as dust	[34]
PDMS/SiO_2	165/<10	Carbon black as dust	[35]
SiO_2	152/10	Carbon black as dust	[36]
Fluorinated-SiO_2/PDMS	156.5/2	Graphite particles as dust	[37]
Methyl phenyl silicone resin/SiO_2	162/2	Silicon carbide particles as dust	[38]
Polytetrafluoroethylene/ SiO_2	153/5	Methyl blue powder as dust	[39]
PMMA/SiO_2	165/7	Mud particles as dust	[40]
SiO_2	160/6	Fine particles of chalk dust	Present study

NPs show regular and ordered structure and good mechanical strength with high thermal and chemical resistance. Moreover, silica-based coatings are highly transparent [41]. Table 14.1 clarifies that the hydrophobic SiO_2 NPs–based superhydrophobic coatings show high water repellency and self-cleaning property. Various types of dust contaminants are picked away by rolling water droplets from the coating surface and left clean surface.

14.4 CONCLUSION

The suspension of SiO_2 NPs was successively deposited on the cover glass of solar cell panel by spray technique. The prepared superhydrophobic SiO_2 NPs coating has revealed a water contact angle of $160° \pm 2°$ along with a sliding angle of 6°. The coating was stable up to four cycles of adhesive tape peeling test and exhibited poor stability for sandpaper abrasion test. The dust particles were effectively removed by the rolling action of water drops, which concludes that the prepared superhydrophobic SiO_2 NPs coating exhibits excellent self-cleaning property. Thus, such coating may be useful for solar cell manufacturing industries due to its simple, low-cost technique and excellent self-cleaning property.

HIGHLIGHTS

- The silica NPs were used for the preparation of superhydrophobic coatings.
- The modest and inexpensive spray deposition technique is utilized.
- The coating layer was applied on cover glass of the solar cell panel.
- The coating exhibits good mechanical stability.
- The coating on the cover glass of solar cell panel revealed excellent self-cleaning capability.

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