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Assessment and analysis of polydimethylsiloxane-coated solar photovoltaic panels for cost-efficient solutions

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Abstract

Solar photovoltaic (PV) is a crucial renewable energy source in the fight against carbon dioxide emissions, aligning well with growing energy demands. However, solar PV efficiency naturally degrades over time, primarily due to uncontrollable outdoor factors such as irradiance, humidity, shading, soiling, aging, and temperature. These collectively lead to decreased efficiency in PV systems. Soiling on PV glass surfaces significantly impacts light penetration and subsequently reduces power generation. To combat this, a self-cleaning nano-calcium carbonate coating has been proposed. The effectiveness of this method is compared with a developed solar PV thermal (PV/T) system, evaluating both performance and cost-effectiveness. After six months of outdoor exposure, the coated glass solar PV achieved an efficiency of 7.6%, surpassing bare glass solar PV at 6.0%. Moreover, the coated glass solution boasts exceptional cost-effectiveness, incurring only an annual expense of 17.6 USD per panel compared to the PV/T system of 59.8 USD per panel. These findings highlight the potential of coatings to enhance solar PV performance and economics, particularly in addressing challenging uncontrollable factors like soiling.

Keywords Electroluminescence, Self-cleaning coating, Solar photovoltaic, Solar photovoltaic-thermal

1 Introduction

Renewable energy (RE) has emerged as the primary energy source due to the depletion of non-renewable resources like coal and fossil fuels. This shift is driven not only by the negative impacts associated with non-RE, such as greenhouse gas emissions, global warming, rising oil costs, and increased electricity demands but also by the need for a more sustainable energy solution. Consequently, RE is positioned to completely transform the landscape of large-scale energy generation. Various forms of RE exist including solar, hydropower, wind, biomass, and geothermal. Among these, solar power stands out as the most prominent, generating electricity through the conversion of solar radiation. The chief advantage of solar PV systems lies in their utilization of inexhaustible solar energy, contributing to both energy security and cleaner air. This has prompted intensive research to enhance solar PV technology's efficiency and effectiveness. The primary goals include cost reduction and minimizing environmental impact [1].

Figure 1 illustrates the net RE capacity contributed by solar PV, wind energy, hydropower, and other renewable sources from 2019 to 2022. As depicted in the figure, it is evident that solar PV maintains a dominant role in this contribution, displaying consistent annual growth. This is

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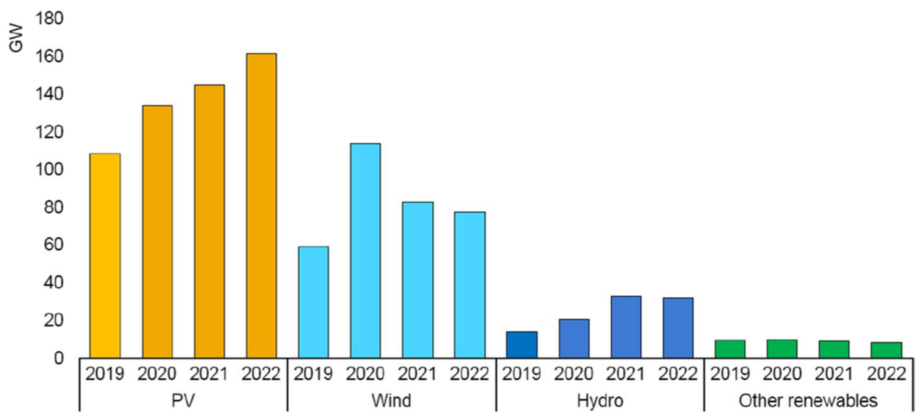

Fig. 1 Net additions of renewable capacity by technology, 2019–2022 [2]

primarily attributed to the maturation of solar PV technology, leading to cost reductions, as well as government policies that support its adoption. In 2021, solar PV contributed around 145 GW, a figure projected to increase to 162 GW in 2022 [2]. On the other hand, other renewable sources like biomass and geothermal exhibit relatively stable contributions, accounting for approximately 3% of the total capacity. Notably, the solar PV contribution is forecasted to reach nearly 60% of the total RE in 2026 [2]. To attain this target, various initiatives have been introduced, including promoting commercial and residential solar PV installations.

One of the recent advancements designed primarily for residential applications is the hybrid solar PV-thermal (PV/T) system. This innovative setup generates both electricity and heat energies simultaneously [3]. The significance of the PV/T system lies in its ability to enhance the efficiency of solar PV technology. It is important to note that over 80% of solar energy is emitted as heat that typically goes unused. Furthermore, this excess heat contributes to a reduction in the efficiency of solar PV as the operating temperature of the PV module rises [4]. Therefore, maintaining a stable temperature for the PV module is crucial to ensuring the sustained efficiency of energy conversion.

Additionally, drops in PV efficiency can be attributed to various outdoor conditions, including soiling, shading, irradiance, humidity, and aging [5]. Except for soiling, these factors are natural phenomena that are difficult to mitigate. Soiling, for instance, results from the accumulation of dust on the PV surface, restricting the penetration of light to the cells. This accumulated dust diminishes both light transmittance and alters the angle of incident light, leading to an uneven distribution of light across the glass cover. Comparatively, a dirty panel can experience up to an 8.4% reduction in maximum power output compared to a clean panel [6, 7]. When evaluating the impact of dust accumulation on PV performance, it is vital to consider the specific region. For instance, in the eastern region of Saudi Arabia, accumulated and uncleaned dust led to approximately a 50% loss of PV power after over six months of exposure [8]. Conversely, in California, annual PV power loss has been reported to be around 1.5–6.2% [9]. In Spain, a daily reduction of 4.4% in PV power is observed, escalating to up to 20% during the dry season [10]. During the Harmattan season, a significant 29% loss in PV performance has been recorded due to accumulated dust [11]. Therefore, it is crucial to routinely clean the panels to maintain optimal PV performance, especially in areas that are rural and prone to dust accumulation. Unfortunately, the utilization of manual cleaning techniques with detergents can lead to panel degradation, demand a considerable amount of time, present safety hazards, and result in significant expenses.

Another cleaning method is by using the wind-blowing method in the water-shortage area. The wind-blowing effectively repels accumulated thermal energy on the panel's surface. The movement of the airstream at high speed also can reduce the temperature of the solar cell [12]. However, the drawback of strong winds is they cause dust deposition on the solar panel surfaces especially in desert areas. For example, the PV panel suffers low efficiency by 32% after 8 months [13], 11% after 3 days in Riyadh [14], 17% after 6 days in Kuwait City [15], more than 65% after 6 months in Egypt [16] and about 40% after 6 months in Saudi Arabia [17].

In general, the performance of PV panels can be maintained during the rainfall period where the natural rain can wash the dust particles off the surface. However, the PV panel is unable to maintain its performance during the summer period which forces the innovation of an automatic robotic cleaning system to clean the PV panel at large-scale PV plants [18]. The robot cleaning can vacuum the sticky power within 7 to 10 min as well and it can detect the highly concentrated dust areas on the PV surface. The active methods such as mechanical and robotic methods consume high power energy for cleaning purposes. A large amount of electrical energy has been consumed to generate the movement of cleaning robots on PV panels, furthermore, the cleaning robot works ineffectively during the rainfall and summer periods. In comparison, the passive coating method does not require any power generation to clean the PV surface. The cleaning process is fully applied using natural rainwater sources and wind-blowing [19].

The principle of solar PV is to convert the absorbed light energy (from sunlight) into electrical energy [20]. The main components of a solar PV module include a junction box, back sheet, solar cells, encapsulant, glass, and frame as shown in Fig. 2. All the components ensure the solar module is well-protected from any interactions, exposure to ultraviolet (UV) radiation, resistance to temperature fluctuation, and enduring mechanical stress [21].

Solar PV technology has evolved through three generations. The first generation comprises monocrystalline and polycrystalline silicon PV cells, boasting the highest efficiency and cost among the generations [22]. The second generation aimed to lower production costs, albeit with a reduction in efficiency. It encompasses cadmium telluride, copper indium gallium selenide, and amorphous silicon technologies. The third generation employs novel materials and technologies to enhance PV cell efficiency at a reduced cost. This includes polymer PV cells, organic solar cells, dye-sensitized solar cells, and perovskite solar cells. A concise comparison of the PV technology generations is presented in Table 1 [23, 24].

Several factors influence the degradation of solar PV, including cracking, corrosion, delamination, discoloration, and bubbles. It is of utmost importance not to overlook these factors as they can cause major problems and are potentially dangerous, as well as degrading the electrical performance of solar PV [25]. Solar cell cracking

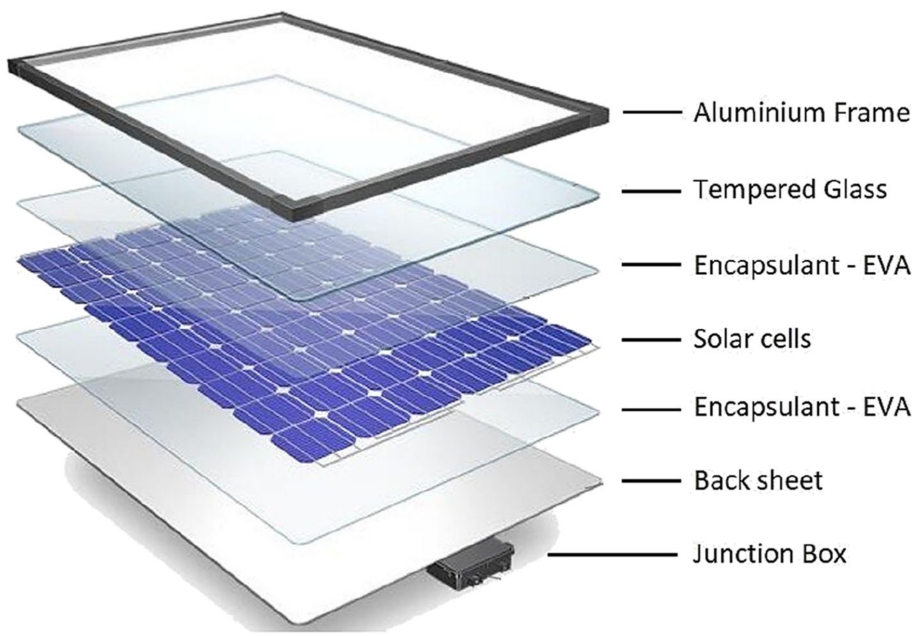

Fig. 2 Solar PV Structure

Table 1 Comparison of three PV generation systems

Technology generation	Efficiency	Cost	Commercialization	Solar technology [23, 24]
First generation	High	High	Yes	Silicon wafers such as single-crystalline, multi-crystalline, and amorphous silicon
Second generation	Low	Low	Yes	Thin film materials such as amorphous silicon, nanocrystalline silicon, cadmium telluride, or copper indium selenide
Third generation	High	Low	No (Lab scale)	Emerging or novel materials such as dye-sensitized solar cells, colloidal quantum dots, perovskite, and organic solar cells

predominantly occurs during transportation, installation, and maintenance processes [26]. The presence of cracks in cells leads to a decline in their electrical output performance. Corrosion primarily arises from moisture infiltrating the edges of the module [27]. Delamination, which denotes a loss of adhesion between the encapsulant and solar cells, induces light reflection and water penetration, thereby contributing to chemical and physical deterioration [28]. Discoloration arises when frequent changes in light transmittance occur due to the interaction of UV rays with water at temperatures exceeding 50 °C [29]. Bubbles are the trapped gases within the PV module and are released during chemical processes after the compromise of ethylene vinyl acetate adhesion [28]. With its potential for producing clean energy, solar PV has been implemented in a wide range of scenarios, including desalination plants [30], building-integrated PV systems [31], solar home systems [32], and other numerous sectors.

On the other hand, it should be noted that the operating temperature has an inverse relationship with the efficiency of a solar PV module. Higher operational temperatures can increase the likelihood of activating several deterioration mechanisms and causing hotspots on the crystalline silicon cells, thereby degrading the power performance of the solar module. Moreover, rooftop-mounted modules tend to experience faster deterioration compared to ground-mounted modules [33]. As a solution to this challenge, an innovative approach has been developed, known as the PV/T system. This integrated system not only converts solar energy into electricity but also harnesses thermal energy. The PV/T system is designed to enhance overall efficiency by actively cooling the temperature of the solar cells. Six primary types of heat transfer mediums are utilized in PV/T systems: water-based PV/T, air-based PV/T, nanofluid-based PV/T, phase change material-based PV/T, heat pipe PV/T, and commercial PV/T [34]. Among these options, water-based PV/T systems are recognized for providing the highest level of efficiency [35].

Self-cleaning coatings can be categorized as hydrophilic or hydrophobic, based on the behavior of water droplets. A hydrophilic surface employs water to spread and clean away dust and dirt. Conversely, a hydrophobic surface uses a rolling motion to carry away dust and dirt. The efficiency of the self-cleaning mechanism is determined by factors such as the roll-off angle and the static wettability contact angle.

The application of self-cleaning coatings is proposed as a solution to enhance the performance of PV systems and to mitigate the challenges posed by the high initial investment and maintenance costs. It is crucial to recognize that the efficiency of solar PV technology relies on its ability to efficiently absorb photons from sunlight. Therefore, the accumulation of dust and dirt on the surface of solar panels can significantly diminish their photon absorption capacity, consequently leading to a notable decline in PV efficiency. However, the traditional manual cleaning approach necessitates substantial amounts of water and detergents, proving to be time-consuming, expensive, and potentially hazardous. Moreover, manual cleaning carries the risk of unintended consequences such as module cracks and scratches.

Various types of hydrophobic polymers are employed in the development of self-cleaning nano-coatings, including polymethylmethacrylate, polytetrafluoroethylene, and polydimethylsiloxane (PDMS). PDMS polymer is widely used due to its low refractive index, which significantly enhances glass transparency by up to 85%. This heightened transparency is crucial for PV systems, enabling them to maximize photon absorption from sunlight. Additionally, the strong adhesion of PDMS polymer to glass ensures the longevity of the coating, further contributing to its effectiveness.

A study by Tayel et al. [36] highlights the effectiveness of PDMS/SiO_2 nanocoating in mitigating the negative impact of dust accumulation on PV panel performance, emphasizing its potential as a viable solution for improving solar energy generation. The proposed nanocoating demonstrated superior performance in reducing dust accumulation on PV panels compared to commercial nanocoating and uncoated panels, with a 31% increase in efficiency after 40 days of outdoor exposure. The effectiveness of super-hydrophilic coatings in mitigating dust deposition on solar PV cell surfaces under water spraying conditions was investigated in [37]. The results prove that the super-hydrophilic coating significantly reduces dust deposition and improves spectral transmittance, with a self-cleaning efficiency 92% higher than bare glass cases, particularly notable with specific deposition and spraying tilt angles. Another study investigated the effectiveness of a self-cleaning hydrophobic nanocoating technique in enhancing PV performance in a semi-arid environment, with a 13% increase in output power generation and a 50% reduction in water consumption compared to uncoated panels [38]. Additionally, the coated panels eliminate the need for conventional cleaning methods, offering potential cost savings and environmental benefits for large-scale PV module production. The enhancement of electrical efficiency in PV systems through a self-cleaning approach was performed in [39], with the use of SiO_2 nanoparticle coatings to mitigate the negative impact of dust accumulation. A significant improvement in electrical performance and temperature uniformity of the PV cells was recorded, with a 10.2% increase in electrical performance and a 29.5% enhancement in temperature uniformity achieved through the installation of cooling fins and the incorporation of graphene nanoparticles in the cooling system.

Lukong et al. investigated the synthesis and characterization of titanium dioxide (TiO_2) thin film for self-cleaning PV applications [40]. It was found that the TiO_2 thin film, synthesized via the sol–gel method and spin coating, exhibits a snowflakes-like morphology with clustered structures, predominantly anatase phase crystal structure, super hydrophilic tendency, and UV–visible light absorption properties, suggesting its potential for enhancing self-cleaning and photocatalytic activities on PV panels. Adak et al. present the development of a highly transparent and self-cleaning coating for PV modules using a sol–gel method, achieving a static contact angle of 150° and contact angle hysteresis of $\sim$ 2° [41]. The coating exhibits improved transmission of solar glass covers from 91.8 to 95.5% and reduced reflectance from 8.7 to 3.2%, attributed to its antireflection properties. Another study investigated the potential of a novel nitrogen-doped TiO_2/single-wall carbon nanotube nanocomposite for self-cleaning coating on solar PV panels [42]. Results demonstrated enhanced photocatalytic activity with a 72.4% degradation rate of Methylene Blue, high wettability of 94.3 ± 2°, and maintained voltage output of solar cells, indicating the effectiveness of the coating in maintaining optimal performance despite dust deposition. A novel anti-reflective and superhydrophobic coating for PV modules, featuring a durable double-layer film structure with improved adhesion, connection strength, and mechanical stability is presented in [43]. Experimental results show that the coating increases glass transmittance by 5%, achieves high hardness and adhesion grades, and enhances the maximum output power of PV modules by 5.7%, with excellent self-cleaning ability demonstrated through simulated dust accumulation and rainfall tests, restoring power to 97% compared to 83% for uncoated modules.

In this paper, the performance of solar PV is analyzed based on the effect of coating on solar PV glass. A composition of self-cleaning nano-coating is applied by spraying it onto the surface of the solar panel, creating robust adhesion to the glass substrate and instilling self-cleaning properties within the solar PV panel. Additionally, the robust mechanical properties of the coating ensure consistent self-cleaning efficacy in outdoor environments. Moreover, the proposed coating materials offer anti-scratch, high transparency, and anti-fogging characteristics. The significant benefits of this formulated coating encompass lowered maintenance and labor costs, shortened cleaning periods, and enhanced efficiency of solar panels. Consequently, a comprehensive comparative analysis is undertaken between solar PV panels with the coating and PV/T systems to pinpoint the most economically advantageous strategy for boosting solar PV performance. In summary, this study begins by comparing the efficiency of coated and uncoated solar PV panels. Subsequently, the paper proceeds to compare the coated solar PV panels with PV/T systems, assessing their cost-effectiveness. The significance and novelty of this paper can be highlighted as follows:

1. The study addresses the natural degradation of solar PV efficiency over time due to uncontrollable outdoor factors such as irradiance, humidity, shading, soiling, aging, and temperature.
2. The proposed novel self-cleaning nano-calcium carbonate coating can combat the impact of soiling, which results from the accumulation of dust on PV glass surfaces that significantly affect light penetration and power generation.
3. The study provides a comprehensive experimental setup and comparative analysis between solar PV panels with the coating and PV/T systems to pinpoint the most economically advantageous strategy for boosting solar PV performance.
4. After six months of outdoor exposure, the coated glass solar PV achieved an efficiency of 7.%, surpassing bare glass solar PV at 6.0%. Moreover, the coated glass solution boasts exceptional cost-effectiveness, incurring only an annual expense of 18 USD per panel compared to the PV/T system.
5. The cost per unit of efficiency (cost/efficiency) of the coated solar PV glass system proves to be the most economical option, with the smallest value of 0.7 USD per percentage point of efficiency as compared to PV/T systems.
6. The study utilizes the electroluminescence (EL) system to detect defects and features in solar cells quickly and effectively.

2 Experimental material and methods

Figure 3 presents a flowchart outlining the study's procedural steps. It commences with the selection of three solar PV modules, two of which are treated with the proposed coating, while the third remains uncoated to serve as a control group. Subsequently, all modules are subjected to outdoor conditions for 6 months. The panels were exposed to environmental stress factors such as temperature, irradiance, humidity, dust accumulation, air pollution, bird droppings, etc. Following this exposure period, EL indoor testing is conducted on the modules to quantify any possible defects on the panels and to measure their efficiency. The data obtained from the EL testing is then analyzed to facilitate a comparison between the efficiency of the coated and uncoated modules.

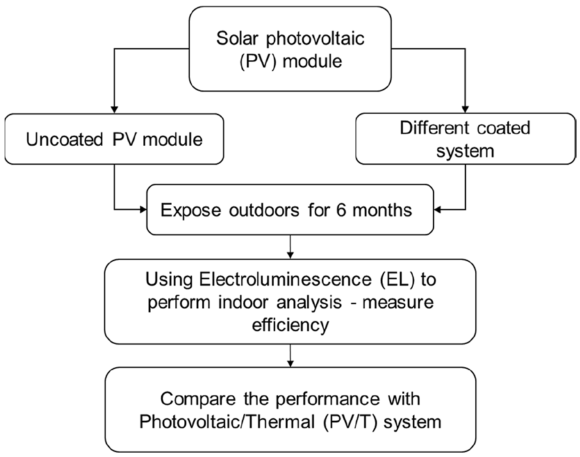

Fig. 3 Flowchart of the study

Upon completing the efficiency assessment, a comprehensive cost analysis is undertaken to evaluate the cost associated with applying the proposed coating against those of a standard PV module. This analysis encompasses an in-depth examination of both material and application costs related to the coating process. Subsequently, the study moves forward to assess how effectively the coated module functions in comparison to a widely recognized PV/T system. This assessment encompasses considerations of both efficiency and cost. By conducting this comparative analysis, the study gains valuable insights into the potential advantages and limitations of the proposed coating when compared with the PV/T system. The provided flowchart establishes a systematic framework for evaluating the efficiency and cost-effectiveness of the proposed coating within an outdoor context, while also facilitating a direct comparison with an existing PV/T system.

2.1 Polymer coating

There are two types of coatings prepared using the sol–gel method. The first coating was developed using hydrophobic PDMS mixed with a curing agent, Sylgard elastomer, in a weight ratio of 1:1. It was stirred on a magnetic stirrer at 50 °C for 24 h. Next, 10 mL of concentrated transparent PDMS/Sylgard resin was dissolved in 250 mL of ethanol solvent at ambient temperature for 2 h. The second coating, PDMS/nano-calcium carbonate (PDMS/nano-$CaCO_3$), was prepared as follows: 5 g of nano-$CaCO_3$ with an average diameter of 50 nm was dispersed in ethanol solvent through an ultrasonication process for 30 min. It was then mixed with 150 mL of PDMS/Sylgard solution at a temperature of 80 °C for 1 h via a stirring process. Finally, 0.3 wt% of 3-aminopropyltriethoxysilane binder system was added to the PDMS/nano-$CaCO_3$ solution and continuously stirred for another hour.

Two application methods were used. For the glass substrate, the dip-coating method was applied with a dipping time of 30 s. For the solar PV panel, the spraying method was used with a distance of approximately 10 cm between the solar PV glass and the spray nozzle. The thickness of both coating systems was measured using an Ellipsometer (M-2000, J.A. Wollam Co., US). The average thickness of the PDMS/Sylgard coated glass was recorded at 58.0 ± 1.2 μm, while the average thickness of the PDMS/nano-$CaCO_3$ coated glass was recorded at 148.8 ± 1.1 μm.

2.2 EL

Detecting defects and features in solar cells can be challenging. To identify such issues quickly and easily, an EL system can be used. This system measures the emitted luminescence's intensity, influenced by the solar cell's optical, electrical, and resistive properties. It is based on radiative recombination of carriers, resulting in emitted photons on the cell's surface.

Energy harvesting's cost-effectiveness depends on efficiency and aging. Efficiency gauges how much sunlight is converted to power while aging tracks change over time. PV modules degrade through processes like encapsulant discoloration, anti-reflective coating degradation, hot-spot formation, moisture damage, delamination, corrosion, tears, bubbles in the back sheet, and cracks from mechanical stress.

The EL system employs a dark current–voltage (I-V) measurement, involving an external power source. Current and voltage points obtained in this way represent the solar cell as a large diode. The light-measured I-V curve is the result of combining the dark-measured solar cell diode I-V curve. Solar panel parameters like short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF), and efficiency can be determined from the dark I-V curves.

2.3 Validation of the proposed coating

To validate the effectiveness of the proposed coating, indoor and outdoor self-cleaning tests have been conducted. The indoor self-cleaning test follows the guidelines of the International Standard BS EN 1096–5:2016. In this test, artificial dust is applied to both coated glasses at a flow rate of 0.6 ± 0.03 L min^{-1}. The dirty coated glass is then washed by sprinkling it with water sprayed at a volume of 30 ± 1.5 mL for 30 s. The coating performance is evaluated by measuring the haze value of each glass after the self-cleaning test.

The outdoor self-cleaning test takes place at the University of Malaya Power Energy Dedicated Advanced Centre Solar Garden. Three solar panels rated at 45 W are exposed to the outdoor environment for 6 months. The first panel serves as a reference and remains bare. The second and third panels are coated with PDMS/Sylgard and nano-$CaCO_3$-PDMS/Sylgard, respectively. During this test, the efficiency of each PV panel is measured using EL to analyze the impact of the coating.

2.4 Cost comparison with PV/T system

PV/T system is a combination of PV technology and solar thermal technology. The system uses air or water as a flowing fluid to cool down the PV panel's surface area. In this study, the cost comparison was based on the PV/T water system. For one PV/T panel, we considered 10 h of water flow and therefore required 4 L min^{-1} or 2400 L d^{-1}. This amount of water was converted to a local water tariff rate whereby 1000 L is equal to 0.1 USD. For one month, the amount of water needed is approximately 72,000 L at the expense of 8.2 USD per month.

3 Results and discussion

3.1 Impact of self-cleaning coating

The initial haze value is measured for all glass substrates using a haze meter following the ASTM D1003 standard. It is observed that the bare glass starts with a haze value of approximately 0.05%. The initial haze values for PDMS/Sylgard and nano-$CaCO_3$-PDMS/Sylgard coated glass are 0.15 and 0.20%, respectively. The adhered nano-$CaCO_3$ particles on the coated glass increase the absorption of coating towards the visible light, thereby increasing the value of haze. However, due to the transparent PDMS polymer property, the discrepancy in initial haze value between the coated and non-coated glasses is around 0.1–0.15%. After the self-cleaning test, the haze value of the glasses increases due to dust impact. As shown in Table 2, the haze value for the bare glass is the highest, indicating the adherence of the dust layer. This is because the bare glass surface is hydrophilic, strongly attracting dust particles and requiring additional mechanical cleaning tools for dust removal.

On the other hand, the hydrophobic coated glasses that were prepared exhibit lower haze values compared to the bare glass. For the PDMS/Sylgard coated glass, the haze value is approximately 10.5%. This is because water droplets slide dust particles away as the coated glass possesses low surface energy. It is important to note that the developed coated glass contains a high density of outer methyl groups with inherent water-repellent properties. As a result, the developed PDMS/Sylgard coated glass causes the water droplets to easily slide off the surface at a sliding angle as low as 25°.

Table 2 Haze value for bare and coated glass

	Haze value (%)	
	Initial	Final
Bare glass	0.05	25.1
Glass coated with PDMS/Sylgard	0.15	10.5
Glass coated with nano-$CaCO_3$-PDMS/Sylgard	0.20	3.5

Furthermore, the movement of water droplets is influenced by the adhesive force and mass of the droplet. It is known that the adhesion of water droplets on the surface can be modified by altering the material's properties. By incorporating nanoparticles, the Van Der Waals forces can be reduced, weakening the contact between dust particles and the glass surface [44]. This developed nano-$CaCO_3$-PDMS/Sylgard coating effectively removes dust at a sliding angle as low as 15°. This is observed when glass coated with nano-$CaCO_3$-PDMS/Sylgard results in the lowest dust haze value of approximately 3.5%. This points to minimal dust impact on the glass surface. Moreover, the embedded inorganic nano-$CaCO_3$ creates more air pockets, known as the solid-air interphase in the PDMS matrix. Consequently, with low adhesive force, dust particles can be easily washed away, leaving no dirt streaks.

3.2 EL analysis on solar PV performance

Figure 4 presents acquired EL images in grayscale format, which effectively highlight microcracks and cracks on both the uncoated (bare) PV panel and the coated PV panels (PDMS/Sylgard and nano-$CaCO_3$-PDMS/Sylgard). There exist three categories of cracks, classified as Mode A (microcracks), Mode B (less severe cracks), and Mode C (severe cracks with a dark region) [45].

Their respective coordinates and the percentage of area ratio are determined and recorded in Table 3. The percentage of area ratio is estimated based on the dimension of each mode following the equation below:

$$area\ ratio(\%) = \frac{dimension\ of\ cracks}{total\ number\ of\ cells}$$

To determine the dimension of cracks, consider one cell as depicted in Fig. 5. We divide the cell into smaller pieces, resulting in 418 tiny boxes within a single cell. As shown in Fig. 5, approximately 4 tiny boxes are covered by Mode C cracks. Therefore, the dimension of the crack in one cell $= 4 \div 418 = 9.6 \times 10^{-3}$. The estimated percentage of area ratio for Mode C cracks in that panel is as follows:

$$area\ ratio(\%) = \frac{9.6x10^{-3}}{36} x100\% =\sim 0.03\%$$

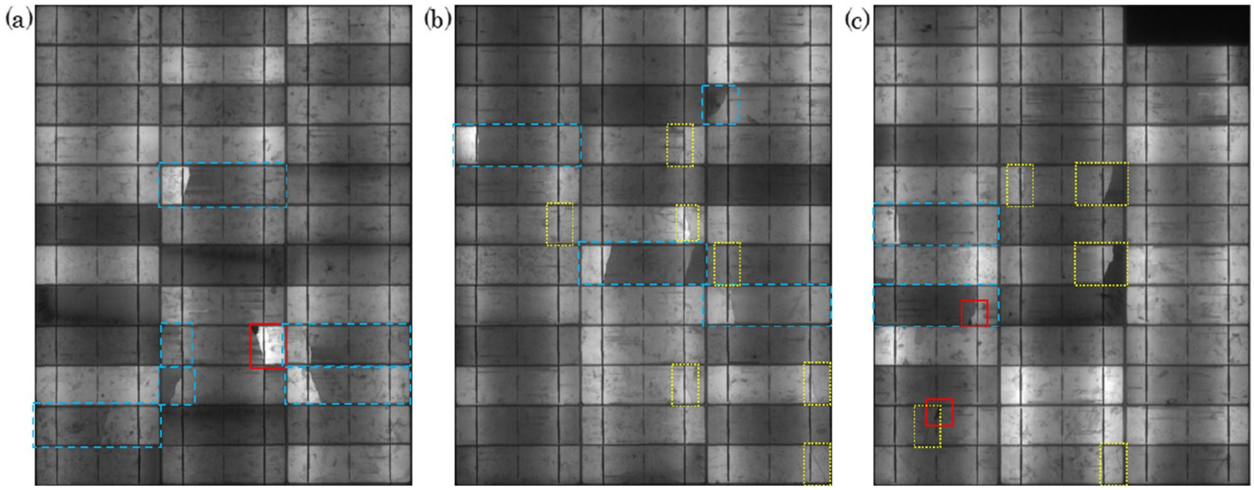

Fig. 4 EL images PV panel with Mode **A** microcracks (yellow squares), Mode **B** cracks (blue squares), and Mode **C** cracks (red squares) (a) bare PV panel, (b) PDMS/Sylgard coated PV panel, (c) nano-$CaCO_3$-PDMS/Sylgard coated PV panel

Table 3 Mode A (microcracks), Mode B (less severe cracks), Mode C (severe cracks with dark region) coordinates for bare and coated panels

Crack mode	Bare panel	PDMS/Sylgard coated panel	nano-$CaCO_3$-PDMS/Sylgard coated panel
Mode A	-	(4,2), (6,1), (6,2), (7,3), (10,2), (10,3), (12,3)	(5,2), (11,1), (12,2)
Mode B	(5,2), (9,2), (9,3), (10,2), (10,3), (11,1) **[~9.7%]**[a]	(3,3), (4,1), (7,2), (8,3) **[~7.2%]**[a]	(6,1), (8,1), (5,2), (7,2) **[~5.5%]**[a]
Mode C	(9,2) **[~0.03%]**[a]	-	(8,1), (11,1) **[~0.04%]**[a]

[a] The number inside the bracket indicates the percentage area of cracks

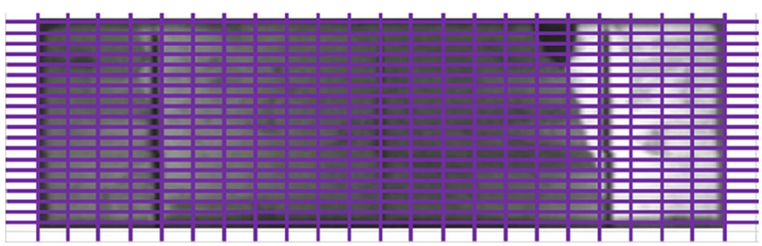

Fig. 5 Cross-section of one cell from Fig. 4a

Microcracks, classified as Mode A, do not significantly impact solar cell efficiency and do not lead to the creation of inactive cell regions causing power losses. In contrast, Mode B cracks denote areas of solar cell fracture that are partially disconnected from the module's electrical circuit. Mode C cracks represent situations where cells are fractured, causing a complete disconnection of the electrical circuit. Mode C cracks are particularly severe as they can result in power losses, hotspot formation, and reverse biasing of solar cells [45, 46]. Early-stage cracks can arise from improper solar panel installation or transportation-related damage. Cracks may also originate during manufacturing due to the delicate nature of solar cells. Over time, thermal stresses from exposure to environmental conditions such as wind, dust, and snow loads can lead to crack development.

Based on Table 3, it can be observed that there are no microcracks captured for the bare PV panel. However, it has six coordinates for Mode B cracks and a tiny spot for Mode C cracks. In contrast, the PDMS/Sylgard coated panel has more microcracks detected on the solar panel with four spots of Mode B cracks. The panel with nano-$CaCO_3$-PDMS/Sylgard coatings consists of all types of cracks and fewer microcracks. There is also one dead cell at coordinate (1,3) and two tiny spots of Mode C cracks at (8,1), and (11,1) coordinates on the panel. A color code has been assigned for Mode A, Mode B, and Mode C with yellow squares, blue squares, and red squares respectively.

To investigate the impact of self-cleaning coating in enhancing the efficiency of the solar module is conducted via solar I-V measurement. The PV performances for the bare and coated PV panels were measured. Table 4 and Fig. 6 highlight the obtained PV parameters such as I_{sc}, V_{oc}, I_{max}, V_{max}, P_{max}, and panel's efficiency, η. I_{sc} represents the amount of electron or current flow throughout the panel and is measured when the voltage across the load is zero. V_{oc} is the maximum voltage available from the solar panel and is measured at zero current. From Table 4, similar V_{oc} values were measured for all panels, hence the increment of I_{sc} influenced the solar panel output and efficiency. Figure 7 shows the I-V and power-voltage (P–V) curves obtained from the I-V measurement. To evaluate the coating performance, the efficiency between bare PV and coated PV panels is compared after the PV panels were exposed outdoors for 6 months. The efficiency of the bare panel is measured at around 6.0, whereas, for the PDMS/Sylgard and nano-$CaCO_3$-PDMS/Sylgard coated panels, the efficiency is at 6.2 and 7.6%, respectively. It shows that the nano-CaCO3-PDMS/Sylgard coated panel has improved the panel's efficiency by 26.2% with I_{sc} of 1.23 A and V_{oc} of 22 V. The panel also obtained the highest P_{max} of 20 W compared to only 16 W for the bare PV panel, and slightly around 16.7 W for the PDMS/Sylgard coated panel. The highest P_{max} of 20 W represents the maximum current, I_{max} of 1.14 A, and maximum voltage, V_{max} of 17.8 V the nanomaterial coated panel can provide at its peak power point or maximum capacity, P_{max}.

Although the panel has one dead cell and a few spots of cracks, the PV performance is still the highest due to the effectiveness of the nano-$CaCO_3$-PDMS/Sylgard coating. It is of utmost importance to understand that the self-cleaning coating does not protect the cells from

Table 4 Photovoltaic performance of the bare panel and two variants of coated panels

Panel	I_{sc} (A)	V_{oc} (V)	I_{max} (A)	V_{max} (V)	P_{max} (W)	Efficiency, *η* (%)
Bare panel	0.96	22	0.89	18.1	16.1	6.0
PDMS/Sylgard coated panel	1.01	22	0.94	17.8	16.7	6.2
nano-$CaCO_3$-PDMS/Sylgard coated panel	1.23	22	1.14	17.8	20.2	7.6

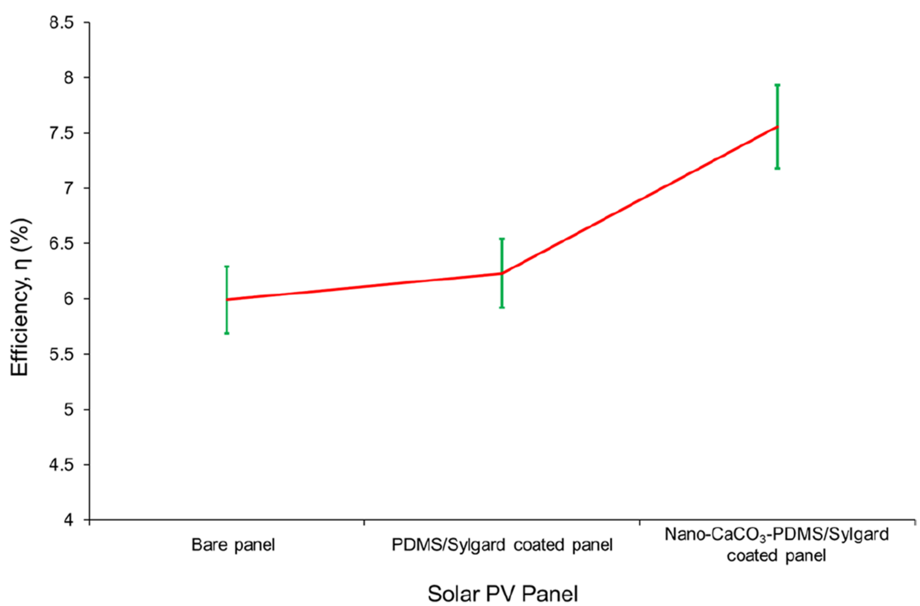

Fig. 6 Efficiency comparison between bare panel and two variants of coated panels

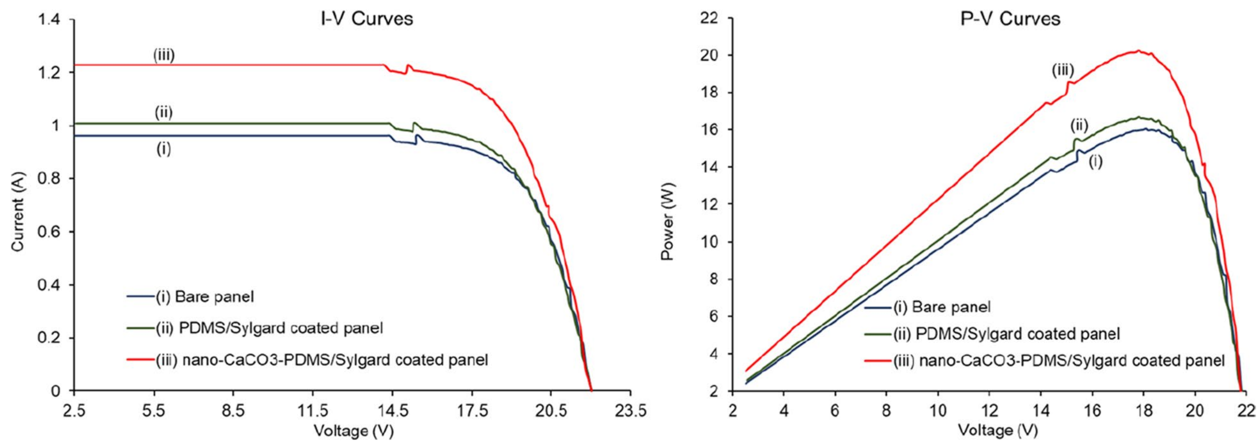

Fig. 7 I-V and P–V curves (i) bare panel (ii) PDMS/Sylgard coated panel (iii) nano-$CaCO_3$-PDMS/Sylgard coated panel

degradation but helps to enhance the panel's efficiency, in which more solar irradiance can be absorbed by the cells and converted to power.

3.3 Discussion on cost-effectiveness

The development of solar PV/T helps to mitigate the rise in temperature in solar cells. Every 1 °C rise in temperature might cause the efficiency of the solar modules to decrease by approximately 0.5% for crystalline silicon solar cells [47]. Extensive research has been conducted to leverage water as a heat transfer medium instead of air, to enhance the efficiency of both thermal and electrical solar modules. This is evident in Table 5, which demonstrates the influence of geographical factors and water flow rates on solar module efficiency. The table highlights the significant role played by geographical factors and water flow rates in affecting solar module efficiency. For instance, the water flow of 4 L min^{-1} amounts to 2400 L d^{-1} (considering a 10 h water flow). In Malaysia, the water tariff is 0.1 USD per 1000 L. Thus, the daily cost would be 0.3 USD. While the daily expense might seem small, it accumulates to 8.2 USD in a month and 98.8 USD in a year. It is important to note that these cost calculations are based on a single panel. This demonstrates the substantial financial investment required for solar PV plants to adopt this approach. Notably, for countries with limited water resources like those in the Middle East, the cost of water would likely be even higher.

While heated water is commonly used for daily tasks such as washing, bathing, and cooking, concerns arise over water quality and safety due to its contact with aluminum pipes or the glass surface. Even with filtration, the water quality remains untested for consumption and skin safety. Furthermore, additional expenses are incurred for filter and hot water tank installation. It is important to recognize that a constant water flow over the glass surface can lead to corrosion within the solar module, facilitated by moisture penetration at the module's laminate edges. This corrosion can subsequently trigger issues like delamination and discoloration.

The proposed coating method offers a significant advantage, requiring only 200 ml of spray coating at an approximate cost of 8.8 USD per bottle. Each solar panel needs two rounds of spraying annually, totalling a mere 17.6 USD per year. The cost comparison presented here is favorable when contrasted with solar PV/T systems, which can account for 1 to 3% of the initial installation cost [52]. For example, if the initial installation cost of a PV/T panel is 880 USD, the estimated annual operating cost would be approximately 26.4 USD per panel. The total annual cost for a PV/T system, including the water bill, is approximately 59.8 USD, with the water bill alone

Table 5 Comparative evaluation of cost and energy efficiency for PV/T systems across diverse geographical locations

	Location and latitude	Flowrate (L min^{-1})	Efficiency increment (%)	Cost per year (USD)
Odeh and Behnia [48] (2009)	Jordan (32.0°)	4	15	99
Nizetic et al [49] (2018)	Croatia (43.5°)	2.4	16	59
Sainthiya et al [50] (2018)	India (26.9°)	2.5	28	62
Nateqi et al [51] (2021)	Iran (15°)	1.35	33	33

costing 33.4 USD. This represents a 240% increase in cost when using a PV/T system as opposed to a coating system. Furthermore, this coating method saves a considerable amount of time spent on regular solar panel cleaning.

Moreover, solar panels typically use covered glass with thicknesses of around 2.0, 3.2, and 4.0 mm. The glass thickness directly impacts light transmittance, which can be disrupted. Moreover, about 8–10% of solar irradiance is reflected by the covered glass, causing optical loss in electrical power. The proposed self-cleaning coating incorporates an antireflective coating with a refractive index of about 1.2–1.3. This helps counteract electrical power losses and enhances light transmittance.

Table 6 presents a comparative analysis of the efficiency of coated solar PV glass and PV/T systems. After six months of exposure to outdoor conditions, the coated solar PV glass demonstrated a significant improvement in efficiency, with an increase of 26% compared to the bare solar PV glass. This data highlights the beneficial impact of the self-cleaning coating on the efficiency of PV modules. It is important to note that even though the efficiency of this system is lower than the PV/T systems studied by Nateqi et al. [51] and Sainthiya et al. [50], when considering cost-effectiveness, defined as the cost per unit of efficiency (cost/efficiency), the coated solar PV glass system proves to be the most economical option, with a value of 0.7 USD per percentage point of efficiency. This finding is particularly significant for the development and operation of large-scale solar PV power plants. The enhanced efficiency and cost-effectiveness of coated solar PV glass can lead to substantial savings over time, making it a highly advantageous solution for these applications.

4 Conclusions

This study aims to evaluate the impact of a proposed self-cleaning coating on the efficiency of solar PV modules, comparing its cost-effectiveness to an alternative PV/T system. The self-cleaning feature of the coating is emphasized as a significant advantage, as it enhances the efficiency of solar PV modules by eliminating accumulated dust. This is crucial since dust can progressively reduce the efficiency of solar panels. Additionally, the application of the coating is straightforward, suitable for solar panels of any size through a simple spray method, and its final preparation can be conducted at room temperature. Despite a reduction in transparency, the coating still maintains 90% transparency in visible regions, preserving aesthetics and functionality considerations.

The proposed coating incorporating nano-calcium carbonate attracts carbonate dust particles due to attractive forces. However, when combined with a hydrophobic PDMS, the dust particles do not adhere to the PV glass. The results show a 26% enhancement in the efficiency of the coated solar PV glass compared to bare solar PV glass after 6 months of outdoor exposure, indicating the positive impact of the self-cleaning coating on PV module efficiency. From a cost-effectiveness perspective, the nano-$CaCO_3$-PDMS/Sylgard coated panel proved to be the most economical option compared to the developed PV/T systems. With the cost per unit of efficiency (cost/efficiency) value of 0.7 USD per percentage point of efficiency, this suggests that the self-cleaning coating can lead to substantial savings over time, making it a highly advantageous solution for large-scale solar PV power plants. However, it's important to note that the self-cleaning coating does not protect the cells from degradation. Whereas PV/T systems present potential issues such as discoloration, corrosion, delamination, and other long-term problems.

For future research, the study proposes subjecting solar PV panels to extended outdoor exposure to assess the long-term sustainability of the coating. Additionally, a durability assessment should be conducted to evaluate the coating's resilience against various environmental conditions, including sunlight, rain, temperature fluctuations, and other weather elements. Continuous monitoring during extended outdoor exposure will verify the coating's efficacy in repelling dust and maintaining improved PV module efficiency. Moreover, long-term

Table 6 Comparative analysis of cost and energy efficiency between PV/T systems and coated PV modules

	Efficiency increment (%)	Cost per year (USD)	Cost/efficiency (USD/%)
Odeh and Behnia [48] (2009)	15	99	6.6
Nizetic et al. [49] (2018)	16	59	3.7
Sainthiya et al. [50] (2018)	28	62	2.2
Nateqi et al. [51] (2021)	33	33	1
PDMS/Sylgard coated panel vs bare panel	4	18	4.5
nano-$CaCO_3$-PDMS/Sylgard coated panel vs bare panel	26	18	0.7

studies can also shed light on the coating's environmental impact, investigating potential negative effects on the environment. The accumulation of continuous data over an extended period can provide insights into performance trends, degradation patterns, and any unforeseen challenges that might emerge.

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Authors' contributions
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Availability of data and materials
The datasets during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

- All authors are aware the given information regarding this manuscript is correct.
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- All authors have declared that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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