



**PREPARATION SELECTIVE NANO-SURFACES
COATING TO ENHANCE SELF-COOLING
TECHNIQUES AND SELF-CLEANING
PROCESSES FOR PHOTOVOLTAIC PANELS**

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Hayder Talal Ali ALKHASHKHASHI

ABSTRACT

Ph.D. Thesis

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Solar panel technology has advanced significantly in the last few years, yet challenges persist in maintaining optimal performance due to adverse outdoor conditions. Factors such as reflection losses at the air-glass interface, dust accumulation, rises in temperature operation and ultraviolet negatively effect on the efficiency of solar panels. This study focuses on the development and evaluation of a multifunctional nanocomposite coating designed to address these issues. The coating was synthesized using a straightforward one-step spray process that incorporates

SiO₂ and ZnO nanoparticles dispersed with chlorophyll in a methylphenyl silicone resin matrix. Laboratory tests on glass slides coated with this nanocomposite revealed exceptional properties, including high light transmittance (~93%), robust UV protection, and outstanding hydrophobicity, characterized by a water contact angle (~153°). These features indicate the coating's strong potential for enhancing solar panel performance. To evaluate its practical application, the coating was applied to small solar panels used in street lighting. The coated panels demonstrated a 22% increase in maximum power generation compared to uncoated panels, a result attributed to the coating high transparency and anti-reflective characteristics. Furthermore, the coating served as a radiant cooler, lowering the panel temperature by 6%, thereby enhancing overall efficiency. The integration of chlorophyll into the nanoparticle matrix also endowed the coating with self-cleaning capabilities. A 7-day dust accumulation test confirmed its ability to maintain a clean surface, ensuring consistent performance over time and reducing the necessity for manual cleaning. The coating and uncoating solar panels were kept operating during the summer season with temperatures exceeding 47 °C. After 10 months operation, the test was repeated in winter and the results were that the maximum power generation of coated solar panel higher than the uncoated one by 18% in sunny weather, 50% in cloudy weather, and 58% in dusty weather. These findings highlight the multifunctional benefits of the developed coating, offering a comprehensive solution to improve solar panel efficiency and reliability in real-world condition.

Key Words : Solar panel, Nano-coating, Superhydrophobic, Self-cooling, Self-cleaning, Anti-reflect, UV-protection.

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ÖZET

Doktora Tezi

FOTOVOLTAİK PANELLER İÇİN KENDİ KENDİNİ SOĞUTMA TEKNİKLERİNİ VE KENDİ KENDİNİ TEMİZLEME SÜREÇLERİNİ GELİŞTİRMEK İÇİN SEÇİCİ NANO YÜZEY KAPLAMA HAZIRLIĞI

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Güneş paneli teknolojisi son birkaç yılda önemli ölçüde ilerleme kaydetti, ancak olumsuz dış koşullar nedeniyle optimum performansı korumada zorluklar devam ediyor. Hava-cam arayüzündeki yansıma kayıpları, toz birikimi, sıcaklık çalışmasındaki artışlar ve ultraviyole gibi faktörler güneş panellerinin verimliliğini olumsuz etkiliyor. Bu çalışma, bu sorunları ele almak üzere tasarlanmış çok işlevli bir nanokompozit kaplamanın geliştirilmesine ve değerlendirilmesine odaklanıyor. Kaplama, metilfenil silikon reçine matrisinde klorofil ile dağıtılmış SiO_2 ve ZnO nanopartiküllerini içeren basit bir tek adımlı püskürtme işlemi kullanılarak sentezlendi. Bu nanokompozitle kaplanmış cam slaytlar üzerinde yapılan laboratuvar testleri, yüksek ışık geçirgenliği ($\sim 93\%$), sağlam UV koruması ve ($\sim 153^\circ$) su temas

açısı ile karakterize edilen olağanüstü hidrofobisite gibi olağanüstü özellikler ortaya koydu. Bu özellikler, kaplamanın güneş paneli performansını artırma konusunda güçlü bir potansiyele sahip olduğunu gösteriyor. Pratik uygulamasını değerlendirmek için kaplama, sokak aydınlatmasında kullanılan küçük güneş panellerine uygulandı. Kaplamalı paneller, kaplamasız panellere kıyasla maksimum güç üretiminde %22'lik bir artış gösterdi; bu sonuç, kaplamanın yüksek şeffaflık ve yansıma önleyici özelliklerine atfedildi. Ayrıca, kaplama radyant bir soğutucu görevi görerek panel sıcaklığını %6 düşürdü ve böylece genel verimliliği artırdı. Klorofilin nanopartikül matrisine entegre edilmesi, kaplamaya kendi kendini temizleme yetenekleri de kazandırdı. 7 günlük bir toz biriktirme testi, temiz bir yüzey sağlama yeteneğini doğruladı, zaman içinde tutarlı bir performans sağladı ve manuel temizlik ihtiyacını azalttı. Kaplama ve kaplamasız güneş panelleri, 47 °C'yi aşan sıcaklıklarda yaz mevsiminde çalışmaya devam etti. 10 aylık çalışmadan sonra, test kışın tekrarlandı ve sonuçlar, kaplamalı güneş panelinin maksimum güç üretiminin, kaplamasız olandan güneşli havalarda %18, bulutlu havalarda %50 ve tozlu havalarda %58 daha yüksek olduğuydu. Bu bulgular, geliştirilen kaplamanın çok işlevli avantajlarını vurgulayarak, gerçek dünya koşullarında güneş paneli verimliliğini ve güvenilirliğini artırmak için kapsamlı bir çözüm sunuyor.

Anahtar Kelimeler : Güneş paneli, Nano kaplama, Süperhidrofobik, Kendi kendini soğutan, Kendi kendini temizleyen, Yansıma önleyici, UV koruması.

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SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS

A_c	: area collector (m ²)
E_{in}	: energy input (W/m ²)
E_{out}	: energy output (W/m ²)
G_T	: solar irradiance (W/m ²)
I	: current (A)
P	: power (W)
V	: voltage (V)
ε	: emissivity
γ	: interfacial surface tension
η	: efficiency of a PV
θ	: contact angle

ABBREVIATIONS

<i>AM</i>	: Air Mass
<i>AR</i>	: Anti Reflect
<i>ARCs</i>	: Antireflective Coatings
<i>SiO₂</i>	: Silicon Dioxide
<i>T_{Max}</i>	: Maximum Transmittance
<i>WCA</i>	: Water Contact Angle
<i>LWIR</i>	: Long-Wave Infrared
<i>MPSR</i>	: Methyl Phenyl Silicone Resin
<i>PCM</i>	: Phase-Change Materials
<i>PV/T</i>	: Photovoltaic/Thermal
<i>SH</i>	: Superhydrophobic Surfaces
<i>STC</i>	: Standard Test Conditions
<i>UV</i>	: Ultraviolet
<i>ZnO</i>	: Zinc Oxide

PART 1

INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

The urgent need to combat climate change and lessen reliance on fossil fuels has caused the demand for renewable energy to rise dramatically on a worldwide scale in recent years [1–4]. Amongst several renewable energy technologies used, solar photovoltaic (PV) systems are one of the most popular renewable energy technologies for producing sustainable electricity [5,6].

But even with its potential, solar panels' effectiveness reduced by outside variables like dust buildup frequently [7–10] and deviations in temperature operation [11–13]. According to studies, dust buildup alone can cut PV panel efficiency by 50%, which has an immediate effect on power generation [14,15]. Moreover, PV panels' temperature coefficient causes an average power loss of -0.446% per degree Celsius [12].

Under Standard Test Conditions (STC), which consider a temperature of 25°C and sun irradiation of 1000 W/m², standard testing of PV systems is usually carried out indoors [16]. However, this controlled conditions did not reflect the challenges faced in natural-world environments, wherever solar panels often encounter temperatures up to 40°C above ambient level [17] .

This is due to the fact that PV cells only produce 15–20% of incident solar energy as electricity; the rest is lost as heat [18]. Variations in temperature have a detrimental effect on important performance indicators such maximum power output, open-circuit voltage, and short-circuit current [19].

As solar PV systems continue to proliferate globally, it is crucial to develop technological solutions to address these challenges. Various strategies have been explored to enhance PV performance beyond STC conditions. Hybrid Photovoltaic/Thermal (PV/T) systems cooled by Nano fluids [20], air [21] or liquid [22], as well as phase-change materials (PCM), have been employed to reduce operating temperatures [23,24]. Additionally, the application of transparent coatings on the surface of solar panels has proven effective in mitigating optical and thermal losses [25]. Thin antireflective coatings (ARCs) have emerged as a cost-effective method to increase solar cell efficiency by reducing reflection losses at the air/glass interface [26] and enhancing light trapping within the cells [27]. Spectral-specific ARCs also mitigate UV-induced degradation, which can otherwise decrease maximum power output by 0.73% annually [28]. Nano coatings have recently gained attention as multifunctional smart materials due to their diverse capabilities, including anti-reflective [29], self-cooling [30,31], self-cleaning [32], anti-wearing [33], and antibacterial properties [34].

These developments in multipurpose Nano coatings offer a viable option to improve PV systems' sustainability, longevity, and efficiency [35]. By integrating properties such as self-UV protection, self-cleaning, and radiative cooling, Nano composite coatings offer a comprehensive solution to the problems faced by solar panels in real-world environments. As research continues to develop, these technologies have the potential to greatly expand the field of solar energy and help create a more sustainable future as long as research into them continues.

These challenges call for innovative approaches to enhance PV panel performance in this study via development of sophisticated nanocomposite coatings which combine several useful materials at the nanoscale offered a viable way around these restricts.

Through the integration of zinc oxide (ZnO), silicon dioxide (SiO₂), and chlorophyll, scientists hope to improve solar panels' passive cooling, anti-reflective, and self-cleaning capabilities.

These multifunctional coatings not only improve energy conversion efficiency but also extend the operational lifespan of PV systems, making them more economically viable and environmentally sustainable.

1.2. THE PHOTOVOLTAIC PANEL (PV)

Photovoltaic (PV) devices directly transform light into electricity, utilizing various types of photovoltaic cells, commonly referred to as solar cells [36]. Among renewable energy technologies, PV systems are among the most widely adopted for generating clean and sustainable energy [31] and the main components of a solar Panel System shown in Figure 1.1.

The efficiency of a PV cell is the ratio of energy output obtained from the PV cell divided by the energy input provided by the sun as represented in Eq. (1.1) [38].

$$\eta = E_{out}/E_{in} \quad (1.1)$$

The power output “P” of a PV installation is given as the product of the PV panels’ real collector area “ A_c ”, the solar irradiance “ G_T ” at the panels’ surface and the efficiency “ η ” of the PV generator Eq. (1.2) [39]:

$$P = \eta \cdot G_T \cdot A_c \quad (1.2)$$

The efficiency of the PV generator depends on several factors:

- The solar irradiance.
- The tracking system (due to solar irradiance angle of attack).
- The manufacturing characteristics of the PV components.
- The dust accumulation.
- The cell temperature.

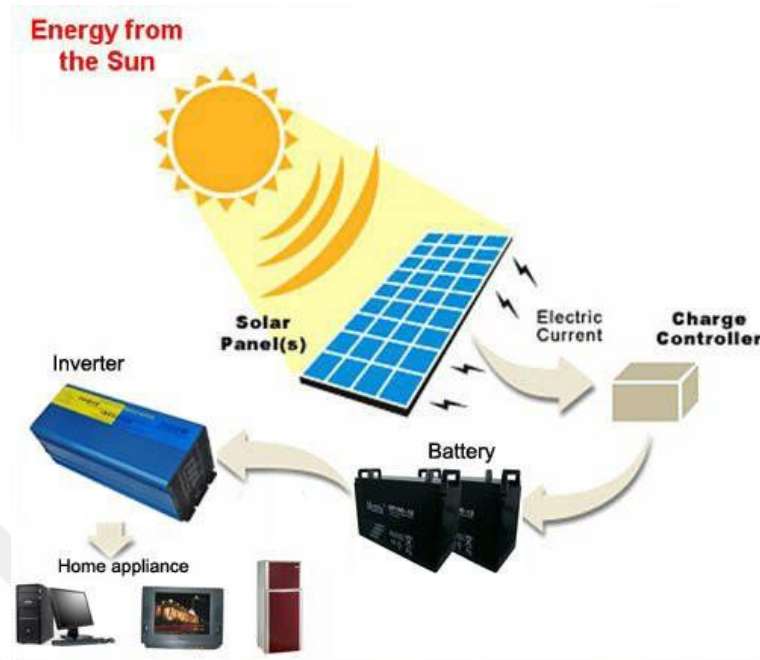


Figure 1.1. Solar panel system.

1.3. STANDARD TEST CONDITIONS (STC)

Photovoltaic (PV) module performance is typically measured and specified under Standard Test Conditions (STC), which include an irradiance of 1000 W/m^2 , an air mass (AM) of 1.5, and a module temperature of 25°C . While these controlled conditions provide a baseline for efficiency ratings, understanding the performance of PV modules under actual field conditions is crucial for accurately predicting their real-world efficiency and power output [16].

1.4. FUNDAMENTALS OF SOLAR PANEL COATINGS

1.4.1. Self-Cleaning Mechanisms

Self-cleaning is defined as the natural capability of a surface to remove debris or bacteria without external intervention. The concept of self-cleaning materials and engineered artificial surfaces is largely inspired by the lotus plant, whose leaves exhibit the "lotus effect" [40]. In this phenomenon, water forms spherical droplets that roll off

the surface Figure 1.2., carrying away contaminants. Such surfaces, characterized by their unique wettability properties, offer valuable insights into naturally occurring superhydrophobic roughness [41]. By mimicking this effect, it is possible to design solar cells with reduced wettability and enhanced transparency, improving their efficiency and durability.

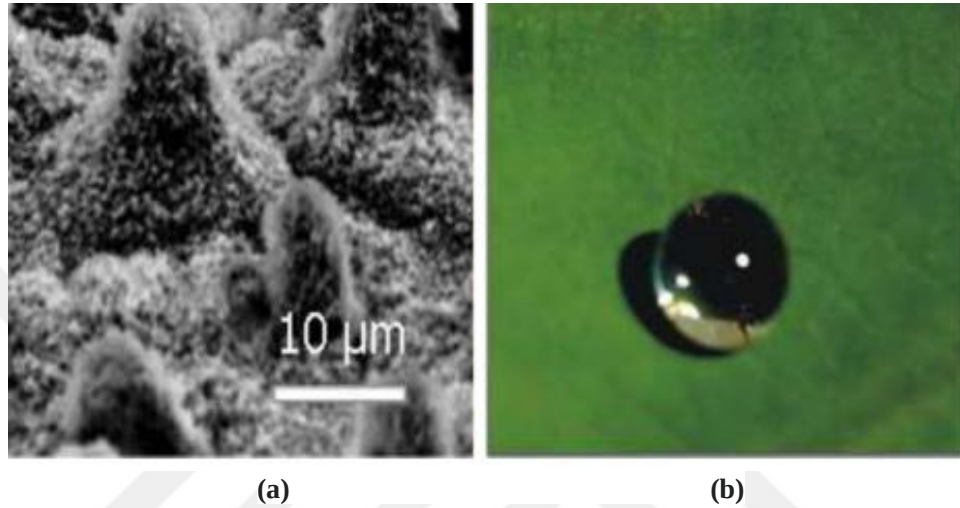


Figure 1.2. (a) SEM image showcasing the hierarchical structural features of a lotus leaf. (b) A water droplet resting on the surface of a lotus leaf [36].

1.4.2. Water Contact Angle (WCA)

The contact angle is the angle formed at the intersection of the liquid-solid and liquid-vapor interfaces. A surface with a water contact angle (WCA) exceeding 150° is classified as superhydrophobic, exhibiting extreme water repellency. On an ideally flat and chemically uniform surface, the contact angle of a liquid droplet can be calculated using Young's equation (1.3) [42]:

$$\cos \theta = (\gamma_{SG} - \gamma_{SL}) / \gamma_{LG} \quad (1.3)$$

Where θ Contact angle ($^\circ$); γ =interfacial surface tension measured in J/m^2 .

The subscript refers to G=gas, L=liquid and S=solid. Young's relation describes the equilibrium of all three interfacial tensions involved at the triple point of a solid, liquid and vaporous of liquid droplet on perfectly smooth solid surface.

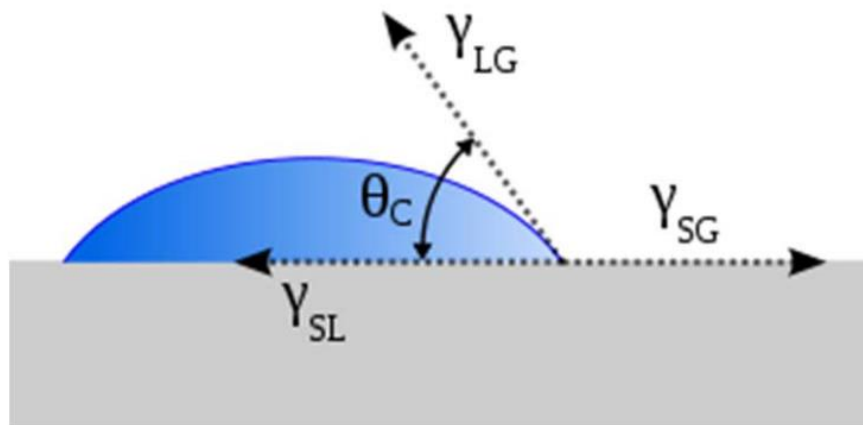


Figure 1.3. Young's model

1.4.3. Wettability

The wetting phenomenon closely resembles the adsorption phenomenon, as both arise from interactions between molecules of different substances. A water droplet will spread out and wet a surface with high surface energy (e.g., glass), whereas it will bead up on a surface with low surface energy (e.g., Teflon). If the water droplet adheres more strongly to itself than to a given surface, the surface is termed hydrophobic and the droplet forms a bead with a contact angle (CA) greater than 90° . Conversely, if the droplet adheres more strongly to the surface than to itself, the surface is termed hydrophilic, and the droplet spreads with a contact angle of less than 90° [43].

In extreme cases, a water droplet that completely wets the surface will have a contact angle close to 0° , indicating total adhesion. On the other hand, if there is no interaction between the droplet and the surface (no wetting), the droplet forms a perfect sphere (ignoring gravity) with a contact angle near 180° [44].

Figure 1.4. illustrates these conditions, providing visual examples of the varying degrees of wetting behavior influenced by surface energy and molecular interactions.

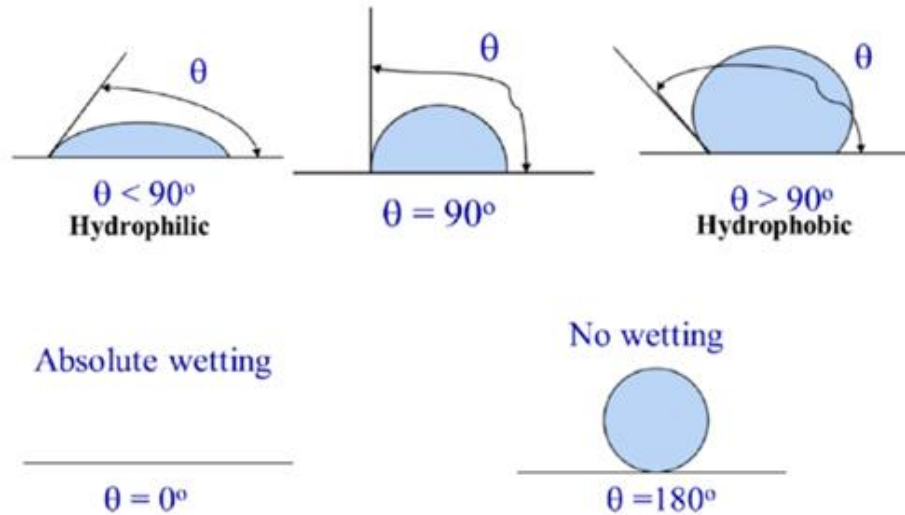


Figure 1.4. Hydrophobic and hydrophilic wetting conditions.

1.4.4. Superhydrophobic Coatings (SHCs)

Superhydrophobic (SH) surfaces having a static water contact angle (CA) of more than 150° can be achieved by a combination of low surface energy materials and micro-nanostructures. (SH) surfaces, inspired by the lotus leaf, achieve self-cleaning by allowing water droplets to remove dust and dirt particles in the process [45].

These surfaces typically exhibit water contact angles greater than 150° [46] and are fabricated using nanostructures that create hierarchical roughness [47]. SH surfaces have been made using a variety of nanoparticles, including zinc oxide (ZnO), titanium, and Nano-silica [48]. Due to its low cost, mechanical stability, and thermal resilience, Nano-silica is especially preferred. [49].

1.4.5. Anti-Reflection (AR) Coating

An optical phenomenon known as reflection happens when the light comes into contact with a different medium's interface, changing the direction of its wavefront. The refractive index of the medium, an optical parameter that characterizes the ratio of the speed of light in the medium to the speed of light in a vacuum, controls this interaction. An optical disturbance occurs when the refractive index at the interface changes

significantly, causing some of the incident light to be reflected and the remainder to pass through the medium.

Except of scattering and absorption effects, this phenomenon is known as loss of Fresnel reflection [50]. Reflectance (R) is the percentage of light that is reflected at the interface, while transmittance is the amount of light that can flow through. The amount of light transmission through the medium is mostly determined by the refractive index. More reflection and less transmittance are usually the results of a larger refractive index difference at the interface [51].

This concept is illustrated in Figure 1.5., where the configuration of a single dielectric thin film is shown. The precise selection of the film's refractive index and thickness ensures optimal destructive interference, enhancing light transmittance through the substrate. Such coatings are critical in solar energy applications, as they minimize reflection losses at the air-glass interface, maximize the absorption of incident light, and improve the overall efficiency of photovoltaic systems.

By leveraging materials with tailored refractive indices, antireflection coatings also contribute to reducing optical losses in various optical and energy-related devices. AR Coating is a technical means to reduce reflection and increase light absorption of solar cells and thus increase its performance. (AR) coatings have been widely used to increase the solar radiation absorption in solar collectors and reduce front surface reflection reached 75% [52]. Most widely used Nano materials for AR coatings are ZnO, alumina, Titania and SiO_2 is the most ideal material due to its low refractive index, good durability and environmental resistance [53].

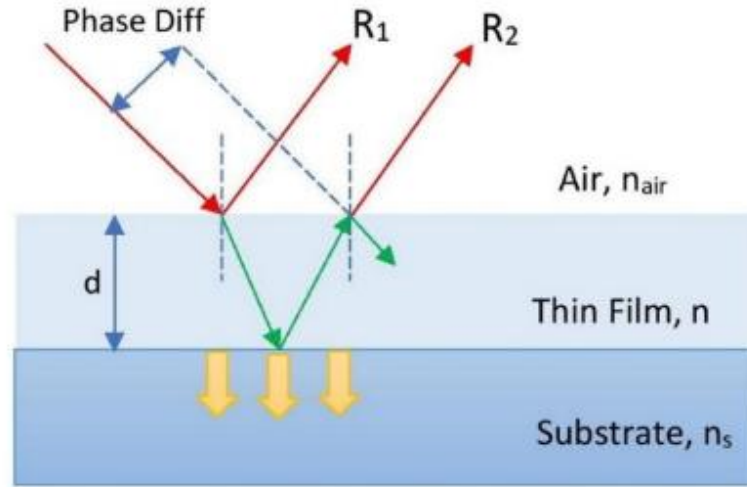


Figure 1.5. Schematic illustration of diffusion of light in single layer film.

1.4.6. Self-Cooling Mechanisms

Conventional daytime radiative cooling works by naturally cooling a surface through the simultaneous reflection of incoming sunlight and the emission of thermal radiation in the long-wave infrared (LWIR) range [54]. While these traditional cooling designs are highly efficient and environmentally friendly, their near-perfect solar reflectance prevents sunlight from being utilized by the underlying devices. This limitation has driven the demand for innovative coatings that can effectively emit thermal energy via radiation while allowing a significant portion of sunlight to pass through [55].

Self-cooling coatings provide an energy-efficient solution for reducing the operating temperatures of photovoltaic (PV) panels by efficiently radiating heat into the atmosphere [30]. These coatings do not require external energy input, making them a sustainable and cost-effective option for thermal management [56]. Materials with inherently high thermal emissivity, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), are particularly well-suited for radiative cooling applications. TiO_2 and ZnO possess unique electronic structures that enable them to emit thermal radiation effectively within the atmospheric transparency window (8–13 μm), facilitating heat dissipation while maintaining high optical performance [57].

1.4.7. UV-Protective Coating

There is an urgent need for the development UV-protective solutions, including visually transparent UV filters and coatings due to depletion of stratospheric ozone in the atmosphere and increase in ultraviolet (UV) radiation from the solar spectrum, which poses significant and widespread risks to human health and other biological systems [58]. Prolonged exposure to sunlight exacerbates biological damage and accelerates the degradation of organic compounds due to UVA (320–400 nm) and UVB (280–320 nm) radiation. Consequently, these advanced materials are essential for safeguarding UV-sensitive materials, lenses, and other applications prone to UV-induced deterioration like photovoltaic panels [59].

In addition, these materials can also contribute to improved durability by protecting PV panels from overheating and reducing the degradation caused by prolonged exposure to high temperatures. Their multifunctional capabilities, including UV shielding and light-scattering properties, further enhance the efficiency and longevity of solar panels. Because of these characteristics, ZnO is an essential part of the creation of sophisticated nanocomposite coatings for high-performance and sustainable solar energy systems [60].

1.5. THE PROBLEM STATEMENT OF STUDY

Outdoor factors like dust accumulation and rising temperatures have a significant impact on solar panel efficiency. Temperature changes drastically lower power production, and dust can diminish photovoltaic (PV) panel efficiency by up to 43%. These problems are made worse by standard test conditions' (STC) inability to accurately represent real-world circumstances. Innovative technological solutions are required to address these issues and improve solar panel performance in real-world operating conditions. Current methods, such as anti-reflective coatings and hybrid cooling systems, have shown potential but lack universal multifunctionality.

To maximize solar panel performance in a variety of environmental circumstances, it is imperative to provide affordable, multipurpose coatings that integrate cooling, light control, and self-cleaning capabilities.

1.6. OBJECTIVES OF STUDY

- The goal of coating development is to create a multifunctional nanocomposite coating using chlorophyll, ZnO nanoparticles, and SiO₂ in a matrix of methyl phenyl silicone resin (MPSR).
- Self-Cleaning Capability: To guarantee that the coating has exceptional hydrophobic qualities that prevent dust buildup and preserve panel cleanliness with the least amount of manual assistance.
- Cooling Enhancement: To lower the operating temperature of solar panels by increasing thermal emissivity for efficient radiative cooling.
- Optical Performance: To improve photon absorption by minimizing reflection and increasing light transmittance through anti-reflective qualities.
- Real-World Testing: To confirm how well the coating works on solar panels in street lighting applications, with an emphasis on thermal control and power-generating enhancements

1.7. RESEARCH SIGNIFICANCE

Through the integration of cutting-edge material research and useful engineering applications, this work fills a significant vacuum in the realm of solar energy. By combining passive cooling and self-cleaning properties into one material, the suggested nanocomposite coating provides a comprehensive way to improve solar panel performance. This research supports international efforts toward a sustainable energy future and helps to expand the use of solar energy technology by increasing energy efficiency and lowering operating costs.

A revolutionary strategy for increasing sustainability and efficiency is the incorporation of nanotechnology into renewable energy applications, especially solar energy. In addition to increasing energy conversion, multifunctional coatings for solar panels save maintenance costs and increase the PV modules' operating lifespan. Such coatings support international initiatives to maximize renewable energy systems and lessen reliance on fossil fuels by improving self-cleaning and cooling qualities.



PART 2

LITERATURE REVIEW

2.1. INTRODUCTION

The worldwide energy and environmental issues are driving up demand for renewable energy alternatives [61]. Photovoltaic (PV) systems are the most advanced renewable technology for producing energy [62]. Despite their advantages, challenges such as reduced efficiency from environmental factors like dust accumulation and heat retention remain unresolved. Multifunctional nanocomposite coatings offer innovative solutions, promising enhanced solar panel performance through properties like self-cleaning, anti-reflection, and cooling [63].

Recently, many research has been focused on reducing the impact of outdoor conditions on panel efficiency. Multifunctional coating application to the front glass surface has been an effective method in the reduction of these losses, leading to improved efficiency of solar cells. Depending on the literature, using Nano-based coating can improve electrical efficiency by up to 50% compared to traditional PV panels.

This chapter critically examines advancements in multifunctional nanocomposite coatings, focusing on the integration of materials such as zinc oxide (ZnO), silicon dioxide (SiO₂), and chlorophyll. Their collective contribution to improving solar panel efficiency through enhanced optical, thermal, and self-cleaning properties is discussed. This literature review is structured to cover coating technologies, materials used, their functionalities, and their impacts on photovoltaic system performance.

2.2. CHALLENGES IN PHOTOVOLTAIC SYSTEMS

Solar PV panels are considered a sustainable solution to the energy crisis due to being environmentally friendly and free of operation cost. Solar electricity from photovoltaic (PV) modules still grabs the higher grade of the harvested energy. However, in real operation conditions several impediments are facing the optimum power harvest from PV modules and these challenges are:

2.2.1. Dust Accumulation

Dust on the surface reduces light absorption by 33.5–43%, drastically decreasing efficiency [64]. Self-cleaning coatings aim to mitigate this problem through hydrophobic and superhydrophobic properties [65].

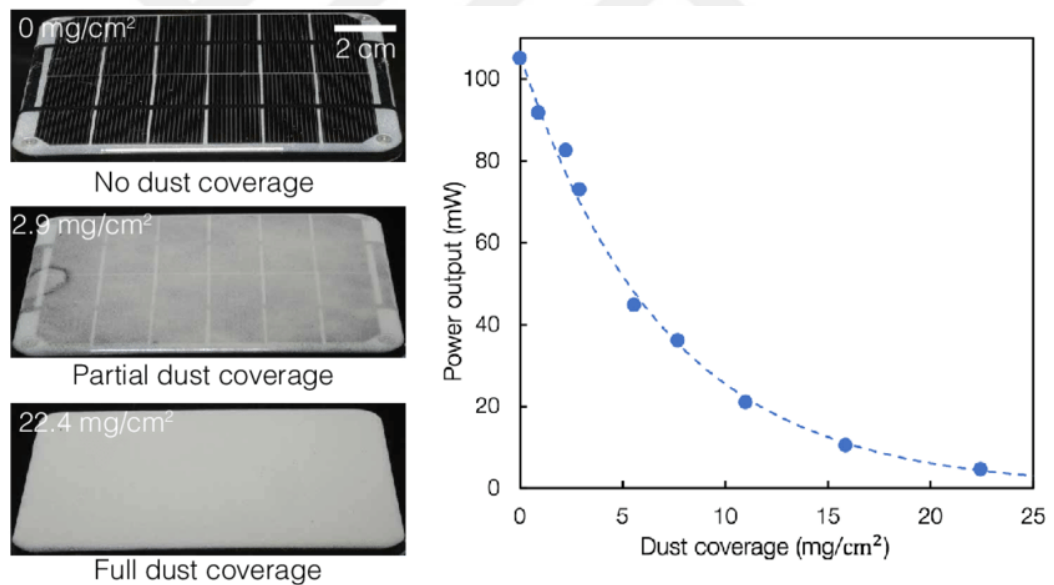


Figure 2.1. Effects of dust accumulation on solar panel power output [61].

2.2.2. Thermal Management

High operating temperatures affect power output as shown in Figure 2.2., with losses averaging -0.446% per degree Celsius increase [66]. Coatings with high emissivity and radiative cooling capabilities reduce thermal retention [67].

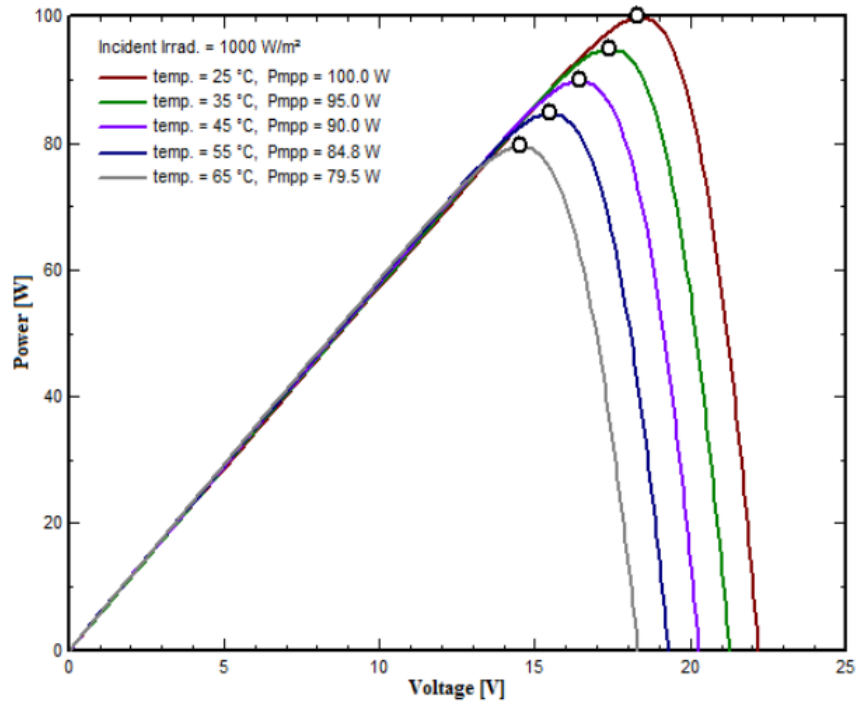


Figure 2.2. Temperature effect on power of solar with constant irradiation [68].

2.2.3. Reflective Losses

Reflection at the air-glass interface causes significant optical losses [69]. Anti-reflective coatings help improve light capture and energy conversion efficiency [70].

The optical losses (L) are made up of Eq.(2.1). By analyzing the properties of light, its spectral regions, and how it interacts with matter, a deeper understanding of film/substrate systems can be achieved. When light encounters a film, it undergoes one of several processes: it may be reflected (R), transmitted (T), absorbed (A), or scattered (S), as depicted in Figure 2.3.

At every interface between two materials, light reflection occurs whenever there is a disparity in their refractive indices. This interaction highlights the critical role of refractive index matching in managing light behavior in film/substrate systems [71].

$$L = A + S \quad (2.1)$$

After this Eq.(2.1) can be written as follows Eq.(2.2):

$$T = 1 - R - L = 1 - R - A - S \quad (2.2)$$

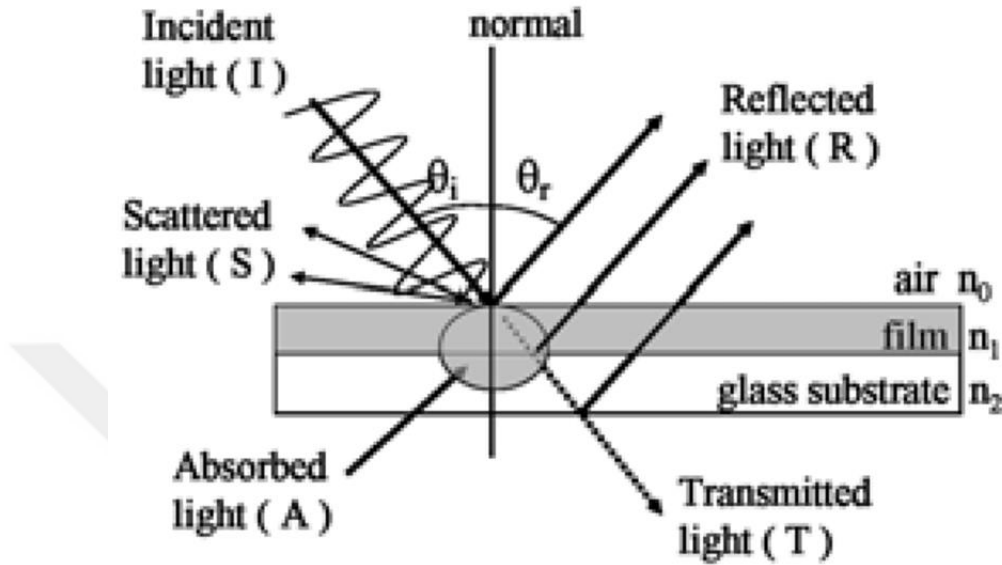


Figure 2.3. The fundamental concept involves the interaction of incident light with the interfaces of air/film, film/glass, and glass/air [71].

2.2.4. UV-Degradation

UV exposure effectively disrupts surface passivation by altering the fixed charge density and rising the interface defect density nearby the silicon surface [72] and UV irradiation, caused decreasing in solar cells lifetime [73]. Nanocomposite coatings can transform ultraviolet (UV) photons into visible photons, thereby minimizing light-induced degradation in amorphous silicon photovoltaic devices [32].

2.3. NANOCOMPOSITE COATINGS: AN OVERVIEW

Nanocomposite coatings have emerged as a transformative solution in surface engineering, offering unique properties that surpass conventional materials [74]. These coatings, which incorporate nanoparticles or nanoscale structures into a matrix material, have applications spanning multiple industries, from renewable energy to biomedical devices [75].

Nanocomposite coatings consist of a base matrix such as a polymer, ceramic, or metal embedded with nanomaterials like carbon nanotubes, graphene, metal oxides, or quantum dots [76]. By leveraging the nanoscale dimensions of these materials, the coatings exhibit enhanced mechanical, thermal, optical, and chemical properties. These advancements address limitations in traditional coatings, such as susceptibility to wear, poor adhesion, or limited functional versatility.

Nanocomposite coatings incorporate Nano-sized materials to achieve multifunctionality [77]. This chapter provides an overview of the fundamental principles, fabrication techniques, properties, and applications of nanocomposite coatings in the surface of solar panels. These coatings offer:

2.3.1. Self-Cleaning:

Self-Cleaning is inspired by lotus leaf structures, which is one of the most remarkable examples of a natural superhydrophobic surface. The lotus leaves have a water contact angle of greater than 160° [78]. By water-repelling properties inspired scientists to explore superhydrophobic phenomena as illustrated in Figure 2.4., for example a superhydrophobic surface can be found in the leaf of the tulip poplar, the state tree of Tennessee [44]. The self-cleaning coatings can be either hydrophobic or hydrophilic determined by the contact angle between water and glass surfaces [35]



Figure 2.4. Tulip poplar leaf shown superhydrophobic behavior.

Cleaning PV panels manually is both challenging and costly, making it necessary to apply self-cleaning coatings on the glass surfaces [79].

In this field, Y. Li et al. (2016) developed a transparent, durable, and self-cleaning superhydrophobic coating using a one-step process involving a sol solution of trimethoxypropylsilane-silica nanoparticles. When applied to glass through spray coating, the resulting superhydrophobic glass demonstrated a high-water contact angle of 158.5° and a low sliding angle of 3.9° . Additionally, the coated glass exhibited over 80% transmittance in the visible light spectrum (400–800 nm) as shown in figure 2.5. [80].

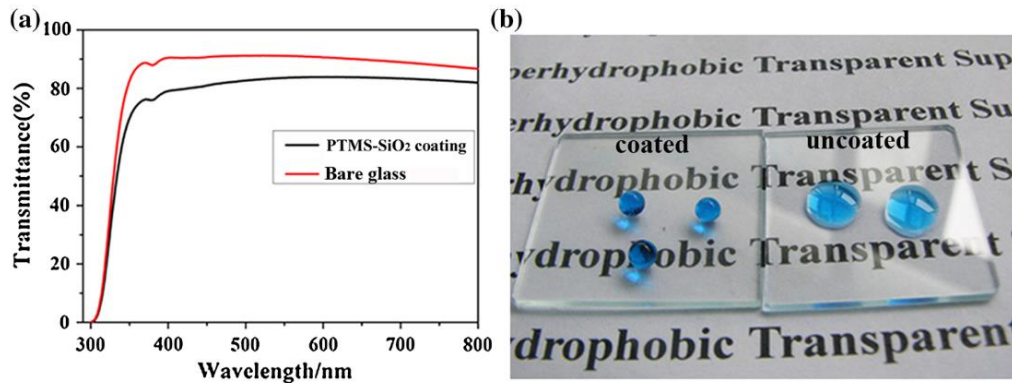


Figure 2.5. (a) Transmittance of glass substrates coated compared to uncoated. (b) Optical image showing methylene blue-dyed water droplets on the surfaces.

In this way, W. Suwaileh et al. (2017) synthesized TiO₂ Nano colloids using the polyol reduction method and applied them as thin film coatings on glass substrates through an adsorptive self-assembly process. The study revealed that the transparent titania coatings possess self-cleaning and anti-reflection (AR) properties, which are crucial for reducing the soiling effect on photovoltaic modules. The self-cleaning properties were evaluated using optical microscopy and UV-Vis spectroscopy. Optical images revealed a 56% reduction in the dust deposition rate on the coated surfaces compared to uncoated glass substrates after seven days of exposure to soiling as illustrated in Figure .2.6 [81].

Arabatzis et al. (2018) used a formulation sold under the SSG brand to investigate the effects of an antireflective, self-cleaning coating on PV panels.. This formulation consists of a mixture of metal oxides, primarily Nano-crystalline anatase/rutile titania (TiO_2) combined with silica (SiO_2) Nano-bridges. The nanostructured, titania-based SSG formulation was applied to the glass surface of photovoltaic panels using a cost-effective, one-step spraying process. The coated glass demonstrated enhanced light transmittance and hydrophilicity, providing superior antireflective and self-cleaning properties, which reduced dust accumulation. These improvements resulted in a power output increase of up to 19%, even under high incident irradiation angles of up to 30% [82].

Recently, Allahdini et al.(2022) developed a durable, transparent, non-fluorinated superhydrophobic coating with improved anti-icing properties. The coating was formulated using a blend of methoxy-functional silicone resin and fumed silica nanoparticles. With a thickness ranging from 100–150 μm , the coating exhibited exceptional water-repellency, self-cleaning, and icephobic characteristics. It achieved a high water contact angle of 163° and maintained 80% optical transmittance in the visible-light range, making it well-suited for applications in solar cells and optical devices [83].

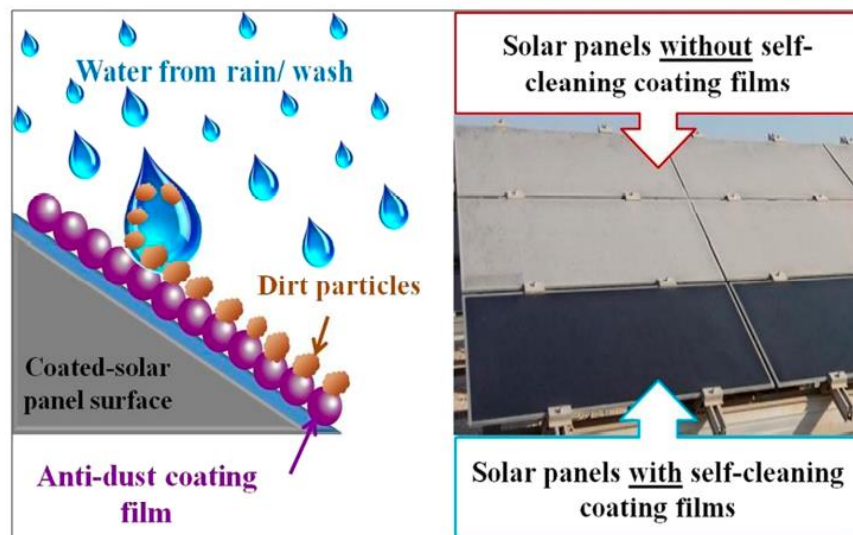


Figure 2.6. Schematic showing self-cleaning coating effect on PV panels in dusty region.

2.3.2. Thermal Management:

High-emissivity coatings radiate excess heat, lowering operational temperatures. Nanomaterials offer an innovative approach to developing green composite materials for radiative cooling [84].

Achieving daytime passive radiative cooling (DPRC) has been a longstanding challenge due to the need for materials with finely tuned properties. These include exceptionally high thermal emissivity in the atmospheric transparency window (8–13 μm) and strong reflectivity within the solar spectrum (0.2–3 μm) [85].

Additionally, materials with high thermal conductivity or radiative cooling properties facilitate passive cooling by efficiently dissipating heat, thereby protecting photovoltaic (PV) cells from thermal stress and performance degradation.

In this regard, a nanocomposite film made of SiO_2 nanoparticles (20 nm) embedded in a polymer matrix was created by Chen et al. (2021) and subsequently used in solar cells. This nanocomposite achieved a high sunlight transmittance of over 90% and an infrared emissivity of roughly 0.85 by optimizing both infrared heat emission and sunlight transmission. Furthermore, the film effectively maintained the power conversion efficiency of the solar cells while passively cooling them by up to 5 °C under sunlight exposure [55].

Similarly, Al-Hasnawi proposed a novel strategy to enhance the efficiency of PV cells by applying two types of coatings: a chlorophyll-only coating and a chlorophyll-polymer mixture. Comparing coated and untreated solar cells, the results showed that the chlorophyll coating increased efficiency by 5.5% while the chlorophyll-polymer mixture increased efficiency by 3.1%. These experiments were conducted under consistent solar irradiation (1000 W/m^2) and a temperature range of 30°C to 80°C. Figure 2.7. illustrates the positive impact of self-cooling coatings on solar panel efficiency [86].

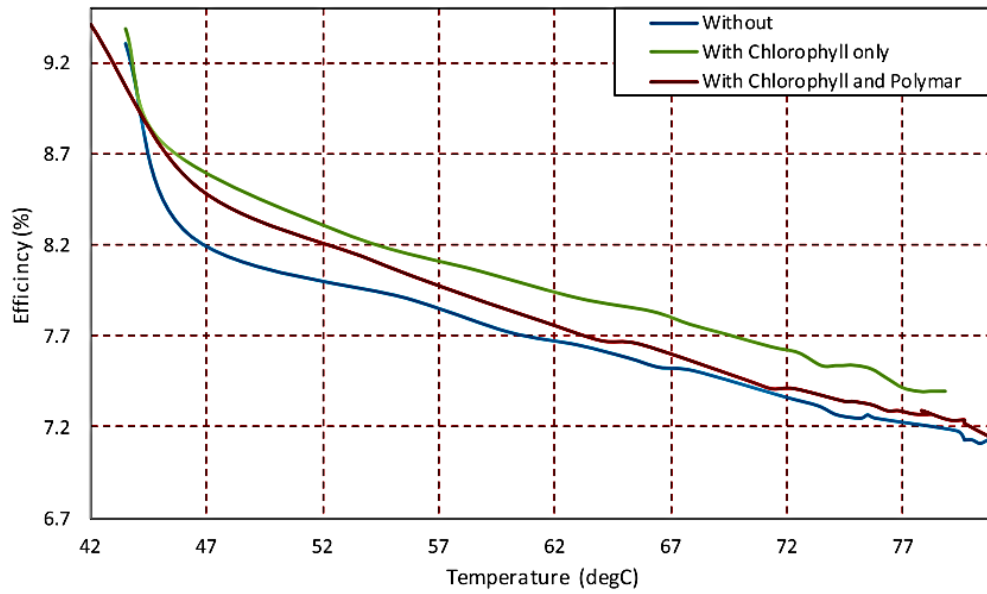


Figure 2.7. The impact of temperature on cell efficiency under constant solar irradiation and load.

2.3.3. Optical Enhancement

Antireflection coatings play a critical role in enhancing the efficiency of solar cells and solar selective coatings by reducing light reflection from the front surface. Mahadik et al. (2015) developed of silica (SiO_2) sol-based coatings, prepared via the sol-gel process, for application on glass substrates. These coatings were deposited using the dip-coating method and subjected to heat treatment at 400°C to achieve optimal performance. The optimized single-layer SiO_2 coating demonstrated a maximum transmittance of 97.5% at a wavelength of 500 nm, showcasing its efficiency in minimizing reflection [53].

X. Li et al. fabricated antireflective (AR) and water-repellent coatings on glass slides by assembling silica nanoparticles and polyelectrolytes using the layer-by-layer (LbL) method. The fabricated coatings achieved a maximum transmittance of 99.0%, significantly higher than that of commercial PV panel cover glass (92–93%). Additionally, the coatings improved the photoelectric current by 6.6%, thereby enhancing the overall efficiency of photoelectric conversion [87].

Meanwhile, Sutha, et al. (2017) developed Superhydrophobic surfaces with aluminum oxide coatings for solar panel cover glass applications using a solution-based method. The 300 nm thick coating featured a gradient refractive index, decreasing from air ($n = 1$) through the coating ($n = 1.35$) to the glass substrate ($n = 1.56$). This gradient resulted in a high average transmittance of 95%, providing effective anti-reflective properties. The study revealed that the aluminum oxide-coated superhydrophobic glass substrates restored the efficiency of sawdust-contaminated solar panels by 91%, compared to 67% for uncoated glass substrates. These findings underscore the effectiveness of the fabricated superhydrophobic glass substrates for self-cleaning cover glass applications, significantly improving the performance and durability of photovoltaic systems [88].

Recently, D Wang et al. (2021) introduced a sol-gel mixed suspension, combining acid-catalyzed silica sol (ACSS) with base-catalyzed solid silica nanoparticles (SSNs), enabling the cost-effective, large-scale, and versatile fabrication of robust Nano coatings on various substrates using simple spray-coating methods, without the need for post-treatments. resulting in improved transmittance (97.6% at 517 nm with an average increase of ~5% in the 400–1100 nm range) [89].

2.3.4. UV Protection

Solar radiation serves as a crucial energy source for the biosphere on Earth but also poses significant environmental challenges to various life forms. The potential for light-induced damage intensifies as wavelengths decrease. Consequently, within the natural sunlight that reaches Earth, the UV-B spectral range (280–315 nm) exhibits the greatest potential for causing harm [90].

Photosynthetic pigments, including chlorophylls and carotenoids, are highly effective at absorbing light within the UV-light [91]. Additionally, ZnO and other nanomaterials absorb damaging UV radiation, preventing panels from deteriorating. Wu et al. (2017) used a colloidal monolayer template and a hydrothermal synthesis approach to create superhydrophobic scallion-like zinc oxide (ZnO) coatings. These coatings showed

outstanding self-cleaning qualities by achieving a sliding angle of less than 10° and a water contact angle of more than 150° .

At a wavelength of 320 nm, the coating transformed ultraviolet (UV) photons into visible photons in addition to decreasing light reflection on photovoltaic (PV) panels. This feature improves the longevity and performance of non-crystalline silicon PV devices by reducing UV-induced deterioration [32].

Polyvinyl alcohol-silicon dioxide (PVA-SiO₂) nanocomposite films were created by Hashim et al. (2020) for lightweight, affordable, and incredibly effective UV-shielding applications. According to experimental results, optical conductivity was improved by increasing the concentration of SiO₂ nanoparticles in the PVA-SiO₂ matrix. This enhancement was ascribed to the material's higher absorption coefficient, which produced better UV-blocking capabilities [59].

Zhu et al. (2017) developed scalable, cost-effective, and multifunctional coating techniques. Traditional approaches often rely on fluorinated compounds, which pose environmental concerns. This study introduced an innovative and sustainable alternative by combining PDMS and ZnO nanoparticles to create superhydrophobic coating by dip-coating process. The key Findings demonstrating superior water repellency exceeding 160° and providing UV protection, making the coating suitable for outdoor applications [92].

2.4. MATERIALS IN MULTIFUNCTIONAL COATINGS

2.4.1. Zinc Oxide (ZnO)

Zinc oxide (ZnO) nanoparticles possess exceptional ultraviolet (UV) absorption capabilities, along with outstanding optical and optoelectronic properties, making them highly beneficial for a wide range of commercial applications [93]. This includes their application in sunscreen products, where they offer transparency and effective protection against broad-spectrum UV radiation [94]. The widespread availability of

ZnO makes it a cost-effective material, and its distinct sharp UV cut-off property makes it highly desirable [95].

Zinc oxide (ZnO) nanoparticles have emerged as a critical component in advanced nanocoatings due to their unique optical and physical properties [96]. With ZnO nanoparticles nanocoatings demonstrated a significant enhancement UV-blocking efficiency while maintaining high transmittance in the visible spectrum, with values exceeding 92% [97].

The integration of ZnO nanoparticles also contributed to improved optical uniformity and reduced reflectance at the air-coating interface, enhancing light trapping. These properties make ZnO-based Nano coatings particularly suitable for applications in solar panels, optical devices, and protective surfaces where both high transparency and UV protection are required.

This study underscores the potential of ZnO nanoparticles to optimize the functional performance of Nano coatings, offering a promising approach for sustainable and efficient energy systems. Numerous antireflection (AR) coatings have been developed utilizing ZnO. For example, Zaier et al. fabricated ZnO thin films through the thermal evaporation method and enhanced their structural, electrical, and optical characteristics by annealing them at varying temperature ranges. These coatings achieved transmission spectra exceeding 90% in the visible wavelength range, demonstrating their efficiency in optimizing optical performance [98].

2.4.2. Silicon Dioxide Nanoparticles (SiO₂)

Silica nanoparticles are composed of silicon dioxide (SiO₂), a widely available mineral commonly found in sand and rock. These nanoparticles are produced through various techniques, such as chemical vapor deposition, hydrolysis, and sol-gel synthesis. Their unique properties, including a high surface area, exceptional thermal and chemical stability, and low toxicity, make them highly valuable for diverse applications.

These include industrial processes, structural materials, and advancements in tissue engineering [99]. SiO₂ is favored for its low refractive index and durability. As an anti-reflective coating, it reduces light loss and enhances surface hydrophobicity. SiO₂ nanoparticles are also used to structure surfaces for hydrophobic or superhydrophobic effects. While SiO₂ is renowned for its excellent light transmission properties, its effectiveness as a photocatalyst under UV light is limited when used alone [100]. This limitation arises because SiO₂ lacks the intrinsic electronic structure required for photocatalytic activity, such as generating electron-hole pairs upon UV excitation [101].

However, its performance can be significantly enhanced when combined with other photocatalytically active materials like ZnO or TiO₂. These combinations enable SiO₂ to serve as a supportive matrix that enhances the dispersion of active nanoparticles, thereby improving light utilization and catalytic efficiency in UV-driven applications [102]. This synergistic approach broadens its applicability in areas such as environmental remediation and advanced coatings for solar panels.

2.4.3. Chlorophyll

Chlorophyll, a natural light-harvesting pigment, enhances photon absorption. Its inclusion in coatings introduces light-trapping properties while contributing to UV absorption and natural hydrophobicity. Chlorophyll, one of the most prevalent pigments on Earth, plays a crucial role in capturing light energy to drive photosynthesis in green plants. This molecule is a metal complex characterized by a highly symmetrical porphyrin ring serving as a ligand, with magnesium as its central ion [103].

All green plants naturally contain chlorophyll, which is an essential pigment for photosynthetic processes. Because of its porphyrin structure, which is linked with a magnesium ion, it absorbs sunlight mostly in the red, blue, and purple wavelengths. Chlorophyll's light-absorbing properties have raised interest in its potential as an optical material in addition to its biological use [104].

Because of its natural propensity to absorb UV and visible light, chlorophyll is a substance that has promise for enhancing solar energy systems, particularly photovoltaic (PV) devices. Chlorophyll, when incorporated into nanocomposite coatings, improves solar panel absorption while potentially providing UV protection by reducing UV-induced deterioration. Its compatibility with other materials, such as silicon dioxide (SiO_2) and zinc oxide (ZnO), has been investigated in order to maximize light absorption while preserving environmental sustainability [97].

Chlorophyll has been shown in recent studies to increase solar panels' energy conversion efficiency. It has been demonstrated to work in concert with nanostructured materials to create multipurpose coatings that combine cooling, anti-reflective, and UV absorption. These coatings solve common problems including heat accumulation and energy losses from surface reflection, which makes chlorophyll an important ingredient for developing solar technology and other light-based applications [104].

In conclusion, chlorophyll is a flexible photosensitizer due to its natural abundance, eco-friendliness, and photophysical characteristics. Its incorporation into cutting-edge nanocomposites provides a viable solution to improve energy efficiency and light usage in renewable energy systems [105].

2.5. METHODS FOR SYNTHESIZING COATINGS

Different processes are used to produce the desired qualities of nanocoatings, which are synthesized according to their intended applications. Novel techniques for creating nanostructured coatings have surfaced in addition to traditional techniques like chemical vapor deposition (CVD) and physical vapor deposition (PVD). These include cutting-edge methods that allow for the production of coatings with improved structural and functional properties, like laser cladding and the sol-gel process [106]. A synopsis of the popular coating techniques is provided below:

2.5.1. Spray Coating

Nanocomposite coatings may be applied in scalable and reasonably priced ways thanks to spray deposition processes [107]. Using a nozzle to distribute a target substance, spray coating creates a coating by impacting the material onto a substrate surface [108].

The substance being sprayed may be molten, liquid, or softened particles [77]. This method is frequently used in industrial settings to apply organic lacquers and binders to surfaces with irregular shapes, such as glass, metals, wood, and fabrics. The size distribution of the coating particles, the feed rate, the distance between the spray gun and the substrate, and the spray velocity are some of the factors that affect the final characteristics of the coating that is spray-applied. To get the appropriate coating quality and performance, these variables are meticulously managed [106].

2.5.2. Sol-Gel Method

To produce a sol system, the sol-gel process uses a solvent that contains a chemically reactive precursor that is hydrolyzed and polycondensed. This sol turns into a gel as it progressively goes through polymerization. After that, the gel is dried and heated to create a long-lasting surface coating [109].

The sol-gel method has many disadvantages. It is a labor-intensive process that frequently necessitates lengthy preparatory times (days or even weeks). Furthermore, the sol-gel process's raw materials are expensive, and some of the organic chemicals it uses are toxic, endangering both human health and the environment [110].

2.5.3. Layer-by-Layer Deposition

The material composition and coating thickness can be precisely controlled with this technology. It is frequently employed to create multi-layered coatings with a variety of functions. Layer-by-layer techniques yield coatings with remarkable mechanical, electrical, optical, and special wetting qualities. But even though this method is economical, a lot of material is frequently wasted [111].

PART 3

METHODOLOGY

3.1. INTRODUCTION

Addressing the performance constraints of photovoltaic (PV) systems under practical circumstances requires the development of sophisticated nanocomposite coatings. The effectiveness and longevity of solar panels are greatly impacted by elements including dust buildup, UV rays, and high surface temperatures.

This work uses a novel approach to create multipurpose coatings with cooling, anti-reflective, and self-cleaning capabilities. The goal of the research is to improve light transmittance, thermal management, and surface cleanliness of PV systems by incorporating zinc oxide (ZnO) and silicon dioxide (SiO₂) nanoparticles with chlorophyll into a matrix of Methyl Phenyl Silicone Resin (MPSR). The materials, preparation procedures, and characterization techniques utilized to design and assess these coatings in both lab and real-world settings are thoroughly described in this chapter.

3.2. THE FLOWCHART METHODOLOGY

The process of creating a flowchart starts with establishing the goal: creating a multipurpose nanocomposite coating that enhances PV performance by having antireflection, UV protection, self-cleaning, and self-cooling qualities. Then, purchasing essential materials and mixed in varying ratios to create the coating suspensions in the lab. After the coating is applied to glass slides using a spray method the laboratory Tests are conducted to evaluate the maximum transmittance, average absorption, contact angle, average emissivity In the Decision Point, If the laboratory results satisfy performance criteria, the coatings are advanced to the next

stage. The next stage, the satisfy nanocomposite coating is applied to small PV panels and install the coated and uncoated PV panels are subjected to real-world conditions for comparison field testing. Parameters such as maximum power output, operating temperature, and dust accumulation are monitored as illustrated by Figure 3.1.



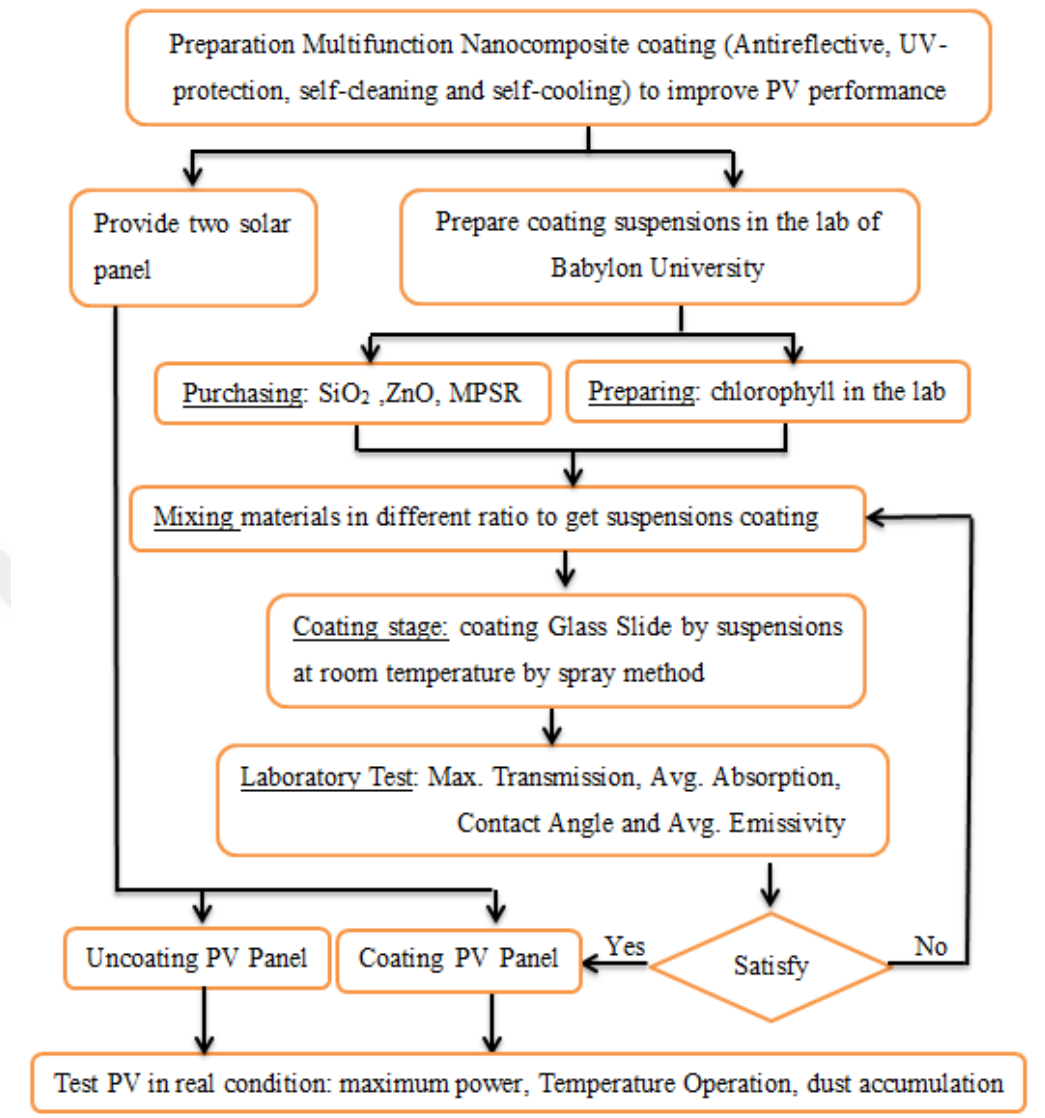


Figure 3.1. Flowchart depicting the overall preparation process employed in this study.

3.3. MATERIALS

Nanocomposite coatings were prepared using high-quality materials tailored for durability and functionality. The primary matrix, Methyl Phenyl Silicone Resins (MPSR), was selected for its excellent thermal and oxidative resistance [112]. The material used for this study were:

Methyl Phenyl Silicone Resins (MPSR): Methyl phenyl silicone resin is synthesized through a specialized post-treatment process using phenyl monomer as the primary

raw material. This product effectively reduces surface tension when applied to a substrate and generates hydroxyl radicals under exposure to ultraviolet and visible light, exhibiting strong [113]. Its operation is straightforward, with high adhesion and no residue formation. The coating process, whether through spraying or dipping, requires only 10 to 30 minutes at room temperature to achieve optimal results.



Figure 3.2. Methyl phenyl silicone resin [114].

Applications of this versatile resin include waterproofing, anti-pollution treatments, and anti-ultraviolet coatings for various surfaces. It is particularly effective for rendering glass surfaces hydrophobic, providing anti-pollution and UV-resistant properties. Additional uses include waterproofing and anti-pollution treatments for ceramics, stone surfaces, and solar cells, where it also offers anti-corrosion benefits. This multifunctional material is ideal for improving the durability, cleanliness, and overall performance of coated surfaces across a range of industries [115].

ZnO nanoparticles: (10–30 nm), in the Figure 3.3. known for their high transparency, UV absorption and photocatalytic properties.



Figure 3.3. ZnO nanoparticles.

SiO₂ nanoparticles (30–50 nm), in Figure 3.4. valued for their hydrophobicity features.

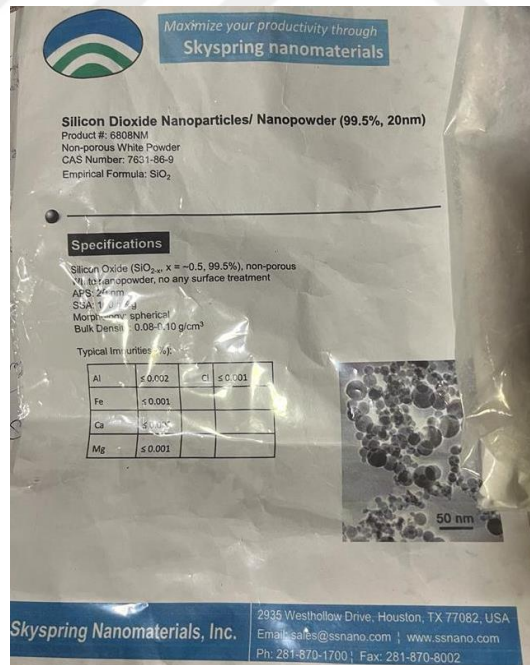


Figure 3.4. SiO₂ nanoparticles.

Chlorophyll pigment, Chlorophyll solvent can be obtained through extraction from sources such as *Hyophila involuta* moss [116] or celery [117]. In this study, a 50 g portion of cleaned celery pieces was immersed in 50 g of alcohol and allowed to soak overnight. The mixture was then filtered to produce a uniform chlorophyll solution, as illustrated in Figure 3.5.

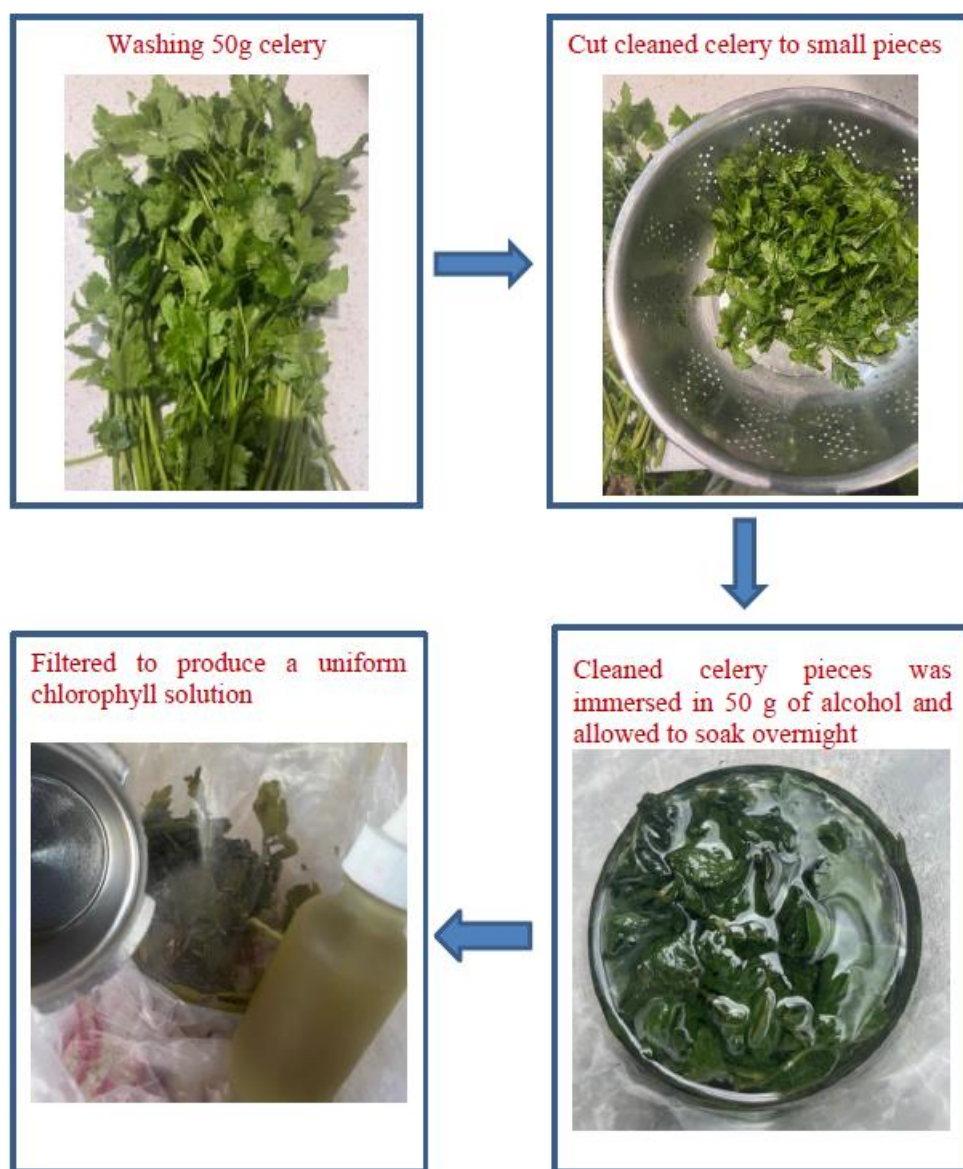


Figure 3.5. Steps of chlorophyll pigment extraction.

Additional materials included:

Benzoyl peroxide as a curing agent. Xylene, acetone, ethanol, microscope Glass slides and deionized water as solvents for substrate cleaning and material dispersion. All materials in Figure 3.6. were purchased from Areej Al-furat Company Co., Ltd. (Baghdad, Iraq) except chlorophyll was prepared in the ab of Babylon University.

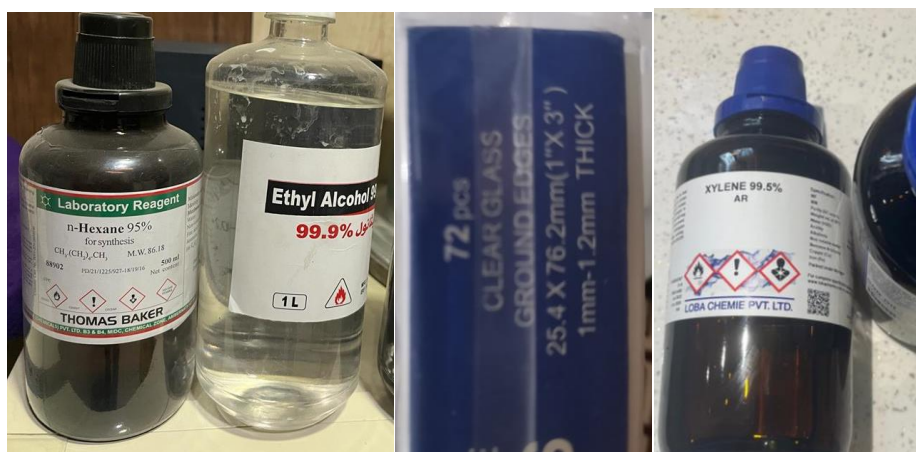


Figure 3.6. Additional materials used in research.

3.4. STEPS OF COATING PREPARATION

Four distinct coating, samples S1, S2, S3, and S4 were fabricated using a multi-step process:

- S1 (MPSR-Chlorophyll Coating): A mixture of 8 g MPSR and 6 g chlorophyll extract were stirred for 1 hour to achieve uniformity as shown in Figure 3.7.

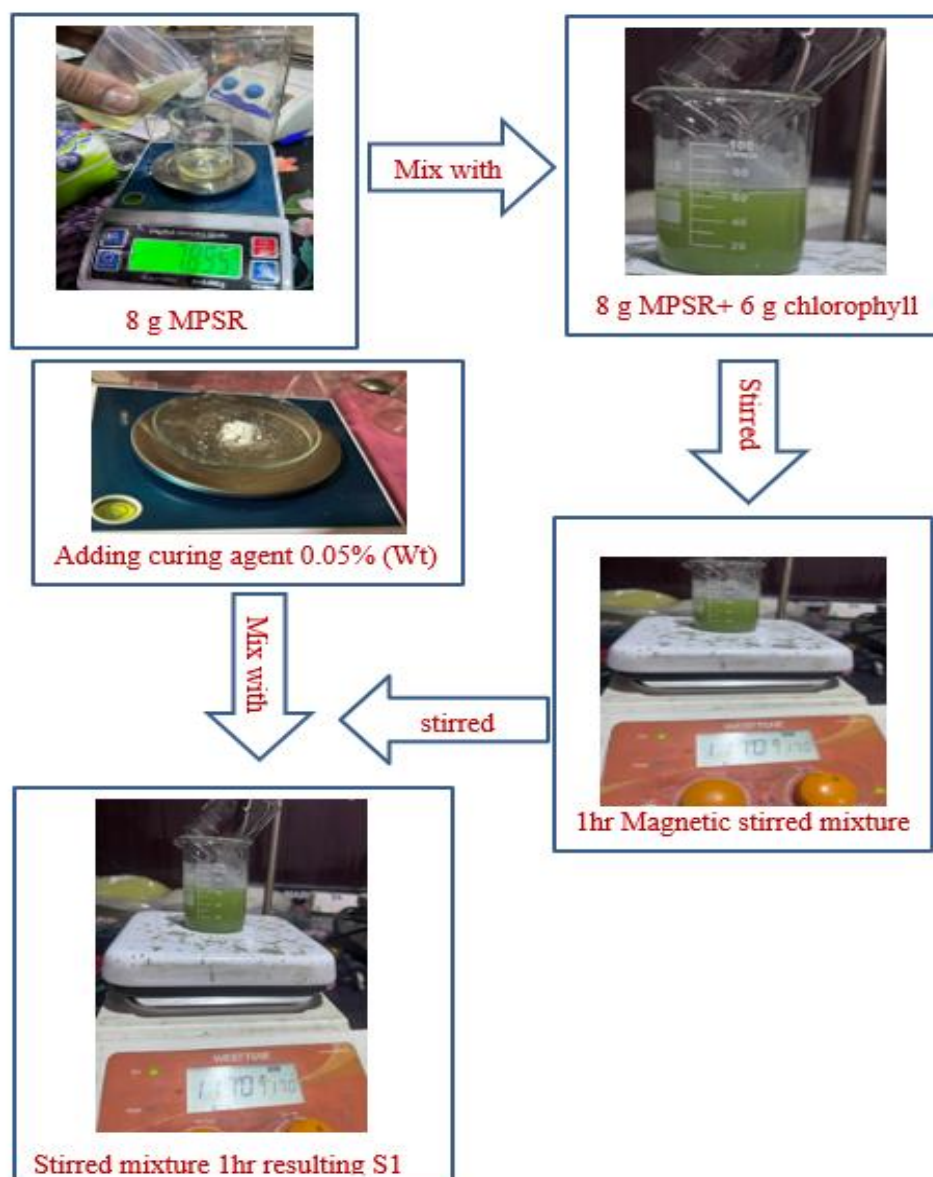


Figure 3.7. Steps preparation S1 (MPSR-chlorophyll coating).

- S2 (MPSR-ZnO Coating): 0.6 g ZnO nanoparticles underwent the same dispersion and stirring process as in S2, with MPSR added for matrix formation this process illustrated in Figure 3.8.

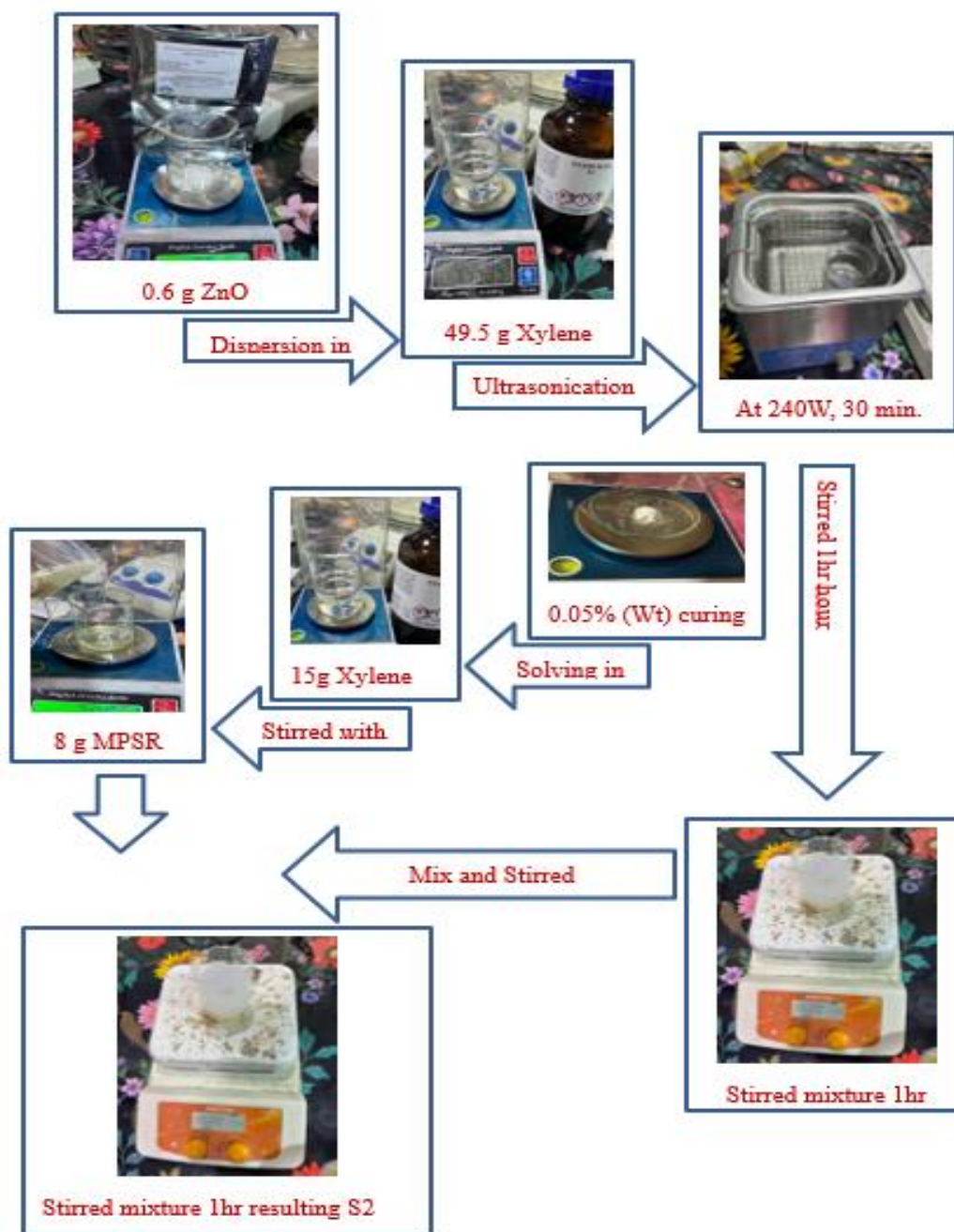


Figure 3.8. Steps preparation S2 (MPSR-ZnO)

- S3 (MPSR-SiO₂ Coating): 2 g SiO₂ nanoparticles were dispersed in 49.5 g xylene using ultrasonication at 240 W for 30 minutes, followed by 2 hours of stirring with 8 g MPSR added as seen in Figure 3.9.

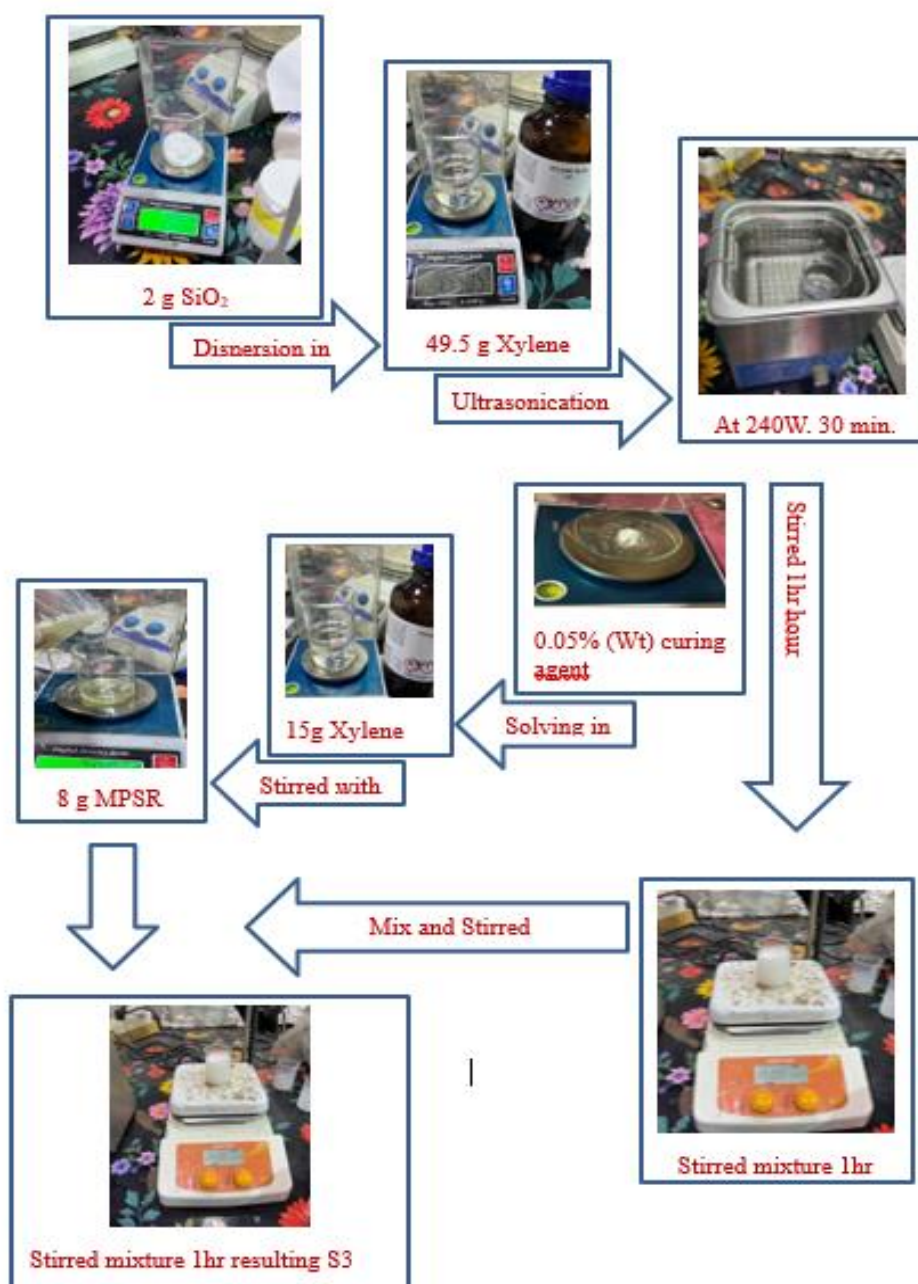


Figure 3.9. Steps preparation S3 (MPSR-SiO₂)

- S4 (MPSR-Chlorophyll-SiO₂-ZnO Coating): A combination of 2 g SiO₂ and 0.6 g ZnO nanoparticles was dispersed together, followed by the addition of 6 g chlorophyll and 8 g MPSR as shown in Figure 3.10.

All solutions were activated with 0.05% benzoyl peroxide and mixed at 1500 rpm for 1hr at 60 °C.

3.5. SUBSTRATE PREPARATION

Preparing substrates is a crucial step in the coating application process, as the quality of the coating depends significantly on the substrate's surface condition. This preparation involves steps such as thorough cleaning and chemical modification to ensure the substrate is free of contaminants, dirt, and oxides or scales. Additionally, to obtain a high-quality, long-lasting coating, surface imperfections like pores and scratches must be addressed, and surface roughness must be optimized [118].

Glass substrates were cleaned for this study to provide the best possible adhesion and coating performance:

- For ten minutes each, substrates ($25.4 \times 76.2 \times 1.1$ mm) were submerged in acetone, ethanol, and deionized water baths.
- Substrates were ultrasonically cleaned and then dried for an hour at 80 °C in an oven.

A K-3 spray nozzle was used to apply the coatings at a pressure of 0.2 MPa while keeping a 15 cm distance from the surface.



Figure 3.10. Steps preparation S4 (MPSR-chlorophyll-ZnO -SiO₂ coating).

3.6. CHARACTERIZATION TECHNIQUES

In this study, the characterization of specimens was conducted using the equipment listed below, which is available in the laboratories of Babylon University. These devices were employed to assess and evaluate the properties and performance of the prepared specimens:

3.6.1. UV-Visible Spectroscopy

Used to measure Maximum Transmittance T_{max} (%) and average absorption Avg. at UV-wavelength between (250-380)Nm assessing light-trapping and anti-reflective capabilities.

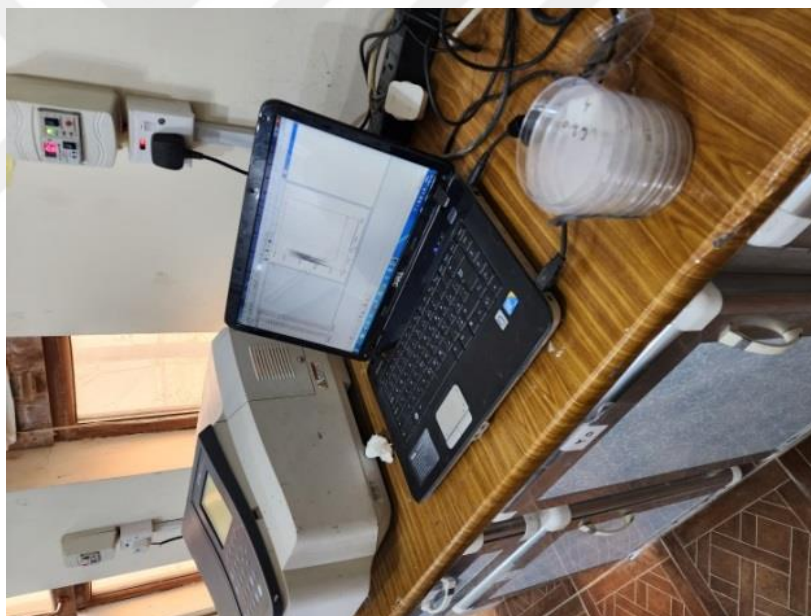


Figure 3.11. UV-visible spectroscopy.

3.6.2. Vio-For Contact Angle.

Device in Figure 3.12. is Vio-For contact angle measurement for contact angle. The contact angles of a 5 μ L water drop deposited on the surfaces of different coatings to determine hydrophobicity, using a Vio-For contact angle meter to assess self-cleaning efficiency.

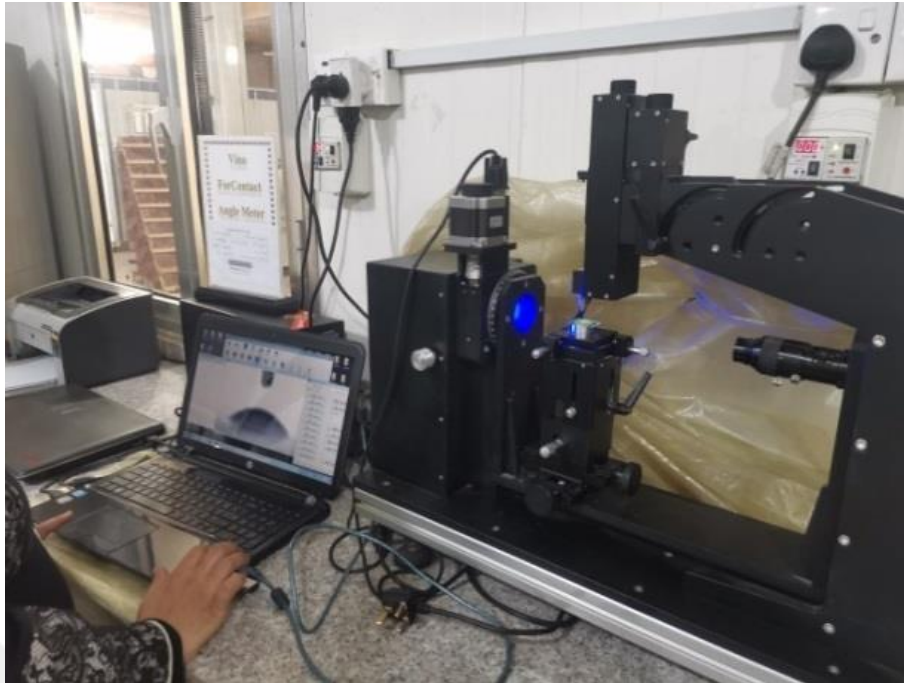


Figure 3.12. Vino-for contact angle measurement.

3.6.3. Fourier Transform/Infrared (FT/IR) Spectroscopy

In Figure 3.13. Fourier Transform Infrared (FT/IR-6100) spectrometer for analyzed emissivity in the 8–13 μm range for radiative cooling potential.



Figure 3.13. Fourier transform infrared (FT/IR-6100) spectrometer.

3.6.4. Fourier-Transform Infrared FTIR Spectrometer

Devise in Figure 3.14. Fourier-Transform Infrared FTIR Spectrometer used to determine the chemical bonds between the MPSR and additives as coating materials



Figure 3.14. Fourier-transform infrared FTIR spectrometer.

3.6.5. Infrared Thermometer

Figure 3.15. Infrared Thermometer used to measure operation Front Surface Temp for solar panels.



Figure 3.15. Infrared thermometer.

3.6.6. Temperature thermostat W1209 DC12V

Figure 3.16. Temperature thermostat W1209 DC12V used to measure operation Rear Surface Temp for solar panels.

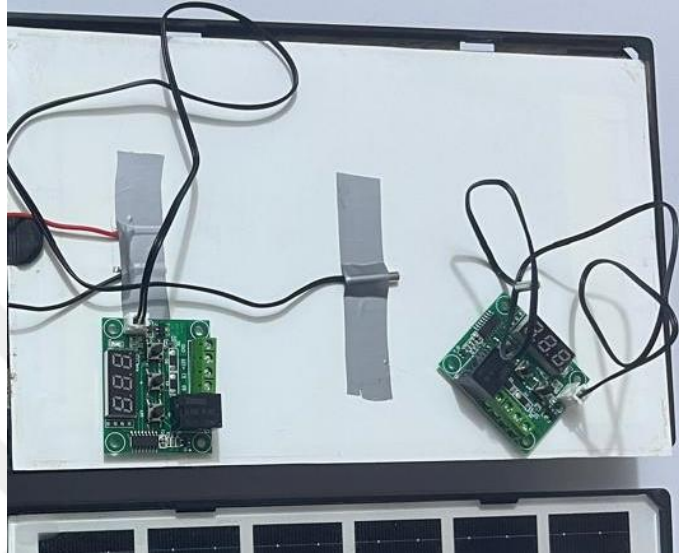


Figure 3.16. Temperature thermostat W1209 DC12V.

3.6.7. Digital Multimeter

Figure 3.17. Digital Multimeter used for DC-Current (Ampere) and DC-Voltage (volt) measurements quantified power output improvements.



Figure 3.17. Digital multimeter

3.6.8. T640 Infrared Thermal Imaging Camera

Figure 3.18. Thermal Imaging Camera used for measuring surface temperature.

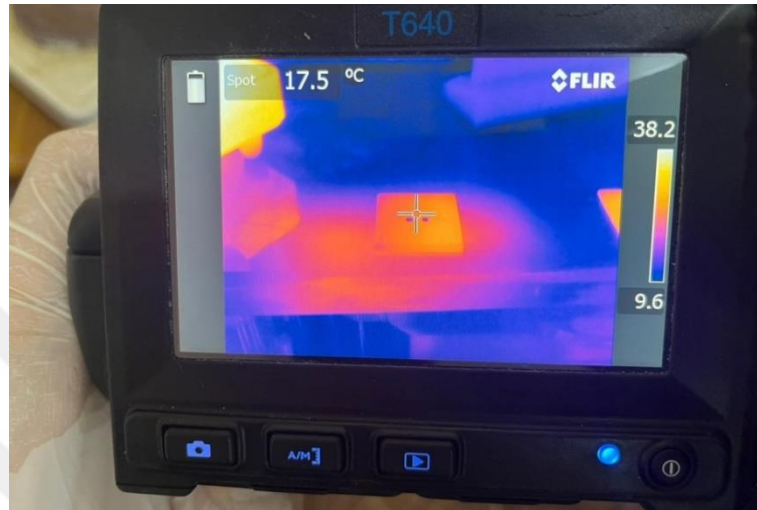


Figure 3.18. Thermal imaging camera.

3.7. LABORATORY TESTING

Laboratory tests are conducted to evaluate the physical and optical properties:

- Maximum Transmittance, indicates light passage through the coating.
- Average Absorption, measures the coating's ability to absorb specific light wavelengths.
- Contact Angle, determines hydrophobicity and self-cleaning potential.
- Average Emissivity, Assesses the thermal radiation capabilities.

3.8. DECISION POINT

If the laboratory results satisfy performance criteria, the coatings are advanced to the next stage of application the coating on Solar Panels. If not, the process is refined and repeated mixing different ratios of materials until satisfy results.

3.9. APPLICATION ON SOLAR PANELS

The satisfied compositions of chlorophyll, ZnO nanoparticles and SiO₂ nanoparticles were applied to the glass of the streetlamp, as shown in Figure 3.19. The uncoated PV panel is used as a reference for comparison.



Figure 3.19. Coating on the glass of lamp street.

3.10. FIELD TESTING

The coated and uncoated PV panels are subjected to real-world conditions. The parameters such as maximum power output, operating temperature, and dust accumulation are monitored. Field tests were conducted at Babylon University under real-world conditions. Panels were exposed to sunlight from May 31 to June 7, 2024, with irradiance levels of 1100 W/m² recorded at peak hours.

PART 4

LABORATORY TESTING

In brief, the nanocomposite coatings were produced through a multi-stage process, with four samples S1, S2, S3, and S4 designed to assess the individual and combined effects of the incorporated materials. The methodology involved precise preparation steps to ensure homogeneous coating solutions, optimal material dispersion, and uniform application to the substrate in laboratory.

4.1. EXPERIMENTAL LABORATORY SETUP

Four distinct coating samples (S1, S2, S3, and S4) were formulated with varying compositions of chlorophyll, ZnO nanoparticles, and SiO₂ nanoparticles, tailored for application to glass substrates, as detailed in Table 4.1. Methyl Phenyl Silicone Resin (MPSR) was added to 6 g of chlorophyll solution to create the S1 coating solution. To guarantee homogeneity, this mixture was stirred regularly for an hour.

For the S2 and S3 coatings, 49.5 g of xylene was used to disperse 2 g of SiO₂ nanoparticles and 0.6 g of ZnO nanoparticles, respectively. For 30 minutes, this dispersion method used ultrasonication at 240 W of power to guarantee even dispersion of the nanoparticles. 8 g of MPSR was then added to each solution after each dispersion had been agitated for two hours at room temperature. For two more hours, the mixtures were stirred to achieve a uniform consistency.

Following the same ultrasonication and stirring procedure as for S2 and S3, 2 g of SiO₂ nanoparticles and 0.6 g of ZnO nanoparticles were combined and dispersed in 49.5 g of xylene to create the S4 coating solution. To reach homogeneity, 8 g of

MPSR was added to this mixture, and the mixture was stirring for two hours to harden the coating solutions (S1, S2, S3, and S4), 0.05% benzoyl peroxide was added. To start cross-linking and guarantee the best coating qualities, the solutions were then stirred at 1500 rpm and kept at 60 °C for 50 minutes. The 25.4 × 76.2 × 1.1 mm glass substrates were carefully prepared to improve coating adherence. This preparation involved ten minutes of sequential ultrasonic cleaning in acetone, ethanol, and deionized water, followed by an hour of drying in an oven set at 80 °C. A K-3 spray nozzle was then used to coat the substrates after they had been cleaned. To produce a uniform coating, the spray-coating procedure was carried out using a nozzle-to-sample distance of 15 cm and a spray pressure of 0.2 MPa. Consistent material distribution was ensured by the final coatings' uniform thickness of 54 µm on the substrates. The goal of this meticulous preparation and application procedure was to maximize the coatings' durability, light transmittance, and hydrophobicity for improved solar panel performance. The combination of ZnO, SiO₂, and chlorophyll nanoparticles gave the coatings multifunctional qualities like enhanced heat dissipation, UV protection, and self-cleaning capabilities.

Table 4.1. Composition of coating samples.

Component	S1	S2	S3	S4
Methyl Phenyl Silicone Resins (MPSR) (g)	8	8	8	8
Chlorophyll (g)	6	-	-	6
ZnO Nanoparticles (g)	-	0.6	-	0.6
SiO₂ Nanoparticles (g)	-	-	2	2
Xylene (g)	49.5	49.5	49.5	49.5
Curing Agent (Benzoyl Peroxide) (w/v)	0.05%	0.05%	0.05%	0.05%

4.2. CHARACTERIZATION OF SAMPLES

A variety of sophisticated analytical methods were used to thoroughly characterize the Nano-composite coatings in order to assess their optical, wetting, and thermal characteristics. A detailed understanding of the coatings' functioning and performance in photovoltaic applications was made possible by these characterizations.

Methyl Phenyl Silicone Resin (MPSR) and the added additives, such as ZnO, SiO₂, and chlorophyll, were examined for chemical bonding and interactions using Fourier Transform Infrared (FT-IR) spectroscopy (IRAffinity-1 S, Shimadzu, Japan). This research confirmed the effective incorporation of functional components into the resin matrix and emphasized the structural changes brought about by the additives. Important bonds like Si-O-Si and organic groups were verified to be present, demonstrating the customized chemistry of the coatings.

Using a UV-Visible Spectroscopy Spectrophotometer, the coatings' transmittance ($T_{\max.}\%$) was measured across the visible light spectrum (200–750 nm). This analysis demonstrated the coatings' anti-reflective and light-trapping qualities, which are essential for raising photovoltaic efficiency. The same apparatus was also used to assess the coatings' UV protection effectiveness in the ultraviolet wavelength range of 200–650 nm. Understanding how well the coatings protect solar cells from damaging UV rays, which can cause deterioration over time, depends on this parameter.

Using a Voino-For contact angle meter to measure the static water contact angle (WCA), the wetting properties a sign of self-cleaning capabilities were assessed. A greater WCA denotes better hydrophobicity and the coating's capacity to ward off water, hence avoiding the buildup of dust and grime.

This characteristic is essential for preserving the cleanliness and effectiveness of solar panels since it replicates the self-cleaning qualities of natural surfaces like lotus leaves.

A Fourier Transform Infrared (FT/IR-6100) spectrometer was used to test the coatings' infrared thermal emissivity in the 8–13 μm wavelength region. One important metric for assessing radiative cooling effectiveness is thermal emissivity. The relation (4.1)

was used to calculate emissivity by examining the samples reflectance over this range [119]:

$$Emissivity = 1 - Reflectance \quad (4.1)$$

This investigation shed light on the coatings' capacity to dissipate heat, which is a crucial property for lowering solar panels operating temperatures and improving their overall efficiency.

The combination of these analytical methods demonstrated the multifunctionality of the Nano-composite coatings in addition to confirming their successful production. High optical transmittance, UV protection, self-cleaning behavior, and efficient heat management were among the qualities that the coatings displayed.

These qualities make them ideal for use in solar panels, tackling important issues including heat stress, UV deterioration, and efficiency loss from reflection. This work highlights the potential of these Nano-composite coatings in developing solar technology by guaranteeing accurate and thorough characterization.

4.3. RESULTS LABORATORY TESTING

4.3.1. The FTIR Analysis

As illustrated in Figure 4.1, the FTIR analysis of Methyl Phenyl Silicone Resin (MPSR) coatings with different additives offers important information about the structural and chemical alterations brought about by these additives for each sample composition, emphasizing their influence on the material's spectral characteristics and functionality:

- **Baseline FTIR Spectrum of Pure MPSR:** The pure MPSR exhibits characteristic peaks associated with specific chemical bonds Si-CH₃. These methyl groups contribute to the hydrophobic nature of the resin, enhancing its water-repellent properties. Si-C₆H₅ (phenyl) Phenyl groups are responsible for

the thermal stability and enhanced UV resistance of the resin. Si-O-Si bonds the stretching vibrations around $1000\text{--}1100\text{ cm}^{-1}$ indicate the siloxane network, which provides structural integrity and flexibility [120].

- Effect of Chlorophyll Addition (Sample S1): Chlorophyll significantly reduces transmittance across the spectrum. The interaction between MPSR and chlorophyll may involve hydrogen bonding or other non-covalent interactions, integrating chlorophyll into the polymer matrix. This incorporation enhances UV absorption and light-absorbing capabilities of the coating.
- ZnO Nanoparticles Addition (Sample S2): ZnO exhibits surface hydroxyls, evident from the enhanced -OH peak ($\sim 3400\text{ cm}^{-1}$), which can provide additional sites for interaction or catalysis. The sharp Si-H peak around 2150 cm^{-1} suggests that ZnO influences the resin's chemical environment, possibly enhancing its UV shielding and photocatalytic properties [121,122].
- The addition of SiO₂ nanoparticles (Sample S3) strengthens the siloxane network by intensifying the Si-O-Si peak, most likely as a result of their contribution. In the $1000\text{--}1100\text{ cm}^{-1}$ range, the S3 coating, which combines MPSR with SiO₂ nanoparticles, exhibits a noticeable Si-O-Si peak that is probably enhanced by the presence of SiO₂ [123]. SiO₂ gives the coating mechanical strength and durability, which guarantees its stability under environmental pressures.
- Combination of All Additives (Sample S4): The spectrum of S4 reflects the synergistic effects of ZnO, SiO₂, and chlorophyll by combining features from the previous samples. Compared to S1, the overall transmittance is greater, indicating that the nanoparticles lessen the excessive absorption brought on by chlorophyll. ZnO, chlorophyll, and the MPSR matrix interact to enhance the coating's multifunctionality, which includes cooling, self-cleaning, and UV protection, as indicated by the prominent -OH peak at about 3400 cm^{-1} .

This study demonstrates the promise of multifunctional nanocomposite coatings in improving the lifespan and performance of solar panels and other applications needing advanced material qualities by examining the spectral features and comprehending the chemical interactions.

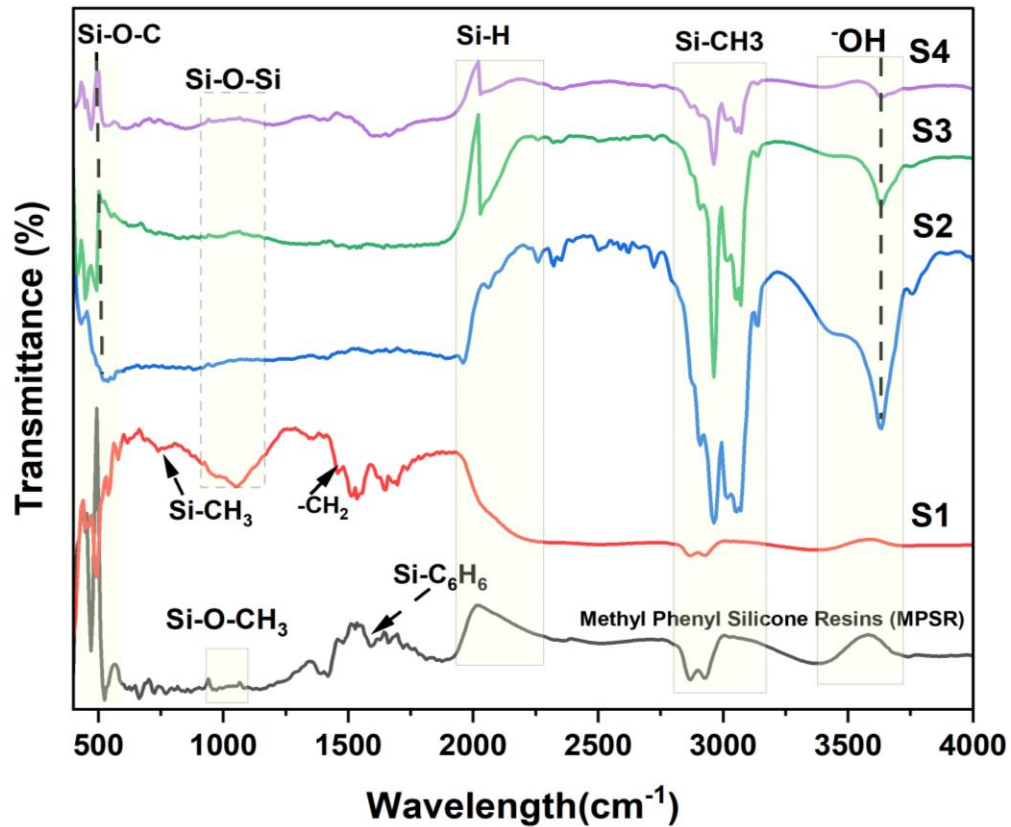


Figure 4.1. The produced coatings FTIR spectra.

4.3.2. UV-Vis Transmittance Spectra Analysis

The performance of an uncoated glass substrate (S) and four distinct nanocomposite coatings MPSR-Chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3), and MPSR-Chlorophyll-ZnO-SiO₂ (S4) is compared using the UV-Vis transmittance spectra. create a baseline for assessing the coated samples, the uncoated glass substrate obtains the greatest transmittance of 91.51%, demonstrating its capacity to permit a considerable amount of visible light to flow through without interference.

- Due to chlorophyll's capability to absorb light, MPSR-Chlorophyll coating (S1) shows a fall in maximum transmittance to 86.47%, as seen in Figure 4.2. This absorption could decrease overall light transmission and its efficiency in photovoltaic (PV) systems, even while it is beneficial for catching particular light wavelengths, especially in applications that utilize light trapping. However, there are additional advantages to the chlorophyll-based coating, including UV protection, which can minimize UV-induced deterioration in solar panels.

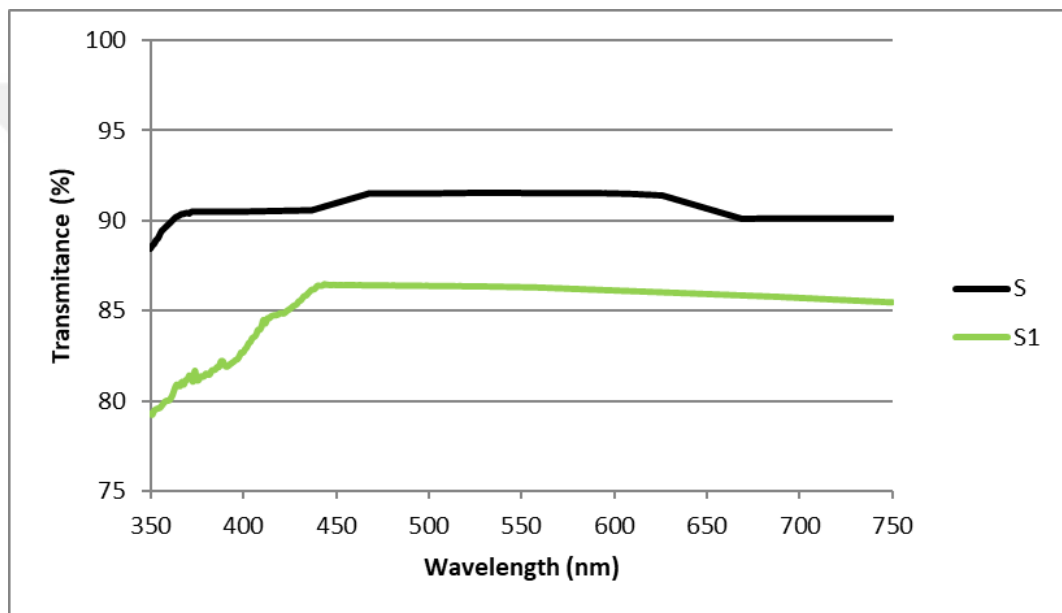


Figure 4.2. UV-transmittance within the visible spectrum of the MPSR-chlorophyll-coated glass substrate (S1) and the uncoated substrate (S).

- As seen in figure 4.3, MPSR-ZnO coating (S2) had the maximum transmittance among of all samples, at 96.38%, indicating that ZnO nanoparticles both effectively block UV rays and enable visible light to pass through. That makes the ZnO-based coating particularly beneficial for solar applications, where UV protection and high transmittance are essential.

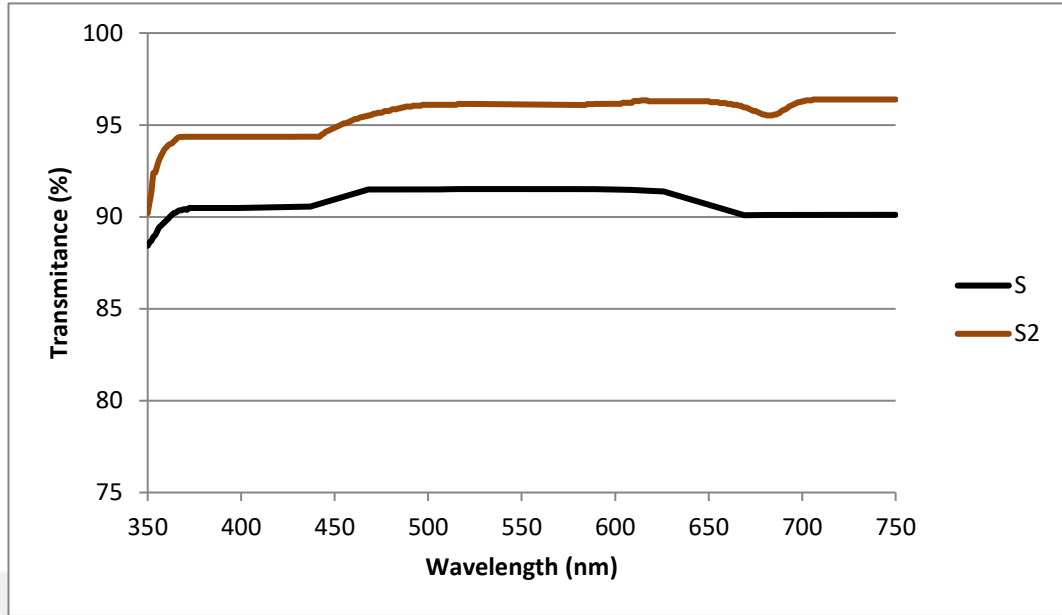


Figure 4.3. UV-transmittance within the visible range of the uncoated glass substrate (S), MPSR-ZnO (S2).

- As shown in Figure 4.4, the MPSR-SiO₂ coating (S3) reaches a maximum transmittance of 92.6%, which is very similar to the performance of uncoated glass. This suggests that SiO₂ nanoparticles could offer extra features like anti-reflective properties and self-cleaning capabilities while having no impact on visible light transmission.
- The combined MPSR-Chlorophyll-ZnO-SiO₂ coating (S4) shown a balanced strategy that combines light trapping, UV protection, and high transmittance. which exhibits a maximum transmittance of 93.48% as seen in Figure 4.5. By tackling important issues in light management and environmental resilience, the combination of chlorophyll, ZnO, and SiO₂ optimizes the coating for improved solar technology performance.

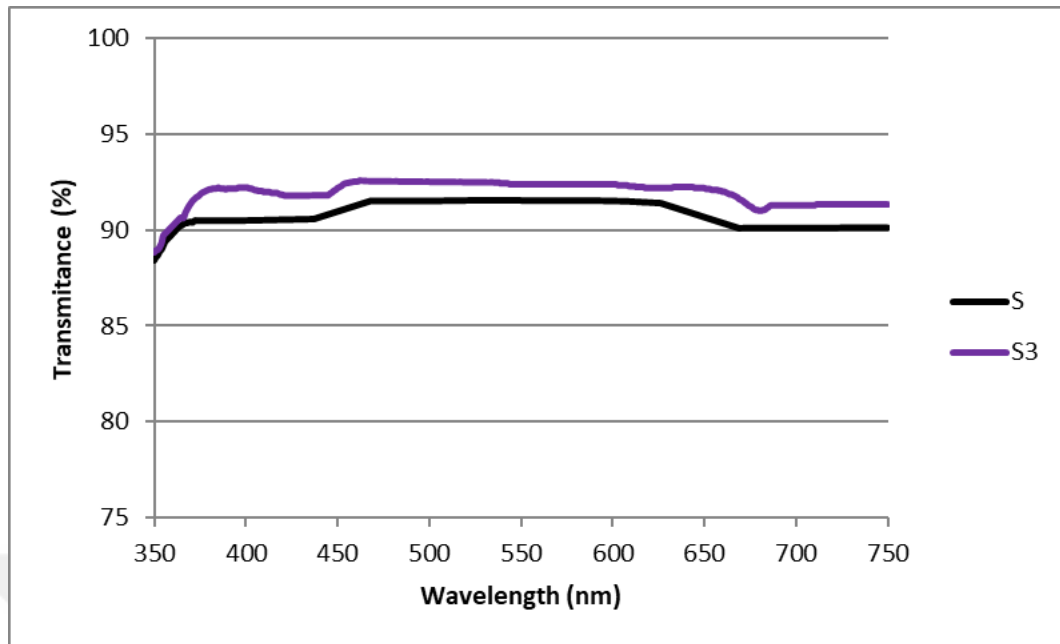


Figure 4.4. UV-transmittance within the visible spectra of MPSR-SiO₂ (S3) and the uncoated glass substrate (S).

These findings illustrate the various ways in which the various materials influence light transmittance. The combination coating (S4) demonstrates great promise for solar technology by combining multiple functions, including light trapping, ultraviolet radiation protection, and environmental endurance, while the MPSR-ZnO coating (S2) excels at optimizing transmittance. These designed nanocomposite coatings can significantly improve solar system's longevity and efficiency, particularly under hard operating circumstances.

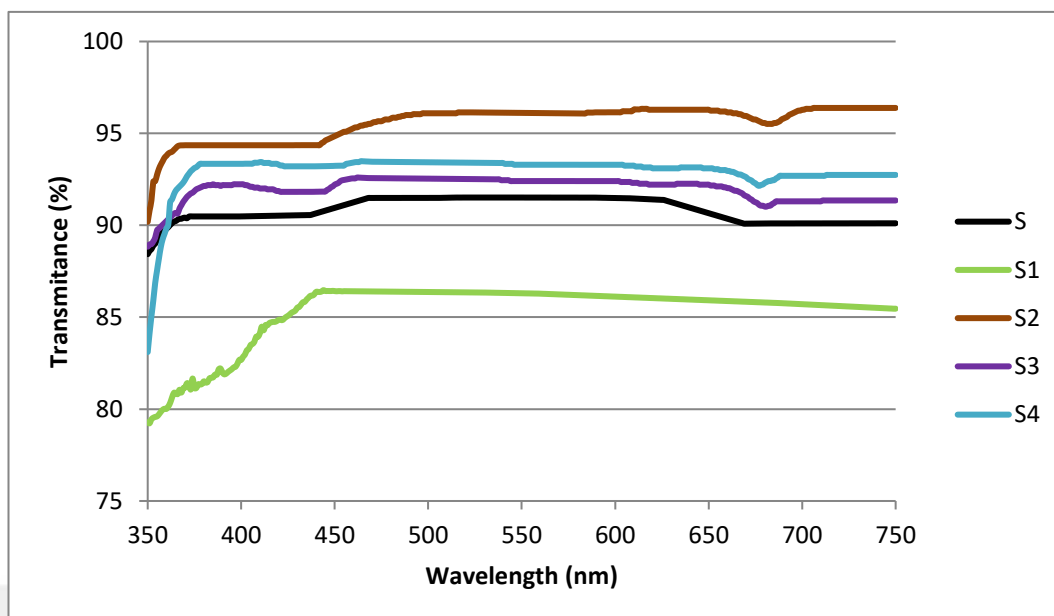


Figure 4.5. UV-transmittance in the visible range of the uncoated glass substrate (S), coating with MPSR-chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3) and MPSR-chlorophyll-ZnO-SiO₂ (S4).

4.3.3. The UV-Vis Absorption Spectra Analysis

The UV-Vis absorption spectra for glass substrates with various coatings. The samples include uncoated glass (S), MPSR-chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3), and a combined MPSR-Chlorophyll-ZnO-SiO₂ (S4). These coatings significantly influence the interaction of UV light with the glass substrate, affecting its optical properties and potential applications.

The uncoated glass demonstrates the lowest absorption across the UV spectrum, signifying minimal interaction with UV light. This characteristic makes it highly transparent but offers no protection against harmful UV radiation. As a baseline, the uncoated glass is ideal for comparison with the coated samples to evaluate enhancements in absorption and UV shielding:

MPSR-Chlorophyll Coating (S1):

Coating S1 exhibits a prominent absorption peak, indicating that chlorophyll effectively absorbs UV radiation as shown in figure 4.6. This absorption capability is beneficial for shielding underlying materials from UV-induced degradation.

Chlorophyll's natural light-absorbing properties make S1 suitable for applications requiring UV protection, though the absorption of visible light may limit its utility for applications where high transparency is essential.

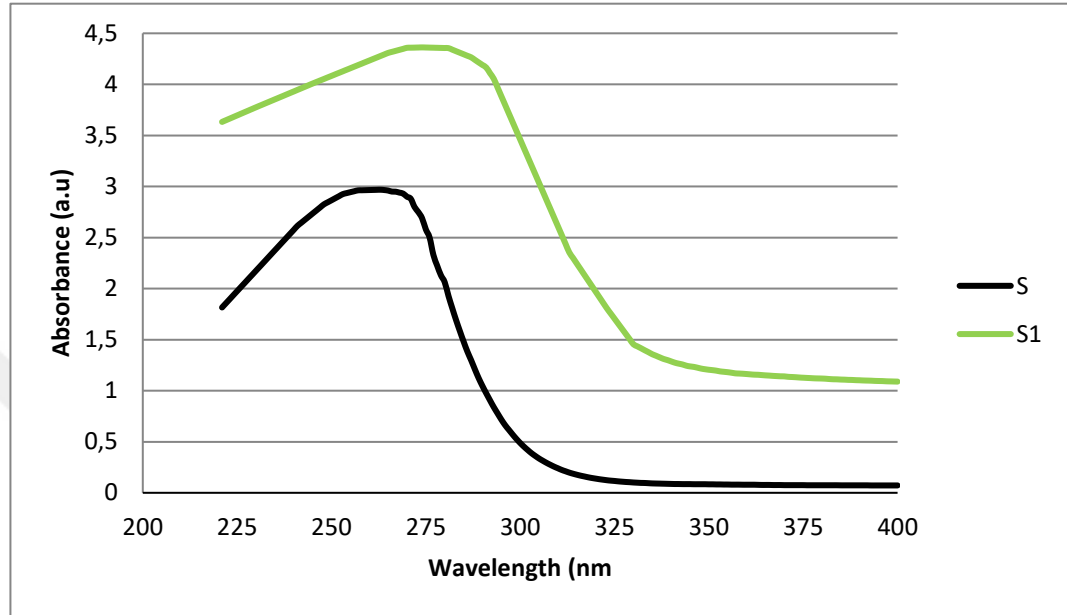


Figure 4.6. UV-absorption in the UV range of the uncoated glass substrate (S), coating with MPSR-chlorophyll (S1).

MPSR-ZnO Coating (S2):

The S2 coating shows moderate UV absorption due to the inclusion of ZnO nanoparticles as seen in Figure 4.7. ZnO contributes to UV protection while maintaining sufficient transparency in the visible spectrum. It is a desirable choice for applications like photovoltaic systems, where reaching a balance between light absorption and transparency is necessary, due to its dual function as an optical enhancer and UV absorbents.

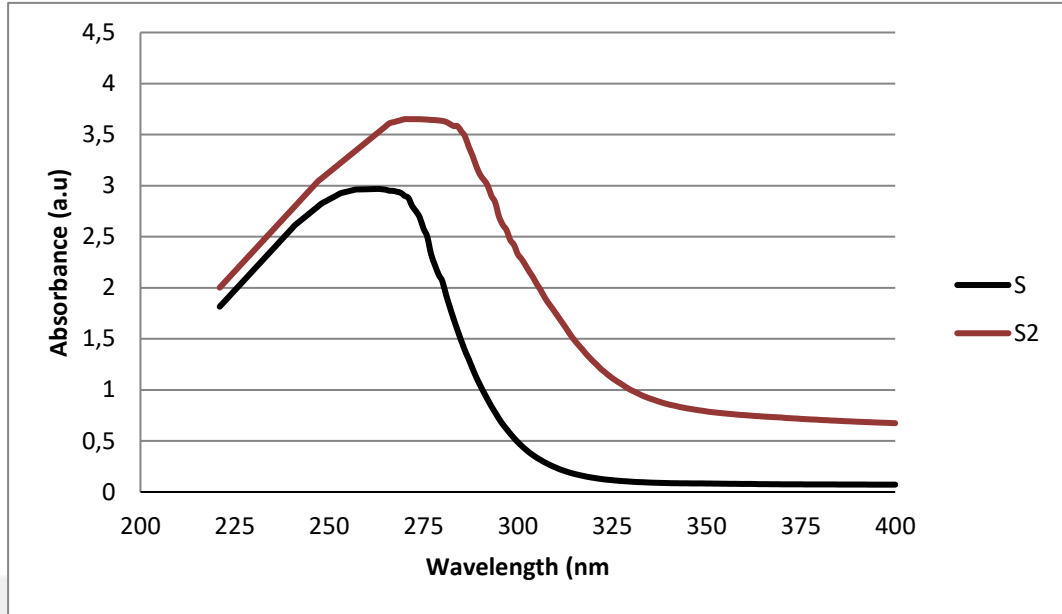


Figure 4.7. UV-absorption within the UV range of the MPSR-ZnO (S2) and uncoated glass substrate (S).

MPSR-SiO₂ Coating (S3):

As shown in Figure 4.8, the S3 coating exhibited absorption levels that are similar to those of uncoated glass, demonstrating its function as a protective barrier with limited interaction with UV radiation. Without reducing transparency, SiO₂ low absorption qualities enhance the coating's self-cleaning properties.

Combined Coating (S4):

Figure 4.8 shown the synergistic interaction between chlorophyll, ZnO, and SiO₂ which results in the optimum UV absorption in the S4 coating. While maintaining balanced optical qualities, this combination improves UV shielding capabilities. SiO₂ provided structural integrity and anti-reflective qualities, ZnO improves protective quality, and chlorophyll assists in UV absorption. All of these elements work together to produce S4, a multipurpose coating suitable for uses requiring efficiency and long life expectancy, including photovoltaic systems subjected to severe weather.

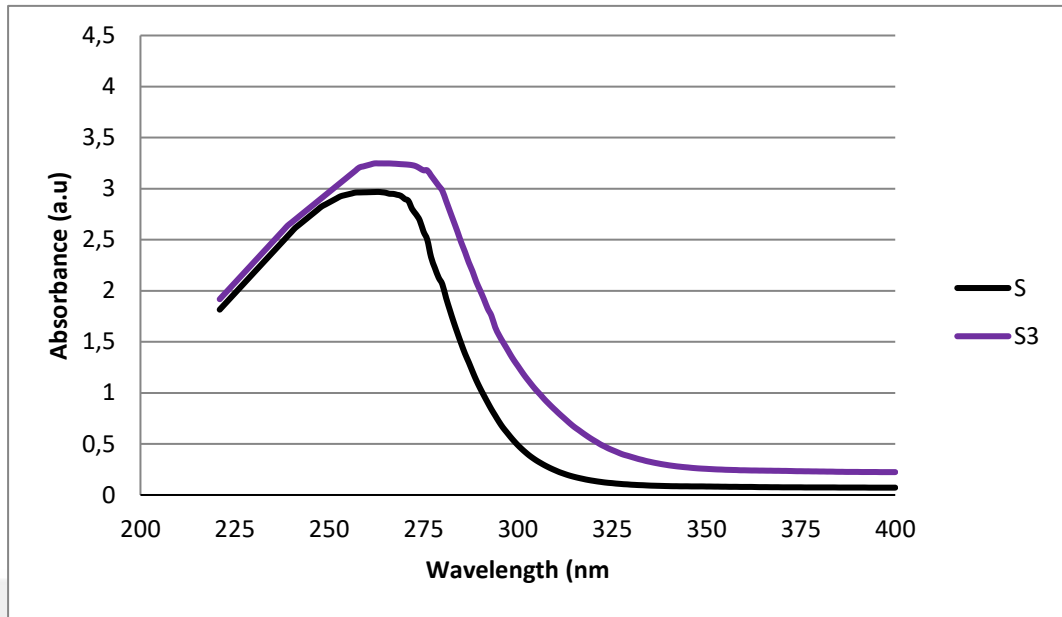


Figure 4.8. UV-absorption within the UV range of the MPSR-SiO₂ (S3) and uncoated glass substrate (S).

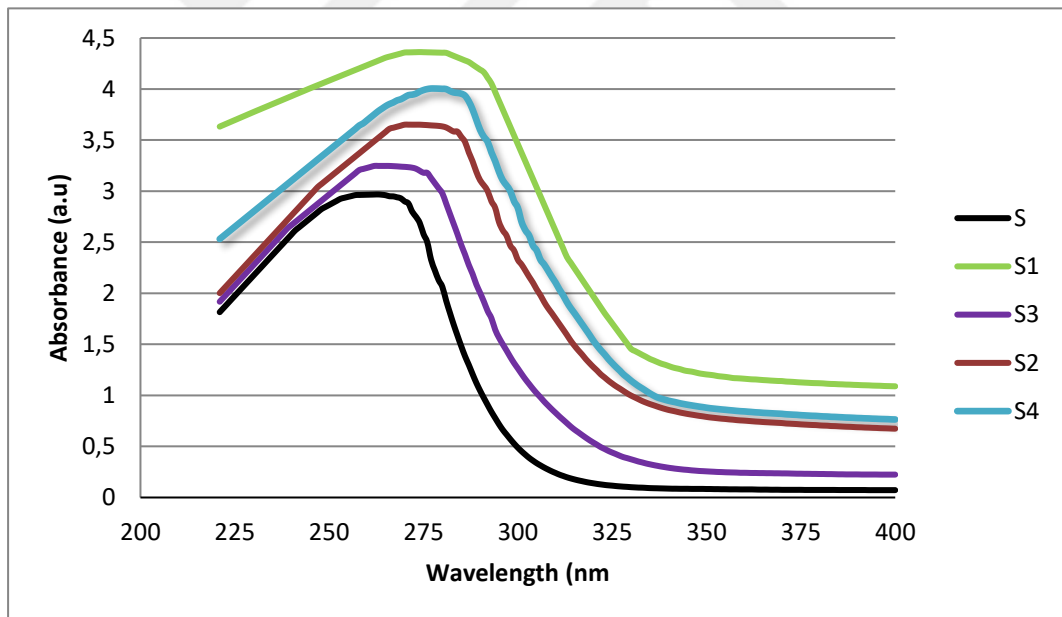


Figure 4.9. UV-absorption in the UV range of the uncoated glass substrate (S), coating with MPSR-chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3) and MPSR-chlorophyll-ZnO-SiO₂ (S4).

4.3.4. The FT/IR Spectra Analysis

The characteristics of various coatings' infrared thermal emissivity when applied on a glass substrate are investigated. The uncoated glass (S) and coatings containing MPSR-Chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3), and a mixture of all three components (S4) are samples of these coatings. For applications such solar panels, the emissive profiles provide essential details about each coating performance for heat management.

The sample that emits the minimal amount of thermal radiation is (S) uncoated glass, because it has the lowest emissivity. Transparent materials that primarily permit light transmission without effectively dissipating heat are known for this property. Despite its beneficial for optical clarity, the glass's low emissivity limitations its use in heat management applications.

Accordingly, the result examination of samples in FTIR for thermal infrared emissivity as listed below:

MPSR-Chlorophyll Coating (S1):

With peaks shown at particular wavelengths which are illustrated in Figure 4.10, the MPSR-Chlorophyll coating (S1) exhibits an obvious increase in emissivity. Due to its distinct chemical structure, which efficiently interacts with infrared wavelengths, chlorophyll cooperation increases the coating capacity for heat radiation. This characteristic leads to its potential use in solar energy devices as well as other applications needing efficient heat dissipation, where thermal management improves longevity and performance.

MPSR-ZnO Coating (S2):

Figure 4.11 demonstrates the moderate emissivity found in the MPSR-ZnO coating (S2), which achieves an equilibrium between heat retention and thermal radiation. By enhancing radiative cooling while preserving structural and functional stability, ZnO nanoparticles contribute to thermal management. ZnO coatings are suitable for settings

needing moderate heat dissipation without considerable energy loss because of its intermediate emissivity.

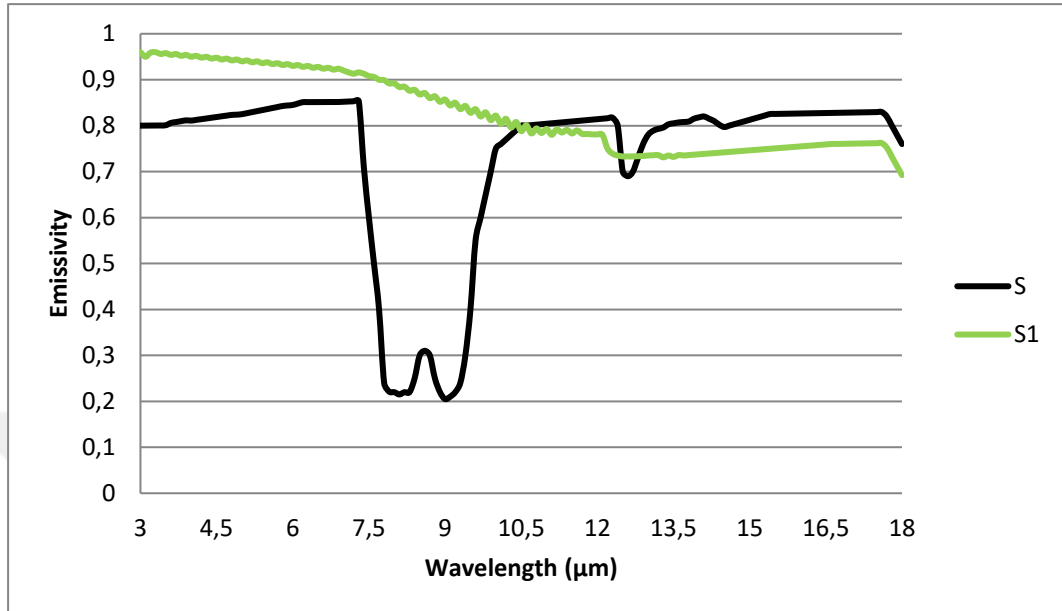


Figure 4.10. FT/IR results of thermal infrared emissivity the uncoated glass substrate (S) and coating with MPSR-chlorophyll (S1).

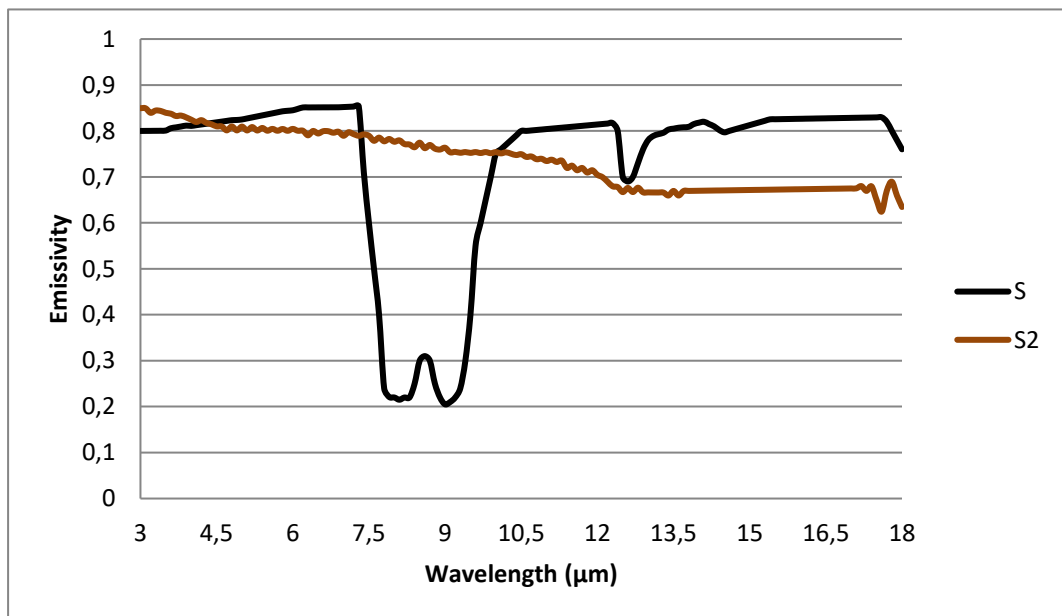


Figure 4.11. FT/IR for thermal infrared emissivity of the (S) uncoated glass substrate and (S2) MPSR-ZnO.

MPSR-SiO₂ Coating (S3):

Figure 4.12 illustrates that the emissivity of the (S3) MPSR-SiO₂ coating is lower compared with (S1) but higher than that of uncoated glass. This suggested that SiO₂ has an advantage on heat dissipation by raising thermal emissivity. SiO₂ is particularly useful for applications that require controlled heat management, such as thermal insulation and solar power systems, due to both its chemical and thermal stability in addition to its interaction with infrared radiation.

Combined Coating (S4):

The MPSR-Chlorophyll-ZnO-SiO₂ (S4) coating a high emissivity compared to uncoating substrate (S) ; Figure 4.13 shows how the three materials perform in concert. ZnO supported radiative cooling, SiO₂ contributed thermal management via its dielectric characteristics, and chlorophyll improved infrared absorption. For solar panels and any other outdoor equipment exposed to high temperatures to operate as efficiently as possible, this comprehensive heat control capability is essential.

The findings align with polymeric photonic systems that embed polar dielectric spheres like silica (SiO₂) in an optical polymer matrix. These systems achieve high emissivity across thermal wavelengths (3–20 μm) due to infrared-active vibration modes. These modes overlap with thermal infrared wavelengths, contributing to efficient heat dissipation.

Notably, bulk SiO₂ exhibits emissivity dips near the polarization resonance wavelength of 9 μm , which can hinder uniform thermal management. However, using SiO₂ microspheres with sizes equivalent to their resonance wavelength minimizes polarization resonance, ensuring consistent emissivity across the atmospheric window. This strategy enhances material performance in thermal applications.

Figure 4.13. visualizes the comparative emissivity spectra, highlighting the distinct thermal behaviors of each coating. The uncoated glass acts as a baseline, while S1 through S4 demonstrates progressively enhanced emissivity, emphasizing the effectiveness of material integration in improving thermal radiation capabilities.

These results underscore the importance of material design and integration in achieving multifunctional coatings that balance optical and thermal properties. Future studies should explore the long-term durability of such coatings under real-world environmental conditions to further enhance their practical applications in renewable energy systems.

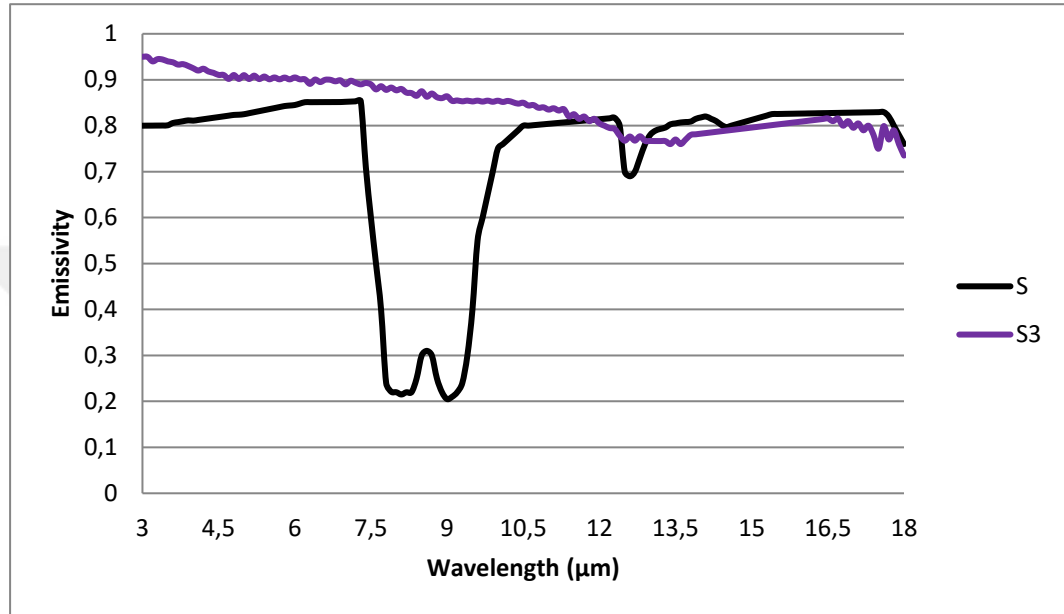


Figure 4.12. FT/IR for thermal infrared emissivity of the uncoated glass substrate (S) and MPSR-SiO₂ (S3).

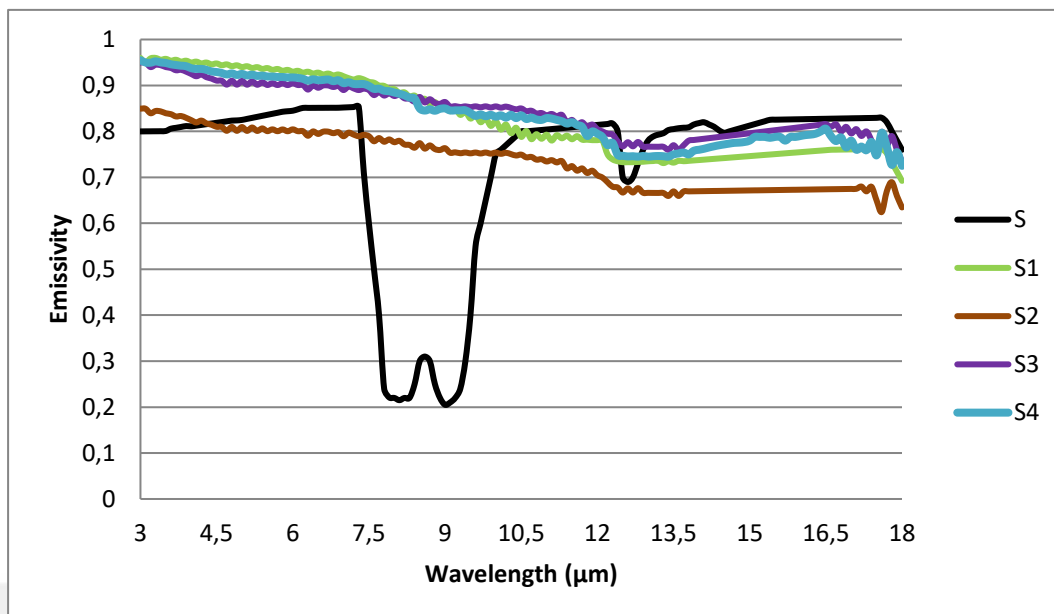


Figure 4.13. FT/IR for thermal infrared emissivity of the uncoated glass substrate (S), coating with MPSR-chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3) and MPSR-chlorophyll-ZnO-SiO₂ (S4).

4.3.5. The Contact Angles Analysis

The study analyzed the wettability of various coatings by measuring the contact angles of a 5 μ L water droplet on their surfaces. Significant variations in wettability were observed across the coatings (S, S1, S2, S3, and S4).

The uncoated glass exhibited a low contact angle of approximately 30° as seen in Figure 4.14, categorizing it as a highly hydrophilic surface. This characteristic promotes water spreading, allowing the water droplet to disperse easily across the surface:

MPSR-Chlorophyll Coating (S1):

The addition of chlorophyll into the MPSR matrix resulted in a moderate contact angle of about 98° as illustrated in Figure 4.15, indicating a decrease in water affinity compared to the uncoated glass. This suggests an improvement in hydrophobicity while retaining moderate wettability.

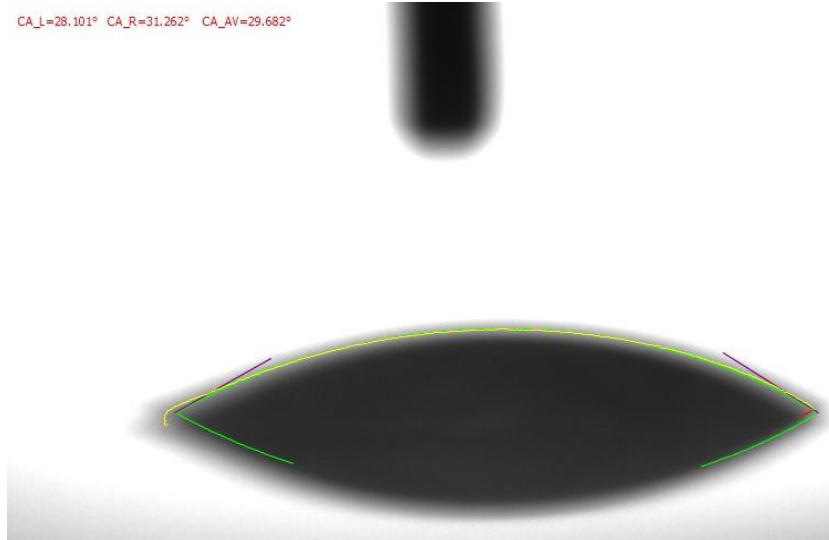


Figure 4.14. Contact angle measurement of the uncoated glass substrate (S).

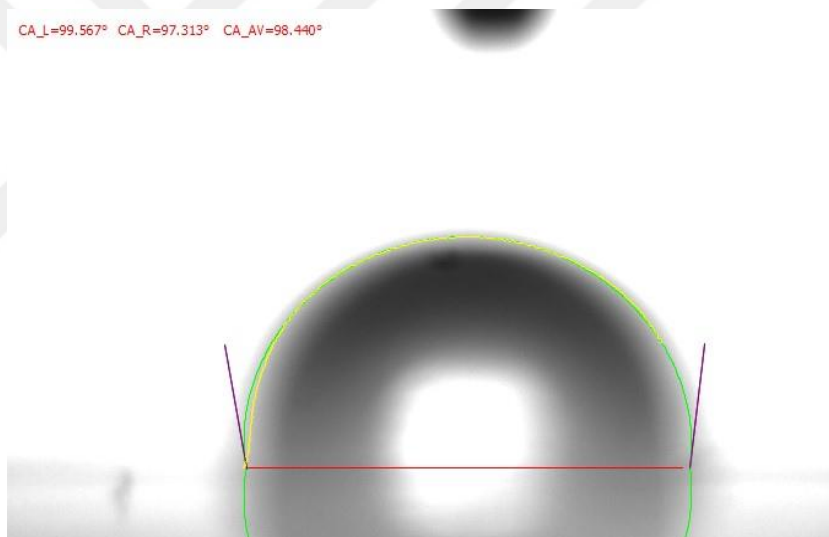


Figure 4.15. Contact angle measurement of the MPSR-chlorophyll (S1) coating.

MPSR-ZnO Coating (S2):

Coated with ZnO nanoparticles, the surface achieved a contact angle of around 136° as seen in Figure 4.16. This increased hydrophobicity is likely due to ZnO unique surface chemistry, which reduces surface energy and enhances water repellency.

CA_L=136.951° CA_R=135.675° CA_AV=136.313°

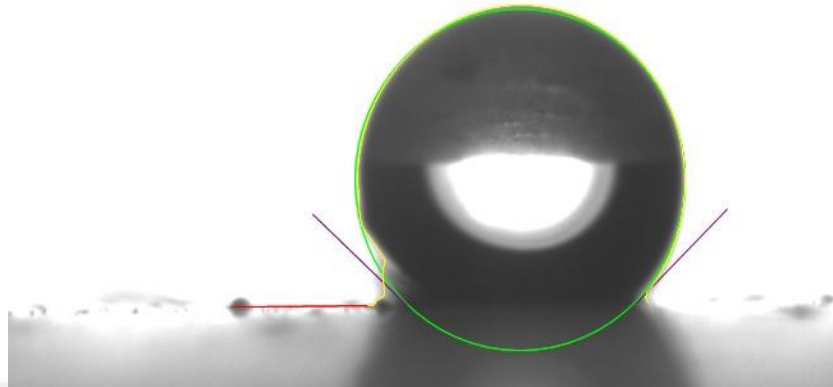


Figure 4.16. Contact angle measurement of the MPSR-ZnO (S2), coating.

MPSR-SiO₂ Coating (S3):

The incorporation of SiO₂ nanoparticles led to a highly hydrophobic surface with a contact angle of approximately 159° as shown in Figure 4.17. This significant water repellency may be attributed to the micro- or nanostructured features of the coating, which effectively trap air and create a "lotus effect," thereby minimizing wettability.

MPSR-Chlorophyll-ZnO- SiO₂ Coating (S4):

In Figure 4.18 combined coating displayed a contact angle of about 153°, showcasing very high hydrophobicity but slightly less than that of the S3 coating. The synergistic integration of chlorophyll, ZnO, and SiO₂ contributes to its excellent water-repelling characteristics

CA_L=158.919° CA_R=158.919° CA_AV=158.919°

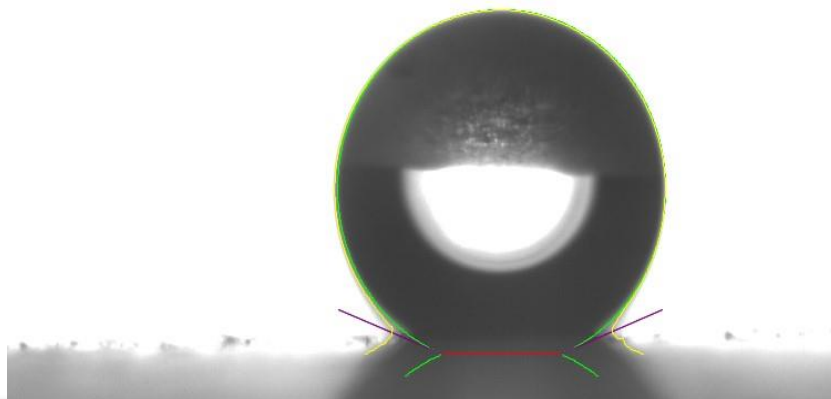


Figure 4.17. Contact angle measurement of the MPSR- SiO₂ (S3), coating.

CA_L=153.637° CA_R=153.637° CA_AV=153.637°

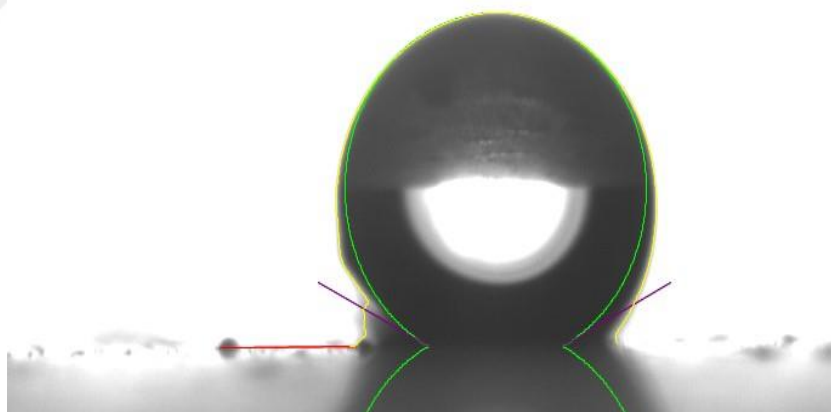


Figure 4.18. Contact angle measurement of the MPSR-ZnO- SiO₂ (S4), coating.

In summary, the contact angles of a 5 μ L water droplet deposited on various coating surfaces (S, S1, S2, S3, and S4) demonstrate notable differences in wettability, as shown in Figure 4.14. The uncoated glass (S) exhibits a low contact angle of approximately 30°, indicating a highly hydrophilic surface that facilitates water spreading. In contrast, the MPSR-chlorophyll-ZnO-SiO₂ coating (S4) achieves a

contact angle of about 153° , signifying a very high level of hydrophobicity, though slightly less than that of S3.

The observed differences in wettability are influenced by modifications in surface chemistry and morphology. Hydrophobic materials like ZnO and SiO₂ incorporated into the coatings reduce surface energy, thereby decreasing wettability. Additionally, the micro- and nanostructures present in the coatings play a crucial role by trapping air, resulting in a lotus effect that further enhances hydrophobic behavior. These combined effects underscore the advanced properties of the coatings, making them effective for applications requiring self-cleaning and water-repellent surfaces.

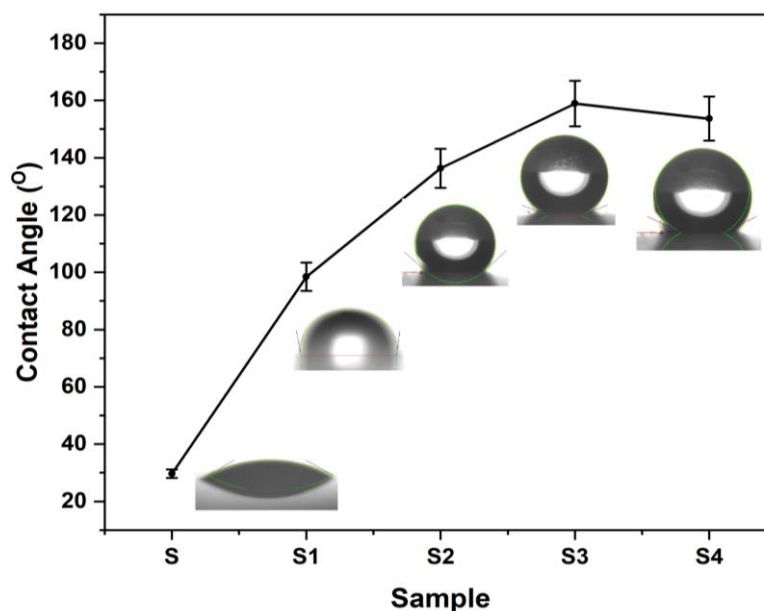


Figure 4.19. Contact angle of nanoparticle coatings. the insets show a 5 μL water droplet deposited on the coating surface of S, S1, S2, S3, and S4.

4.4. DISCUSSIONS LABORATORY RESULT

This study investigates multifunctional nanocomposite coating for solar panels by integrating zinc oxide (ZnO), silicon dioxide (SiO₂), and chlorophyll to improve light transmittance, UV protection, thermal management, and self-cleaning capabilities. Table 4.2. summarizes the laboratory results of hydrophobicity, optical, and thermal properties for various coatings applied to glass substrates.

Table 4.2. Characteristics of the samples with different coating.

Sample	Contact Angle(°)	Transmittance T _{Max} . %	IR-Emissivity ε _{Ave} .	UV-Protection A _{max} (a.u)
S	29.7	91.51	73.42	2.968
S1	98.4	86.47	82.92	4.362
S2	136.3	96.38	73.72	3.651
S3	158.9	92.60	84.45	3.247
S4	153.6	93.48	83.79	4.001

Table 4.2. included the max transmittance spectra for an uncoated glass substrate (S) and four distinct coatings: MPSR-Chlorophyll (S1), MPSR-ZnO (S2), MPSR-SiO₂ (S3), and MPSR-Chlorophyll-ZnO-SiO₂ (S4). The uncoated glass achieves the highest transmittance of 91.51%, signifying efficient visible light transmission without interference [124].

In comparison, the MPSR-Chlorophyll coating (S1) exhibits a reduced transmittance of 86.47%, primarily due to chlorophyll's strong light-absorbing properties [125]. While this absorption enhances light utilization for specific wavelengths, it may limit its overall effectiveness in photovoltaic applications by reducing visible light transmission. On the other hand, the MPSR-ZnO coating (S2) records the highest transmittance at 96.38%, indicating that ZnO nanoparticles facilitate visible light passage while simultaneously providing UV protection, making them particularly beneficial for solar applications [126].

The MPSR-SiO₂ coating (S3) has minimal effect on visible light transmission through it maintains a high transmittance around 92.6%, which is close to that of uncoated glass. In the meanwhile, the combined (S4) MPSR-Chlorophyll-ZnO-SiO₂ coating successfully integrated the advantages of light trapping and transmission, reaching a balanced transmittance of 93.48%. [127].

These findings show how composite materials have distinct effects on light transmission. With its optimal composition, the S4 coating offered great promise for

advancing solar power technology by improving photovoltaic performance as well as light management.

The UV-Vis absorbance spectra obtained from different coatings applied on glass substrates (S1) MPSR-Chlorophyll, (S2) MPSR-ZnO, (S3) MPSR-SiO₂, and a mixture of all three materials (S4) sample offer significant details about the absorption properties of the (S) uncoated glass in comparison to those of the fourth coated samples. With minimal absorption across the UV spectrum, the (S) uncoated glass indicated the lowest amount of interaction with UV light.

On the opposite, a noticeable remarkable absorbance peak is shown in the (S1) MPSR-Chlorophyll coating, indicating that chlorophyll efficiently absorbs UV light [103]. Because of this characteristic, it can be used in cases where UV protection is required, which includes protecting underlying materials from UV-induced damage. The absorbance of the (S2) MPSR-ZnO coating gives a demonstration of the ZnO nanoparticle's capacity to absorb UV radiation [128], but not as much as chlorophyll. By contrast, the MPSR-SiO₂ coating (S3) exhibited low absorption, close to that of untreated glass, emphasizing its function as an efficient UV barrier with minimal UV light interaction.

The combined sample S4 (MPSR-Chlorophyll-ZnO-SiO₂) coating exhibited the highest absorbance, demonstrating a synergistic effect. The integration of Nanoparticles ZnO and SiO₂ with chlorophyll improved the overall UV absorption property. This illustrates how effectively of multi-component coatings work to absorb harmful UV radiation while employing the unique properties for each material.

These findings imply that ZnO significantly enhances protective properties and improves the overall performance of the Nanocomposite coatings, even though chlorophyll is essential to UV absorption. The combined effect of these materials, in sample S4, has the potential for improving solar panel robustness and effectiveness. The specific interactions between these compounds and their combined effect on solar technology, especially for practical applications, should be the subject of future study.

The development of transparent UV-shielding clear coatings involves considerations that parallel those of transparent photocatalytic coatings. However, UV-protective clear coatings typically require greater thickness compared to their photocatalytic counterparts, which intensifies concerns regarding scattering and absorption.

Since UV-protective coatings are generally designed to be colorless, light absorption by inorganic semiconducting nanoparticles and organic additives within the visible spectrum must be minimized [129,130] such as ZnO are known for their photoactivity and UV absorption due to their electronic structures, featuring a filled valence band and an empty conduction band [131].

Conversely, SiO₂ acts as dielectric material, offering a contrasting role [132]. While high photoactivity can sometimes have autocatalytic behavior that generates undesirable byproducts and can degrade the host material, ZnO nanoparticles exhibit lower photocatalytic efficiency than SiO₂. Nonetheless, ZnO nanoparticles are luminescent, emitting visible light when exposed to UV radiation, making them particularly advantageous for UV-protective applications [133].

Numerous studies emphasize the benefits of applying anti(AR) layers, particularly those composed of porous or nanostructured SiO₂, to solar cover glass. These AR layers significantly enhance light transmission by reducing reflection losses at the air-glass interface by approximately 4% [134,135]. Luo et al. introduced an innovative method for fabricating AR coat spheres and analyzed their impact on photovoltaic (PV) efficiency in perovskite solar cells [136].

The optimized SiO₂ Nano sphere-based AR coating resulted in a notable efficiency improvement, increasing from 14.81% to 15.82%. This enhancement was attributed to an average transmittance gain of about 3.8% across the 300–800 nm wavelength range.

These findings highlight the importance of material selection and structural design in UV-protective and AR coatings. By leveraging materials like ZnO for their UV absorption and luminescence, and SiO₂ for its anti-reflective and dielectric properties,

researchers can develop multifunctional coatings that improve solar device performance while maintaining transparency and durability [137].

Table 4.2 displays results of the FT/IR spectra. show the characteristics for the four coatings (S1, S2, S3, and the combined coating, S4) in addition to the uncoated glass substrate (S) regard to infrared thermal emissivity. As is common for transparent materials designed mainly for light transmission rather than heat management, the uncoated glass substrate has the lowest emissivity, emphasizing its limited ability to emit thermal radiation. With peaks at wavelengths, the MPSR-Chlorophyll coating (S1) exhibits a noticeable increase in emissivity. This results suggesting that chlorophyll greatly improves thermal emissivity, most likely as a result of its molecular makeup and capacity to both absorb and re-emit infrared light. In applications such as solar panels, where effective thermal management can improve performance, such qualities are beneficial for heat regulation.

The MPSR-ZnO coating (S2) gives a demonstration of moderate emissivity, and propose that ZnO nanoparticles slightly contribute to thermal radiation emission, although not as effectively as chlorophyll. This moderate thermal emissivity makes ZnO nanoparticles suitable for applications needing balanced UV protection and heat dissipation.

The MPSR-SiO₂ coating (S3) emphasizes the function of SiO₂ in improving thermal emissivity by showing a higher emissivity than the uncoated glass (S) but a lower emissivity than the chlorophyll coating (S1). SiO₂ operates well in heat dissipation applications such as radiative cooling systems due to its polar dielectric characteristics and ability to sustain infrared-active vibrations.

The sample with the highest emissivity was the MPSR-Chlorophyll-ZnO-SiO₂ coating (S4). This finding indicates a synergistic effect in which the combined influences of ZnO, SiO₂, and chlorophyll enhance the total capacity to emit heat radiation. This combination operates very well for managing heat, which is necessary for optimizing the longevity and efficiency of solar panels as well as other heat-sensitive equipment.

Using polar dielectric spheres such as silica (SiO_2) dispersed within the optical polymer matrix, polymeric photonic systems can achieve high emissivity throughout the thermal wavelength range of 3–20 μm [138]. This high emissivity is attributed to the abundance of infrared-active vibration modes present in the system. These modes include intrinsic absorption bands of functional groups like Si-O (1100 cm^{-1}), C-H (1380 cm^{-1}), and C=O ($2000\text{--}1500\text{ cm}^{-1}$), which overlap with thermal infrared wavelengths [139].

The dispersion of nanoparticles within the polymer matrix further enhances infrared absorption through multiple scattering effects, boosting overall emissivity. Bulk SiO_2 often exhibits strong dips in emissivity near the polarization resonance wavelength of 9 μm due to prominent extinction coefficient peaks. However, using SiO_2 microspheres with dimensions matching their infrared polarization resonance wavelength (approximately 9 μm) allows for broadband emissivity across the entire atmospheric window. This method, as demonstrated by Yang et al., effectively minimizes polarization resonance and associated reflectance, resulting in a more uniform emissivity profile [138].

In glass coverslips, emissivity dips are often attributed to phonon-polarization resonances, which occur when optical phonons interact with electromagnetic radiation. These resonances create impedance mismatches between SiO_2 and air, leading to increased reflectivity and reduced thermal emission at specific wavelengths. By optimizing material composition and surface structuring, these effects can be mitigated, ensuring consistent thermal emissivity and improved heat management across diverse applications [55].

The contact angles of a 5 μL water droplet placed on the surfaces of various coatings (S, S1, S2, S3, S4) reveal notable differences in wettability, as illustrated in Table 4.2. The uncoated glass substrate (S) demonstrated a small contact angle of about 30° , meaning a highly hydrophilic surface. On the contrary, the MPSR-chlorophyll coating (S1) illustrated a moderate contact angle of approximately 90° , demonstrating a lowered affinity for water. The MPSR-ZnO coating (S2) exhibited a contact angle of

around 120°, reflecting increased hydrophobicity property, likely referred to its distinctive surface chemistry.

The MPSR-SiO₂ coating (S3) achieved a significantly higher contact angle of nearly 160°, signifying exceptional of water repellency resulting in superhydrophobic coating. That is potentially improved by the presence of nanostructures that trap air and create a barrier effect. The combined MPSR-chlorophyll-ZnO-SiO₂ coating (S4) exhibited a contact angle of around 150°, indicating exceedingly high hydrophobicity, although slightly lower than S3.

Differences in surface chemistry and its morphology are responsible for such wettability distinction. When contained in coatings, hydrophobic materials like SiO₂ and ZnO change the surface energy, meaning lower wettability. Furthermore, the coating's physical properties, such as their nanoscale structures, may hold air pockets, creating a lotus effect which greatly increases hydrophobicity. Applications require self-cleaning surfaces and moisture resistance can find this feature especially useful.

These coatings that increased hydrophobicity introduced a lot of promises for applications including self-cleaning surfaces, greater moisture resistance, and anti-fogging. For example, Ogihara et al. applied alcohol solutions consisting of SiO₂ nanoparticles on the paper to fabricate transparent superhydrophobic coatings. The type of alcohol employed in the suspension impacted the aggregation state of the nanoparticles, which in response affected the superhydrophobic capabilities of these coatings, underscoring the importance of material composition in achieving desired attributes [140].

Jesus et al. executed a comparative analysis of functionalized SiO₂ hydrophilic coatings and hydrophobic TiO₂/SiO₂-based films in the different countries in Italy, Spain, and Brazil under different environmental circumstances. The findings indicated that TiO₂/SiO₂ films generally performed better, exhibiting the lowest transmittance losses and superior anti-soiling capabilities. This highlights the utility of hydrophilic films in maintaining surface cleanliness over time [141].

Jang et al. investigated the dirt-repellent performance of highly reflective superhydrophilic coated mirrors compared to superhydrophobic mirrors fabricated using surface-modified SiO₂ nanoparticles. Their results revealed that while the adhesion forces of simulated dust particles were comparable for both coatings, outdoor field tests demonstrated that superhydrophilic coatings were 2.5 times more effective than superhydrophobic coatings in reducing organic dirt and moisture-induced contamination. This superior performance is attributed to the enhanced ability of superhydrophilic coatings to reduce dirt and prevent dust accumulation, particularly in environments with high moisture content [142].

Barshilia et al. demonstrated the potential stable photothermal absorber coatings deposited on stainless substrates using magnetron sputtering. These coatings combined antireflection and superhydrophobic properties with a Nano metric multiscale rough ZnO coating applied to glass substrates. The ZnO coatings exhibited remarkable transparency, with a water contact angle exceeding 155°, indicating significant hydrophobicity. Furthermore, these ZnO-based spectral-selective coatings demonstrated very low thermal emission (0.18) and exceptionally high solar absorption (0.972), making them ideal for solar energy applications [143].

These studies underscore the versatility of hydrophilic and hydrophobic coatings and their critical role in diverse applications, from maintaining optical clarity in mirrors to ensuring clean and efficient surfaces in challenging environmental conditions.

4.5. OVERVIEW AND FINAL THOUGHTS

The multifunctional nanocomposite coatings demonstrated distinct advantages in enhancing solar panel performance through improved light transmission, UV protection, thermal management, and self-cleaning properties.

- S1 (MPSR- Chlorophyll): offers strong light-absorbing properties enhance light utilization for specific wavelengths, it also improves UV absorption, effectively protecting underlying materials from UV degradation.

- S2 (MPSR-ZnO): Excels in optical clarity and UV protection, making it ideal for high-transmittance applications.
- S3 (MPSR-SiO₂): Provides exceptional superhydrophobicity and thermal emissivity, suitable for dust-prone and high-temperature environments.
- S4 (Combined Coating): Offers a well-rounded solution, combining high transmittance, UV absorption, and self-cleaning capabilities, essential for versatile solar technologies.

4.6. EFFICIENCY TESTING OF COATED SOLAR CELLS

4.6.1. Preparation Samples

In this stage two samples mini-Solar panel 45*45mm 5V 50mA maximum output power is 0.250W in figure 4.20. used to test the coating effect on solar cell efficiency in the library. One of them coating and another stay without coating for comparison. After cleaning the surface of solar panel in acetone, ethanol and deionized water respectively. The coating solutions of MPSR-Chlorophyll-ZnO-SiO₂ (S4) was sprayed on the surface of mini panel by a K-3 spray nozzle at a spray pressure of 4.5 MPa as shown in figure 4.21.

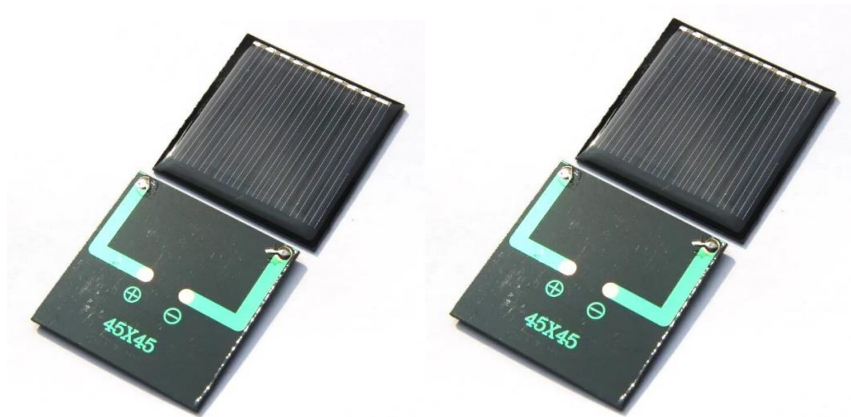


Figure 4.20. Mini solar panel 45*45mm 5V 50mA.



Figure 4.21. Process of coating mini solar panel by spray method.

4.6.2. Measurement Power Output and Efficiency

Measuring the output and efficiency of solar panel is a critical process in evaluating their performance under varying conditions. Typically, the output has been determined by measuring the electrical power generated by the cells under a particular level of solar irradiation. In this method, the solar cells are connected to a circuit, and a multimeter or any comparable instrument is employed for measuring the voltage and current generated. On the other hand, efficiency can be calculated as a percentage via comparing the cells electrical power output to the input power from the incident sunlight [144].

A solar simulator, which introduces a constant light source at a standard intensity of 1000 W/m^2 with an ambient temperature of 25°C , is frequently employed in controlled laboratory settings for ensuring precise measurements. These conditions are known as Standard Test Conditions (STC).

Moreover, real-world efficiency analysis in direct sunlight is done with take into consideration environmental parameters that may influence performance, such as temperature, shading, and dust deposition [145]. The efficiency of a PV cell is the ratio

of energy output obtained from the PV cell divided by the energy input provided by the sun as represented in Equation (4.1) [146].

$$\eta = P_{\text{out}}/P_{\text{in}} \quad (4.1)$$

$$P_{\text{out}} = V \cdot I \quad (4.2)$$

$$P_{\text{in}} = G_T \cdot A_C \quad (4.3)$$

The power output “P” of a PV installation is given as the product of the PV panels’ real collector area “ A_C ”, the solar irradiance “ G_T ” at the panels’ surface and the efficiency “ η ” of the PV generator .

In this laboratory test, the following equipment was utilized:

- Power DC supply in Figure 4.22. using to control light source.



Figure 4.22. Power DC supply.

- Light source can control its density light by power DC supply as shown in Figure 4.23.



Figure 4.23. Light source.

- Irradiance Meter (W/m^2) Figure 4.24



Figure 4.24. Irradiance meter.

4.6.3. Library Result

For testing selected coating (S4) on the efficiency of solar panel in the library, the experimental setup in three cases, first and second cases done in the lab and all equipment connecting as illustrated in Figure 4.25. The voltage and current settings were adjusted to achieve specific irradiance levels on the mini solar panel surface. The irradiance levels in three case detailed in Table 4.3.



Figure 4.25. Setup equipment in the lab.

In first case, the DC power supply was set to a voltage of 17V and a current of 3.8A, producing an irradiance density of 300 W/m^2 on the surface of the mini solar panel. In this scenario, the power output from the coated and uncoated panels was measured at 0.033W and 0.032W, respectively. The nanocomposite coating S4 enhanced the mini solar panel's efficiency by 2.59 %, demonstrating the coating's potential to improve light absorption and energy conversion under low irradiance conditions.

For second case, higher irradiance conditions, the DC power supply was adjusted to 22V and 4.6A, achieving an irradiance density of 600 W/m^2 . In this case, the power

output from the coated panel was 0.047W, compared to 0.045W for the uncoated panel. This translated to a 2.7% increase in efficiency for the coated solar panel. Additionally, the operational surface temperatures of both panels were measured using a T640 Infrared Thermal Imaging Camera. The coated panel recorded a surface temperature of 37.3°C, whereas the uncoated panel registered 38.4°C as shown in figure 4.26. under the same operating conditions. This temperature reduction for the coated panel highlights the coating's radiative cooling properties, which contribute to enhanced efficiency.



Figure 4.26. Measuring operation temperature surface of mini solar panel for (a) uncoating (b) coating panel.

Third case involved exposing the mini solar panels directly to sunlight under real-world conditions. The experiment was conducted on 17/01/2024 at 12:41 PM in the Babylon University campus, Iraq, on this day the maximum irradiance was 1300 W/m² as seen in Figure 4.27. All equipment was set up as shown in Figure 4.28 The results indicated a significant improvement in efficiency, with the coated panel showing a 4.9% increase compared to the uncoated panel. This notable enhancement under high irradiance conditions further emphasizes the effectiveness of the nanocomposite coating S4 in improving solar panel performance.

Table 4.3. Cases study of labrary tests.

Case No.	Energy Source	Irradiance Meter reader
<u>First case</u> $I=3.8A$ $V=17V$ $G_T=300W/m^2$	 DC Power reader	
<u>Second case</u> $I=4.6A$ $V=22V$ $G_T=600W/m^2$	 DC Power reader	
<u>Third case</u> $G_T=1100W/m^2$ Place/Iraq- Babylon university	Direct sun light At 12:41PM On 17/01/2024	

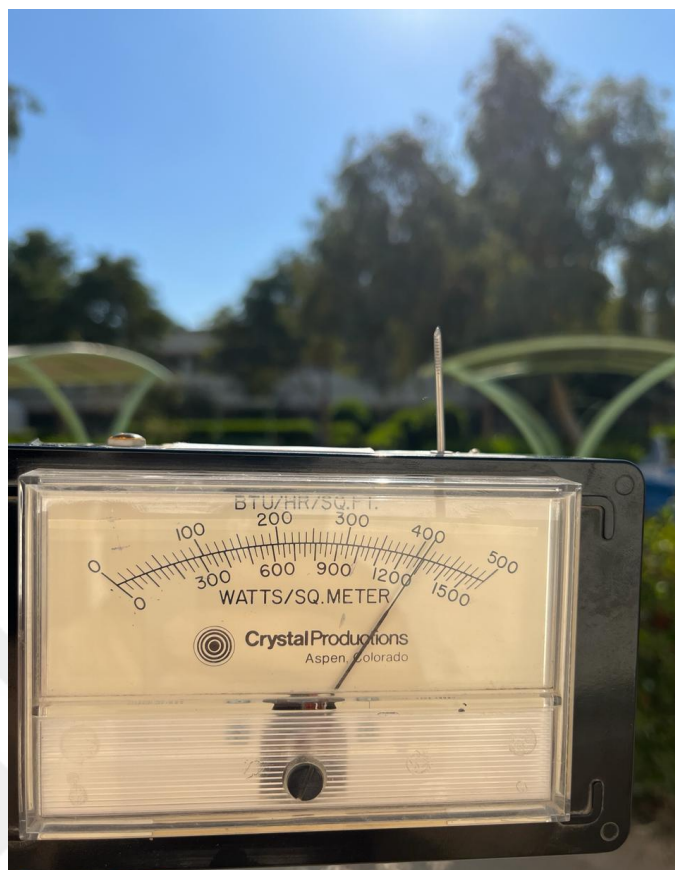


Figure 4.27. Maximum irradiance in Iraq-Babylon University on 17/01/2024.

The calculation of power output and efficiency with different density lights and its source is demonstrated in Table 4.4. These findings collectively highlight the multifunctional benefits of the nanocomposite coating, including increased efficiency, better thermal management, and superior performance under both controlled and real-world conditions.

Table 4.4. Calculation efficiency of coating and uncoating mini solar penal.

Place Test Source Light	Irradiance G W/SQ.Meter	Type of solar cell	Voltage V(volt)	Current I(Amp)	Power P(W)	Efficiency =(P/Ac)/G	Improv. %
Lab. lump	300	coating	3.20	0.0102	0.033	0.0537	2.59
		uncoating	3.15	0.0101	0.032	0.0524	
Lab. lump	600	coating	3.53	0.0134	0.047	0.0389	3.87
		uncoating	3.45	0.0132	0.046	0.0375	
real condition Sun	1100	coating	4.53	0.0352	0.159	0.0716	4.91
		uncoating	4.51	0.0337	0.152	0.0682	



Figure 4.28. DC voltage measurement of uncoating mini solar panel.

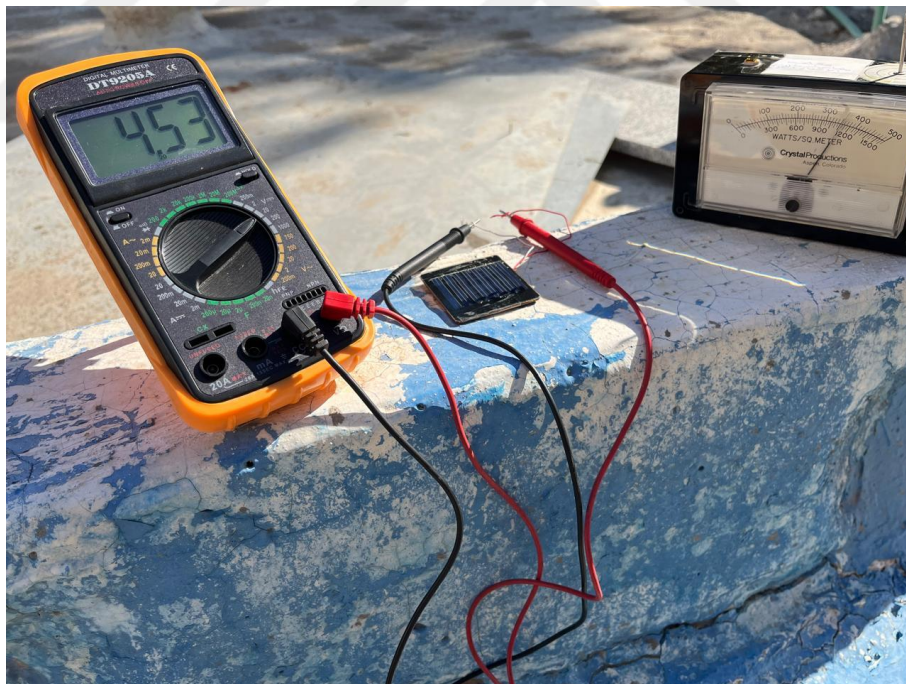


Figure 4.29. DC voltage measurement of coating mini solar panel.

PART 5

FIELD TESTING

This section focuses on the experimental evaluation of the multifunctional nanocomposite coating S4 (composed of MPSR, 0.06g ZnO, 2g SiO₂, and 6g chlorophyll) under real-world conditions by applying it to the glass surfaces of streetlamp solar panels. The primary objective of this section is to assess the coating's performance in actual environmental conditions, particularly its impact on solar panel power output at varying ambient temperatures and its ability to resist dust accumulation.

5.1. PREPARING SAMPLES FOR TESTING

Before the application of the coating, the glass surfaces of the streetlamp were meticulously cleaned using acetone and deionized water to ensure a contaminant-free surface, as cleanliness is critical for optimal coating adhesion and performance. The coating solution was then uniformly applied to the lamp glass using a K-3 spray nozzle operating at a high spray pressure of 4.5 MPa, ensuring an even and consistent layer of the nanocomposite coating. The process of coating is shown in Figure 5.1.

This experiment aims to simulate real-world circumstances and evaluate the coating's numerous advantages, like its ability for self-cleaning as well as self-cooling. The test offers significant insights into the environmental resilience, longevity, and general effectiveness of the S4 coating for solar panel applications, especially in requiring hard outdoor environments, by monitoring dust accumulation and investigating the effect of ambient temperature variations during summer and winter season.



Figure 5.1. Application method for coating on street lamp solar panels.

5.2. COLLECTING DATA

In order to offer a control for comparison in the research, the first streetlamp solar panel was coated and the second was left uncoating for comparative analysis. A thermometer sensor was securely attached to the rear surface of each solar panel to monitor and record temperature variations on the rear surface, as illustrated in the accompanying Figure 5.2. The streetlamps were then installed in Hillah city/Iraq, to evaluate their performance under real-world environmental conditions. The study evaluated parameters such as power generation, surface temperature, and self-cleaning efficacy under outdoor conditions.

5.2.1. Summer Season Results

Data collected over the period from May 31 to June 7, 2024, revealed notable variations in performance, emphasizing the impact of applying multifunctional nanocomposite coatings.

During this duration the temperature was reported in Figure 5.3.

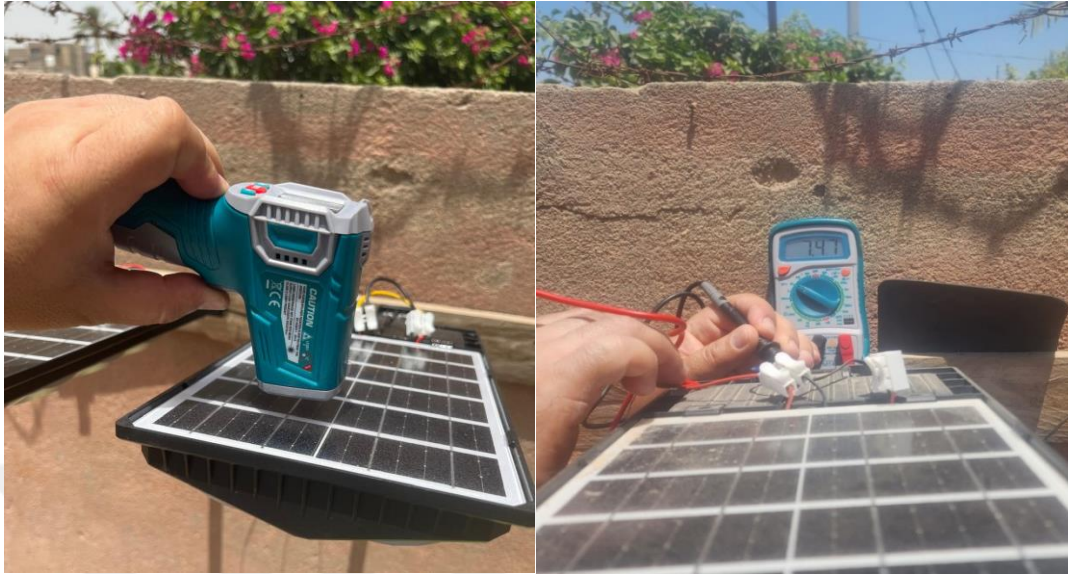


Figure 5.2. Collect data of power production and surface temperature.

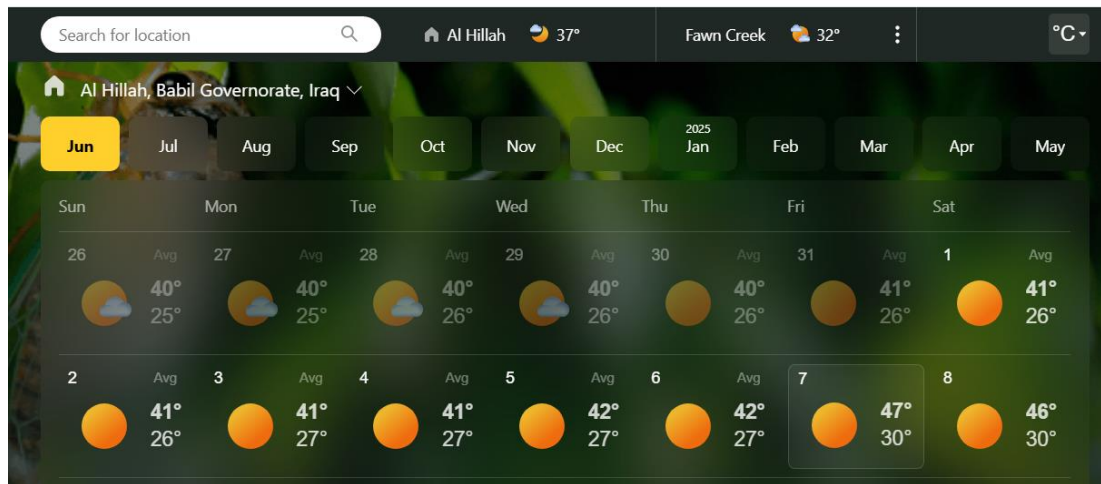


Figure 5.3. Temperature report in Iraq/Al Hillah city between 31-May and 7-Jun.

The surface temperature of solar panels is significantly affected by ambient temperature and incident solar radiation. As these environmental factors increase, the panel surface temperature also rises. Initially, this temperature rise leads to an increase in the panel's power output, which peaks at an optimal temperature. Beyond this point, further temperature elevation causes a decline in power generation. This decrease is

attributed to the diminished mobility of charge carriers, such as electrons, within the solar cells at elevated temperatures.

The reduced charge carrier mobility hinders their efficient movement, thereby lowering the overall power output of the solar photovoltaic (PV) panel. As highlighted in Table 5.1, the coated solar panels consistently demonstrate superior maximum power output compared to uncoated panels across various time intervals and ambient temperature conditions, underscoring the benefits of the coating in enhancing performance under real-world conditions.

Table 5.1. Comparison of maximum power production for coating and uncoating solar panels in summer season.

Time/ date	Ambient Temp. (C)	Type of solar panel	Voltage V (volt)	Current I (Amp.)	Power P _{Max} - (Watt)	Improvement %
10:00/ 31-5-2024	39	coating	7.81	0.78	6.09	11.41
		uncoating	7.71	0.70	5.40	
12:00/ 31-5-2024	41	coating	7.20	0.76	5.47	17.78
		uncoating	7.03	0.64	4.50	
2:00/ 31-5-2024	40	coating	7.65	0.78	5.97	18.30
		uncoating	7.50	0.65	4.88	
4:00/ 31-5-2024	39	coating	7.66	0.44	3.37	22.12
		uncoating	7.50	0.35	2.63	
3:00/ 04-6-2024	45	coating	7.51	0.74	5.56	21.44
		uncoating	7.40	0.59	4.37	
11:00/ 07-6-2024	43	coating	7.66	0.89	6.82	14.53
		uncoating	7.47	0.78	5.83	
10:00/ 08-6-2024	42	coating	7.62	0.86	6.55	16.27
		uncoating	7.22	0.76	5.49	
12:00/ 08-6-2024	45	coating	7.44	0.85	6.32	17.74
		uncoating	7.03	0.74	5.20	

At 10:00 AM on May 31, the coated solar panel achieved a power output of 6.09 Watts, representing an 11.41% improvement compared to the uncoated panel, which produced 5.40 Watts. Throughout the observation period, this pattern of high

performance remained, with the maximum improvement recorded around 4:00 PM on the same day.

The coated panel generated 3.37 Watts at that time, an impressive 22.12% increase compared to the uncoated panel. The information also illustrated the coated panel consistent benefit in a range of environmental circumstances. On June 4, for instance, when the ambient temperature was recorded at 45°C, the coated panel remained operated at high level, generating 5.56 Watts, 21.44% more than of uncoated panel.

The improved efficiency in the coated solar panels can be attributed to the incorporation of the nanoparticles zinc oxide (ZnO) and silicon dioxide (SiO₂) within the nanocomposite coating. The nanoparticles ZnO are renowned for its exceptional light-scattering abilities and their property in improving electron transport, which increases light absorption and enhances the efficiency of solar cells [147]. Furthermore, SiO₂ nanoparticles play a crucial role in surface passivation, effectively minimizing charge carrier recombination in the surface of solar cells, thereby improving overall efficiency [148].

Additionally, the anti-reflective property of nanoparticles SiO₂ increases light transmission and decreases energy losses via reflection [149]. The solar panel optical and electrical characteristics enhanced in coated panel under real-world settings indicated how this leads to enhanced power production and excellent of thermal management. These results focus attention on how nanocomposite coatings can greatly enhance solar panel system dependability and efficiency.

Table 5.2. shown the surface temperature recorded for coated and uncoated solar panels, indicating significant advancements in the thermal management performed by the nanocomposite coatings. The coated panel consistently shows lower front surface temperatures compared to the uncoated panels. For example, at 10:00 AM on May 31, the coated panel measured a front surface temperature was 58.4°C, while the uncoated panel recorded a higher temperature of 62.1°C. This trend kept throughout the observation period, with a prominent maximum cooling improvement of 7.26% observed on June 8.

The cooling advantage of the coating was further demonstrated by the rear surface temperatures. The rear surface temperature of the coated panel was measured at 77.6°C on June 8 at noon, which is 11.89% higher than the uncoated panel registered temperature of 80.9°C. Since they optimize energy conversion efficiency and minimize thermal losses, these lowering surface temperatures are significant for enhancing solar panel performance.

This study emphasized how important it is to integrate chlorophyll into the nanocomposite coating to obtain these advantages for thermal management. Due to its natural ability to absorb light, chlorophyll helped disperse excess heat, consequently lowering surface temperatures. This method aids maintaining constant of power production during a range of different operating conditions and the same time reduces thermal stress on the panels.

The coating (S4) provides a perfect alternative for practical solar panel applications by utilizing the combined effects of SiO₂ and ZnO nanoparticles with chlorophyll. The results highlighted the opportunity for these multifunctional coatings to greatly enhance solar panel efficacy, longevity, and efficiency in hot climates. Due to of this, the technology is promising for developing sustainable solar energy systems.

Table 5.2. Temperature surfaces at the front and rear for coating and uncoating solar panels at different times

Time date	Ambient T(°C)	Type of Solar panel	Front surface temp.	Cooling Improve. %	Rear surface temp.	Cooling Improve. %
10:00/ 31-5-2024	39	coating	58.4	5.96	54.3	6.70
		uncoating	62.1		58.2	
12:00/ 31-5-2024	41	coating	61.4	5.39	62.9	6.68
		uncoating	64.9		67.4	
2:00/ 31-5-2024	40	coating	65.6	6.15	67.4	6.91
		uncoating	69.9		72.4	
4:00/ 31-5-2024	39	coating	58.9	6.21	61.4	6.12
		uncoating	62.8		65.4	
3:00/ 04-6-2024	45	coating	71.8	6.02	73.1	6.16
		uncoating	76.4		77.9	
11:00/ 07-6-2024	43	coating	70.0	6.03	72.2	6.11
		uncoating	74.5		76.9	
10:00/ 08-6-2024	42	coating	67.7	7.26	65.8	9.62
		uncoating	73.0		72.8	
12:00/ 08-6-2024	45	coating	77.6	4.08	77.8	11.89
		uncoating	80.9		88.3	

Over a 7-day monitoring period, solar panel coated with a nanocomposite coating that included chlorophyll with ZnO, SiO₂ demonstrated noticeably less dust collection, as seen in Table 5.3. This reduction in dust accumulation indicated the fact that the coating self-cleans, minimizing debris formation. By the end of the same period time, however, the uncoated solar panel showed a noticeable buildup of dust, which might have decreased their effectiveness and energy production. The observed difference highlights how the nanocomposite coating keeps surfaces sustains performance without requiring frequent manual cleaning.

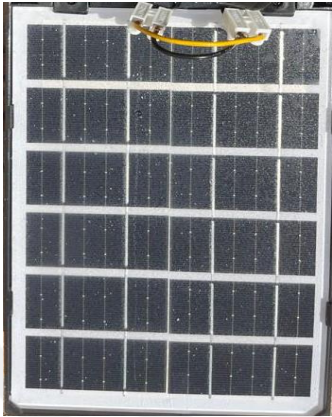
By acting as a protective barrier, the nanocomposite coating reduced the adherence of dust or any other particles. This makes it the perfect way to enhance the robustness and performance of solar panels, especially in harsh environments like deserts where dust particles buildup is a major issue. According to this study, these coating provides

a workable and environmentally friendly means of improving the long-term dependability and effectiveness of solar panel systems that are used in arid and dusty regions.

The nanocomposite coating self-cleaning mechanism depends on two main processes. First, organic filth on the surface is broken down via a photocatalytic reaction that begins by ultraviolet (UV) light. Because it reduces the presence of sticky residues that would normally draw and retain dust particles, this response is crucial. Second, water drops more easily across the surface due to the hydrophobic nature of the coating. This property is particularly useful in areas with limited water available since it makes effective use of water to dissolve and wash away debris during planned cleaning.

By distributing water evenly, the coating ensures thorough cleaning without requiring abrasive or aggressive methods, which could potentially damage the solar panels. This dual-action self-cleaning system not only maintains the optical clarity and efficiency of the panels but also reduces maintenance costs and labor. The integration of ZnO, SiO₂, and chlorophyll in the coating contributes to its effectiveness, making it a promising technological advancement for optimizing solar energy systems in harsh environmental conditions.

Table 5.3. Images of coating solar panels surfaces and uncoating without cleaning for seven days.

Type	Pic.in First day	Pic.in seventh day
coating		
uncoating		

5.2.2. Winter Season Results

In this season, the performance of coated solar panels was studied and compared to uncoated ones in winter as well as studied in various conditions, including sunny, cloudy and dusty weather. These solar panels still work in the same place summer test 30- May/2024 until winter testing on 5 February/2025 as seen in Figure 5.3.



Figure 5.4. Image of solar panels working in wintter season.

Table 5.4 shows the significant potential of nanocomposite coating in improving efficiency of solar panels, at the test results in dusty conditions as seen in Figure 5.5 and Figure 5.6. an improvement in the maximum power output of the coated solar panel reached approximately 58% compared to the uncoated panel, which is attributed to the properties of the coating such as anti-reflection due to the presence of nanomaterials and the ability of chlorophyll to absorb light. On the other hand, energy production was tested in a cloudy environment as shown in Figure 5.7 and Figure 5.8 and the superior potential of the coated panel was shown by an improvement of 50% over the uncoated panel due to the ability of chlorophyll to absorb light.

Table 5.4. Comparison of maximum power production for coating and uncoating solar panel in winter season.

Weather Statues	Time/ date	Type of solar panel	Voltage (volt)	Current (Amp.)	Power P_{Max} - (W)	Improve %
Sunny	12:00	coating	8.74	0.68	5.94	18.40
	05/02/2025	uncoating	7.95	0.61	4.85	
Dusty	12:00	coating	7.3	0.22	1.61	58.07
	06/02/2025	uncoating	4.81	0.14	0.67	
Cloudy	12:00	coating	7.45	0.45	3.35	50.65
	07/02/2025	uncoating	5.17	0.32	1.65	

In this study, the increasing in power production under diffused light (cloudy day) by coating solar panels were related to the anti-reflecting nanocomposite property and reached ~50% . These results are close to the research conducted by Arabatzis et al, (2018) which increase of ΔP_{Max} under cloudy day reached 30% [150].

While, in dusty weather the increasing in power production reached ~58% due the characteristics of nanocomposite coating resulting from integrated chlorophyll with nanoparticles to improve light absorption and self-cooling and self-cleaning properties. These result was identical with study Ahmed et al., (2024) [151].

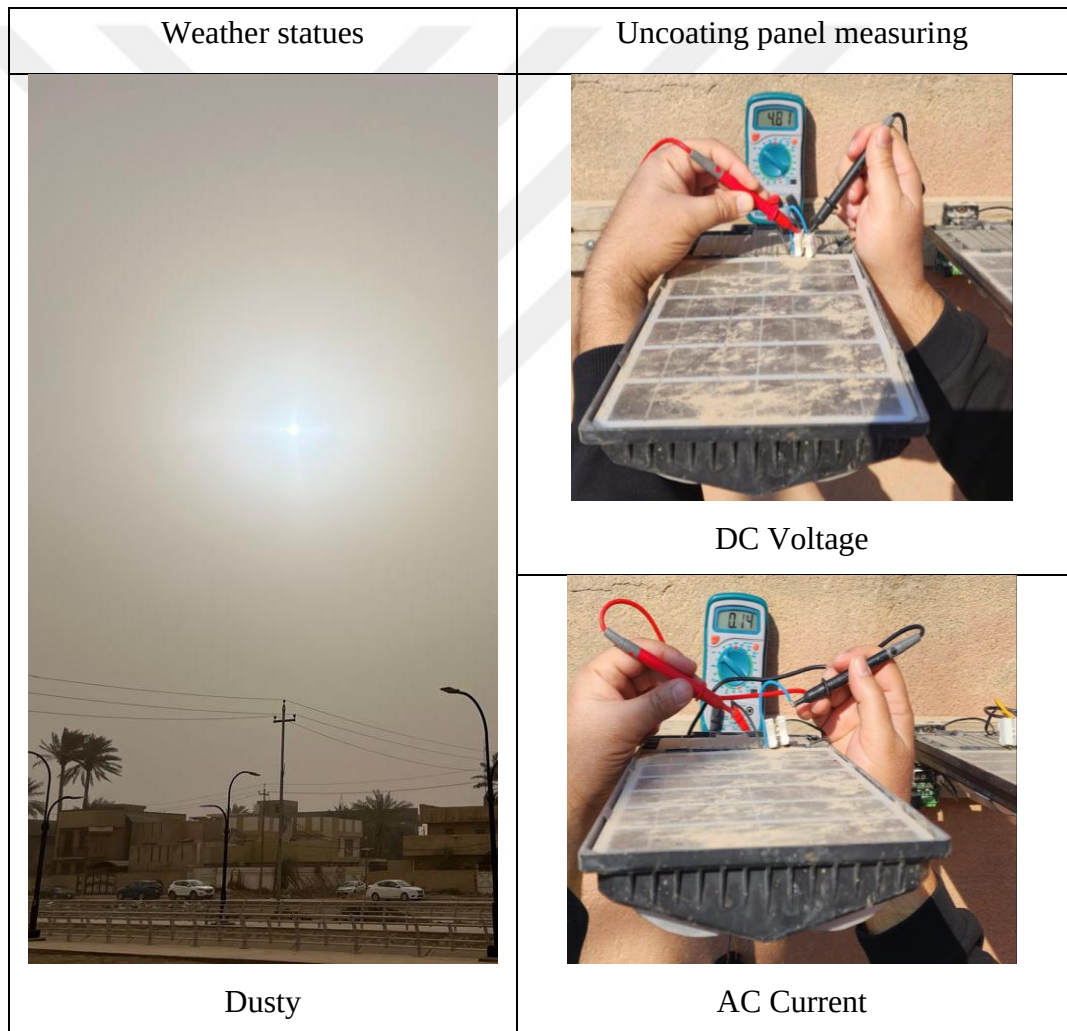


Figure 5.5. Dusty weather measuring maximum power output of uncoating panel.

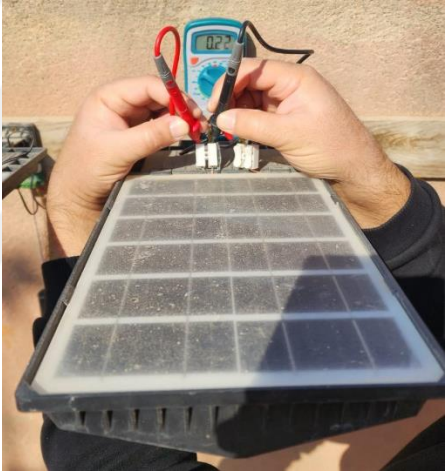
Weather statues	Coating panel measuring
	 DC Voltage
Dusty	 DC Current

Figure 5.6. Dusty weather measuring maximum power output of coating panel.

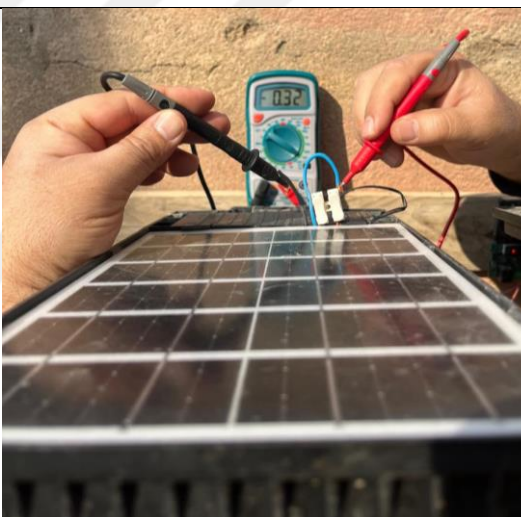
Weather statues	Uncoating panel measuring
 Cloudy	 DC Voltage
	 DC Current

Figure 5.7. Cloudy weather measuring maximum power output of uncoating panel.

Weather statues	Coating panel measuring
 Cloudy	 DC Voltage
	 DC Current

Figure 5.8. Cloudy weather measuring maximum power output of coating panel.

5.3. UNCERTAINTY ANALYSIS

To analyze quantitative uncertainty for the results in the Table 5.5. applied the propagation of uncertainty method for estimating the uncertainty in power measurement across cloudy, sunny, and dusty conditions.

The key element affecting measurement were:

- DC-Voltage and DC-Current Variability

Voltage and current fluctuate depend on sunlight intensity and ambient temperature. Instrumentation errors at measuring voltage (V) and current (I) impact power calculations.

- Environmental cases (Sunny, Cloudy, Dusty)

Sunlight intensity changes in dusty and cloudy weather.

Dust accumulation on panels prevents light absorption and temperature variations effect on solar panel efficiency.

From the Table 5.5.:

DC-Voltage (V) and DC-Current (I) are measured quantities. Power (P_{max}) is calculated using Eq. (5.1)

$$P_{Max} = V * I \quad (5.1)$$

Improvement Percentage is calculated using Eq. (5.2):

$$Improvement (\%) = ((P_{coating} - P_{uncoating})/P_{uncoating}) * 100 \quad (5.2)$$

Assuming measurement uncertainties for the DC-voltage and DC-current are:

$\Delta V = \pm 0.02$ V (precision of the voltage meter).

$\Delta I = \pm 0.01$ A (precision of the current meter).

The uncertainty in . Power (P_{max}) is calculated using uncertainty propagation Eq. (5.3):

$$\Delta P_{Max} = P_{Max} * \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \quad (5.3)$$

Result in Table 5.5 shown the uncertainty of results in sunny weather was lowest (1.22%) due to stable factor measuring voltage and current readings.

While, cloudy weather results increase uncertainty (1.59%) due to variations in sunlight intensity. In dusty weather results have the highest uncertainty (1.75%) due to dust accumulation decreasing voltage and current stability.

In general, the result with a percentage uncertainty less than 10% can be considered reliable. However, the result was acceptant and reliability in this study.

Table 5.5. Uncertainty analyzing

Weather Statuse	Type of Solar Panel	Voltage (V)	Current (Amp.)	Pmax (W)	Power(W) Uncertainty	Relative Uncertainty	Absolute Uncertainty in Power (W)	Percentage Uncertainty (%)
Sunny	Coating	8.74	0.68	5.94	0.00015	0.0149	± 0.88452	1.49
	uncoating	7.95	0.61	4.85	0.00017	0.0166	± 0.080431	1.66
Dusty	Coating	7.30	0.22	1.61	0.00046	0.0455	± 0.073132	4.55
	uncoating	4.81	0.14	0.67	0.00072	0.0715	± 0.048181	7.15
Cloudy	Coating	7.45	0.45	3.35	0.00022	0.0224	± 0.075041	2.24
	uncoating	5.17	0.32	1.65	0.00031	0.0315	± 0.052095	3.15

PART 6

CONCLUSION

6.1. SUMMARY OF FINDINGS

This research has successfully exhibited the fabrication and application of multifunctional nanocomposite coating prepared to enhance the efficiency of solar panels. This coating was created using a simplified one-step spraying process, which combines nanoparticles of silicon dioxide (SiO_2) and zinc oxide (ZnO) with chlorophyll in a matrix of methyl phenyl silicone resin (MPSR). This creative combination offers ideal solution for optimizing photovoltaic (PV) system performance via successfully addressing the problems of dust buildup and heat management in solar panels.

6.2. KEY RESULTS AND INSIGHTS

- **Optical Properties:**
According to testing in the laboratory, the nanocomposite coating has a high transmittance of light (~93%), which allows for efficient use of sunshine. Addition chlorophyll to the coating caused improving UV absorption and shields the underlying components from UV deterioration. ZnO aids by promoting visible light transmission and improving UV protection.
- **Thermal Management:**
The coating illustrated excellent thermal emissivity, significantly acting such a radiant cooler. Real-world applications exhibited a 6% reduction in surface temperatures of solar panel coating compared to uncoated panel, significantly optimizing conversion energy efficiency.

- **Self-Cleaning Capabilities:**

The hydrophobic nature of the coating, with a water contact angle of 153° , facilitates self-cleaning by preventing dust adhesion. Over a seven-day dust accumulation study, the coating-maintained surface cleanliness, reducing maintenance needs.

- **Performance Enhancement:**

Field tests on small solar panels in street lighting applications revealed a 22% improvement in maximum power output. This was attributed to the coating's anti-reflective properties and its ability to optimize light absorption and reflection.

- **Synergistic Integration:**

The combination of ZnO, SiO₂, and chlorophyll demonstrated a balanced approach to improving optical, thermal, and self-cleaning properties. The coating's multifunctional capabilities make it ideal for use in diverse environmental conditions, particularly in dust-prone and high-temperature regions.

6.3. IMPLICATIONS AND CONTRIBUTIONS

The results underscore the potential of multifunctional nanocomposite coatings to address key limitations of traditional solar panels. By reducing energy losses caused by dust accumulation and high operating temperatures, the coating promotes improved efficiency and durability. Additionally, the simple and cost-effective fabrication process makes this technology scalable for industrial applications, aligning with the global push toward sustainable and renewable energy solutions.

6.4. FUTURE DIRECTIONS

While the short-term effectiveness of the ZnO-SiO₂-chlorophyll coating is well-documented in this study, further research is necessary to:

- **Evaluate Long-Term Durability:**
Investigate the coating's resistance to prolonged environmental exposure, including temperature fluctuations, humidity, and UV radiation.
- **Optimize Material Composition:**
Fine-tune the proportions of ZnO, SiO₂, and chlorophyll to further enhance performance metrics, such as light transmittance and thermal emissivity.
- **Expand Application Scope:**
Explore the coating's utility in other PV applications, such as large-scale solar farms, and its compatibility with different substrate materials.
- **Develop Advanced Coating Techniques:**
Innovate the current spraying process to accommodate complex geometries and ensure uniform application in various industrial settings.

6.5. DEDUCTION

The development of a multifunctional nanocomposite coating integrating ZnO, SiO₂, and chlorophyll represents a significant advancement in solar technology. This study highlights the coating's transformative potential for improving the efficiency, durability, and sustainability of PV systems. By addressing pressing challenges like dust accumulation and thermal management, this coating contributes to the broader adoption of renewable energy technologies, paving the way for a greener and more sustainable future.

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RESUME

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