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Banana leaf wax performance as a coating material to reduce fouling and heat for photovoltaic improvement

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ABSTRACT

The growing dependence on limited fossil fuels and their environmental impact drive the adoption of renewable energy, with photovoltaics (PV) being a leading option. However, PV performance often declines due to elevated operating temperatures and surface soiling, especially in tropical climates, leading to reduced efficiency. To address this, coating materials with dual functionalities of passive cooling and self-cleaning are highly desirable. This study investigates banana leaf wax as a natural coating to enhance PV performance. The wax was extracted using n-hexane, applied via spray-coating, and characterized through light transmittance tests, scanning electron microscope (SEM) imaging, water contact angle (WCA), adhesion analysis, and field trials on PV modules. The wax demonstrated an average WCA of 127°, with a microcrystalline structure supporting hydrophobic and self-cleaning properties. Field implementation showed that a 9 μm wax layer reduced the PV module operating temperature by approximately 5 °C and increased output power by 15–20% under high solar irradiance (G ≈1200 W/m²). The cooling effect proved more significant than transmission losses, confirming the potential of banana leaf wax as an effective tropical PV coating. Nevertheless, further studies are required to optimize thickness, strengthen adhesion through hybrid formulations, and integrate the material into advanced optoelectronic coatings for sustainable efficiency improvements.

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1. INTRODUCTION

Solar energy has become one of the most promising renewable energy solutions due to the abundance of solar radiation and its lower environmental impact compared to fossil fuels [1]-[3]. Photovoltaic (PV) technology has continuously advanced in terms of efficiency improvement and cost reduction [4]; however, its performance is still strongly influenced by environmental conditions [5]. One of the main challenges is the reduction in PV panel efficiency caused by high operating temperatures [6]. Experimental studies have shown that the conversion efficiency of solar modules decreases significantly as operating temperature increases. The efficiency of monocrystalline modules can drop from approximately 12% to only 2–3% when the temperature rises above 55–58 °C [1], [6], [7]. This efficiency reduction is proportional to the increase in panel temperature, generally resulting in power losses of about 0.3–0.6% per degree Celsius [1], [8].

Furthermore, surface soiling caused by dust, dirt, and other particulate pollutants significantly reduces light absorption [9]. Dust accumulation on solar panels can decrease power output by 10–20% per year if panels are not cleaned regularly [10]-[12]. In dry and dusty regions, power losses due to soiling can even reach several percent per day [1], [10]. Consequently, high operating temperatures and progressive surface soiling act synergistically to degrade both the immediate performance and durability of PV panels under real-world operating conditions [12].

Various approaches have been developed to mitigate the negative effects of temperature and dust on PV panels. For instance, passive cooling coatings (radiative cooling) and active cooling systems (air or liquid circulation) are capable of reducing panel surface temperature by up to 10–20 °C and improving electrical efficiency by several percent [2]. On the other hand, hydrophobic and superhydrophobic surface coatings (self-cleaning coatings) have been developed to prevent dust accumulation on PV cover glass [10], [12], [13].

Nevertheless, many of these solutions focus on only a single function. Conventional cooling coatings generally do not mitigate dust accumulation, while radiative-cooling layers are not inherently self-cleaning [2]. Similarly, superhydrophobic coatings are typically designed to remove dust through water repellency but do not provide a significant cooling effect [13]. Furthermore, most multifunctional coating studies still rely on synthetic materials (such as silicon nanoparticles, fluorosilanes, or titanium dioxide), which are often translucent or opaque and therefore not optimal for all applications [10], [12], [14].

In tropical regions in particular, detailed studies on PV panel performance and coating solutions remain limited [15]. As reported in the literature, investigations into the effects of soiling in humid tropical climates are still scarce. This is despite the fact that tropical climates present a unique combination of high solar irradiance, high humidity, and organic pollution. Consequently, a research gap exists in the development of solar panel coatings capable of simultaneously addressing both thermal and soiling issues, especially through the use of environmentally friendly natural materials.

This study proposes a novel solution by utilizing banana leaf wax as a multifunctional natural coating material for photovoltaic panels. Banana leaf wax exhibits hydrophobic properties with a water contact angle (WCA) of 110°–130° [16], similar to those of natural wax found on lotus leaves, which can reduce dust adhesion and facilitate self-cleaning behavior when exposed to rainwater [17]. Banana leaf wax can also reflect 60–80% of infrared rays [18]. From an ecological perspective, banana leaf wax is biodegradable and can be obtained from abundant agricultural waste in tropical regions such as Indonesia. These properties make banana leaf wax a promising multifunctional coating candidate for addressing soiling and thermal issues in photovoltaic systems.

Beyond its self-cleaning capability, the wax coating is also expected to enhance PV efficiency through passive cooling. Wax-coated surfaces generally have low thermal conductivity and can reflect a portion of infrared radiation, thereby reducing heat absorption by the PV module. This integrative approach has rarely been reported in the literature; although several studies have examined cooling materials and self-cleaning coatings separately, only a few have successfully integrated both functions within a single bio-derived natural material [10], [14].

Therefore, this research offers a novel contribution by utilizing local resources (banana leaves) to develop a dual-function PV coating that simultaneously reduces panel temperature and suppresses surface soiling. The ecological advantages and originality of this approach lie in the use of low-cost, readily available, and environmentally friendly natural materials compared to synthetic alternatives. Consequently, banana leaf wax coatings are expected to represent an innovative and underexplored solution for improving photovoltaic performance in tropical climates.

2. METHOD

This research was conducted using an experimental method according to the research flowchart in Figure 1. The material was prepared in the form of wax extracted from banana leaves. The extraction process began with preparing clean banana leaves, cutting them into approximately 3×3 cm^2 pieces, and then drying them. Wax extraction was carried out using a maceration process using 1 liter of n-hexane solvent per 100 g of dried banana leaves, followed by filtration and purification to yield a homogeneous banana leaf wax solution in n-hexane with a solid wax concentration of 5%–10 wt% [19].

After the banana leaf wax solution was successfully extracted and formulated into a homogeneous solution, the next step was to prepare test samples for material characteristic analysis. This process involved coating the wax solution on a microscope slide using a spray-coating method, known to be effective in producing thin films with controlled thickness and uniform distribution. The coating thickness was varied within a range of approximately 3, 5, 7, 9, 11, and 13 µm to evaluate the effect of morphology on the material's functional properties. Spray-coating techniques are also widely used in optoelectronic coating research due to their film uniformity and scalability [20]. A series of tests were then conducted to analyze the transmittance, hydrophobicity, surface microstructure, and wax adhesion properties. A coating with a transmittance of approximately 90% was selected for implementation and full-scale field testing.

Transmittance was obtained by comparing the measurement of sunlight irradiation that successfully penetrated the wax layer on the glass test sample with the incident irradiation received directly, using a solar meter. This transmittance value indicates the proportion of light that passes through the wax layer without being absorbed or reflected, making it an important indicator for assessing the material's effectiveness as a coating. Higher transmittance allows more incoming light to reach the photovoltaic panel surface [21].

SEM analysis examined the wax layer's micrometer-scale morphology, revealing protrusions, pores, and textures that define its physical properties. The link between morphology and hydrophobicity is key, as microstructure shape and distribution affect water-repellent ability. High hydrophobicity enables self-cleaning, with dirt removed by rolling droplets. Thus, SEM results provide both visual evidence of the wax structure and insights into mechanisms supporting its functional performance in practical applications [22].

Hydrophobicity testing was performed by measuring the WCA using the droplet goniometry method with the help of the ImageJ application. This measurement quantitatively determines the surface's water-repellent ability. The expected WCA value should be greater than 90° (>90°), indicating the surface's hydrophobicity. This property is essential for the self-cleaning mechanism, as rolling water droplets easily pick up and carry away dust particles, mitigating particulate accumulation [23].

The infrared (IR) transmittance percentage in the 700-1100 nm spectrum is obtained by comparing the illuminance of sunlight passing through the wax layer on the glass of the test sample to the illuminance of the incident light, measured using a TSL2591 lux sensor [24]. This measurement provides an indication of how much IR illumination can pass through the wax layer. This IR illumination that passes through plays a crucial role because it directly affects the temperature increase in the silicon of photovoltaic (PV) modules. Therefore, the IR transmittance level is a crucial parameter in assessing the effectiveness of the wax layer in controlling overheating in PV modules.

Adhesion is a critical parameter for ensuring coating durability under environmental conditions. Measurements are made using the Pull-Off Adhesion Test method, which can provide precise quantitative data on adhesion strength. Strong adhesion between the coating and the substrate is a prerequisite for coating durability [25].

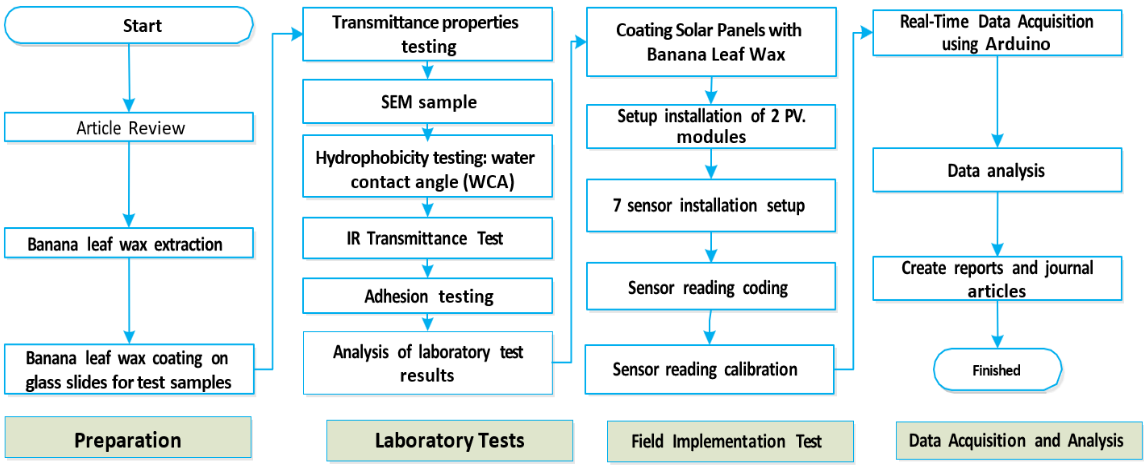


Figure 1. Research flowchart for evaluating the potential of banana leaf wax as a dual-functional PV coating material

The field implementation phase is designed as a comparative study to validate the performance of the wax layer under real-world operational conditions. This methodology uses two PV modules installed side by side to ensure that both modules experience identical environmental conditions. One PV module was coated with a banana leaf wax solution, while the other was left in its standard condition (without the wax coating) to serve as a control module. Both modules were then installed in the same location for comparative testing.

To automatically and continuously collect performance data, an Arduino microcontroller-based real-time data acquisition system was installed with seven sensors, as shown in the test schematic in Figure 2. The sensors used included: two RTD PT100 temperature sensors, two INA226 voltage/current sensors on each

PV module, one ambient temperature sensor (DS18B20), one solar irradiance sensor (SEM228A), and one infrared light sensor (TSL2591). The Arduino microcontroller-based data acquisition system is an efficient and cost-effective solution for real-time PV monitoring. Automation of data collection is key to minimizing human error and enabling continuous and accurate monitoring [26], [27].

Before testing begins, all sensors are calibrated against standard measuring instruments to ensure the reliability and accuracy of the collected data. This calibration process is carried out by generating a curve of the measurement results from the standard (reference) instrument as a function of the sensor measurement data. The linear regression equation from the resulting curve is used as the calibration equation for the sensor readings.

After calibration, the real-time data acquisition process begins, recording irradiance, temperature, current, and voltage data from both modules. Data collection is carried out intensively, with a frequency of one data point every 30 seconds for 30 days. This high-frequency data collection over a long period allows for a very detailed analysis of the panel's response to variations in solar irradiance

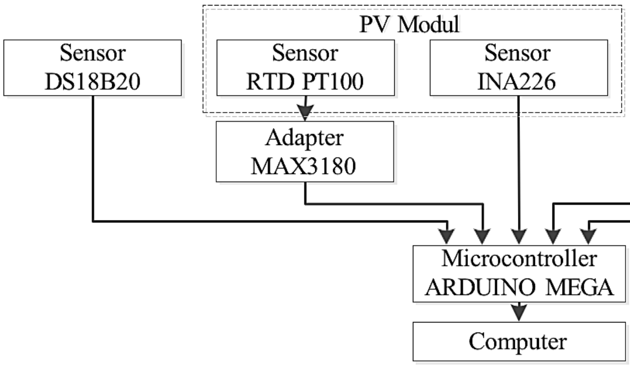


Figure 2. Schematic diagram of the real-time outdoor testing setup and data acquisition system for the PV modules, featuring RTD PT100 temperature sensors with MAX31865 adapters and INA226 current monitor

3. RESULTS AND DISCUSSION

3.1. Wax extraction from banana leaves

Banana leaf wax extract is obtained in the form of an n-hexane solvent-based wax solution as shown in Figure 3(a). This form can produce a homogeneous dispersion that allows application as a solvent-based coating. This liquid phase strongly supports the spray-based deposition method, which is known to be effective in producing a uniform thin layer on glass substrates and PV modules. With this technique, material distribution can be well controlled, resulting in the formation of a continuous film that is optically stable and functions optimally as a protective layer and thermal control.

3.2. Transmittance of solar irradiation on banana leaf wax

The results of the solar irradiance (G) transmittance characteristics test of banana leaf wax irradiation coating on glass are shown in Figure 3(b). The measurement was carried out by placing a layer of banana leaf wax on a thin glass. The transmittance percentage was obtained by comparing the light that penetrates the wax to the incident light. It can be seen that the light transmittance decreases with increasing wax thickness. The transmittance decreases by 1.36% for every 1 μm increase in layer thickness.

Wax transparency decreases with increasing thickness, and although the cooling effect is dominant under high irradiance, transmission losses still occur at low light intensities. This trade-off indicates that increasing the wax thickness does not always improve the overall performance of the photovoltaic module. Therefore, further research is needed to determine the optimal wax layer thickness that balances the cooling-induced power gain and the power loss caused by reduced light transmittance, thereby achieving higher overall power output.

3.3. Transmittance IR illuminance on banana leaf wax

Analysis of the infrared (IR) illumination transmission graph in Figure 3(b) shows that the banana leaf wax layer has a clear ability to block IR radiation. This characteristic is particularly important for silicon photovoltaic (PV) solar cell applications because IR radiation carries heat that increases the operating temperature of the cells. By reducing the transmission of IR radiation, the wax layer has the potential to minimize heat accumulation and help maintain the efficiency of PV solar cells.

The results indicate an inverse relationship between layer thickness and IR transmission: the thicker the wax layer, the less IR rays can penetrate it. For example, increasing the layer thickness from 3 µm to 13 µm decreases IR transmission from approximately 62.5% to 59.0%. This decrease in transmission directly indicates that the layer's effectiveness in blocking (absorbing or reflecting) IR rays increases with thickness.

Quantitatively, this wax layer is capable of achieving IR blockade levels between 37.5% and 41.0%. This ability to block approximately 40% of infrared heat makes banana leaf wax a potential material to function as a thermal filter layer in solar panels. By reducing the amount of heat reaching the silicon PV cell, this layer can help keep the cell's operating temperature lower, thereby maintaining or improving electrical conversion efficiency.

3.4. Banana leaf wax adhesion

Tests show that the adhesion of banana leaf wax to the glass sample is relatively stable in the range of 180–200 kPa as shown in the graph in Figure 3(b). A marginal but discernible decreasing trend as the coating thickness increases from 3 to 13 µm. This phenomenon can be directly attributed to the uneven volumetric distribution of internal shear stress and localized cohesive defects in the thicker coatings, which collectively reduce the effective microscopic interfacial contact area. Mathematically, the adhesion strength is expressed as σa = F/A, force F (N) per unit area A (m^2). The adhesion value obtained is sufficient for PV module coating applications, as long as the thickness is kept thin to maintain optimal optical transparency and thermal stability, however, for long-term applications, reinforcement is necessary.

Although banana leaf wax exhibits adequate adhesion in the range of 180–200 kPa on glass substrates, the soft and easily peeled nature of the wax poses a challenge for long-term applications in outdoor environments. Polymer matrix reinforcement studies are needed by developing hybrid coating formulations by mixing banana leaf wax into an inert and transparent polymer matrix, such as polydimethylsiloxane (PDMS) or polyurethane, to improve hardness, abrasion resistance, and adhesion without compromising hydrophobic and optical properties. Substrate surface modification is also needed by analyzing the pre-treatment of the PV module glass surface (e.g., plasma treatment or ultrathin primer layer deposition) to improve the adhesion interaction between the wax and the glass.

3.5. Coating contact angle testing

The results of WCA measurements on banana leaf wax coatings show that the average contact angle of six test samples reached 127°. The contact angle of one sample is shown in Figure 4. With this value, it is generally categorized as a hydrophobic surface. This characteristic indicates that banana leaf wax coatings have the potential to produce a self-cleaning effect through the rolling mechanism of water droplets carrying dirt particles from the surface. A similar phenomenon has been reported on natural wax-based biomimetic surfaces, where contact angles above 120° have been shown to improve optical durability and self-cleaning capabilities [28], [29].

(a)

(b)

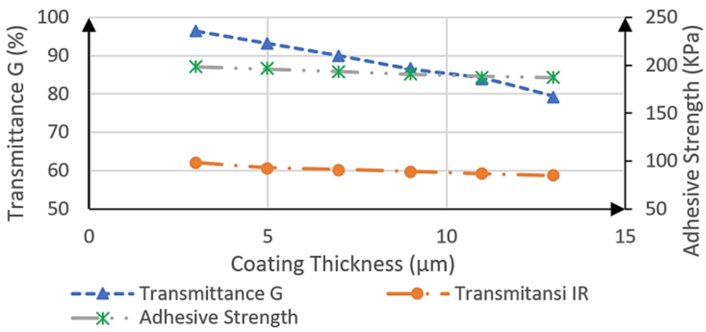


Figure 3. Characteristics of the banana leaf wax: (a) extracted wax solution in n-hexane and (b) solar transmittance (G), near-infrared (NIR) transmittance, and pull-off adhesion strength as functions of coating thickness

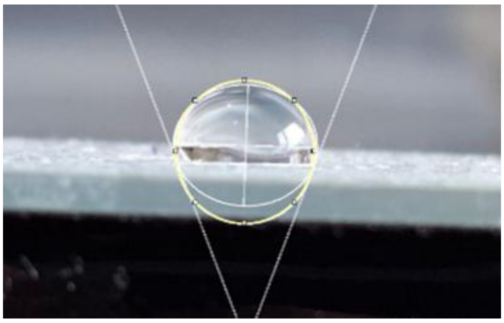


Figure 4. Wetting behavior and water contact angle (WCA) measurement on the spray-coated banana leaf wax layer

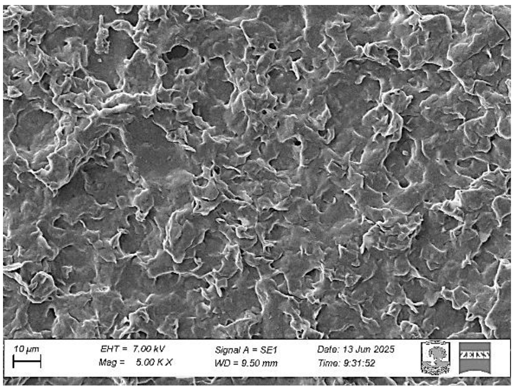
3.6. Microstructural morphology of the banana leaf wax coating

Observations using a Scanning Electron Microscope (SEM) show that the surface of banana leaf wax is composed of a microcrystalline structure that forms platelet-shaped and tabular aggregates with random orientations, as seen in Figure 5. This morphology produces a surface topography that is rough at the micro- to nanoscale, with a dense distribution of overlapping wax crystals. This distinctive texture creates microscopic air pockets within the hierarchical topography that covers the substrate surface.

This micro- and nano-scale surface roughness plays a crucial role in increasing the WCA. According to the Cassie–Baxter model, a surface that combines intrinsic hydrophobic properties with micro- and nano-roughness traps air between its surface structures, allowing water droplets to only partially contact the leaf. As a result, the adhesive force between the water and the surface is very small, and the droplets tend to form nearly perfect spheres. This explains why banana leaf wax can achieve a WCA of around 127°, which is considered high and indicates strong hydrophobicity.

Furthermore, the homogeneous distribution of wax crystals enhances the "self-cleaning" effect, similar to the lotus effect. Water droplets rolling over the surface not only easily detach but also carry away dirt particles, thus keeping the leaf surface clean. Thus, the microcrystalline structure of banana leaf wax not only determines hydrophobicity but also provides ecological benefits by protecting against excess moisture and the accumulation of foreign particles.

Overall, the SEM results demonstrate that the extreme hydrophobicity of banana leaves is a direct consequence of the combination of the intrinsically hydrophobic chemical composition of the cuticular wax and its micro- and nanoscale surface architecture. This synergistic combination increases the water contact angle to approximately 127°, thereby enhancing the leaf's water-repellent properties. These findings underscore the importance of wax morphology as a key factor in the design of biomimetic surfaces for water-repellent and self-cleaning applications.

(a)


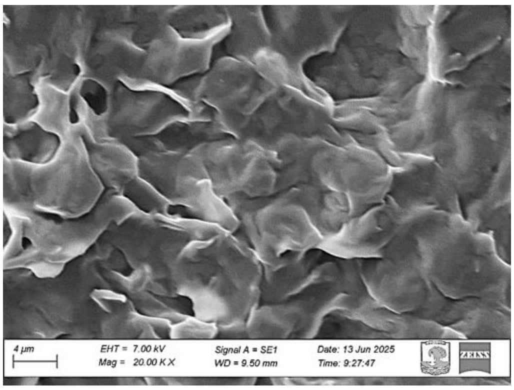
(b)


Figure 5. Surface morphology and microstructural architecture of the banana leaf wax coating: SEM micrographs at (a) 10-µm scale and (b) 4-µm scale

3.7. Thermal performance and PV module temperature mitigation

The data from the field test of the temperature relationship of the test PV module to solar irradiation on the PV module coated with 9 µm banana leaf wax and the standard PV module are shown in Figure 6(a). The green curve (ambient temperature) shows a linear increase with a low slope. The ambient temperature increases from a temperature-to-solar irradiation relationship of ~28 °C at low irradiation to ~38 °C at high irradiation (~1200 W/m²). The red curve (standard PV) shows the most significant increase in the temperature of the standard module to 60.5±2.1 °C at 1200 W/m² irradiation. The yellow curve (PV module coated with banana leaf wax) shows a lower temperature increase than the standard PV, with a maximum value of around 55.3±1.9 °C at 1200 W/m² irradiation. The temperature of the photovoltaic module (T_m) depends on the thermal relationship with the ambient temperature (T_a), the intensity of solar irradiation (G), and the convection heat transfer coefficient (h_c), and the module efficiency η (T_m) is expressed by the empirical (1).

$$T_m \approx T_a + \frac{1-\eta(T_m)}{G} h_c G \quad (1)$$

Where T_m represents the ambient environmental temperature, G defines the total incident solar irradiance (W/m²), h_c_is the calculated convective heat transfer coefficient (W/m²·K), and $\eta(T_m)$ signifies the precise temperature-dependent electrical conversion efficiency of the underlying solar cell.

PV modules coated with banana leaf wax operate at lower temperatures than standard modules due to the coating's optical and thermal properties. The hydrophobic surface can reflect part of the solar irradiation, especially in the infrared range that causes heating. In addition, the coating enhances surface emissivity, allowing heat to dissipate more effectively through radiation and convection. As a result, excess radiant energy not converted into electricity is released faster into the environment instead of being stored as heat in the module. This leads to a gentler temperature rise with increasing irradiation, keeping the coated module cooler than the standard one. The reduced temperature lowers efficiency losses caused by the PV power temperature coefficient. Consequently, banana leaf wax coating improves electrical performance and helps maintain higher efficiency under strong solar irradiation, offering a simple yet effective approach to enhance PV system performance in tropical regions.

The performance of the banana leaf wax coating presents a competitive advantage when compared to recent literature: While standard superhydrophobic coatings discussed by Ingole *et al.* [13] are effective for self-cleaning, they typically do not offer significant cooling effects. This study demonstrates that banana leaf wax provides a dual function: high hydrophobicity (WCA 127°) and a measurable cooling effect (≈ 5 °C). Kargaran *et al.* [2] reviewed various cooling strategies capable of reducing temperatures by 10–20 °C; however, these often require complex setups or active energy consumption. In contrast, this bio-based coating offers a simple passive cooling solution that, despite a more moderate reduction (≈ 5 °C) is cost-effective and sufficient to mitigate the efficiency degradation reported in tropical climates.

3.8. Influence banana leaf wax coating on PV module output power

The results of the field experiment in Figure 6(b) show that the PV module coated with banana leaf wax exhibits a significant enhancement in output power under medium to high solar irradiance, while a modest performance penalty is observed under low-irradiance conditions due to reduced optical transmittance. At irradiance levels exceedingly approximately 500 W·m⁻², the thermal mitigation effect of the 9-μm wax layer outweighs the minor transmission loss. Consequently, the coated module delivers an average increase in maximum power of about 13.3% within the 500–800 W·m⁻² range and up to 19.9–20.5% at irradiance levels above 800 W·m⁻² (≥1000 W·m⁻²), relative to the uncoated reference module. These improvements are statistically significant based on paired-sample analysis (p « 0.001).

The observed power enhancement is directly associated with a reduction in module operating temperature. On average, the banana leaf wax coating reduces the module temperature by approximately 2.0 °C across all operating conditions, with a more pronounced reduction of about 4.2–4.6 °C under high irradiance (>800–1000 W·m⁻²). A strong correlation between solar irradiance, temperature reduction, and power gain confirms that thermal regulation plays a dominant role in the performance improvement. This behavior is primarily attributed to the combined effects of partial infrared (IR) radiation blocking and enhanced thermal emissivity of the wax layer, which promote passive cooling of the PV module [2], [14].

From a theoretical perspective, the maximum power output of a PV module can be expressed as a function of irradiance and module temperature. The maximum power output is expressed as (2).

$$P_{pv}(G, T_m) = \eta_{ref} G A_{mod} \left[1 - \beta\left(T_m - T_{ref}\right)\right] \quad (2)$$

Where $\eta_{\{ref\}}$ is the reference efficiency at $T_{\{ref\}}$ = 25 °C T, $A_{\{mod\}}$ is the module area, β is the temperature coefficient of power, G denotes solar irradiance, and T is the module temperature. The presence of the banana leaf wax coating effectively reduces the operating temperature by ΔT_{coat}, leading to a relative power gain that can be approximated as (3).

$$\frac{\Delta P}{P_{std}} \approx -\beta \Delta T_{coat} \quad (3)$$

Where $\Delta P = P_{coated} - P_{std}$ represents the net positive power increase, P_{std} is the baseline electrical power of the standard uncoated control module, β is the negative temperature coefficient of power characteristic of the semiconductor material (typically recorded as, e.g., $\beta \approx$ -0.4%/ºC, and $\Delta T = T_{coated} - T_{std}$ represents the differential temperature change. Since the coated temperature is consistently lower ($T_{coated} < T_{std}$), the value for ΔT_{coated} is strictly negative. Consequently, multiplying the physically negative β coefficient by the negative ΔT_{coated} variable directly produces a positive resultant value, yielding a substantial net positive power gain. Given the established negative physical value of β resulting from elevated electron-hole recombination rates at high temperatures, the experimentally observed and verified temperature reduction directly and proportionally translates into a highly measurable, significant increase in total electrical power output, placing the theoretical framework in perfect agreement with the empirical field data robustly obtained throughout this study.

When compared with multifunctional coatings reported in the literature, the banana leaf wax coating occupies a distinct and practical niche. Many transparent superhydrophobic coatings primarily enhance self-cleaning performance but provide only limited thermal benefits, typically resulting in marginal or statistically insignificant power gains [14]. In contrast, advanced radiative-cooling or metamaterial-based coatings can achieve larger temperature reductions (often exceeding 8–10 °C), yet they involve complex fabrication processes and higher material costs [2]. Hybrid hydrophobic–IR-reflective coatings reported in recent studies offer moderate cooling (3–5 °C) and partial self-cleaning functionality, but often rely on synthetic or engineered materials [14], [30].

In this context, banana leaf wax represents a low-cost, bio-derived multifunctional coating that simultaneously provides effective passive cooling and high surface hydrophobicity (WCA ≈127°). This dual functionality leads to statistically significant power enhancement under high irradiance without the need for active cooling systems or complex material architectures. Therefore, the proposed coating is particularly well suited for PV deployment in tropical regions, where high solar irradiance and elevated module temperatures are dominant factors limiting PV performance [30].

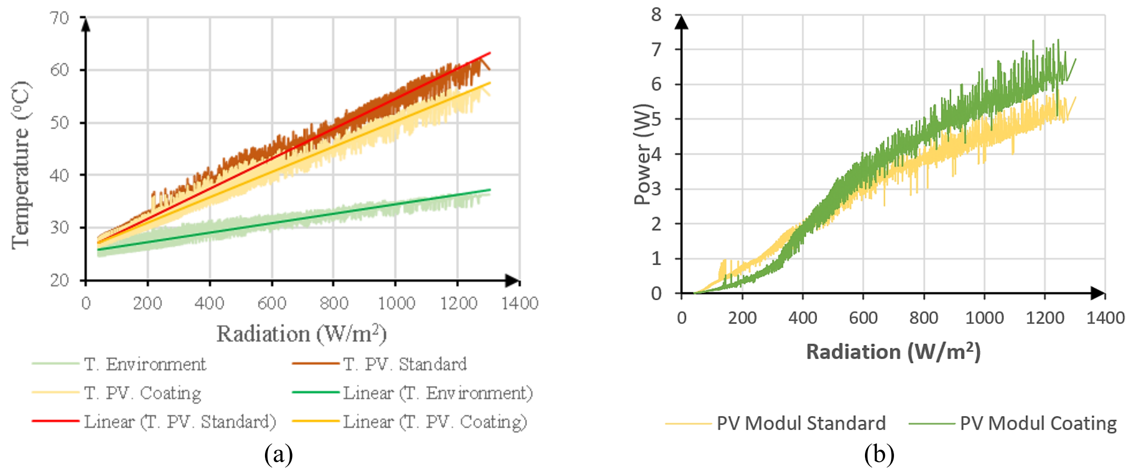


Figure 6. Outdoor performance results of PV modules coated with banana leaf wax: (a) temperature PV module test and temperature and (b) output power of test PV module

4. CONCLUSION

This study successfully proved that the proposed hypothesis regarding the potential of banana leaf wax as a coating for dual-functional PV modules to overcome degradation due to high temperature and fouling in tropical climates has been strongly validated by the results and discussion. The main problems of PV efficiency degradation due to high temperature, dust, and water scale, can be overcome by banana leaf wax. Microscopically, the extracted and spray-applied wax layer produces a random microcrystalline structure which, according to the Cassie–Baxter model, forms an extremely hydrophobic surface with an average WCA of 127°, thus enabling an effective self-cleaning mechanism. Furthermore, thermal testing demonstrated significant heat-reducing effectiveness, where a 9 µm layer was able to keep the PV module temperature down by ≈5 °C compared to a standard module at a high irradiance of 1200 W/m^2. Crucially, this cooling effect has been shown to outweigh the small optical transmittance losses, resulting in a 15–20% increase in PV module output power at high irradiance. This compatibility of problems and results positions banana leaf wax as a prime candidate for tropical applications.

Future work should improve durability, as the wax's softness and low adhesion (180–200 kPa) need reinforcement. Studies may use polymer matrices like PDMS, surface modification (e.g., plasma treatment), and thickness optimization to balance thermal and optical effects. Integration with optoelectronic coatings could create multifunctional solutions, enhancing energy efficiency and extending solar panel lifespan in tropical regions, with broader applications in PV systems for zero energy buildings (ZEB).

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Fajril Akbar	✓		✓						✓		✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available upon reasonable request to the corresponding author.

REFERENCES

[1] D. Yadav *et al.*, "Experimental analysis of elevated temperature and soiling loss on the rooftop PV modules performance under composite climatic conditions," *Scientific Reports*, vol. 15, no. 1, p. 42035, Nov. 2025, doi: 10.1038/s41598-025-25846-z.

[2] M. Kargaran, H. R. Goshayeshi, I. Zahmatkesh, and S. R. Saleh, "Next-generation cooling strategies for photovoltaics: a review of pathways toward high efficiency, low carbon, and climate resilience," *Results in Engineering*, vol. 29, p. 108556, Mar. 2026, doi: 10.1016/j.rineng.2025.108556.

[3] E. E. Michaelides, "Solar energy," in *Green Energy and Technology*, vol. 20, E. E. Michaelides, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 195–230, doi: 10.1007/978-3-642-20951-2_7.

[4] A. Asnil, R. Nazir, K. Krismadinata, and M. N. Sonni, "Performance analysis of an incremental conductance MPPT algorithm for photovoltaic systems under rapid irradiance changes," *TEM Journal*, vol. 13, no. 2, pp. 1087–1094, 2024, doi: 10.18421/TEM132-23.

[5] M. Mohamed-Abdulhussein and R. Mohd-Mokhtar, “Estimation of solar energy based on solar angles: cities of Iraq case study,” *International Journal of Applied Power Engineering (IJAPE)*, vol. 13, no. 3, pp. 628–636, Sep. 2024, doi: 10.11591/ijape.v13.i3.pp628-636.

[6] J. Adeeb, A. Farhan, and A. Al-Salaymeh, “Temperature effect on performance of different solar cell technologies,” *Journal of Ecological Engineering*, vol. 20, no. 5, pp. 249–254, Apr. 2019, doi: 10.12911/22998993/105543.

[7] B. Rtimi, A. Benhmidene, M. Dhaoui, and B. Chaouachi, “The overall efficiency of a solar panel under various conditions,” *Desalination and Water Treatment*, vol. 273, pp. 34–42, Oct. 2022, doi: 10.5004/dwt.2022.28887.

[8] Y. Shen, M. Fouladirad, and A. Grall, “Impact of dust and temperature on photovoltaic panel performance: a model-based approach to determine optimal cleaning frequency,” *Heliyon*, vol. 10, no. 16, p. e35390, Aug. 2024, doi: 10.1016/j.heliyon.2024.e35390.

[9] D. Matusz-Kalász and I. Bodnár, “Operation problems of solar panel caused by the surface contamination,” *Energies*, vol. 14, no. 17, p. 5461, Sep. 2021, doi: 10.3390/en14175461.

[10] A. K. Padhan, V. Singh, S. Ray, and R. K. Voolapalli, “High-performance multi-functional solar panel coatings: recent advances, challenges, strategies and industrial aspects,” *RSC Applied Polymers*, vol. 3, no. 2, pp. 317–335, Dec. 2024, doi: 10.1039/d4lp00295d.

[11] K. R. C. Lakshmi and G. Ramadas, “Dust deposition’s effect on solar photovoltaic module performance: an experimental study in India’s tropical region,” *Journal of Renewable Materials*, vol. 10, no. 8, pp. 2133–2153, 2022, doi: 10.32604/jrm.2022.019649.

[12] A. Pawawoi, N. Refdinal, and M. I. Hamid, “Systematic review: enhancing photovoltaic performance through hydrophobic surface coatings and heat mitigation,” *Jurnal Teknik Elektro*, vol. 16, no. 2, Dec. 2024, doi: 10.15294/jte.v16i2.19586.

[13] S. S. Ingole *et al.*, “A review on transparent superhydrophobic coatings for self-cleaning solar cell panels: its fabrication, robustness and industrial implementation,” *Surfaces and Interfaces*, vol. 70, p. 106794, Aug. 2025, doi: 10.1016/j.surfin.2025.106794.

[14] G. Huang *et al.*, “Radiative cooling and indoor light management enabled by a transparent and self-cleaning polymer-based metamaterial,” *Nature Communications*, vol. 15, no. 1, p. 3798, May 2024, doi: 10.1038/s41467-024-48150-2.

[15] M. Sheikholeslami dan Z. Khalili, “Enhancing photovoltaic solar panel performance with integration of PCM-based spectral filter and self-cleaning coating,” *Journal of Building Engineering*, vol. 94, p. 110019, Oct. 2024, doi: 10.1016/j.jobe.2024.110019.

[16] D. G. Prajapati and S. Rowthu, “Unravelling the anisotropic wetting properties of banana leaves with water and human urine,” *Surfaces and Interfaces*, vol. 29, p. 101742, Apr. 2022, doi: 10.1016/j.surfin.2022.101742.

[17] H. A. Hassan, M. J. Ghazali, C. Meric, and C. H. Azhari, “Wettability effect of the surface morphologies of Musa acuminata leaves,” *BioResources*, vol. 14, no. 4, pp. 8331–8344, Sep. 2019, doi: 10.15376/biores.14.4.8331-8344.

[18] C. Li, D. Xiang, S. Yang, X. Wang, and C. Li, “Fusarium wilt of banana latency and onset detection based on visible/near infrared spectral technology,” *Agronomy*, vol. 14, no. 12, p. 2994, Dec. 2024, doi: 10.3390/agronomy14122994.

[19] D. Singh *et al.*, “Natural wax recovery from musa acuminata biomass using organic solvents,” *Chemosphere*, vol. 363, p. 142919, Sep. 2024, doi: 10.1016/j.chemosphere.2024.142919.

[20] V. Vatanpour, Z. Mehrabi, A. H. Behroozi, B. Kose-Mutlu, R. Kaya, and I. Koyuncu, “Spray-coating technique in the fabrication and modification of membranes: a review,” *Separation and Purification Technology*, vol. 378, 2025, doi: 10.1016/j.seppur.2025.134752.

[21] P. Bharadwaj and V. John, “Design, fabrication and evaluation of solar irradiation meter,” in *2014 IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2014*, Mumbai, India: IEEE, Dec. 2014, pp. 1–6, doi: 10.1109/PEDES.2014.7041993.

[22] W. Sun, Y. Xu, Y. Zhou, Z. Zeng, L. Wang, and J. Ouyang, “Topographic scanning electronic microscopy reveals the 3d surface structure of materials,” *Advanced Functional Materials*, vol. 35, no. 17, p. 2420372, Apr. 2025, doi: 10.1002/adfm.202420372.

[23] Z. Xu, Q. You, S. Hu, P. Miao, and F. Lü, “Influence of hydrophobicity on accuracy of goniometry method used for static contact angle calculation,” *Gaodianya Jishu/High Voltage Engineering*, vol. 39, no. 11, 2013, doi: 10.3969/j.issn.1003-6520.2013.11.009.

[24] S.-I. Cho, Y.-J. Kim, J.-H. Lee, K.-H. Baek, and S. Kim, “An ultra-low-power ambient light sensor for portable devices,” in *Optoelectronic Integrated Circuits XI*, San Jose, CA, Feb. 2009, p. 72190U, doi: 10.1117/12.807927.

[25] J. F. Fletcher and D. J. Barnes, “Pull-off adhesion testing of coatings - improve your technique,” in *Australasian Corrosion Association Annual Conference: Corrosion and Prevention 2015, ACA 2015*, Australasian Corrosion Association, 2015.

[26] F. Akbar, V. Pujani, and R. Nazir, “Design of realtime electricity consumption monitoring system using campus web,” *TEM Journal*, vol. 12, no. 2, pp. 840–849, May 2023, doi: 10.18421/TEM122-29.

[27] J. C. Franklin, M. Chandrasekar, and D. A. Mattius, “Development of cost effective data acquisition system to evaluate the performance of solar photovoltaic thermal systems,” *Journal of Solar Energy Engineering*, vol. 143, no. 1, Feb. 2021, doi: 10.1115/1.4047453.

[28] K. Koch, B. Bhushan, and W. Barthlott, “Multifunctional surface structures of plants: an inspiration for biomimetics,” *Progress in Materials Science*, vol. 54, no. 2, pp. 137–178, Feb. 2009, doi: 10.1016/j.pmatsci.2008.07.003.

[29] P. V. Wettstein-Knowles, “Ecophysiology with barley eceriferum (cer) mutants: the effects of humidity and wax crystal structure on yield and vegetative parameters,” *Annals of Botany*, vol. 126, no. 2, pp. 301–313, Jul. 2020, doi: 10.1093/aob/mcaa086.

[30] Z. Li, S. Ahmed, and T. Ma, “Investigating the effect of radiative cooling on the operating temperature of photovoltaic modules,” *Solar RRL*, vol. 5, no. 4, p. 2000735, Apr. 2021, doi: 10.1002/solr.202000735.

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