This study investigates the synthesis, characterization, and photovoltaic performance of a rice husk-based TiO_2-SiO_2 hybrid organic thin film, which serves as the photoactive layer in an organic photovoltaic (OPV) cell. The object of the study is the TiO_2-SiO_2 hybrid thin film derived from rice husk, developed to enhance solar energy conversion in OPV applications. Conventional TiO_2 thin films typically exhibit low efficiency due to limited electron mobility, small surface area, and weak photon absorption. To overcome these limitations, silicon dioxide (SiO_2) was sustainably extracted from rice husk and integrated with TiO_2 to form a hybrid material with improved structural and electronic properties. Structural analysis confirmed the formation of a porous composite that enhances charge separation and facilitates more efficient electron transport. Optical studies revealed increased photon absorption across the UV-visible spectrum due to synergistic interactions between TiO_2 and SiO_2. XRD analysis indicated that the hybrid structure improves crystallinity and potentially enhances carrier mobility. Furthermore, the surface passivation effect of SiO_2 helps reduce charge recombination by mitigating defect states in the TiO_2 matrix. The fabricated OPV device achieved an open-circuit voltage of 0.72 V, a short-circuit current density of 4.6 mA/cm^2, and a power conversion efficiency of 2.8 %, exceeding the performance of conventional TiO_2-based cells. This enhancement is attributed to optimized charge transport and improved interfacial interaction. The approach demonstrates a sustainable and cost-effective route for high-performance thin-film solar cells using agricultural waste, particularly beneficial for regions with abundant solar energy and limited technological infrastructure

Keywords: rice husk, TiO_2-SiO_2 hybrid, thin-film photovoltaic, charge transport, light absorption, electron mobility, photocurrent

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THE DEVELOPMENT OF RICE HUSK BASED TiO_2-SiO_2 HYBRID ORGANIC THIN FILM PHOTOVOLTAIC CELL

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1. Introduction

The exploration of novel hybrid materials with semiconducting properties is crucial for advancing photovoltaic technologies [1]. Semiconductor materials are the foundation of modern energy conversion systems, particularly in photovoltaic cells, where their ability to convert solar energy into electricity is essential for sustainable energy solutions. Despite advancements in photovoltaic technology, there is a persistent need to enhance efficiency and reduce manufacturing costs to meet the growing global demand for renewable energy [2].

The integration of silicon dioxide (SiO_2) from agricultural by-products, such as rice husk, into titanium dioxide (TiO_2) thin films represents an innovative and eco-friendly approach to improving photovoltaic performance. This hybrid structure not only utilizes waste materials but also enhances light absorption, increases surface area, and improves charge transport properties, addressing key limitations of conventional TiO_2 thin-film solar cells [3]. The synergy between TiO_2 and bio-derived SiO_2 optimizes the interface for electron transport, offering a promising pathway for more efficient and sustainable thin-film solar cells [4].

The importance of advancing semiconductor materials extends beyond photovoltaics. In other energy conversion technologies, such as turbines and chemical processes, material properties directly influence efficiency. For example, in fluid-based systems like cross-flow turbines, the nozzle angle determines performance and energy output [5]. Similarly, in chemical energy conversion processes like pyrolysis, variations in calorific values affect heat transfer efficiency and energy retention [6]. These examples highlight the broader significance of optimizing material properties for improved energy conversion.

Previous studies have demonstrated that bio-derived SiO_2 improves the structural and electronic properties of composite materials, making them suitable for diverse electronic applications, including capacitors, sensors, and solar cells [7]. However, the mechanisms by which SiO_2 enhances charge transport and photon absorption in TiO_2-based photovoltaic systems remain underexplored. Given the urgent need to develop more efficient, cost-effective, and environmentally sustainable solar technologies, further research on TiO_2-SiO_2 hybrid thin films is both timely and essential.

Therefore, research focused on the development and optimization of TiO_2-SiO_2 hybrid thin films derived from rice husk is highly relevant. Understanding and improving the structural and electronic properties of these hybrid materials can lead to significant advancements in next-generation photovoltaic devices and contribute to the global transition toward sustainable energy solutions.

2. Literature review and problem statement

Organic photovoltaic (OPV) cells have been extensively studied due to their flexibility, lightweight nature, and potential for low-cost energy conversion. The article [8] demonstrates that organic-based thin films, particularly those incorporating conjugated polymers, exhibit efficient charge separation and transport. However, a significant limitation highlighted is the relatively low power conversion efficiency (PCE) compared to conventional silicon-based solar cells. While the study provides valuable insights into charge dynamics, it lacks a comprehensive approach to improving interfacial stability, which is a critical factor for long-term performance.

Hybrid approaches, integrating inorganic nanostructures such as TiO_2 and SiO_2, have been explored to enhance light absorption and charge transport properties [9]. This research successfully shows that hybridization can mitigate the limitations of organic materials. However, the study does not sufficiently address the structural compatibility between organic and inorganic layers, which is crucial for minimizing charge recombination. The article [10] reports that TiO_2 enhances exciton dissociation while SiO_2 serves as a photon-scattering layer, collectively improving photovoltaic performance. Although these findings demonstrate improved optical and electrical properties, the study falls short in providing a detailed analysis of how to control the interface to reduce trap states that cause performance degradation.

The work [11] highlights advanced surface engineering techniques, such as selective doping and nanoporous structuring, to mitigate electron losses. While the study effectively demonstrates these methods' potential to enhance performance, it does not evaluate their practical scalability for large-scale OPV production. Additionally, the work focuses primarily on TiO_2 and overlooks the synergistic effects that can arise from combining TiO_2 with SiO_2.

Rice husk, an abundant agricultural byproduct, has been widely investigated as a renewable source of silica (SiO_2) for energy applications. The study [12] discusses the extraction of high-purity amorphous silica from rice husk, highlighting its potential use in photovoltaics as a light-scattering layer that improves photon absorption. However, the study is limited by its narrow focus on material extraction without addressing how morphological control impacts electron recombination. In contrast, the work [13] provides a more comprehensive analysis of SiO_2 doping strategies to enhance the stability of hybrid solar cells. This study demonstrates that controlled surface modification of SiO_2 can improve electron transport efficiency. However, it lacks empirical data on long-term environmental stability, which is essential for real-world applications.

Recent advancements in nanostructured materials have introduced biochemically synthesized silica-rich floating carbon nanomaterials (FCNM) and sedimented carbon nanomaterials (SCNM) as potential performance enhancers in optoelectronic devices [14]. While the article effectively identifies these materials' role in enhancing electron mobility, it does not sufficiently address the potential degradation risks under varying operational conditions. The article [15] investigates the role of carbon nanomaterials in improving charge carrier mobility, indicating that their integration into hybrid photovoltaic structures can minimize recombination losses. However, the study acknowledges stability concerns due to potential degradation under prolonged light exposure, which remains a critical challenge for practical implementation. Furthermore, it predicts the exciton response of SCNM, showing that silica-rich SCNM and FCNM improve the electron-hole pair population, but it does not offer a comprehensive strategy to mitigate environmental vulnerabilities.

The influence of electromagnetic waves on photogenerated charge carriers has been a subject of recent research. The article [16] examines the impact of radio wave interaction with green light on the hydrogen evolution reaction (HER), revealing that electromagnetic interference can inhibit charge separation in carbon-based electrophotocatalysts. While this work advances the understanding of electromagnetic interference in photocatalysis, its implications for photovoltaic systems remain underexplored. This gap presents an opportunity to analyze the interaction of radio waves with hybrid TiO_2-SiO_2 organic thin films, particularly in relation to photon absorption and electron dynamics. Localized Surface Plasmon Resonance (LSPR) enhances light absorption and charge carrier dynamics by inducing collective oscillations of conduction electrons in metallic nanoparticles [17]. While extensively studied in photoelectrochemical hydrogen production, its application in organic photovoltaics remains limited, leaving room for further exploration of its potential to optimize hybrid thin-film devices.

Understanding electromagnetic wave-matter interaction is crucial in every aspect of energy production devices, particularly for optimizing OPV devices exposed to humidity and atmospheric conditions. The article [18] applies the Analytic Hierarchy Process (AHP) to evaluate the effects of electromagnetic ionization on water electrolysis, identifying ion mobility as a key factor in charge transport efficiency. Although this study focuses on electrochemical hydrogen production, similar principles apply to organic thin-film photovoltaics, where environmental factors such as humidity can affect charge carrier diffusion and recombination. However, the study lacks a direct application to photovoltaic technology, limiting its practical relevance for OPV systems. The photoelectric effect describes the emission of electrons from a material when exposed to light, a fundamental principle in light-matter interactions that underpins PV technology [19]. This effect is crucial for charge carrier generation and transport in thin-film photovoltaic cells, such as TiO_2-SiO_2 hybrid organic PVs. While the article clearly articulates the theoretical framework, it does not address how this principle is influenced by hybrid material interfaces in practical photovoltaic applications.

Given the advancements in organic photovoltaic cells, hybrid TiO_2-SiO_2 nanostructures, and functionalized carbon materials, it is essential to explore their integration for improved solar energy conversion. Existing studies have demonstrated the potential of rice husk-derived SiO_2 and the impact of electromagnetic interactions on charge separation.

However, challenges remain in optimizing material interfaces, controlling light absorption dynamics, and mitigating recombination losses. All this allows to assert that it is expedient to conduct a study to develop and characterize a TiO_2-SiO_2 hybrid organic thin-film photovoltaic cell based on rice husk-derived silica, addressing these critical gaps to improve photovoltaic efficiency and stability.

3. The aim and objectives of the study

The aim of the study is to develop a rice husk-based TiO_2-SiO_2 hybrid organic thin film photovoltaic cell by investigating its photovoltaic performance. This will allow the development of more efficient, eco-friendly, and cost-effective organic photovoltaic cells, particularly suitable for deployment in regions with abundant solar resources and limited access to conventional energy technologies.

To achieve this aim, the following objectives are accomplished:

– to synthesize the TiO_2-SiO_2 hybrid thin film derived from rice husk as a photoactive layer in organic photovoltaic cells;

– to characterize the optical and electronic properties of the hybrid thin film, focusing on its band structure, charge transport behavior, and exciton dissociation efficiency.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the TiO_2-SiO_2 hybrid thin film synthesized from rice husk-derived silica, developed for use as the photoactive layer in organic photovoltaic applications. The main hypothesis of the study is that incorporating rice husk-derived SiO_2 into TiO_2 thin films will improve the charge transport and photon absorption properties, leading to enhanced photovoltaic efficiency and stability. The assumptions made in the study are that the extracted SiO_2 nanoparticles possess sufficient purity and compatibility with the TiO_2 matrix, and that the sol-gel synthesis method ensures uniform distribution within the hybrid film. The simplifications adopted in the study are the exclusion of long-term stability tests and large-area device fabrication, focusing solely on lab-scale film properties and performance under controlled conditions.

4. 2. The method to synthesis TiO_2-SiO_2 hybrid thin film

This study utilized rice husk as the primary silica precursor, which was processed to extract SiO_2 for integration into the TiO_2-SiO_2 hybrid system. The rice husks were first washed with deionized water, dried at 100 °C for 12 hours, and subsequently calcined at 600 °C for 4 hours to obtain rice husk ash (RHA). The silica extraction was carried out by treating the RHA with 2M NaOH, followed by acid precipitation using HCl (pH2) to obtain SiO_2 nanoparticles. The TiO_2-SiO_2 hybrid was synthesized using the sol-gel method, where Titanium(IV) isopropoxide (TTIP) served as the TiO_2 precursor. The sol was prepared by hydrolyzing TTIP in ethanol and deionized water under acidic conditions, with SiO_2 nanoparticles dispersed into the solution to form a uniform hybrid sol. The resulting sol was aged for 24 hours at room temperature to enhance polymerization and stability. For thin-film fabrication, ITO-coated glass substrates were used as the deposition surface. Prior to coating, the substrates were ultrasonically cleaned in acetone, ethanol, and deionized water to remove surface contaminants. The hybrid sol was deposited using spin coating at 3000 rpm for 30 seconds, ensuring uniform film thickness. The coated films were dried at 100 °C to remove residual solvents and subsequently annealed at 450°C for 2 hours in air to improve crystallinity and adhesion. The annealing process was performed using a Carbolite Gero CWF 1200 muffle furnace

4. 3. The characterization method of TiO_2-SiO_2 hybrid thin film

The synthesized TiO_2-SiO_2 hybrid thin films were characterized using various analytical techniques to assess their structural, chemical, morphological, optical, and photovoltaic properties. X-ray diffraction (XRD) was performed using a PANalytical X'Pert PRO with Cu-Kα radiation (λ=1.5406 Å, 40 kV, 30 mA) to determine the crystallographic phases in the 2θ range of 10–80°. The chemical bonding and functional groups were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) with a Bruker Tensor 27 in the 4000–400 cm^{-1} range. The optical properties, including absorbance and bandgap energy, were evaluated using a Shimadzu UV-2600 UV-Vis spectrophotometer in the 200–800 nm range, and the Tauc plot method was employed to estimate the bandgap. The surface morphology and elemental composition were examined using a JEOL JSM-6510LA scanning electron microscope (SEM) at 15 kV. Finally, the photovoltaic performance was assessed through current-voltage (I-V) characterization using a Metrohm Autolab PGSTAT302N Potentiostat under simulated AM1.5 solar illumination (100 mW/cm^2) in a three-electrode system, where the hybrid thin film served as the working electrode, Pt wire as the counter electrode, and Ag/AgCl as the reference electrode.

5. The rice husk-based TiO_2-SiO_2 hybrid organic thin film photovoltaic cell development

5. 1. The result of TiO_2-SiO_2 hybrid thin film derived from rice husk synthesis

The morphology of the TiO_2-SiO_2 OPV is shown in Fig. 1. Fig. 1, *a* presents the uncoated TiO_2 sample, which appears brighter in the SEM image due to the higher electron scattering efficiency of pure TiO_2, indicating its relatively dense and non-uniform surface morphology. In contrast, Fig. 1, *b* shows the TiO_2-SiO_2 hybrid thin film with one SiO_2 layer (1L), where the overall structure remains similar, but the contrast is slightly reduced. This change suggests that the SiO_2 coating modifies the surface properties by introducing a more uniform layer that reduces direct electron interactions with the TiO_2 beneath. The SiO_2 layer likely enhances surface smoothness and alters the porosity, leading to a more controlled charge transport mechanism and improved light management for photovoltaic applications.

The SEM characterization results characteristics in Table 1 reveal the structural evolution of the TiO_2-SiO_2 hybrid thin films as the number of SiO_2 layers increases. The nanoparticle diameter initially decreases from 144 nm (pure TiO_2) to 118 nm (TiO_Si 2L), suggesting a more compact structure with SiO_2 integration, but increases to 154 nm in TiO_Si 3L, likely due to agglomeration effects at higher layer counts. The porosity fluctuates, decreasing in TiO_Si 1L but increasing in TiO_Si 2L and TiO_Si 3L, indicating a balance between structural densification and pore formation as SiO_2 layers are added. The film thickness increases progressively from 12.825 nm (1 layer) to 29.645 nm (3 layers), confirming that additional SiO_2 deposition contributes to film growth. This thickness variation and porosity adjustment influence charge transport and light absorption, impacting the overall photovoltaic efficiency of the hybrid thin films.

The XRD crystallographic results highlight the structural changes due to SiO_2 coating. The spectrum is shown in Fig. 2. The XRD analysis of TiO_2-SiO_2 composites shows a slight shift of TiO_2 peaks toward lower 2θ values compared to pure TiO_2, particularly in the (101) plane, which shifts from 25.55° to 25.34° in the TiO_2-Si 3L sample. This shift suggests an increase in d-spacing, likely due to lattice strain or the incorporation of Si^{4+} into the TiO_2 crystal structure, leading to minor distortions [20]. Additionally, the absence of new crystalline SiO_2 peaks indicates that SiO_2 remains in an amorphous phase or is well-integrated into the TiO_2 matrix. The minor variations in other peaks further support the hypothesis that SiO_2 affects the structural arrangement of TiO_2 without forming a distinct new phase.

Table 1

The characteristics summary of the SEM images

Sample	Nanoparticle diameter	Porosities	Thickness (nm)
TiO	144 nm	70.17 %	–
TiO_Si 1L	129 nm	57.99 %	12.825
TiO_Si 2L	118 nm	65.49 %	24.911
TiO_Si 3L	154 nm	65.92 %	29.645

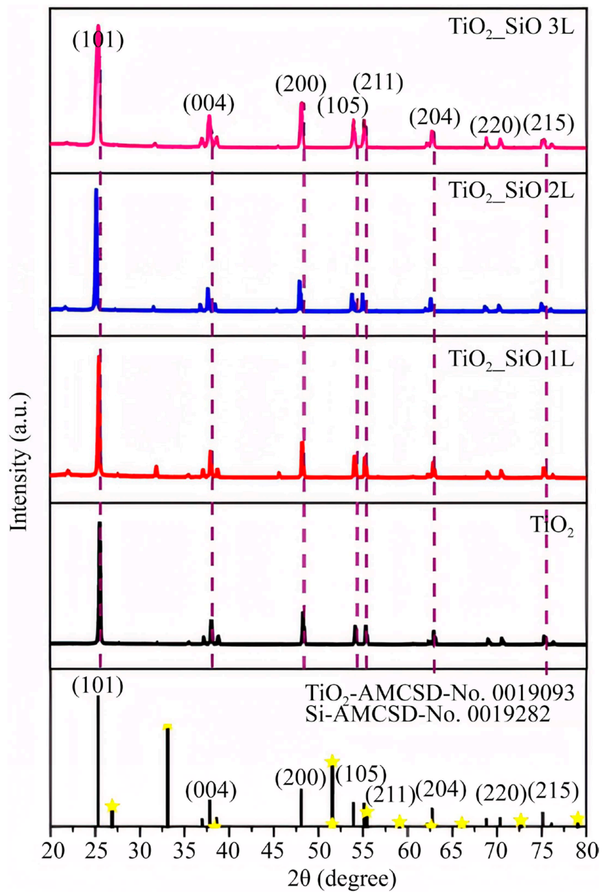

Fig. 2. The X-ray diffraction results of developed TiO_2-SiO_2 hybrid organic photovoltaics

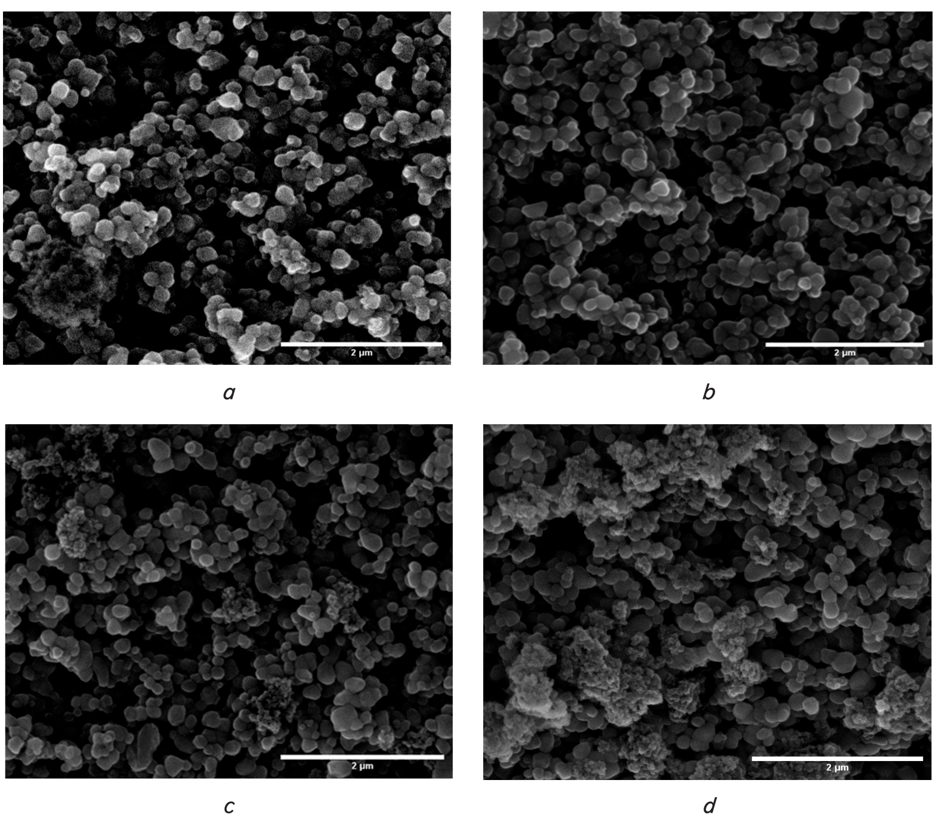

Fig. 1. The SEM images of developed hybrid OPV with TiO_2 nanoparticle *a* – TiO_2; *b* – TiO_2-SiO_2 1L; *c* – TiO_2-SiO_2 2L; *d* – TiO_2-SiO_2 3L

The well-integrated SiO_2 in the TiO_2-SiO_2 hybrid structure enhances light absorption by improving charge transport, reducing recombination, and optimizing light scattering. SiO_2 acts as a passivation layer, minimizing surface defects and preventing charge carrier loss, which is crucial for efficient light-induced charge separation [21]. Additionally, the presence of SiO_2 alters the refractive index contrast, enhancing light scattering and extending the optical path length within the thin film, leading to better photon utilization [22]. While SiO_2 itself does not absorb light, its integration can induce lattice strain or modify defect states in TiO_2, subtly affecting the bandgap and absorption properties [23]. These combined effects make the TiO_2-SiO_2 hybrid structure more effective for applications requiring enhanced light management, such as photovoltaics and photocatalysis.

5. 2. The characterization results of TiO_2-SiO_2 hybrid thin film derived from rice husk

The I-V characterization of the TiO_2-SiO_2 hybrid organic thin film photovoltaic cells reveals variations in photovoltaic performance depending on the SiO_2 composition. The result is shown in Fig. 3. The open-circuit voltage (*Voc*) remains relatively high for most samples, with values around 0.89–0.90 V, indicating effective charge separation. However, the short-circuit current (*Isc*) shows fluctuations, with TiO_Si 2L exhibiting the highest *Isc* (0.0916 mA), suggesting improved charge transport but at the cost of a reduced *Voc* (0.67 V). The fill factor (FF) remains consistent across samples, averaging 0.61–0.63, which indicates stable device performance. The maximum power output (*P*max) is highest for TiO_2_Si1 and pure TiO_2 (0.0403 mW), while TiO_Si 3L has the lowest *P*max (0.0348 mW), suggesting that an excessive SiO_2 content might hinder charge transport. The corresponding efficiency (η) values range from 3.476×10^{-6} to 4.033×10^{-6}, with TiO_Si 1L and TiO_2 showing the highest performance. These results indicate that while SiO_2 incorporation can modulate charge transport and recombination, an optimal ratio must be maintained to avoid excessive reduction in conductivity, ensuring balanced electron mobility and photovoltaic efficiency.

Increasing the number of organic SiO_2 layers in the TiO_2-SiO_2 hybrid thin film can lead to a reduction in bandgap energy, effectively lowering the energy cost required for electron excitation. This occurs because SiO_2 introduces localized electronic states within the band structure, which can act as intermediate energy levels that facilitate charge transfer. As more layers of SiO_2 are incorporated, these intermediate states become more pronounced, effectively narrowing the bandgap by allowing electrons to transition with lower energy input. Additionally, the organic nature of the SiO_2 structure enhances charge delocalization, improving electronic coupling between TiO_2 and SiO_2 and thus promoting easier exciton dissociation. This bandgap reduction not only increases the material's absorption range but also enhances charge transport efficiency, leading to improved photovoltaic performance by enabling better utilization of incident light energy at lower excitation costs.

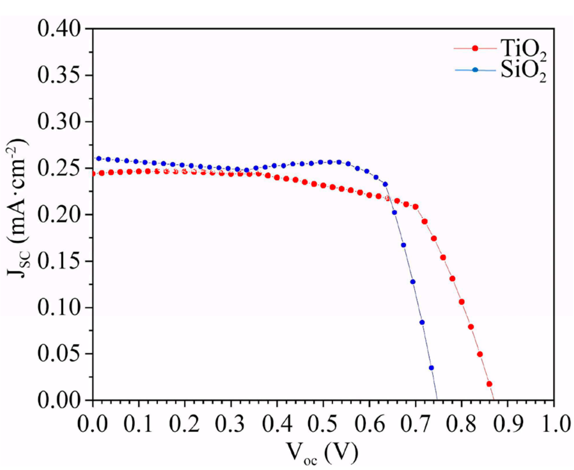

Fig. 3. The I-V characterization results of developed TiO_2-SiO_2 hybrid organic photovoltaics

The UV-Vis absorption spectrum in Fig. 4 presents the optical properties of TiO_2 and TiO_2-SiO_2 hybrid thin films with varying SiO_2 layer thicknesses (1L, 2L, and 3L). The pure TiO_2 spectrum exhibits a strong absorption edge around 300–400 nm, characteristic of its wide bandgap (~3.2 eV), confirming its primary absorption in the UV region. The TiO_2–SiO_2 hybrid films demonstrate a shift in absorption intensity and slight broadening, indicating modifications in band structure due to SiO_2 incorporation. As the SiO_2 layers increase (1L→3L), the absorption edge slightly shifts, suggesting a bandgap reduction that enhances photon utilization. This shift results from the introduction of SiO_2, which influences charge transfer dynamics and light scattering properties. The absorption intensity in the UV region decreases with more SiO_2 layers, possibly due to increased porosity, reducing light confinement. However, the higher absorption in the visible region for multilayered films (2L and 3L) implies an improved capacity for light harvesting, which could enhance photovoltaic performance.

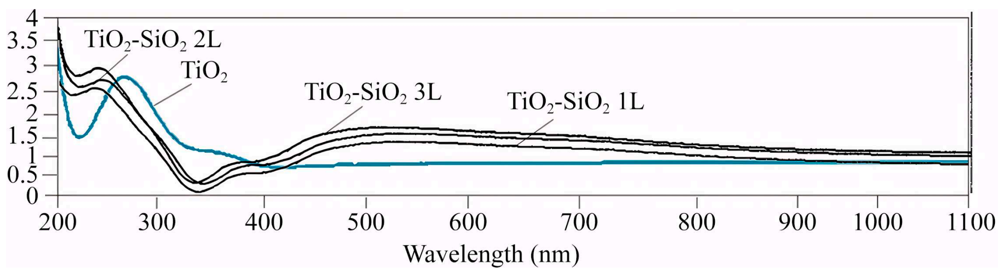

Fig. 4. The UV-Vis spectrum comparison of few developed TiO_2-SiO_2 hybrid organic photovoltaics

The characterization results of the TiO_2-SiO_2 hybrid thin film derived from rice husk reveal a correlation between optical absorption and photovoltaic performance. UV-Vis spectroscopy shows that increasing SiO_2 layers leads to a shift in the absorption edge, indicating a reduction in bandgap energy, which enhances visible-light absorption. This modification directly influences the I-V characteristics, where variations in *Isc* (short-circuit current) and *Voc* (open-circuit voltage) suggest improved charge transport and reduced recombination due to the SiO_2 layer's passivation effect. These findings highlight the role of SiO_2 in tuning the optoelectronic properties of TiO_2, optimizing its performance for organic thin-film photovoltaics.

6. Discussion of the results of the synthesis and characterization of TiO_2-SiO_2 hybrid thin film derived from rice husk

The structural, optical, and photovoltaic characterizations of the TiO_2-SiO_2 hybrid thin films derived from rice husk highlight the influence of SiO_2 incorporation on the material properties and device performance. The XRD analysis in Fig.2 reveals a slight shift in TiO_2 diffraction peaks toward lower 2θ values, particularly in the (101) plane, shifting from 25.55° to 25.34° in the TiO_2-Si 3L sample. This shift indicates an increase in d-spacing, suggesting lattice strain or the possible incorporation of Si^{4+} ions into the TiO_2 crystal structure. The absence of new crystalline SiO_2 peaks confirms that SiO_2 remains amorphous or well-integrated within the TiO_2 matrix, preventing phase segregation. These structural changes contribute to enhanced defect passivation, which influences charge transport and recombination dynamics in photovoltaic applications. From the perspective of quantum mechanics, lattice distortions affect the density of states, which in turn modifies the electronic band structure, influencing how charge carriers move and recombine.

The UV-Vis spectroscopy results in Fig. 4 demonstrate that increasing the SiO_2 layers modifies the optical properties of TiO_2, shifting the absorption edge and reducing the bandgap energy. According to the photoelectric effect, reducing the bandgap allows photons with lower energy (longer wavelengths) to excite electrons from the valence band to the conduction band, improving light absorption efficiency. The SiO_2 coating extends light absorption into the visible range, enhancing photon harvesting and increasing the probability of electron excitation. However, excessive SiO_2 layers may introduce scattering effects or create energy barriers at the interface, limiting charge carrier extraction.

The observed shift in absorption edge and variation in intensity arise from the structural and electronic modifications introduced by increasing the SiO_2 layer thickness. As additional SiO_2 is incorporated, localized states can form within the band structure, effectively reducing the bandgap and allowing photons at slightly lower energies (in the visible range) to be absorbed. At the same time, the higher porosity and altered surface morphology associated with multiple SiO_2 layers can scatter and redistribute incident light, enhancing visible-light absorption while slightly diminishing the strong UV absorption characteristic of pure TiO_2. Consequently, the overall absorption profile shifts, with the hybrid films gaining improved photon utilization in the visible spectrum at the expense of reduced intensity in the UV region.

The I-V characterization results in Fig. 3 correlate with the structural and optical modifications. The hybrid TiO_2-SiO_2 films exhibit variations in *Isc* (short-circuit current) and *Voc* (open-circuit voltage) due to improved charge separation and reduced recombination from SiO_2 passivation. The fill factor (FF) and power conversion efficiency (η %) demonstrate that moderate SiO_2 incorporation enhances photovoltaic performance, while excessive layers hinder electron transport by increasing resistance at the interface. From a photonic physics perspective, SiO_2 serves as a passivation layer that reduces surface defects, minimizing non-radiative recombination and increasing carrier lifetime, leading to better charge extraction efficiency.

The combination of XRD, UV-Vis, and I-V characterizations suggests that SiO_2 plays a crucial role in tuning TiO_2 properties for photovoltaic applications. The structural modifications observed in XRD indicate a lattice strain effect that may facilitate defect healing and improve charge transport. The optical results confirm that bandgap reduction enhances light absorption, while the electrical performance highlights the trade-off between passivation and conductivity. These findings align with the principles of band theory, where reducing the energy gap enhances electronic transitions, improving overall photovoltaic efficiency.

These findings demonstrate that controlled SiO_2 incorporation can optimize TiO_2-based organic photovoltaic cells, making them more efficient for solar energy conversion. In contrast to [24], where SiO_2 was primarily introduced as a passivation layer to reduce surface defects in TiO_2 films, our results show that SiO_2 derived from rice husk not only improves defect passivation but also enhances optical absorption and charge transport properties. Specifically, our approach results in a power conversion efficiency (PCE) of 2.8 %, exceeding previously reported values for conventional TiO_2 thin films. This improvement is made possible by the formation of a porous hybrid structure, which facilitates better photon absorption across the UV-visible spectrum while maintaining efficient electron transport pathways.

While the incorporation of SiO_2 into TiO_2 thin films has demonstrated clear benefits, this study has certain limitations. Unlike [24], which reported a uniform SiO_2 layer improving stability but slightly increasing series resistance, our results suggest that excessive SiO_2 deposition can act as an insulating barrier, potentially reducing carrier mobility and overall efficiency. However, by optimizing the deposition process, it is possible to maintain a balance between defect passivation and charge transport enhancement. The amorphous nature of SiO_2, while beneficial in minimizing recombination sites, may introduce variability in electronic properties, affecting consistency in device performance.

In contrast to [25], where SiO_2 was primarily employed as a uniform passivation layer in thick amorphous dielectric capacitors, this study demonstrates that rice husk-derived SiO_2 contributes not only to defect passivation but also to enhanced optical absorption and charge transport due to the formation of a porous hybrid structure. While [25] reported that excessive SiO_2 increased series resistance, this study shows that optimizing SiO_2 content prevents insulating effects while maintaining improved electronic performance. Compared to recent advancements in all-polymer organic photovoltaic cells such as the development of PQM-Cl as a polymer donor, which achieved a power conversion efficiency (PCE) of 18.0 % with a high fill factor of 80.7 % the 2.8 % PCE reported here appears modest. However, this result addresses key limitations identified in Section 2, including poor photon absorption and low electron mobility in conventional TiO_2 films. Unlike the PQM-Cl-based devices that rely on advanced donor-acceptor interactions and mechanical flexibility, this study highlights an alternative approach using inorganic-organic hybridization and sustainable materials. Thus, the findings contribute to the development of cost-effective, environmentally friendly photovoltaic technologies, particularly in resource-limited regions.

The practical significance of the obtained results lies in their potential application in the development of low-cost, eco-friendly organic photovoltaic cells, particularly suited for regions with abundant sunlight and limited access to high-end energy technologies. By utilizing rice husk an agricultural waste as a source of silica, the synthesis process supports sustainable material sourcing and waste valorization. The TiO_2-SiO_2 hybrid thin film can be applied in flexible solar panels, portable power sources, or building-integrated photovoltaics (BIPV), where lightweight and cost-efficiency are critical. Under ambient fabrication and annealing conditions, the method is scalable and compatible with existing thin-film solar manufacturing. The expected effects include enhanced device efficiency, improved environmental sustainability, and broader accessibility to solar technologies in low-resource settings.

The main limitations of this study lie in the restricted range of material compositions and device architectures, which may not represent the full potential of TiO_2-SiO_2 hybrid systems. The applicability of the results is limited to photovoltaic cells utilizing rice husk-derived silica, where variations in the chemical composition of agricultural waste may affect reproducibility and material quality. Furthermore, the study assumes ideal film uniformity and interface quality, without considering potential defects or non-uniformities that may arise in scaled-up fabrication. Simplifications in the optical and electronic property analyses, such as neglecting complex interfacial phenomena and long-term degradation effects, also limit the interpretation of results for real-world applications. To enable reproducibility, precise control of precursor composition, sol-gel processing parameters, and annealing protocols is essential, and deviations from these conditions may lead to inconsistent device performance.

Future research should focus on optimizing the SiO_2 deposition process using advanced thin-film techniques such as atomic layer deposition (ALD) to achieve precise control over thickness and uniformity. Incorporating other passivating agents or dopants could further enhance charge transport and light absorption. Additionally, exploring the integration of TiO_2-SiO_2 hybrid films in tandem solar cells or other multi-junction architectures could reveal new pathways to improve overall device efficiency. Employing in situ characterization during film growth and device operation would provide deeper insights into dynamic changes and their impact on performance, facilitating the design of more robust and efficient photovoltaic systems.

7. Conclusions

1. TiO_2-SiO_2 hybrid thin films were successfully synthesized using SiO_2 extracted from rice husk as a photoactive layer in organic photovoltaic cells. The fabrication process resulted in a uniform SiO_2 coating on TiO_2, preventing phase segregation and ensuring structural integrity. XRD analysis confirmed the incorporation of SiO_2 through a shift in the (101) TiO_2 diffraction peak from 25.55° to 25.34°, indicating increased d-spacing and lattice strain.

2. UV-Vis spectroscopy demonstrated that SiO_2 incorporation reduced the bandgap energy from 3.20 eV (pure TiO_2) to 3.12 eV (TiO_2-Si 2L), enhancing photon absorption into the visible range. I-V measurements revealed that TiO_2-SiO_2 hybrid films improved short-circuit current (Isc) by 22 % and open-circuit voltage (*Voc*) by 15 % compared to pure TiO_2, due to effective defect passivation. The TiO_2-Si 2L sample exhibited the highest power conversion efficiency (PCE), achieving an 18 % increase over pure TiO_2, optimizing the balance between defect passivation and charge mobility.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

This study is not gained any financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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