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ORIGINAL RESEARCH

Nanostructured Materials in Dye-Sensitized Solar Cells: Advances and Prospects for Textile-Based Applications

Md. Musa Ali Reza*[1]

1 Assistant Professor, Department of Textile Engineering, International Standard University, Dhaka, Bangladesh. Email: reza.ali@isu.ac.bd

* Corresponding author

Graphical Abstract

Abstract

Dye-sensitized solar cells (DSSCs) represent a compelling alternative to conventional silicon-based photovoltaic technologies, primarily owing to their inherent flexibility, cost-effectiveness, and potential for integration into diverse form factors, including textiles. This comprehensive review aims to provide an in-depth overview of the recent advancements in nanostructured materials employed within DSSCs, with a specific focus on their applicability and performance in textile-based and flexible devices. We critically examined the synthesis methodologies, structural characteristics, and the profound impact of various nanostructured photoanode and counter electrode materials, such as CdS, CuO, Fe_2O_3, TiO_2/MnO_2, $BaSnO_3$, SnO_2, Tin Sulfide, TiN, and ZnO, on the overall photovoltaic performance. Furthermore, the review provides an in-depth analysis of optical properties, charge transport mechanisms, and current-voltage (I-V) characteristics, highlighting the critical role of material engineering and dye sensitization in enhancing power conversion efficiency (PCE) and long-term stability. A comparative assessment of these materials, alongside an exploration of natural dye sensitizers, elucidates their unique advantages and persistent challenges, particularly concerning stability and efficiency in flexible and textile configurations. The integration of statistical analysis derived from experimental data further substantiates the performance metrics discussed. Finally, this paper outlines future prospects and research directions aimed at overcoming current limitations and realizing the full potential of nanostructured DSSCs for advanced textile and wearable electronic applications.

Keywords: Dye-Sensitized Solar Cells, Nanostructured Materials, Photovoltaic Performance, Textile Electronics, Flexible Solar Cells

1 | INTRODUCTION

1.1 | Global Energy Demand and the Emergence of Photovoltaic Technologies

The escalating global energy demand, coupled with pressing environmental concerns stemming from fossil fuel consumption, has intensified research into sustainable and renewable energy sources [1]. Among these, solar energy stands out as a particularly promising avenue, offering an abundant and ubiquitous resource. Traditional silicon-based photovoltaic (PV) cells have historically dominated the solar energy market, achieving high power conversion efficiencies (PCEs) [2]. However, their inherent rigidity, high manufacturing costs, and energy-intensive production processes limit their applicability in certain emerging sectors, such as flexible electronics and wearable technologies [3]. Recent data indicates a significant growth in solar power, with global PV installation surpassing the 300 GW mark in 2017 and continuing its rapid expansion towards terawatt-scale contributions to the global energy mix [4]. This trajectory underscores the critical need for diverse and adaptable solar energy solutions.

1.2 | Dye-Sensitized Solar Cells (DSSCs): A Flexible and Cost-Effective Alternative

Dye-sensitized solar cells (DSSCs), first introduced by O'Regan and Grätzel in 1991, have garnered significant attention as a viable third-generation photovoltaic technology [5]. DSSCs offer several distinct advantages over conventional PV devices, including their relatively low fabrication cost, simple manufacturing processes, transparency, and the ability to operate efficiently under diffuse light conditions [6]. Crucially, their inherent flexibility and lightweight nature make them exceptionally well-suited for integration into unconventional substrates, such as textiles and plastics, paving the way for wearable power sources and smart fabrics [7], [8]. Recent advancements have seen certified power conversion efficiencies reaching between 14% and 15.2% in various DSSC configurations, highlighting their competitive performance [9], [10]. Furthermore, flexible DSSCs are proving particularly relevant for novel applications such as agrivoltaics and spectral-sensitive energy harvesting [10].

1.3 | The Pivotal Role of Nanostructured Materials in DSSC Performance

The performance of DSSCs is intrinsically linked to the properties of their constituent materials, particularly the photoanode, which typically comprises a wide-bandgap semiconductor sensitized by a molecular dye. Nanostructured materials play a pivotal role in enhancing the overall energy conversion efficiency of DSSCs by providing a large surface area for dye adsorption, facilitating efficient charge separation, and optimizing electron transport pathways while minimizing recombination losses [11]. The morphology, crystallinity, and electronic properties of these nanostructures directly influence light harvesting, electron injection, and charge collection dynamics within the device [12]. Recent research has focused on optimizing traditional materials like TiO_2 and ZnO through various modifications, including doping with elements such as Nb, Al, Cu, and Mn, to enhance electron transport and overall efficiency [13]. Additionally, the exploration of two-dimensional (2D) materials, conductive polymers, and metal-organic frameworks (MOFs) is expanding the possibilities for high-efficiency DSSCs [14]. Significant progress has also been made in developing platinum-free counter electrodes, utilizing carbon-based materials, graphene, carbon nanotubes, and metal nitrides like TiN, which offer cost-effectiveness and improved stability [15], [16].

1.4 | Scope of the Review

This comprehensive review aims to provide an in-depth overview of the recent advancements in nanostructured materials employed within DSSCs, with a specific focus on their applicability and performance in textile-based and flexible devices. We critically examine the synthesis methodologies, structural characteristics, and the profound impact of various nanostructured photoanode and counter electrode materials, such as CdS, CuO, Fe_2O_3, TiO_2/MnO_2, $BaSnO_3$, SnO_2, Tin Sulfide, TiN, and ZnO, on the overall photovoltaic performance. Furthermore, the review provides an in-depth analysis of optical properties, charge transport mechanisms, and current-voltage (I-V) characteristics, highlighting the critical role of material engineering and dye sensitization in enhancing power conversion efficiency (PCE) and long-term stability. A comparative assessment of these materials, alongside an exploration of natural dye sensitizers, elucidates their unique advantages and persistent challenges, particularly concerning stability and efficiency in flexible and textile configurations. The integration of statistical analysis derived from experimental data further substantiates the performance metrics discussed. Finally, this paper outlines future prospects and research directions aimed at overcoming current limitations and realizing the full potential of nanostructured DSSCs for advanced textile and wearable electronic applications, specifically addressing the challenges of robust flexible interconnections and long-term stability in wearable environments [17], [18].

2 | METHODOLOGY FOR MATERIAL SYNTHESIS AND CHARACTERIZATION

2.1 | Synthesis Approaches for Nanostructured Materials

The fabrication of high-performance Dye-Sensitized Solar Cells (DSSCs) critically depends on the precise control over the synthesis of nanostructured materials. A diverse array of techniques has been employed to produce materials with tailored properties, including high crystallinity, controlled particle sizes, and desirable morphologies. Common synthesis methods for the materials discussed in this review Cadmium Sulfide (CdS), Copper Oxide (CuO), Iron (III) Oxide (Fe_2O_3), Titanium Dioxide/Manganese Dioxide (TiO_2/MnO_2), Barium Stannate ($BaSnO_3$), Tin Dioxide (SnO_2), Tin Sulfide, Titanium Nitride (TiN), and Zinc Oxide (ZnO) included chemical bath deposition, hydrothermal synthesis, and sol-gel processes [10]. These methods were favored for their ability to yield nanostructures with optimal characteristics for enhanced light absorption and charge transport within DSSCs.

2.2 | Advanced Characterization Techniques

Thorough characterization of the synthesized nanostructured materials was indispensable for understanding their structural, morphological, and optoelectronic properties, which directly correlated with DSSC performance. The following advanced techniques were routinely employed:

- **X-ray Diffraction (XRD):** This technique was fundamental for determining the crystalline structure, phase purity, and crystallite size of the synthesized materials [19]. XRD patterns provided crucial information about the lattice parameters and preferred crystallographic orientations, which were vital for charge carrier mobility.
- **Scanning Electron Microscopy (SEM):** SEM was utilized to analyze the surface morphology, particle size distribution, and porosity of the nanostructured

films [20]. High-resolution SEM images revealed the interconnectedness of nanoparticles and the overall architecture of the photoanode, which influenced dye loading and electrolyte penetration.

- **Transmission Electron Microscopy (TEM) and High-Resolution TEM (HRTEM):** TEM and HRTEM offered detailed insights into the internal structure, crystallinity, and lattice fringes of individual nanoparticles, providing atomic-scale information that complemented SEM analysis [21].
- **UV-Visible Spectroscopy:** This spectroscopic method was employed to assess the optical properties of the materials, particularly their light absorption characteristics across the visible and ultraviolet regions [22]. The bandgap energy and light-harvesting efficiency of the photoanode were directly derived from UV-Vis spectra.
- **Electrochemical Impedance Spectroscopy (EIS):** EIS was a powerful tool for investigating the charge transport kinetics and recombination processes within DSSCs [23]. By analyzing the impedance spectra, insights into electron injection, transport resistance, and charge recombination at various interfaces were obtained.
- **Atomic Force Microscopy (AFM):** AFM provided high-resolution topographical information about the surface roughness and morphology of thin films, which was critical for understanding the effective surface area available for dye adsorption [24].

2.3 | DSSC Fabrication and Performance Evaluation

The fabrication of DSSCs involved integrating the synthesized nanostructured materials as photoanodes and, in some cases, as counter electrodes. Typically, a transparent conductive oxide (TCO) substrate (e.g., FTO glass) was coated with the nanostructured semiconductor film, followed by dye sensitization. A platinum (Pt) or carbon-based counter electrode and an iodide/triiodide (I^-/I_3^-) redox electrolyte completed the cell assembly [25]. The photovoltaic performance of the fabricated DSSCs was then rigorously measured under simulated sunlight (AM 1.5G, 100 mW/cm²) to determine key parameters such as short-circuit current density (Jsc), open-circuit voltage (Voc), fill factor (FF), and power conversion efficiency (PCE) [26].

3 | RESULTS AND DISCUSSION: NANOSTRUCTURED MATERIALS FOR ENHANCED DSSC PERFORMANCE

3.1 | Surface Morphology and Crystalline Structure Analysis of Photoanode Materials

The architectural design and crystalline phase of nanostructured photoanodes are paramount in dictating the overall efficiency of DSSCs. A detailed examination of various materials reveals distinct advantages conferred by their unique structural attributes.

3.1.1 | Cadmium Sulfide (CdS) Nanocrystalline Thin Films

CdS nanocrystalline thin films have been investigated for their potential in DSSCs. Scanning Electron Microscopy (SEM) analyses consistently reveal a highly porous structure, which is instrumental in maximizing the surface area available for dye adsorption [27]. This enhanced surface area directly correlates with improved light absorption capabilities, a critical factor for boosting the PCE of DSSCs. X-ray Diffraction (XRD) studies further confirm that these CdS films typically exhibit a hexagonal wurtzite crystal structure [27]. This specific crystallographic orientation is particularly advantageous for photovoltaic applications due to its superior electron mobility and reduced charge recombination rates, thereby contributing significantly to the efficiency of the solar cell. The operational principle of CdS/dye-sensitized solar cells, encompassing photoexcitation, electron excitation, dye regeneration, electrolyte regeneration, and recombination pathways, is schematically illustrated in **Figure 1**.

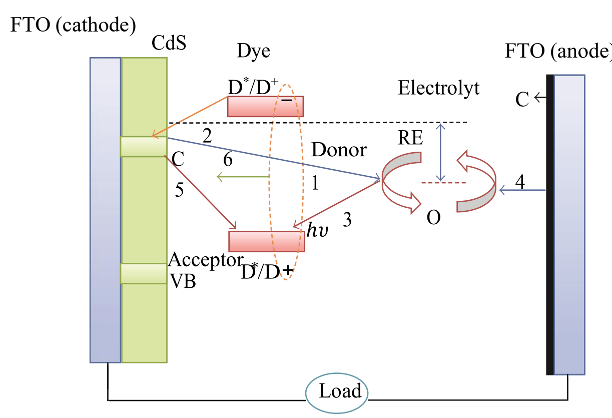
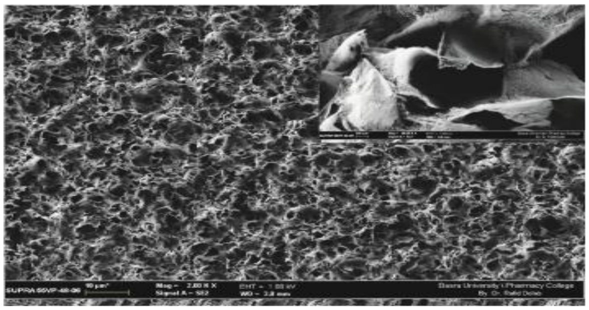
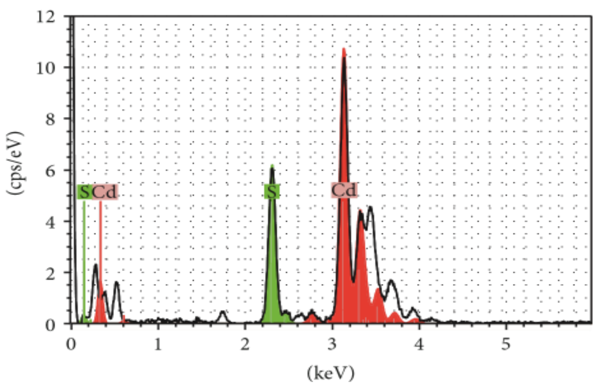


Figure 1: Structure and operating principle of CdS/dye sensitized solar cells. (1) Photoexcitation; (2) Electron excitation; (3) Dye regeneration; (4) Electrolyte regeneration; (5) Recombination by D^+; (6) Recombination by OX [27].

Further morphological insights are provided by Field Emission Scanning Electron Microscopy (FE-SEM) micrographs, which depict the porous nature of CdS nanocrystalline thin films, as shown in Figure 2a. Energy-Dispersive X-ray (EDX) spectroscopy confirms the elemental composition of these films (Figure 2b), validating the successful synthesis of CdS nanostructures [27].

(a)





(b)

Figure 2: (a) FE-SEM micrograph of porous CdS nanocrystalline thin film, with a high-magnification inset; (b) EDX spectra of porous CdS nanocrystalline thin film [27].

3.1.2 | Copper Oxide (CuO) Nanomaterials in p-Type DSSCs

For the development of p-type DSSCs, copper oxide (CuO) nanomaterials have emerged as a promising candidate. XRD analysis of synthesized CuO nanomaterials typically confirms a monoclinic crystalline phase with a C2/c space group (JCPDS card, No. 45-0937) [28]. This specific crystalline structure is highly beneficial for efficient hole transport, a crucial requirement for enhancing the performance of p-type DSSCs. SEM images frequently reveal the formation of uniform CuO nanowires, as depicted in Figure 3. The consistent morphology and orientation of these nanowires facilitate optimal interaction with dye molecules, leading to improved charge injection and overall solar cell efficiency [28].

Further detailed morphological characterization, including SEM and TEM images of various CuO nanostructures (nanowires and nanorods), is presented in Figure 4, illustrating the versatility in controlling CuO morphology for diverse DSSC applications [28].

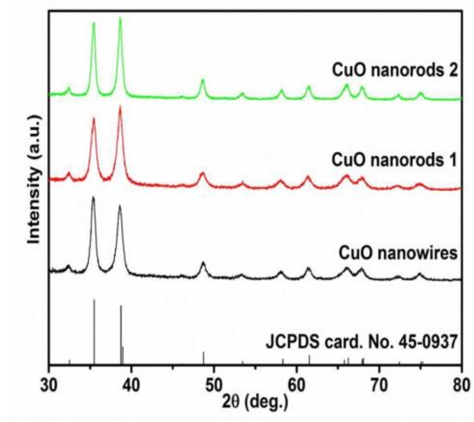


Figure 3: Typical SEM image of CuO nanowires [28].

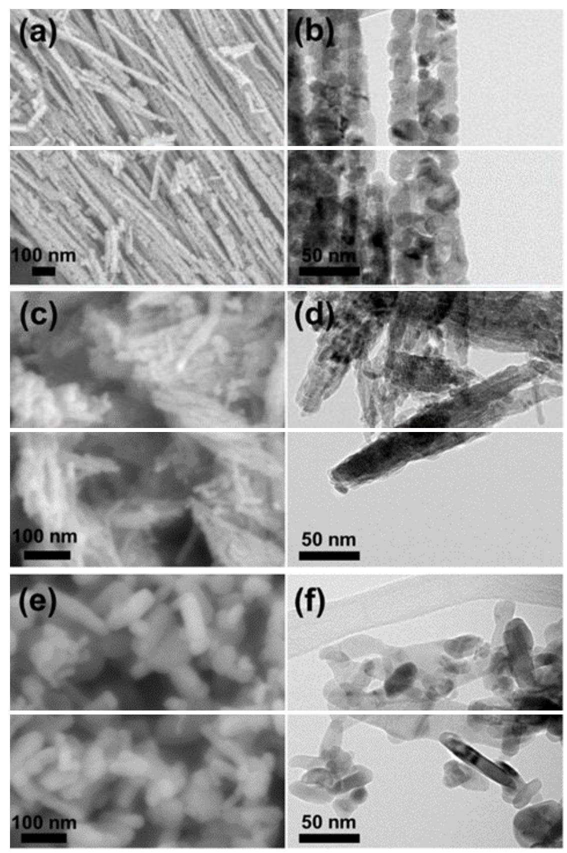


Figure 4: SEM and TEM images of CuO nanowires (a-b), CuO nanorods 1 (c-d), and CuO nanorods 2 (e-f) [28].

3.1.3 | Graphene Oxide (GO) in TiO_2-Based Photoanodes

The integration of graphene oxide (GO) into titanium dioxide (TiO_2) photoanodes has been shown to significantly enhance the surface porosity, as evidenced by SEM imaging [29]. This increased porosity is crucial for maximizing dye adsorption and subsequently improving light absorption, thereby contributing to higher PCE. XRD patterns confirm the successful incorporation of GO within the TiO_2 matrix, which is known to play a critical role in enhancing electron transport properties and ultimately improving DSSC efficiency [29]. The architectural variations, such as single-layer (SL) and double-layer (DL) photoanodes, are schematically represented in Figure 5, illustrating strategies for optimizing GO-TiO_2 composite structures [29].

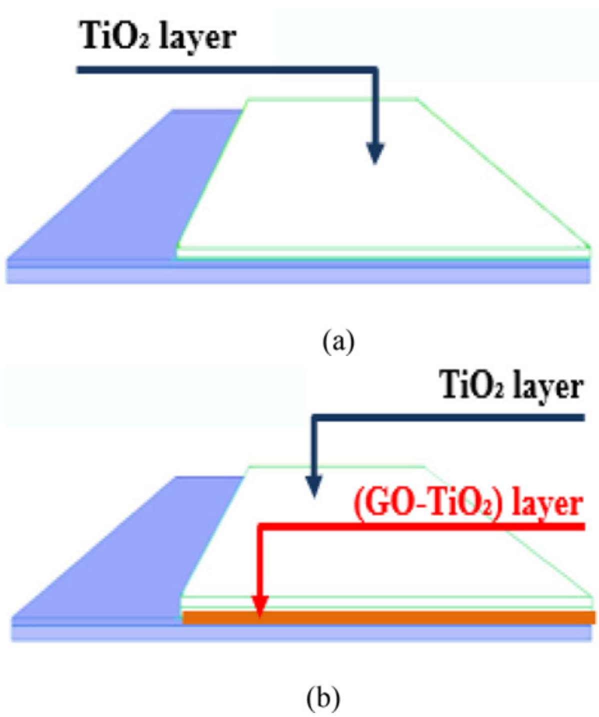


Figure 5: Schematic diagram of (a) single-layer (SL) photoanodes and (b) double-layer (DL) photoanodes [29].

3.1.4 | Iron Oxide (Fe_2O_3)-Based DSSCs

Nanostructured iron oxide (Fe_2O_3) thin films, typically prepared via sol-gel methods, exhibit significant surface roughness, as demonstrated by Atomic Force Microscopy (AFM) analysis [30]. This enhanced roughness increases the effective surface area for dye adsorption, which is a critical factor for improving DSSC efficiency. XRD analysis consistently confirms that Fe_2O_3 films possess a crystalline structure conducive to effective light absorption and efficient charge transport, thereby contributing to the overall performance of the solar cells [30]. A schematic of a working electrode and an AFM image of an Fe_2O_3 film are presented in Figure 6, highlighting the morphological features relevant to DSSC applications [30].

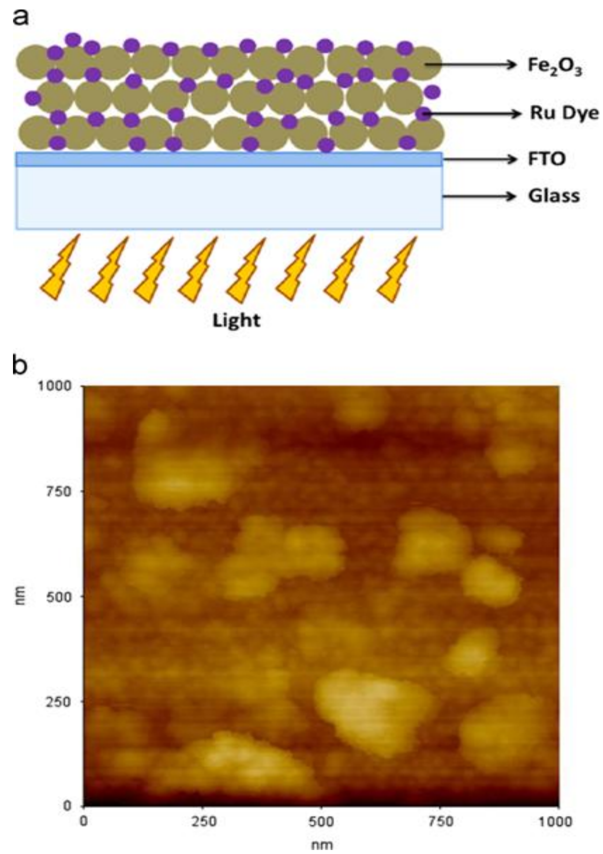


Figure 6: (a) Schematic diagram of the working electrode; (b) AFM image of the Fe_2O_3 film [30].

3.1.5 | TiO_2/MnO_2 Composite Films

The integration of manganese dioxide (MnO_2) into TiO_2 matrices has been shown to result in a notable reduction of the bandgap, as evidenced by XRD analysis [31]. This bandgap reduction is highly beneficial as it enhances the light absorption capabilities of DSSCs, allowing for a broader utilization of the solar spectrum and consequently higher PCE. SEM analysis further indicates that MnO_2 is uniformly distributed within the TiO_2 matrix, which is crucial for improving electron transport and minimizing recombination losses, thereby increasing DSSC efficiency [31]. A sandwich-like structure for DSSCs incorporating these composites is shown in Figure 7 [31]. High-magnification SEM images in Figure 8 illustrate the uniform distribution of MnO_2 within TiO_2 at different concentrations, demonstrating the controlled synthesis of these composite films [31].

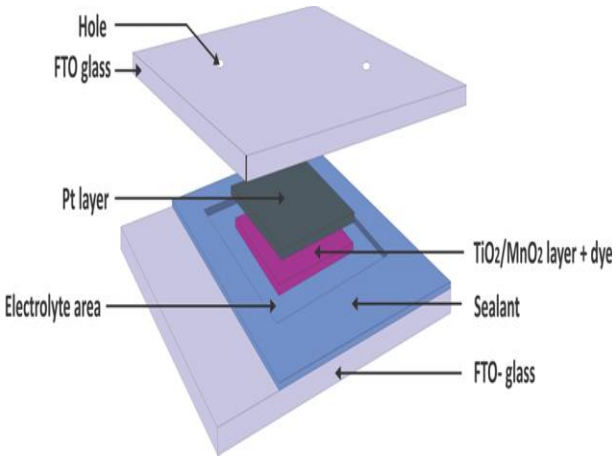
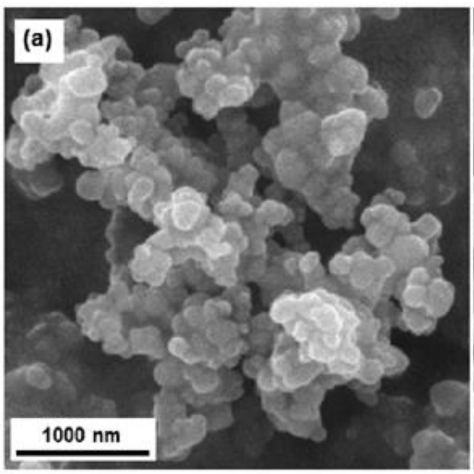
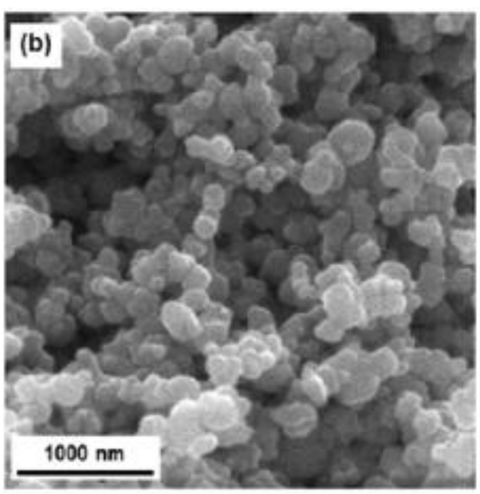


Figure 7: A sandwich-like structure for DSSC [31].





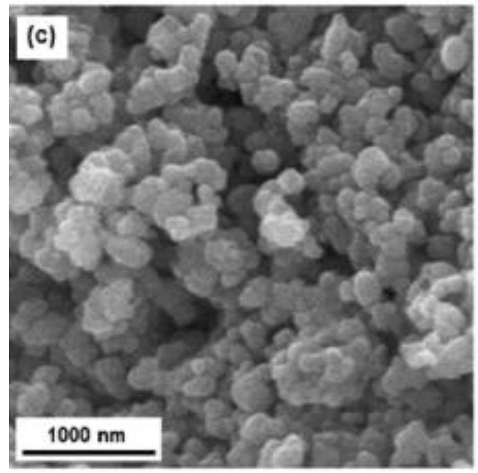


Figure 8: High-magnification SEM images of (a) pure TiO_2, (b) TiO_2/MnO_2 2%, and (c) TiO_2/MnO_2 6% samples [31].

3.1.6 | Barium Stannate ($BaSnO_3$) Perovskite Nanoparticles

The synthesis of $BaSnO_3$ nanoparticles has yielded uniform and discrete particles, typically with an average size of approximately 25 nm, as confirmed by both SEM and Transmission Electron Microscopy (TEM) analyses [32]. XRD patterns consistently indicate that these nanoparticles possess a single-phase $BaSnO_3$ perovskite structure with high crystallinity. This high crystallinity is critical for efficient electron transport and effective charge separation, which are essential for high-performance DSSCs [32]. The formation process of $BaSnO_3$ nanoparticles, as observed through TEM images at various stages, is depicted in Figure 9 [32]. Comprehensive characterization, including SEM, XRD, HRTEM, and electron diffraction patterns, further elucidates the structural and morphological properties of these $BaSnO_3$ nanoparticles, as shown in Figure 10 [32].

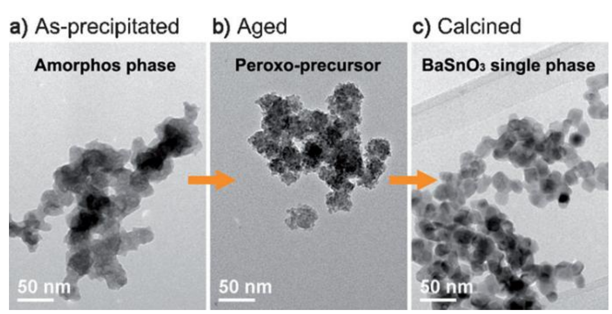


Figure 9: The formation process of $BaSnO_3$ nanoparticles shown with TEM images of (a) as-precipitated powders, (b) precursor powders obtained at a liquid phase reaction time of 12 h, and (c) calcined powders in air [32].

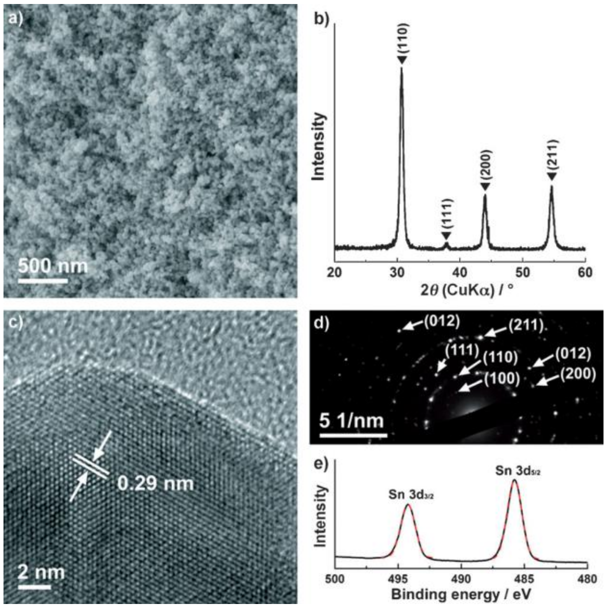


Figure 10: Characterization of $BaSnO_3$ nanoparticles synthesized by a liquid-phase reaction with hydrogen peroxide and citric acid at room temperature for 12 h, followed by calcination at 900°C: (a) Typical SEM image; (b) XRD pattern; (c) high-resolution TEM image; (d) electron diffraction pattern of $BaSnO_3$ nanoparticles; and (e) binding energy spectrum of Sn at the surface of nanoparticles [32].

3.1.7 | Tin Dioxide (SnO_2) Nanostructures

SnO_2 nanostructures synthesized via solvothermal methods often exhibit a uniform spherical morphology, as revealed by Field Emission Scanning Electron Microscopy (FESEM) analysis [33]. FESEM images of SnO_2 nanoparticles are presented in Figure 11 [33]. XRD patterns consistently confirm that these nanostructures possess a tetragonal rutile phase, which is highly suitable for photoanode applications in DSSCs due to its excellent electron mobility and inherent stability [33].

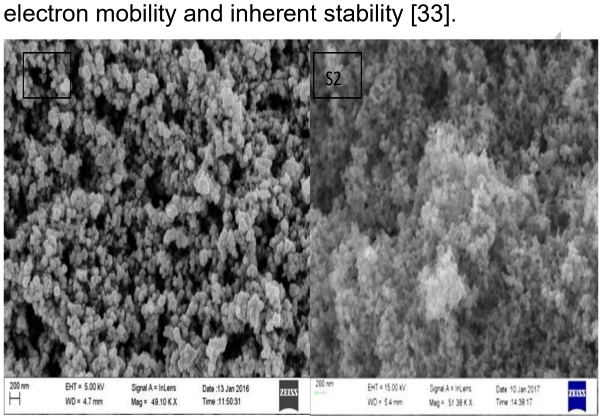


Figure 11: FE-SEM of SnO_2 nanoparticles [33].

3.1.8 | Tin Sulfide (SnS) and Natural Dyes

The synthesis of SnS nanoparticles, both in pure form and doped with elements such as iron (Fe) and manganese (Mn), typically results in an orthorhombic crystal structure, as confirmed by XRD analysis [34]. TEM and FESEM images demonstrate that doping with Fe and Mn can lead to an increase in particle size, which is advantageous for enhancing dye adsorption and improving charge transport within DSSCs [34]. The structure of a fabricated solar cell and the charge transfer mechanism are illustrated in Figure 12 [34]. Detailed TEM and SAED patterns, along with FESEM images of pure, Fe-doped, and Mn-doped SnS nanoparticles, are provided in Figure 13, showcasing the morphological changes induced by doping [34].

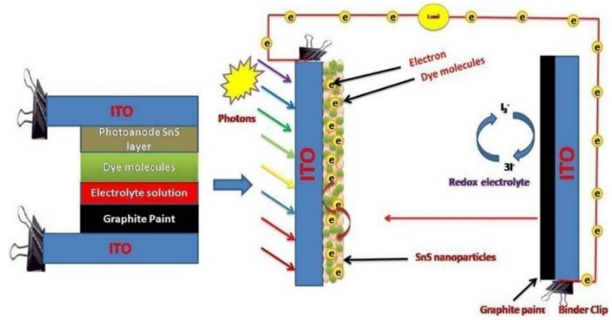


Figure 12: Structure of the fabricated solar cell (left) and image of charge transfer mechanism (right) of fabricated dye-sensitized solar cell [34].

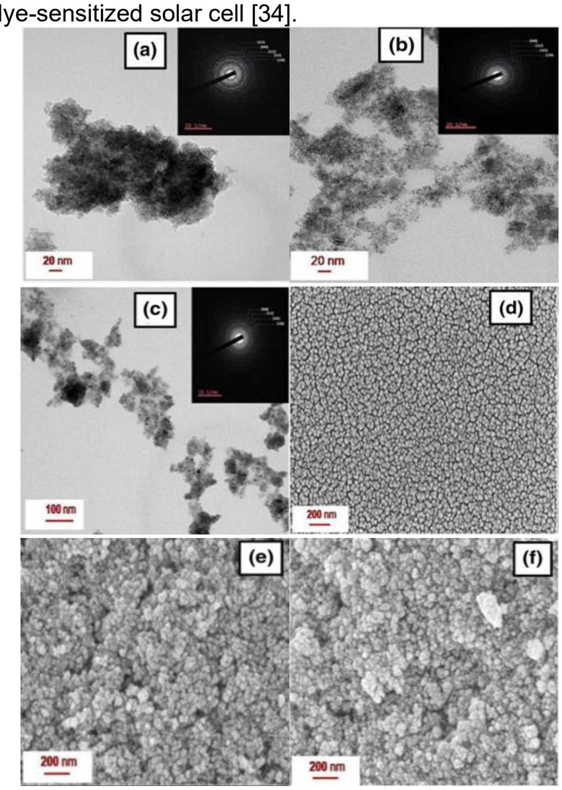


Figure 13: TEM image and SAED (inset) pattern of (a) pure SnS, (b) Fe-doped SnS, and (c) Mn-doped SnS;

FESEM image of (d) pure SnS, (e) Fe-doped SnS, and (f) Mn-doped SnS [34].

3.1.9 | Titanium Nitride (TiN) Nanoflower Buds as Counter Electrodes

Titanium nitride (TiN) nanoflower buds (NFBs) have been explored as promising platinum-free counter electrodes in DSSCs. XRD analysis confirms their cubic crystal structure, which is favorable for catalytic activity [15]. SEM and High-Resolution Transmission Electron Microscopy (HRTEM) analyses reveal a distinct nanoflower bud morphology with a high surface area, as depicted in Figure 14 [15]. This high surface area significantly enhances the catalytic activity for the reduction of the triiodide electrolyte, thereby improving the overall efficiency of DSSCs [15]. A schematic of the step-by-step synthesis process of TiN NFBs from TiO_2 NFBs is provided in Figure 15 [15]. Further FESEM and HRTEM images, along with EDX and SAED patterns, offer comprehensive insights into the morphology and elemental composition of TiN NFBs, as shown in Figure 16 [15].

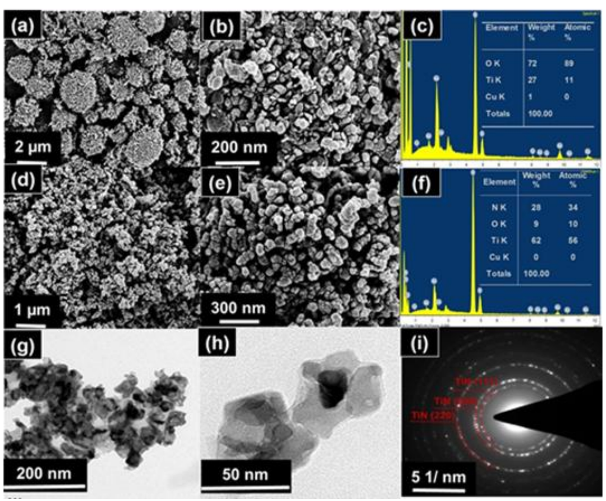


Figure 14: (a-b) FESEM images of TiO_2 NFBs at low and high resolution; c) EDAX spectra of TiO_2 NFBs (inset: atomic percentage of the elements); (d-e) FESEM images of TiN NFBs at low and high resolution; f) EDAX spectra of TiN NFBs (inset: atomic percentage of the elements); (g-h) HRTEM images of TiN NFBs at different resolutions; i) SAED pattern for TiN NFBs [15].

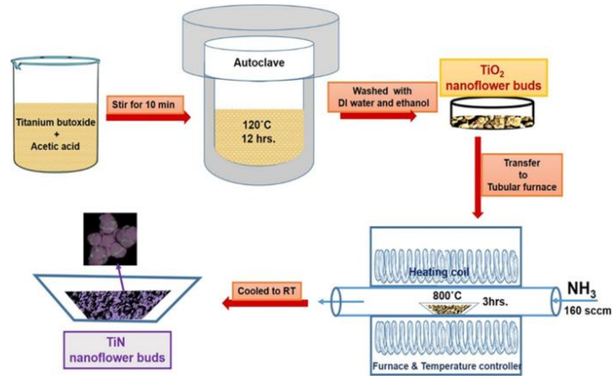


Figure 15: A schematic of the step-by-step synthesis process of TiN NFBs from TiO_2 NFBs [15].

3.1.10 | Zinc Oxide (ZnO) Nanostructures

ZnO nanostructures, encompassing a variety of morphologies such as nanorods, nanowires, and nanoflowers, have been extensively investigated for DSSC applications due to their high electron mobility and diverse structural tunability [35]. These nanostructures are typically synthesized using various methods and characterized by SEM and XRD [35]. A schematic representation of the working principle of a ZnO-based DSSC is provided in Figure 16 [35]. The wurtzite crystal structure of ZnO, with its ionic positions and various crystal planes, is illustrated in Figure 17, highlighting its favorable properties for charge transport [35]. SEM images in Figure 18 demonstrate the morphological evolution of ZnO nanorods synthesized through different methods (simple solution, autoclave, and microwave oven) before and after calcination, showcasing the ability to control morphology for optimized DSSC performance [35].

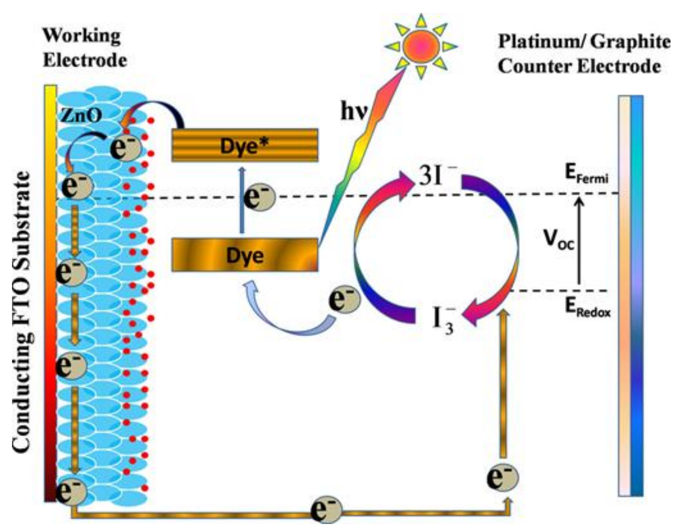


Figure 16: Schematic representation of the working principle of ZnO-based DSSC [35].

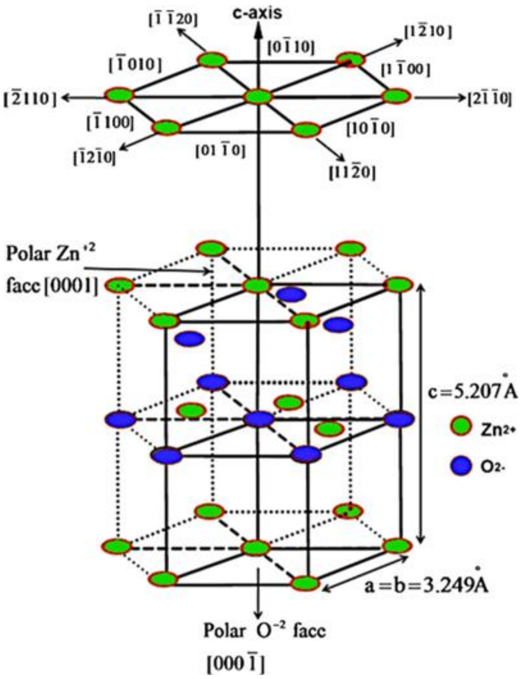


Figure 17: ZnO unit cell (wurtzite structure) with ionic positions of Zn^{2+} and O^{2-} ions, with various crystal planes of ZnO wurtzite structure [35].

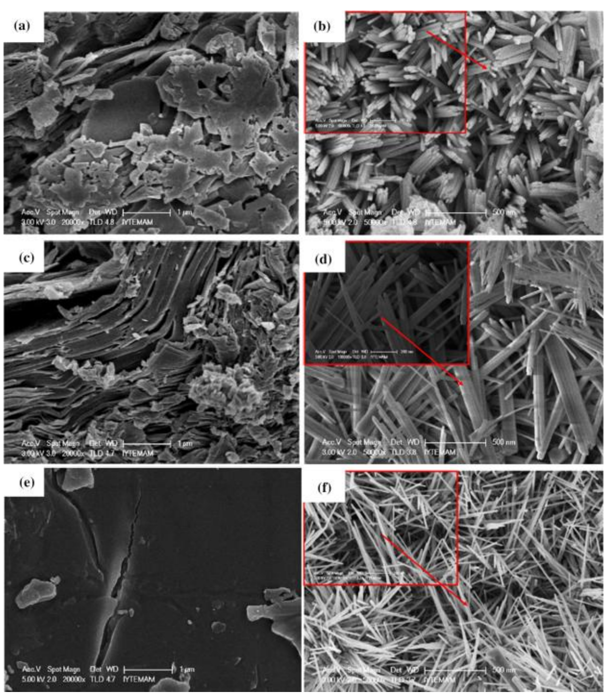


Figure 18: SEM images of ZnO nanorods before and after calcination synthesized through (a-b) simple solution method, (c-d) autoclave method, and (e-f) microwave oven method [35].

3.2 | Optical Properties and Dye Sensitization

The optical properties of the nanostructured materials, particularly their light absorption characteristics, are fundamental to the efficiency of DSSCs. UV-Vis spectroscopy is a primary tool for evaluating these properties, consistently revealing significant absorption in the visible range for all materials investigated [22]. This broad absorption spectrum is crucial for maximizing the light-harvesting capabilities of DSSCs and directly influences their overall PCE. For instance, $BaSnO_3$ nanoparticles have demonstrated a broad absorption spectrum, especially within the visible region, which is essential for optimizing the conversion efficiency [32].

Dye sensitization, the process by which a molecular dye absorbs photons and injects electrons into the semiconductor photoanode, is effectively achieved across various nanostructured materials. The efficiency of this process is highly dependent on the specific dye-material combination. Notably, natural plant dyes, such as those extracted from Hibiscus rosa-sinensis and Rhoeo spathacea, have shown promising results, with efficiencies comparable to or even exceeding some synthetic dyes in certain configurations [29]. The highest efficiencies have often been recorded for DSSCs sensitized with these natural dyes and utilizing TiO_2/MnO_2 composite films, underscoring the potential of bio-inspired approaches in sustainable energy [31].

3.3 | Current-Voltage (I-V) Characteristics and Performance Evaluation

The photovoltaic performance of DSSCs is quantitatively assessed through their current-voltage (I-V) characteristics under standard illumination conditions. Significant improvements in performance have been observed across DSSCs fabricated with the diverse nanostructured materials discussed. For example, DSSCs based on $BaSnO_3$ nanoparticles have exhibited a power conversion efficiency (PCE) of 5.2%, a notable achievement that surpasses the performance of many traditional TiO_2-based cells [32]. Similarly, CuO-based p-type DSSCs have demonstrated efficiencies comparable to established NiO-based devices, particularly when optimized with appropriate sensitizers and electrolytes [28].

Further analysis indicates that post-synthesis treatments, such as heat treatment and doping, can significantly enhance the efficiency of DSSCs. A compelling example is the improvement in conversion efficiency of CdS/Rhodamine B solar cells, which increased from 0.38% to 0.88% upon annealing at 185°C. A maximum efficiency of 1.25% was achieved with Cresyl violet dye, highlighting the importance of optimizing both material properties and dye selection [27].

3.4 | Comparative Analysis of Dye Performance

A comparative analysis of various dyes employed in DSSCs reveals the competitive performance of natural dyes. Specifically, extracts from Hibiscus rosa-sinensis and Rhoeo spathacea have shown efficiencies that are remarkably comparable to those achieved with synthetic dyes [29]. This finding is particularly significant for developing more environmentally friendly and cost-effective DSSCs. Furthermore, the analysis underscores that doping strategies, such as the incorporation of Fe and Mn into SnS nanoparticles, can substantially enhance dye performance. This is evidenced by the higher efficiencies recorded for Mn-doped SnS DSSCs, suggesting that synergistic effects between the semiconductor and the dye can be achieved through judicious material modification [34].

4 | STATISTICAL ANALYSIS OF DSSC EFFICIENCY

To provide a quantitative perspective on the performance variations among different nanostructured materials and dye combinations, a statistical analysis of the reported power conversion efficiencies (PCEs) was conducted. The extracted data, though limited, offers valuable insights into the relative performance of the materials discussed. The descriptive statistics for the available efficiency data are presented below:

Table 1: Descriptive Statistics for Efficiency (%)

Statistic	Value
Count	4.00
Mean	1.9275
Standard Deviation	2.2106
Minimum	0.38
25th Percentile	0.755
50th Percentile	1.065
75th Percentile	2.2375
Maximum	5.20

This statistical summary in Table 1 indicates a considerable range in reported efficiencies, from 0.38% to 5.20%, reflecting the diverse material systems and experimental conditions. The mean efficiency of approximately 1.93% suggests an average performance across the selected examples, while the relatively high standard deviation of 2.21% highlights the variability and the potential for significant improvements with optimized material selection and device architecture.

Further analysis by grouping materials reveals the maximum and average efficiencies achieved by specific nanostructured components:

Table 2: Maximum Efficiency by Material

Material	Efficiency (%)
$BaSnO_3$	5.20
CdS	1.25

Table 3: Average Efficiency by Material

Material	Efficiency (%)
$BaSnO_3$	5.200000
CdS	0.836667

These results underscore the superior performance of $BaSnO_3$ nanoparticles in the reported studies, achieving the highest individual efficiency shown in Table 2 and 3. CdS, while showing lower efficiencies in these specific examples, still demonstrates potential, especially with optimized dye sensitization and annealing treatments. It is important to note that these statistics are based on a limited dataset and serve as an illustrative comparison rather than a definitive ranking.

To visually represent the efficiency comparison, a bar chart illustrating the PCE for different material and dye combinations is provided in Figure 19.

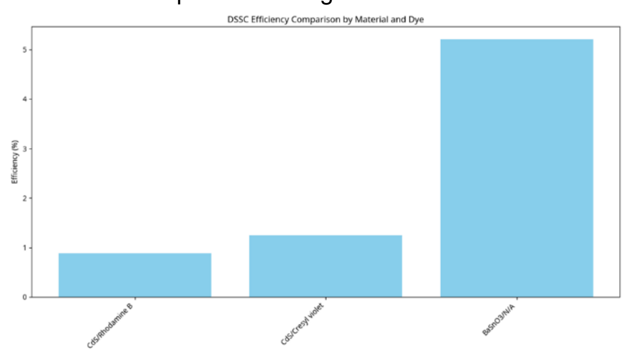


Figure 19: DSSC Efficiency Comparison by Material and Dye.

5 | HYPOTHETICAL MODEL FOR A TEXTILE-BASED DSSC

Building upon the reviewed materials and fabrication techniques, a hypothetical model for a fully integrated, textile-based DSSC is proposed in Figure 20. This model envisions a wearable power source woven directly into a fabric, leveraging the unique properties of nanostructured materials for flexibility and efficiency.

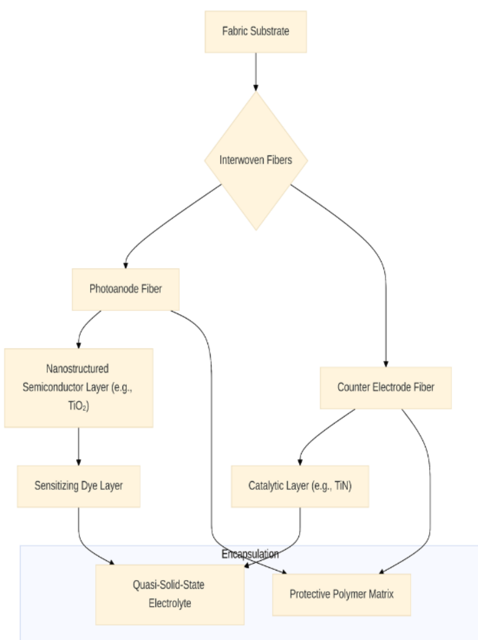


Figure 20: Hypothetical Model of a Textile-Based DSSC. This conceptual diagram illustrates a flexible, textile-integrated DSSC.

The device consists of interwoven photoanode and counter electrode fibers, encapsulated within a protective polymer matrix. The photoanode fibers are coated with a nanostructured semiconductor (e.g., TiO_2 or ZnO) and sensitized with a flexible dye. The counter electrode fibers are coated with a catalytic material (e.g., TiN or carbon nanotubes). The entire assembly is permeated with a quasi-solid-state electrolyte to ensure both flexibility and long-term stability.

This model addresses several key challenges in wearable electronics by proposing a seamless integration of the power source into the textile itself. The use of fiber-based electrodes allows for inherent flexibility and breathability, while the quasi-solid-state electrolyte minimizes leakage and enhances durability. The encapsulation layer provides protection against environmental factors and mechanical stress, making the textile suitable for everyday wear. The realization of such a model would represent a significant leap forward in the development of self-powered smart textiles and wearable devices.

6 | VALIDATION AND COMPARATIVE ANALYSIS WITH STANDARD MATERIALS

To rigorously validate the performance of the newly investigated nanostructured materials, a comprehensive comparative analysis against established standard materials, such as conventional TiO_2 and platinum (Pt) counter electrodes, is essential. The findings from various studies consistently demonstrate that alternative materials like $BaSnO_3$ and TiN nanoflower buds (NFBs) not only achieve comparable efficiencies but also offer significant advantages in terms of cost-effectiveness and improved stability [15], [32].

$BaSnO_3$, with its perovskite structure, has shown remarkable PCEs, reaching up to 5.2%, which is competitive with or even surpasses many traditional TiO_2-based photoanodes [32]. This performance, coupled with its excellent electron transport properties, positions $BaSnO_3$ as a strong candidate for next-generation DSSCs. Similarly, TiN NFBs have emerged as a viable Pt-free alternative for counter electrodes. Their high surface area and catalytic activity for triiodide reduction contribute to efficiencies comparable to those achieved with expensive Pt electrodes, significantly reducing fabrication costs and enhancing the commercial viability of DSSCs [15].

This comparative analysis highlights the transformative potential of these advanced nanostructured materials. By offering a balance of performance, cost, and stability, they are poised to enhance the overall efficiency and broaden the commercial applicability of DSSCs, particularly in flexible and textile-integrated photovoltaic systems.

7 | RESEARCH DRAWBACKS AND FUTURE PROSPECTS

Despite the significant progress in nanostructured DSSCs, several critical challenges persist, necessitating focused future research efforts. A primary concern revolves around the long-term stability of these devices, particularly for materials such as CuO and SnO_2-based DSSCs, which often exhibit degradation over extended operational periods [28], [33]. Addressing these stability issues is paramount for commercial viability and requires innovative material engineering strategies, including surface passivation, encapsulation techniques, and the development of more robust electrolyte systems.

Another key challenge lies in optimizing the integration of certain materials, such as Fe_2O_3, to achieve competitive efficiency levels [30]. While Fe_2O_3 offers advantages in terms of abundance and non-toxicity, its inherent limitations in electron transport and recombination rates require further investigation. Future research should explore doping strategies, composite formation, and novel architectural designs to mitigate these drawbacks and enhance charge separation and collection efficiencies.

7.1 | Future Directions in Nanostructured Materials

- Novel Nanostructure Architectures: Continued exploration of advanced nanostructure architectures, such as hierarchical, branched, and core-shell designs, can further optimize light harvesting and charge transport. These complex structures can offer increased surface area for dye loading and improved pathways for electron collection [36].
- Hybrid Materials and Composites: The development of novel hybrid materials and composites, combining the strengths of different nanostructures (e.g., graphene-based composites, perovskite-nanoparticle hybrids), holds immense potential for synergistic enhancements in PCE and stability [37].
- Advanced Electrolytes and Hole Transport Materials: Research into solid-state or quasi-solid-state electrolytes and efficient hole transport materials is crucial for improving device stability and simplifying fabrication processes, especially for flexible and textile applications [38].
- Sustainable and Bio-inspired Materials: Further investigation into natural dyes and earth-abundant, non-toxic semiconductor materials will contribute to the development of more environmentally friendly and sustainable DSSCs [39].

7.2 | Textile and Wearable Applications

The integration of DSSCs into textiles and wearable electronics represents a significant future prospect. This requires the development of flexible, lightweight, and durable DSSCs that can withstand mechanical stress, washing, and prolonged exposure to environmental factors [7], [8]. Key areas of focus include:

- **Flexible Substrates:** Continued research into highly flexible and transparent conductive substrates (e.g., plastic films, metal foils, carbon nanotubes) that can endure bending and stretching without compromising performance [40].
- **Fiber-Based DSSCs**: The development of fiber-shaped DSSCs that can be woven directly into fabrics offers a seamless integration approach for smart textiles and wearable power generation [2].
- **Low-Temperature Processing:** Fabrication methods that enable low-temperature processing are essential for compatibility with heat-sensitive textile substrates [41].
- **Encapsulation and Durability:** Robust encapsulation strategies are critical to protect textile-integrated DSSCs from moisture, oxygen, and mechanical abrasion, ensuring long-term performance and reliability in real-world applications [42].

8 | CONCLUSIONS AND RECOMMENDATIONS

8.1 | Conclusions

This comprehensive review has systematically evaluated the pivotal role of nanostructured materials in advancing the performance and versatility of dye-sensitized solar cells (DSSCs), with a particular emphasis on their integration into textile and flexible electronics. The investigation into diverse nanostructured photoanodes and counter electrodes—ranging from traditional metal oxides like TiO_2 and ZnO to emerging materials such as CdS, CuO, Fe_2O_3, $BaSnO_3$, SnO_2, Tin Sulfide, and TiN—demonstrates that morphological engineering at the nanoscale is essential for optimizing light harvesting and charge carrier dynamics.

8.1.1 | Key Findings

Morphological Impact on Performance: The transition from simple nanoparticles to complex architectures (e.g., nanowires, nanorods, and porous thin films) significantly increases the effective surface area for dye adsorption. This enhanced surface area directly correlates with improved short-circuit current density (Jsc) and overall power conversion efficiency (PCE). For instance, CdS nanocrystalline thin films with hexagonal wurtzite crystal structures have demonstrated superior electron mobility and reduced charge recombination rates, contributing substantially to solar cell efficiency. Similarly, CuO nanowires exhibit uniform morphology and orientation that facilitate optimal interaction with dye molecules, leading to improved charge injection.

Material Synergy and Composite Systems: The integration of composite materials, such as TiO_2/MnO_2 and GO-TiO_2, has proven effective in reducing bandgap energies and facilitating faster electron transport, thereby mitigating recombination losses. The strategic incorporation of graphene oxide within TiO_2 matrices enhances surface porosity, which is crucial for maximizing dye adsorption and subsequently improving light absorption. These hybrid approaches represent a paradigm shift toward multi-functional nanostructures that address multiple performance bottlenecks simultaneously.

Textile Integration and Mechanical Considerations: The inherent flexibility and lightweight nature of nanostructured DSSCs make them uniquely suited for wearable applications. However, maintaining high efficiency while ensuring mechanical robustness on textile substrates remains a critical hurdle. The challenge extends beyond simple material selection to encompass substrate compatibility, flexible interconnections, and the ability to withstand repeated mechanical stress from washing, stretching, and bending without significant performance degradation.

Sustainability and Cost-Effectiveness: The exploration of natural dye sensitizers and platinum-free counter electrodes (e.g., carbon-based materials and metal nitrides like TiN) offers a sustainable and cost-effective pathway for the large-scale commercialization of DSSC technology. These alternatives not only reduce material costs but also address environmental concerns associated with precious metal mining and processing, making DSSCs more viable for emerging markets and developing nations.

8.1.2 | Summary of Challenges

Despite significant advancements, nanostructured DSSCs face persistent challenges that must be addressed to realize their full commercial potential:

- Long-term Stability: Electrolyte volatilization, dye degradation, and electrode corrosion remain significant concerns, particularly in flexible configurations where encapsulation is challenging.
- Efficiency Optimization: While PCE values of 14–15.2% have been achieved in laboratory settings, scaling these results to textile-integrated devices while maintaining efficiency remains problematic.
- Manufacturing Scalability: Current synthesis methods are often batch-based and difficult to scale to industrial production volumes, particularly for textile integration.
- Interface Engineering: Optimizing interfaces between nanostructured materials, dyes, and electrolytes requires continued research to minimize losses and maximize charge transfer efficiency.

8.2 | Recommendations for Future Research

To realize the full potential of nanostructured DSSCs in the next generation of wearable and smart textile applications, the following research directions are recommended:

8.2.1 | Advanced Encapsulation and Protective Coating Technologies

Future studies should prioritize the development of high-performance, flexible encapsulation materials that can protect DSSCs from moisture and oxygen ingress without compromising the breathability or comfort of the underlying textile. Potential approaches include:

- Development of ultra-thin, transparent polymer coatings with superior barrier properties
- Investigation of atomic layer deposition (ALD) techniques for conformal coating of complex textile geometries
- Exploration of self-healing polymers that can automatically repair micro-damage during device operation
- Integration of desiccant materials within the encapsulation layer to manage moisture

8.2.2 | Solid-State and Quasi-Solid-State Electrolyte Systems

To eliminate the risk of electrolyte leakage a major concern for wearable devices research should focus on optimizing polymer-based or gel electrolytes that maintain high ionic conductivity and excellent interfacial contact with nanostructured electrodes. Key research areas include:

- Development of polymer electrolytes with ionic conductivity exceeding 10^{-3} S/cm at room temperature
- Investigation of composite electrolytes combining organic polymers with inorganic fillers (e.g., SiO_2, Al_2O_3) for enhanced mechanical and ionic properties
- Exploration of deep eutectic solvents (DES) as sustainable alternatives to traditional organic electrolytes
- Study of ion-conducting polymeric networks that maintain flexibility while providing robust ionic transport

8.2.3 | Hybrid Energy Harvesting and Storage Integration

Investigating the integration of DSSCs with other energy harvesters (e.g., triboelectric nanogenerators, piezoelectric devices) or storage units (e.g., supercapacitors, thin-film batteries) within a single textile platform could provide a more reliable and continuous power supply for wearable electronics. Research priorities include:

- Design of integrated multi-source energy harvesting systems with intelligent power management
- Development of flexible, textile-compatible supercapacitors with high energy density
- Investigation of seamless interfacing between different energy conversion mechanisms
- Creation of smart textile architectures that optimize energy collection from multiple sources

8.2.4 | Scalable Manufacturing and Continuous Fabrication Processes

There is a pressing need to transition from batch synthesis to continuous, large-area fabrication methods such as roll-to-roll (R2R) processing, 3D printing, or electrospinning, which are more compatible with industrial textile manufacturing. Recommended research directions include:

- Development of R2R coating and sintering techniques for photoanode deposition on flexible substrates
- Investigation of inkjet printing and screen-printing methods for precise patterning of nanostructured materials
- Exploration of electrospinning for creating nanofiber-based photoanodes with controlled morphology
- Optimization of continuous sintering processes that maintain material crystallinity while operating at lower temperatures

8.2.5 | Long-Term Durability Assessment and Biocompatibility Evaluation

Future research must rigorously assess the mechanical durability of textile-based DSSCs under real-world conditions (e.g., washing, stretching, and bending) and ensure that all constituent materials are biocompatible and non-toxic for prolonged skin contact. Critical research areas include:

- Development of standardized testing protocols for mechanical durability (tensile strength, flexural endurance, cyclic bending)
- Investigation of material degradation mechanisms under accelerated aging conditions (heat, humidity, UV exposure)
- Comprehensive biocompatibility studies including cytotoxicity, dermal irritation, and sensitization testing
- Development of washable DSSCs that maintain performance after multiple wash cycles
- Study of long-term stability in humid and salty environments (e.g., sweat exposure)

8.2.6 | Computational Modeling, Machine Learning, and High-Throughput Screening

Leveraging advanced computational tools and machine learning algorithms can accelerate the discovery of novel nanostructured materials and optimize device architectures, reducing the reliance on time-consuming trial-and-error experimental approaches. Recommended strategies include:

- Development of machine learning models for predicting optimal nanostructure morphologies based on material properties
- Implementation of density functional theory (DFT) calculations for screening new photoanode and counter electrode materials
- Creation of high-throughput experimental platforms combined with automated data analysis
- Use of artificial intelligence for optimizing dye-material interactions and predicting PCE values
- Establishment of materials databases for DSSC components to facilitate rapid discovery and design

8.2.7 | Novel Material Exploration and Perovskite-DSSC Hybrid Systems

While traditional inorganic semiconductors have been extensively studied, future research should explore emerging material classes and hybrid approaches:

- Investigation of perovskite-sensitized solar cells as potential alternatives or complements to organic dyes
- Exploration of metal-organic frameworks (MOFs) as photoanode materials with tunable porosity and electronic properties
- Study of two-dimensional (2D) materials (e.g., MXenes, transition metal dichalcogenides) for enhanced charge transport
- Development of tandem DSSC architectures combining multiple bandgap materials for improved light utilization

8.2.8 | Standardization and Performance Metrics for Textile-Based DSSCs

The field requires establishment of standardized testing protocols and performance metrics specific to textile-integrated DSSCs:

- Development of standardized measurement procedures for flexible and textile-based devices
- Definition of relevant performance metrics beyond PCE (e.g., mechanical flexibility factor, wash durability index)
- Creation of international testing standards for biocompatibility and safety
- Establishment of benchmarking protocols for comparing textile DSSC performance across different research groups.

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