Gurukul International Multidisciplinary Research Journal (GIMRJ)*with* International Impact Factor 8.357
Peer Reviewed Journal
https://doi.org/10.69758/GIMRJ/2505I5VXIIIP0026
e-ISSN No. 2394-8426
Monthly Issue
MAY-2025
Issue–V, Volume–XIII

Poly(aniline)-Based Dye-Sensitized Solar Cells: Synthesis, Performance, and Future Prospects

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Abstract

Dye-Sensitized Solar Cells (DSSCs) have garnered substantial attention due to their cost-effectiveness, ease of fabrication, and promising photovoltaic performance. Poly(aniline) (PANI), a conductive polymer with remarkable electrical properties, environmental stability, and facile synthesis, has emerged as a potential material for enhancing DSSC performance. This review delves into the synthesis methods of PANI for DSSC applications, its influence on performance metrics, stability challenges, and prospective research directions. The integration of PANI into DSSCs opens avenues for improved charge transport, reduced recombination, and enhanced efficiency, positioning it as a key material in the quest for sustainable solar energy technologies.

Introduction

With the growing global demand for renewable energy, dye-sensitized solar cells (DSSCs) have garnered considerable attention as a promising alternative to conventional silicon-based photovoltaic technologies. First introduced by O'Regan and Grätzel in 1991, DSSCs offer several advantages, such as low production costs, simple fabrication techniques, and the ability to function efficiently under diffuse light conditions. These features make DSSCs particularly attractive for applications ranging from portable electronics to building-integrated photovoltaics.

A typical DSSC consists of four key components: a photoanode, a sensitizer (dye), an electrolyte, and a counter electrode (CE). The counter electrode plays a crucial role in facilitating the reduction of the redox couple in the electrolyte, ensuring efficient charge transfer and minimizing charge recombination. Traditionally, platinum (Pt) has been used as the counter electrode material due to its excellent catalytic activity and high conductivity. However, the high cost, scarcity, and susceptibility to corrosion of platinum have driven the search for alternative materials that are cost-effective, stable, and capable of achieving comparable performance.

In this context, poly(aniline) (PANI), a conducting polymer, has emerged as a promising alternative due to its unique physicochemical properties. PANI is known for its high electrical conductivity, environmental stability, and ease of synthesis. Furthermore, PANI's conductivity and electrochemical behavior can be tuned through doping, making it highly versatile for different applications. When incorporated into DSSCs, poly(aniline) can serve either as a standalone counter electrode material or as part of composite structures with other conductive materials, enhancing the overall device performance.

Over the past decade, researchers have extensively investigated the synthesis, modification, and integration of poly(aniline) into DSSCs, leading to notable improvements in power conversion efficiency (PCE) and long-term stability. Various synthesis methods, such as chemical oxidative polymerization, electrochemical polymerization, and template-assisted synthesis, have been explored to optimize PANI's structure and morphology. Additionally, the formation of composites with materials like carbon nanotubes, graphene, and metal oxides has shown promise in further enhancing conductivity and catalytic activity.
Despite these advancements, several challenges remain. Issues such as long-term stability, charge transfer efficiency, and the potential for degradation under prolonged exposure to light and moisture require further investigation. Understanding these factors is critical for the practical deployment of poly(aniline)-based DSSCs in real-world applications.
This review aims to provide a comprehensive overview of the synthesis methods, performance metrics, stability concerns, and future prospects of poly(aniline)-based DSSCs. By examining recent developments and identifying existing challenges, this work seeks to highlight the potential pathways for further enhancing the efficiency and durability of DSSCs, paving the way for more sustainable and economically viable solar energy solutions.

Results and Discussion

Synthesis Methods

Poly(aniline) (PANI) has been synthesized using various methods to optimize its properties for dye-sensitized solar cell (DSSC) applications. The most commonly explored techniques include chemical oxidative polymerization, electrochemical polymerization, and template-assisted synthesis, each offering unique advantages and challenges.

1. Chemical Oxidative Polymerization: This method is widely employed due to its simplicity, cost-effectiveness, and scalability. In this process, aniline monomers are polymerized using oxidizing agents like ammonium persulfate (APS) or ferric chloride in acidic media. Wang et al. (2017) synthesized PANI via chemical oxidative polymerization, achieving a power conversion efficiency (PCE) of 6.5% when used as a counter electrode in DSSCs, attributing the improvement to the increased surface area and enhanced catalytic activity. Similarly, Li et al. (2018) optimized the reaction conditions, adjusting factors like monomer-to-oxidant ratio and reaction temperature, achieving a slightly higher PCE of 7.1%. One notable limitation of this method is the tendency for overoxidation, which can lead to structural inhomogeneity and reduced conductivity. Recent studies have explored dopants such as sulfuric acid and camphorsulfonic acid to enhance conductivity and improve stability.

2. Electrochemical Polymerization: Electrochemical polymerization offers precise control over film thickness and morphology by adjusting parameters like current density, deposition time, and applied potential. Zhang et al. (2019) demonstrated that PANI synthesized electrochemically exhibited superior conductivity and strong adhesion to the substrate, resulting in a PCE of 7.3%. The electrochemical process allows for the direct deposition of PANI onto the desired substrate, simplifying fabrication. Kim et al. (2020) further refined this method by introducing pulse deposition techniques to enhance uniformity, resulting in fewer defects and better charge transport. However, the formation of pinholes and non-uniform films remains a concern, requiring meticulous control over deposition parameters.

3. Template-Assisted Synthesis: Template-assisted synthesis involves using templates such as porous membranes, surfactants, or hard templates (e.g., silica spheres) to guide polymer growth, producing nanostructured PANI with enhanced surface area and porosity. Singh et al. (2021) synthesized PANI nanofibers through this method, reporting a PCE of 7.8%. The enhanced performance was attributed to the increased surface area, which facilitated better dye adsorption and charge transfer. Another approach involved using polystyrene spheres as templates, which produced PANI hollow spheres with improved charge transport properties (Chen et al., 2022). While this method improves catalytic activity and reduces charge recombination, template removal can introduce impurities and complicate large-scale production.

4. Composite Formation: To further enhance PANI's properties, researchers have explored composites with materials like carbon nanotubes (CNTs), graphene, and metal oxides. For instance, Rao et al. (2022) synthesized a PANI-graphene composite that achieved a PCE of 8.2%, citing improved conductivity, increased surface area, and reduced charge recombination. The incorporation of CNTs has shown potential in enhancing mechanical stability and long-term durability by providing robust conductive pathways. Additionally, Ahmed et al. (2023) reported that a PANI-TiO_2 composite not only improved efficiency but also exhibited enhanced stability, maintaining 90% of its initial performance after 1000 hours of continuous operation. Hybrid structures leveraging synergistic effects between PANI and nanostructured materials have opened new avenues for improving both efficiency and stability.

Comparative Analysis: Each synthesis method presents distinct trade-offs. Chemical oxidative polymerization offers simplicity, scalability, and cost-effectiveness but often results in structural inconsistencies and reduced conductivity due to overoxidation. Electrochemical polymerization provides better control over film properties and enables direct deposition onto substrates, but non-uniform coatings and pinhole formation require optimization. Template-assisted synthesis delivers well-defined nanostructures, improving catalytic activity and charge transfer, though the complexity of template removal poses challenges for large-scale applications. Composite formation stands out as a highly promising approach, leveraging the synergistic effects of PANI with other conductive materials to significantly boost performance and stability.

Overall, the choice of synthesis method depends on the desired balance between efficiency, stability, and fabrication complexity. Combining techniques — such as using electrochemical polymerization for film deposition followed by composite formation with carbon-based materials — has shown potential in achieving superior performance metrics. The growing body of research underscores the importance of fine-tuning synthesis parameters and exploring novel composites to unlock the full potential of poly(aniline)-based DSSCs.

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Performance Metrics

The performance of poly(aniline)-based DSSCs is typically evaluated using key parameters such as power conversion efficiency (PCE), fill factor (FF), short-circuit current density (Jsc), and open-circuit voltage (Voc). These metrics provide insight into the effectiveness of different synthesis methods and composite strategies in enhancing device performance.

1. Power Conversion Efficiency (PCE): PCE is a crucial indicator of DSSC performance, representing the ratio of electrical power output to incident solar power input. Chemical oxidative polymerization has yielded PCEs ranging from 6.5% (Wang et al., 2017) to 7.1% (Li et al., 2018), attributed to improved surface area and catalytic activity. Electrochemical polymerization has demonstrated higher efficiencies, with Zhang et al. (2019) reporting a PCE of 7.3% due to better film uniformity and charge transport. Template-assisted synthesis further improved PCEs, reaching 7.8% (Singh et al., 2021) by enhancing surface area and dye adsorption. The highest PCE of 8.2% was achieved with PANI-graphene composites (Rao et al., 2022), showcasing the potential of hybrid materials.

2. Fill Factor (FF): FF reflects the quality of the photovoltaic device, indicating the ratio of maximum power output to the theoretical power output. Electrochemically polymerized PANI exhibited a higher FF (0.72) compared to chemically polymerized PANI (0.65), attributed to reduced internal resistance and improved charge transport (Kim et al., 2020). Composite structures further enhanced FF, with PANI-TiO_2 composites achieving values of 0.75 due to better interfacial contact and reduced recombination losses (Ahmed et al., 2023).

3. Short-Circuit Current Density (Jsc): Jsc measures the current generated per unit area when the DSSC is exposed to light under short-circuit conditions. Electrochemical polymerization yielded higher Jsc values (18.2 mA/cm²) compared to chemical oxidative polymerization (16.5 mA/cm²), likely due to enhanced charge mobility and improved conductivity (Zhang et al., 2019). Composite formation further improved Jsc, with PANI-CNT composites achieving 20.1 mA/cm², attributed to the formation of conductive networks that facilitated electron transport (Rao et al., 2022).

4. Open-Circuit Voltage (Voc): Voc represents the maximum voltage output under open-circuit conditions. Variations in Voc across synthesis methods were less pronounced, typically ranging between 0.72 V and 0.78 V. Electrochemical and composite-based PANI showed marginal improvements due to reduced charge recombination and enhanced interfacial contact.

Overall, performance metrics indicate that electrochemical polymerization and composite formation consistently outperform other methods in enhancing PCE, FF, and Jsc, while Voc improvements remain modest. Future work could explore further tuning of synthesis parameters and composite ratios to maximize performance across all metrics.

Conclusion:

Poly(aniline)-based dye-sensitized solar cells have demonstrated significant potential in enhancing performance metrics through various synthesis methods. Chemical oxidative polymerization offers simplicity and scalability, though at the cost of structural consistency. Electrochemical polymerization provides superior control over film morphology, leading to enhanced conductivity and better charge transport. Template-assisted synthesis improves surface area and dye adsorption, while composite formation with materials like graphene and CNTs further boosts efficiency and stability. Comparative analysis highlights that combining these approaches could unlock further performance gains, making PANI a promising candidate for next-generation DSSCs. Future research should focus on optimizing composite structures and exploring hybrid synthesis techniques to enhance PANI's stability and efficiency in practical applications.

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