*Ibrahim Zakariya'u[1], Badiya Tukur[2] ,Muhammad Abdullahi Adam[2], Mamudu Aliyu[2], Abubakar Tijjani Abu[2], Pramod K. Singh[1]**

[1]Centre of Excellence in Solar cell and Renewable Energy, Deptt. Of Physics & Eni.Sci., SSES, Sharda University, 201306, India, [2]Department of Chemistry & Biochemistry, SSES, Sharda University, 201306, India

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Tailored pema based polymer electrolyte for highly efficient and stable dye synthesized solar cells

ABSTRACT

This research paper provides a comprehensive analysis of polymer electrolytes in the development of dye-sensitized solar cells (DSSCs), an emerging photovoltaic technology offering a low-cost and flexible alternative to conventional silicon-based solar cells. Polymer electrolytes are investigated as promising substitutes for traditional liquid electrolytes due to their improved stability, flexibility, and ionic conductivity, all of which are critical for enhancing DSSC performance and longevity. The paper categorizes polymer electrolytes into solid, gel, composite, and ionic liquid-based types, discussing each category's unique properties, composition, advantages, and limitations. Key materials, including various polymer matrices, ionic conductors, additives, and nanofillers, are examined in detail to understand their roles in achieving optimal ionic conductivity, thermal stability, and mechanical strength. Performance metrics such as conductivity, stability, flexibility, and photovoltaic efficiency are evaluated to provide insights into the practical application of these materials in DSSCs. Recent advancements, including novel polymer blends, nanocomposite electrolytes, and enhanced thermal stability, are highlighted to showcase the latest innovations in the field. Additionally, the review addresses significant challenges, such as ion transport limitations, durability, electrolyte leakage, and economic scalability, which currently hinder the widespread adoption of polymer electrolyte-based DSSCs. The paper concludes by identifying potential research gaps, including the need for further advancements in stability, eco-friendly materials, and scalable manufacturing methods. This review serves as a critical resource for researchers aiming to develop efficient, sustainable, and commercially viable DSSCs powered by advanced polymer electrolyte technologies.

***Keywords**: Dye-Sensitized Solar Cells (DSSCs), polymer electrolytes, ionic conductivity, photovoltaic efficiency, thermal stability, nanocomposites, gel polymer electrolytes (GPEs), solid polymer electrolytes (SPEs), electrolyte leakage, scalability, eco-friendly materials, flexible solar cells, nanofillers, and photovoltaic technology.*

INTRODUCTION

Dye-sensitized solar cells (DSSCs), initially introduced by Grätzel in 1991, present a promising, cost-effective alternative to traditional solar cells, prompting extensive global research aimed at improving their efficiency and stability [1]. These cells feature three main components: a photoelectrode consisting of titanium dioxide (TiO_2) nanoparticles coated with dye on indium tin oxide (ITO) glass, a liquid electrolyte containing iodide/triiodide ions as charge carriers, and a platinum counter electrode[2].

DSSCs using ruthenium-based dyes have achieved efficiencies of approximately 12% in laboratory settings, supporting their potential for affordable, efficient solar energy conversion—a key focus in the shift towards sustainable energy sources [3]. With growing global energy needs and the environmental and economic costs of fossil fuels, the development of renewable energy technologies is increasingly critical. Solar energy is particularly appealing due to its abundance and renewability on a human timescale[4]. Despite efficiencies exceeding 10%, DSSCs' dependence on liquid electrolytes has limited their use in outdoor applications. As a result, researchers are actively investigating solid polymer electrolytes as replacements, though these alternatives currently face challenges such as low conductivity and

*Corresponding author: Pramod K. Singh
Email: pramodkumarsingh@sharda.ac.in
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partial crystallinity. To improve performance, studies are exploring various plasticizers and inorganic fillers like titania, silica, and alumina to boost electrolyte conductivity and decrease crystallinity, which are crucial steps toward advancing DSSC technology[5]. A typical DSSC consists of a mesoporous TiO_2 film coated with dye, placed between two transparent, conductive electrodes, with a liquid electrolyte—typically containing the iodide/triiodide redox couple—penetrating the pores and contacting the TiO_2 nanoparticles. The photovoltaic effect in DSSCs originates from the interaction between this redox electrolyte and the dye-sensitized TiO_2 electrode. The electrolyte's role is essential for internal conductivity, as it diffuses through the TiO_2 layer, significantly impacting cell performance. DSSCs with liquid electrolytes, using solvents like acetonitrile, propylene carbonate, or ethylene carbonate paired with the iodide/triiodide redox couple, have reached light-to-electricity conversion efficiencies of 10–11% under AM1.5 solar irradiation. However, the use of liquid electrolytes presents issues, including leakage, volatility, dye desorption, photodegradation, and counter electrode corrosion, all of which affect long-term stability and practical applications[6]. To address electrolyte leakage in DSSCs, several strategies have been developed. One such approach is the replacement of volatile solvents with ionic liquids, while other solutions include the use of p-type semiconductors, organic and inorganic hole-transport materials, and polymer/redox blends in solid-state DSSCs[7]. Additionally, the exploration of nanocomposites, polymer gels, and solid or quasi-solid-state materials presents promising alternatives to traditional liquid electrolytes. Among these, polymer electrolytes stand out for their practicality, offering ease of fabrication, low cost, and stability. These electrolytes are typically made from low-lattice-energy metal salts dissolved in a polymer matrix containing polar groups such as ether, ester, or amide linkages. Metal ions interact with these polar groups, enhancing both conductivity and stability. The electrolyte's role is crucial in facilitating dye regeneration during the redox process. In traditional DSSCs, liquid electrolytes consisting of salts and solvents with redox mediators like I−/I3−, Co(II/III), and (SCN)2/SCN− are used to achieve high ionic conductivity, with photoconversion efficiencies reaching up to 14.3%[8]. However, issues like evaporation, leakage, and platinum counter electrode corrosion limit the practical application of these liquid electrolytes. Solid and gel polymer electrolytes help mitigate these challenges by reducing the risks associated with liquid electrolytes[9]. While solid polymer electrolytes offer certain advantages, they typically suffer from low conductivity and poor interfacial contact, which can reduce performance. Gel polymer electrolytes (GPE), on the other hand, provide higher conductivity, long-term stability, and better interfacial contact with the electrodes, making them a more suitable option[10]. GPEs typically consist of a polymer network that holds dissolved salts within a solvent. Various polymers, such as poly(ethylene oxide) (PEO), polyacrylonitrile (PAN), poly(vinyl alcohol) (PVA), and carboxymethylcellulose (CMC), as well as blends like CMC–PVA and PEO–PVA, are used as the polymer host in these electrolytes[11].The electrolyte is essential in DSSCs and other electrochemical cells like fuel cells, batteries, supercapacitors, and electrochromic windows, as it enables the transport of charge carriers. In DSSCs, electrolytes can be in solid, gel, or liquid form. Liquid electrolytes generally offer the best performance but are prone to issues such as evaporation, leakage, and corrosion over prolonged use. In contrast, solid and gel-based electrolytes are more stable, with significantly lower risks of volatility and leakage. Solid polymer electrolytes (SPEs) are made with polymers like poly(vinyl alcohol) (PVA), poly(ethylene oxide) (PEO), polyvinylidene fluoride (PVdF), and chitosan, which serve as host materials for ion conduction[12]. These polymers need to contain at least one polar functional group to form dative bonds with the salt's cations. However, SPEs face challenges with low ionic mobility and limited interfacial contact between the electrolyte and electrodes, which can affect performance. Gel polymer electrolytes (GPEs), also known as quasi-solid-state polymer electrolytes (QS-PEs), combine the cohesive properties of solids with the diffusive characteristics of liquids. GPEs offer high ionic conductivity similar to liquid electrolytes, along with good electrode interfacial contact, making them a suitable option for DSSCs. A typical GPE consists of a polymer, salt, solvent, and redox mediator[13]. The electrolyte plays a crucial part in the energy conversion process of DSSCs. When the dye molecules in the photoanode are excited by sunlight, they inject electrons into the titanium dioxide (TiO_2) layer, which then travel through an external circuit to generate current. To maintain charge balance, the oxidized dye molecules need to regain electrons. The electrolyte facilitates this by transporting electrons from the counter electrode back to the oxidized dye, regenerating the dye molecules and enabling the continuous energy conversion cycle[13]. This charge transport process is typically achieved through a redox couple, often the iodide/triiodide (I^-/I_3^-) system, within the electrolyte[14]. The redox couple undergoes cyclic oxidation and reduction, ensuring a steady flow of electrons between the electrodes and the dye. The effectiveness of the electrolyte in facilitating this redox reaction directly impacts the efficiency and stability of the DSSC.

Polymer electrolytes have gained significant attention as a promising alternative to traditional liquid electrolytes in DSSCs due to their unique properties as in Fig 1. Unlike liquid electrolytes, which can suffer from leakage, evaporation, and instability with prolonged exposure, polymer electrolytes offer greater stability and flexibility. These materials are more resistant to environmental conditions, making them suitable for long-term applications in DSSCs. Furthermore, polymer electrolytes are less corrosive and present a lower risk of degradation at the counter electrode, which can further extend the life of the solar cell[15]. One of the key advantages of polymer electrolytes lies in their balanced solid-liquid characteristics, providing both structural stability and high ionic mobility. For instance, gel polymer electrolytes (GPEs) exhibit ionic conductivity comparable to liquid electrolytes while maintaining solid-like mechanical properties, enabling efficient electron flow within the cell – a crucial factor for the DSSC's overall performance[16]. Furthermore, polymer electrolytes offer the flexibility to incorporate a variety of polymer hosts, such as poly (ethylene oxide) (PEO) and poly (vinyl alcohol) (PVA), which can be tailored to enhance compatibility with the DSSC architecture and support ionic transport through the presence of polar functional groups that allow salts to dissolve and interact with the polymer matrix, ultimately promoting efficient ion movement and improving the overall device efficiency[17].

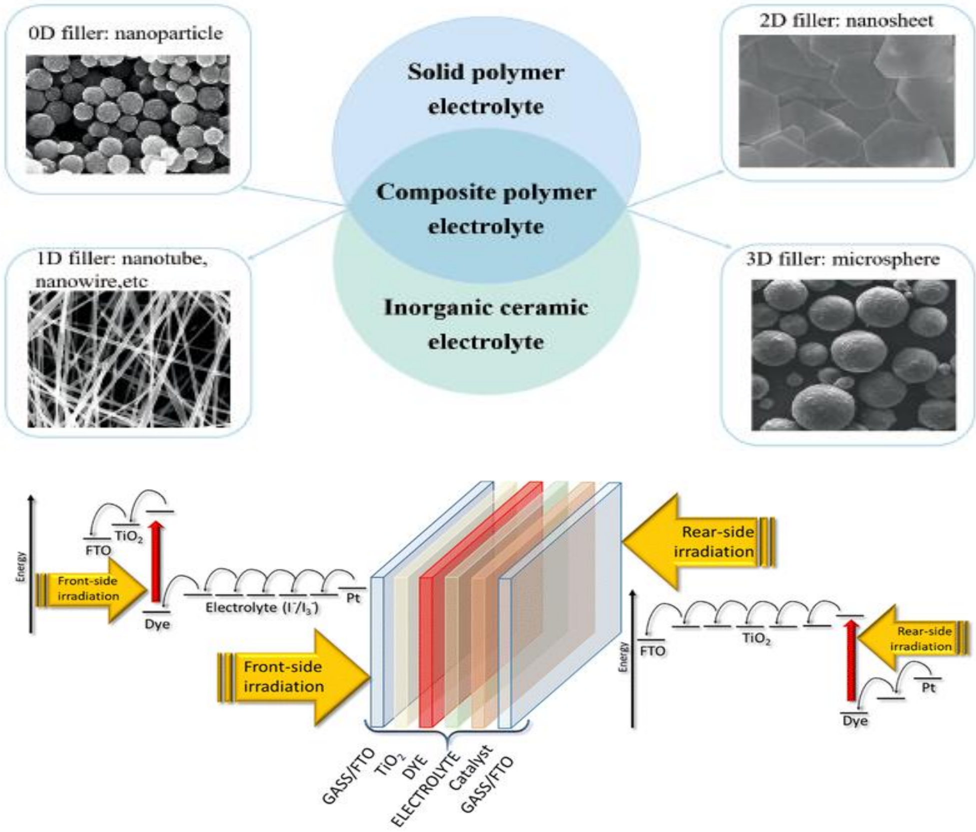

Figure 1. A schematic diagram of a DSSC consisting of three main components sandwiched between two conductive sheet glasses

Research Gap

- **Enhanced Long-Term Stability**: Further research is needed to develop polymer electrolytes with improved resistance to degradation and stability over extended periods.
- **Scalability of Polymer Electrolytes**: Investigations into cost-effective and scalable production methods for advanced polymer electrolytes are essential to facilitate large-scale DSSC applications.
- **Eco-Friendly and Biodegradable Electrolytes**: Developing sustainable, environmentally friendly, and biodegradable polymer materials for DSSCs is a priority to reduce the environmental impact of solar technology.

- **Advanced Nanocomposites**: Research into novel nanomaterials that enhance ionic conductivity and maintain stability is needed to further improve electrolyte performance in DSSCs.
- **Compatibility with Hybrid Solar Cell Technologies**: Exploration of polymer electrolytes that can be adapted for use in hybrid and emerging solar cell technologies, such as perovskite and organic solar cells, to expand application possibilities.
- **Improved Ion Transport Mechanisms**: New designs or additives that can optimize ion transport within polymer matrices could lead to more efficient charge transport and overall DSSC efficiency.
- **Durability under Variable Environmental Conditions**: There is a need for polymer electrolytes that can maintain performance under diverse environmental conditions, including high temperatures and humidity, for greater reliability in practical applications.
- **Enhanced Thermal Stability**: Research is needed to develop electrolytes with high thermal tolerance, crucial for maintaining DSSC efficiency and lifespan under varying temperature conditions.
- **Integration for Flexible and Wearable Electronics**: Innovative designs and materials that can meet the mechanical flexibility required for wearable and flexible electronics applications of DSSCs.
- These research gaps outline potential areas for advancing polymer electrolytes in DSSCs, addressing current limitations, and supporting the development of efficient and scalable solar technology.

Types of polymer electrolyte

In DSSCs, various types of polymer electrolytes—Solid Polymer Electrolytes (SPEs), Gel Polymer Electrolytes (GPEs), Ionic Liquid Polymer Electrolytes (ILPEs), and Composite Polymer Electrolytes (CPEs)—each offer distinct characteristics and benefits, allowing for tailored trade-offs based on the specific needs of the cell design[18].

Solid Polymer Electrolytes

Solid Polymer Electrolytes (SPEs) present a viable alternative to traditional liquid electrolytes in Dye-Sensitized Solar Cells (DSSCs), mainly because they are solid-state materials offering superior thermal stability and resistance to leakage and evaporation. This makes them safer and more durable compared to liquid-based systems. SPEs are typically composed of a polymer host, such as poly(ethylene oxide) (PEO) or poly(vinylidene fluoride) (PVDF), combined with ionic salts like lithium iodide (LiI), which enable the necessary ionic conductivity for charge transport within the solar cell. They provide excellent mechanical properties and dimensional stability, making them a good choice for flexible DSSCs. However, the ionic conductivity of SPEs is often lower than that of liquid electrolytes, which can reduce the efficiency of charge transport and, therefore, the overall energy conversion performance of the DSSC[19].

While SPEs offer the advantage of improved safety and long-term stability compared to liquid electrolytes, they also present challenges such as reduced contact between the solid electrolyte and the dye-sensitized TiO_2 photoelectrode, which can affect the dye regeneration and charge collection efficiency. Some SPE systems may also struggle with thermal stability at high operational temperatures[20]. To address these limitations, researchers are investigating advanced formulations that include plasticizers, nanofillers, and new polymer blends to enhance ionic conductivity and improve electrolyte-electrode interaction. While solid polymer electrolytes are particularly suitable for applications where stability is a priority, their relatively lower efficiency makes them more suitable for situations requiring solid-state stability rather than peak performance[21].

Figure 2. The structural representation of different components of Li-ion Battery

Gel Polymer Electrolytes (GPEs)

Gel polymer electrolytes (GPEs) are a hybrid material that combines the benefits of both solid and liquid electrolytes. They consist of a polymer matrix, such as poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP), that is swollen with a liquid electrolyte, typically a solution of iodide/triiodide (I^-/I_3^-) in an organic solvent. The polymer network provides structural stability, while the liquid phase ensures high ionic conductivity. This combination allows GPEs to offer a favorable balance of mechanical, thermal, and electrochemical properties, making them ideal for use in Dye-Sensitized Solar Cells (DSSCs)[22]. GPEs maintain the flexibility and high ionic conductivity of liquid electrolytes while offering the mechanical strength of solid electrolytes. Although they provide good interfacial contact with the electrodes and are generally stable, GPEs are still less mechanically robust than solid electrolytes and may experience solvent evaporation over time, which can affect their long-term performance[23].

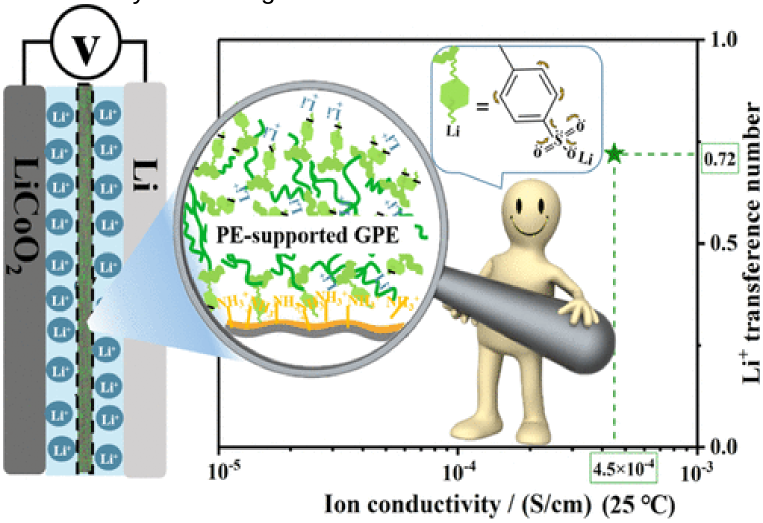

Figure 3- Working of gel polymer electrolyte

Ionic Liquid Polymer Electrolytes (ILPEs)

Ionic liquid polymer electrolytes (ILPEs) are created by integrating ionic liquids—salts that remain in a liquid state at room temperature—into a polymer matrix, which provides a strong mechanical and thermal framework as in Fig 4. The ionic liquid component, such as 1-ethyl-3-methylimidazolium iodide (EMII), imparts high ionic conductivity, while polymers like poly(ethylene oxide) (PEO) or poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) contribute stability and structure. ILPEs are valued for their non-volatility, excellent thermal and electrochemical stability, and resistance to chemical degradation, making them well-suited for applications that require both efficiency and durability under diverse conditions[24]. Although they provide high performance, ILPEs can be costly and may require reinforcement within the polymer network to achieve adequate mechanical strength[25].

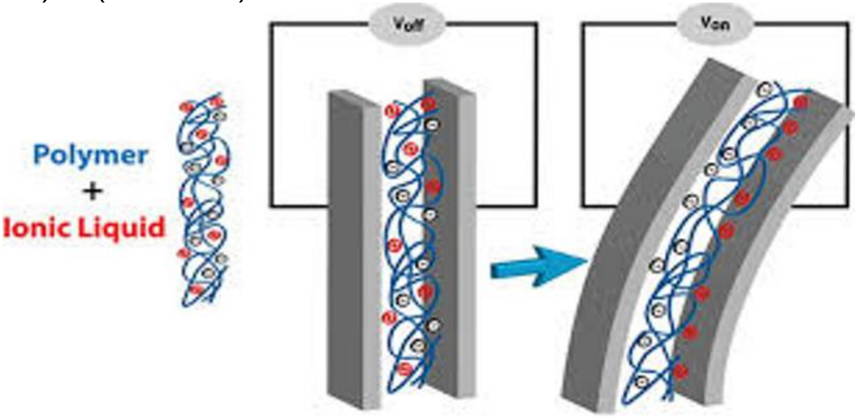

Figure 4. Ionic Liquid Polymer Electrolytes

Composite Polymer Electrolytes (CPEs)

Composite polymer electrolytes (CPEs) are created by embedding inorganic fillers, such as TiO_2, SiO_2, or Al_2O_3, into a polymer matrix as in figure 5. These inorganic particles enhance the electrolyte's ionic conductivity, mechanical resilience, and thermal stability, making CPEs a strong candidate for use in dye-sensitized solar cells (DSSCs). The fillers promote ion mobility by disrupting the polymer's crystalline structure, which increases the amorphous regions within the polymer matrix. This enhanced ion transport, combined with improved mechanical and thermal properties, enables CPEs to perform effectively under various conditions. The choice of polymer electrolyte depends on the specific requirements of the DSSC, such as desired levels of conductivity, thermal stability, mechanical durability, and compatibility with the cell's architecture[26]. Each type of electrolyte offers distinct advantages, and CPEs are particularly appealing for designs where strength and conductivity must be balanced.

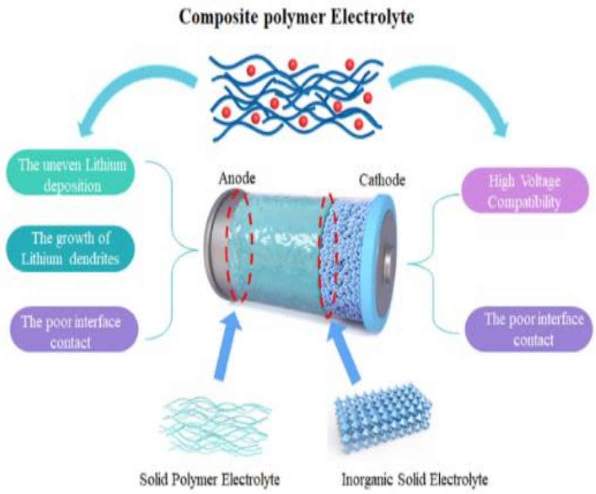

Figure 5. Composite Polymer electrolyte

Solid polymer electrolytes (SPEs) also serve as alternatives to traditional liquid electrolytes in DSSCs, primarily due to their structural and chemical stability. Composed of polymers like poly(ethylene oxide) (PEO) or poly(vinylidene fluoride) (PVDF) and doped with ionic salts like lithium iodide (LiI), SPEs facilitate the essential ionic conductivity needed for charge transport within the cell. While SPEs provide enhanced safety, reducing risks of leakage and evaporation, their conductivity is generally lower than that of liquid electrolytes, potentially affecting charge transport efficiency. Their solid nature can also lead to suboptimal contact with the dye-sensitized TiO_2 photoelectrode, possibly impacting dye regeneration and overall cell efficiency [27].To address these issues, research continues to improve SPEs by incorporating plasticizers, nanofillers, and advanced polymer blends to enhance both conductivity and interface contact. For CPEs, incorporating fillers improves mechanical strength and stability, yet requires careful processing to prevent filler aggregation, which could negatively impact conductivity and uniform distribution [28].

3. MATERIALS USED IN POLYMER ELECTROLYTES

The choice and composition of materials are vital in shaping the characteristics and performance of polymer electrolytes for dye-sensitized solar cells (DSSCs). Commonly used polymers in the matrix include polyethylene oxide (PEO), which is valued for its salt solubility, high ionic conductivity, and good film-forming ability; polymethyl methacrylate (PMMA), which provides excellent mechanical strength, thermal stability, and compatibility with DSSC components; and polyvinylidene fluoride (PVDF), known for its thermal and electrochemical stability alongside adequate ionic conductivity. The ionic conductivity within these polymer electrolytes is mainly influenced by dissolved salts, such as lithium iodide (LiI) and sodium iodide (NaI), which supply the ions needed for charge transport, as well as the iodide/triiodide (I^-/I_3^-) redox couple that facilitates dye regeneration [29]. Adding materials like ethylene carbonate, propylene carbonate, and ionic liquids can further boost ionic conductivity and improve the electrolyte's wettability. Additionally, incorporating inorganic nanofillers and modifiers, including titanium dioxide (TiO_2), silica (SiO_2), and carbon-based additives, enhances the electrolyte's thermal, mechanical, and ionic transport properties, leading to optimized DSSC performance and stability [30].

Polymer Matrix Materials

The choice of host polymer matrix is essential to optimize the performance and characteristics of polymer electrolytes in DSSCs, as each material provides distinct advantages. Polyethylene oxide (PEO) has been extensively studied for use in solid and gel polymer electrolytes due to its ability to dissolve various salts, high ionic conductivity, and potent film-forming capabilities. Polymethyl methacrylate (PMMA) offers excellent mechanical strength and thermal stability, as well as high compatibility with DSSC components, making it suitable for both solid and gel formulations. Polyvinylidene fluoride (PVDF) is a highly versatile polymer used in solid, gel, and composite electrolytes, valued for its thermal and electrochemical stability, as well as its moderate ionic conductivity. Each of these polymers contributes uniquely to the electrolyte matrix, improving the stability and overall efficiency of DSSCs [31].

The ionic conductivity of polymer electrolytes is significantly influenced by the dissolved salts and redox mediators**. Lithium iodide (LiI**) is commonly used to provide lithium ions that facilitate ionic transport, while **sodium iodide (NaI**) can also enhance conductivity in polymer matrices. The **iodide/triiodide (I^-/I_3^-)** redox couple is critical for regenerating oxidized dye molecules in DSSCs, enabling continuous energy conversion. Additionally, **additives** such as e**thylene carbonate, propylene carbonate**, and **ionic liquids** are often incorporated to further improve ionic conductivity, enhance the wetting properties, and optimize the overall performance of the polymer electrolyte in DSSCs [32].

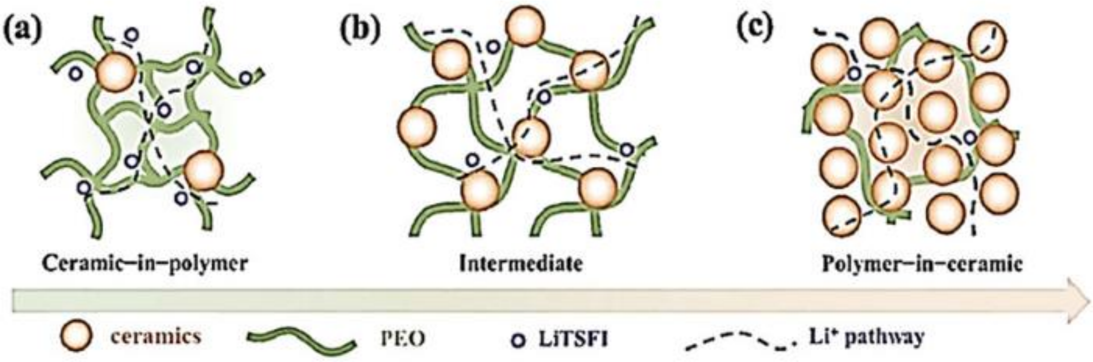

Figure 6. Schematic illustration for PEO-ceramic composite solid electrolyte

Nanofillers and Modifiers

Incorporating inorganic nanofillers and modifiers into polymer electrolytes can significantly enhance their thermal, mechanical, and ionic transport properties, improving the overall performance of DSSCs. Titanium dioxide (TiO_2) nanoparticles are commonly used to boost ionic conductivity, thermal stability, and mechanical strength within the polymer matrix. Silica (SiO_2) nanofillers improve the interfacial interactions between the polymer and ionic species, which helps enhance ionic transport. Additionally, carbon-based materials such as graphene, carbon nanotubes, and carbon black serve as conductive additives, further improving ionic conductivity and overall performance. The combination of these nanofillers and modifiers creates synergistic effects that optimize the functionality and reliability of the polymer electrolyte in DSSCs [33].

Properties and Performance Metrics of Polymer Electrolytes give me in details

The **properties and performance metrics of polymer electrolytes** are crucial for determining their effectiveness in applications such as **Dye-Sensitized Solar Cells (DSSCs**), fuel cells, batteries, and supercapacitors. These properties govern the electrolyte's ability to conduct ions, maintain stability under different conditions, and efficiently interact with other components in the system[34]. Key properties and performance metrics include:

- Ionic Conductivity:

Ionic conductivity refers to the ability of an electrolyte to transport charge carriers, typically ions, and is a critical factor in ensuring efficient ion movement within polymer electrolytes, which directly impacts the overall performance of electrochemical devices like DSSCs. Higher ionic conductivity enhances the flow of charge between the photoanode and counter electrode, thereby improving power conversion efficiency. Conductivity is commonly measured using impedance spectroscopy or by calculating the electrolyte's resistance under an applied voltage, with desired values for DSSCs typically ranging from 10^{-3} to 10^{-2} S/cm at room temperature [35].

Thermal Stability

Thermal stability is the ability of an electrolyte to resist chemical degradation or phase changes when exposed to high temperatures. This property is crucial for polymer electrolytes, particularly in solar applications, where the device must function effectively under prolonged sunlight exposure and in outdoor environments with fluctuating temperatures. Thermal stability is typically assessed through techniques like thermogravimetric analysis (TGA) or differential scanning calorimetry (DSC), which monitor weight loss or phase transitions as the electrolyte is heated. For optimal performance, polymer electrolytes should maintain their structural integrity and functionality at temperatures up to 200°C without significant decomposition or property alterations [36].

- Mechanical Properties:

Mechanical properties, including flexibility, strength, and durability, are essential for ensuring that the polymer electrolyte maintains its integrity during both fabrication and operation, particularly in flexible devices. These properties help prevent issues such as cracking, leakage, or deformation, especially when the electrolyte is in gel or solid form. Mechanical properties are assessed through tensile strength tests, elongation at break, and Young’s modulus measurements. For optimal performance, DSSC electrolytes should exhibit a balance of flexibility and tensile strength, with elongation at break typically above 20% to ensure durability[37].

- Electrochemical Stability:

Electrochemical stability refers to the ability of the polymer electrolyte to resist oxidation or reduction reactions at both the anode and cathode during operation. If the electrolyte undergoes undesirable redox reactions, it can degrade, losing its ionic conductivity, which negatively impacts device performance and lifespan. Electrochemical stability is evaluated through cyclic voltammetry (CV), where the electrolyte is cycled through different voltage ranges to monitor the onset of electrochemical degradation. A wide electrochemical stability window, ideally from -0.5 V to +2 V vs. Ag/AgCl, is desired to prevent decomposition or side reactions under typical operating voltages [38].

- Viscosity and Wettability:

Viscosity is the resistance of the electrolyte to flow, while wettability refers to how well the electrolyte spreads on surfaces, especially the electrodes. A low viscosity is desirable for easy fabrication and processing, but the electrolyte must have sufficient viscosity to prevent leakage. Good wettability ensures uniform coverage of the electrodes, improving contact and overall efficiency. Viscosity is measured with a viscometer, while wettability is evaluated using contact angle measurements. The desired values are a small contact angle (indicating good wettability) and balanced viscosity to allow smooth application without excessive flow[39].

Interfacial Contact:

Interfacial contact refers to the quality of the interaction between the electrolyte and electrode materials, particularly at the electrode-electrolyte interface. Strong interfacial contact improves ion transfer, reduces resistance, and enhances overall performance. This quality is typically evaluated using impedance spectroscopy or by examining the charge transfer resistance at the interface. A low charge transfer resistance at the interface is desired to ensure efficient ion transport and minimal energy loss, contributing to improved device performance [40].

- Stability and Durability:

Stability and durability refer to the ability of the polymer electrolyte to maintain its properties over time, even under environmental stresses like UV light, humidity, and temperature fluctuations. Long-term stability is crucial for ensuring that DSSCs and other devices operate efficiently throughout their lifespan without significant degradation. Stability is typically assessed through long-term aging tests, monitoring performance and physical changes over time. Polymer electrolytes should demonstrate minimal degradation after 1000-2000 hours of exposure to simulated operational conditions to ensure durability [41].

Redox Mediator Efficiency:

The redox mediator plays a critical role in regenerating the dye molecules and maintaining charge balance in DSSCs. A highly efficient redox mediator facilitates efficient charge transfer, thereby improving cell efficiency and reducing recombination losses. Redox mediator efficiency is usually evaluated through electrochemical analysis, such as cyclic voltammetry and impedance spectroscopy. The desired redox mediator should exhibit fast and reversible redox reactions, with low overpotentials for both oxidation and reduction steps, which are crucial for enhancing overall device performance [42].

Cost-Effectiveness:

Cost-effectiveness refers to the affordability and scalability of the polymer electrolyte material for large-scale commercial applications. For DSSCs and other energy technologies, low-cost materials are vital for ensuring the feasibility of widespread adoption. Cost analysis is typically carried out by evaluating the raw material prices, processing costs, and scalability of the production methods. Polymer electrolytes should offer a good balance between performance and affordability, ensuring economic viability through the use of materials sourced from abundant and inexpensive precursors [43].

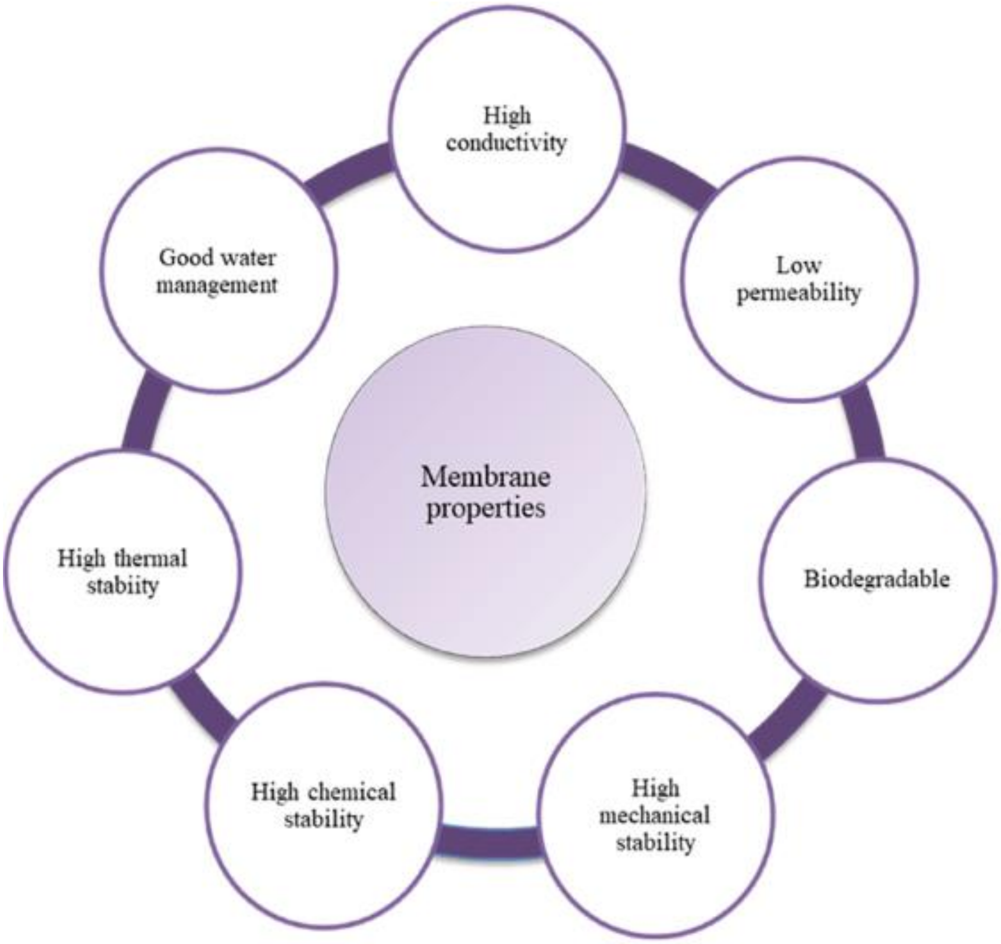

Figure 7. Properties of DSSC

Recent Advancements in Polymer Electrolytes for DSSC

Recent years have seen significant advancements in the development of polymer electrolytes for dye-sensitized solar cells (DSSCs). Researchers have focused on overcoming the limitations of traditional liquid electrolyte systems, which can suffer from issues like leakage, solvent evaporation, and poor long-term stability. One of the primary strategies has been the exploration of polymer blends, where two or more polymers are combined to leverage their complementary properties and achieve enhanced performance. Common polymer blends used in DSSCs include polyethylene oxide (PEO) with polyvinylidene fluoride (PVDF), as well as PEO or PVDF blended with poly(methyl methacrylate) (PMMA). By blending these polymers, researchers have been able to create electrolyte materials with improved mechanical strength, higher ionic conductivity, and better compatibility with the photoanode, compared to single-component polymer electrolytes[44]. The synergistic effects of the polymer blend components help to overcome the limitations of individual polymers. In addition to polymer blends, the development of polymer copolymers has emerged as a promising approach. Copolymers are formed by the polymerization of two or more different monomers, allowing for precise tuning of the physical and chemical properties of the electrolyte material. By adjusting the monomer composition, researchers can increase the amorphous regions, reduce crystallinity, and boost ionic mobility within the polymer structure [45].These modifications to the polymer microstructure lead to improved electrolyte performance and enhanced long-term stability in DSSC devices. The ability to precisely control the polymer properties through copolymerization is a significant advantage over using single-component polymer systems. To further enhance ion transport within the polymer electrolyte, researchers have incorporated various additives, such as plasticizers, ionic liquids, or nanofillers. These components can disrupt the polymer's crystalline structure, leading to increased amorphous regions and faster ion migration. This, in turn, results in higher ionic conductivity and better compatibility between the electrolyte and the electrodes. Improving the mechanical properties of the polymer electrolyte, particularly flexibility and strength, is also crucial for the long-term durability and stability of DSSC devices[46]. This is especially important for applications in flexible or wearable electronics, where the electrolyte-electrode interface must withstand bending, twisting, and other mechanical stresses without delamination or cracking. Overall, the recent advancements in polymer electrolytes for DSSCs have focused on developing innovative polymer materials that can overcome the limitations of traditional liquid electrolytes. By leveraging polymer blends, copolymers, and strategic additives, researchers have been able to enhance the ionic conductivity, mechanical properties, and overall performance of DSSC devices, paving the way for improved efficiency and reliability in these promising solar energy technologies [47].

Incorporation of Nanomaterials

The incorporation of nanomaterials into polymer electrolytes has been a transformative advancement for dye-sensitized solar cells (DSSCs), particularly with materials like graphene and carbon nanotubes (CNTs). Graphene's high surface area and excellent conductivity enhance ionic conductivity within the polymer matrix and facilitate more efficient electron transport, while CNTs contribute both mechanical strength and conductive pathways, boosting the electrolyte's stability and overall conductivity. Beyond graphene and CNTs, researchers are exploring a range of nanomaterials such as silica, titanium dioxide, and metal oxides, which each provide a unique benefit. These materials can significantly improve the thermal stability, mechanical strength, and ionic conductivity of the electrolyte, ultimately increasing the longevity and efficiency of DSSCs. Nanoparticles modify the polymer's internal structure, creating conductive pathways and enhancing ion diffusion channels, which can prevent liquid electrolyte leakage and add to the electrolyte's operational stability. Through these interactions, nanomaterials help to refine the electrolyte's morphology and electrochemical properties, leading to DSSCs with improved durability and performance under various conditions[48].

Electrolytes with Enhanced Thermal Stability

Thermal stability is a significant concern for dye-sensitized solar cells (DSSCs), as high operating temperatures can cause electrolyte evaporation or degradation, ultimately reducing the cell's efficiency and lifespan. To address this, recent research has focused on developing thermally robust polymer electrolytes. Polymers that incorporate cross-linking and stabilizing agents have shown promise in maintaining structural integrity and functionality at elevated temperatures. For example, cross-linked poly (ethylene glycol) (PEG) and poly (ethylene oxide) (PEO) have demonstrated improved stability, as their cross-linked networks can better retain electrolyte properties under thermal stress[49]. Additionally, solid and gel polymer electrolytes are gaining interest for their thermal stability advantages over traditional liquid electrolytes. These solid or semi-solid forms are less susceptible to leakage and evaporation, preserving their structure and functionality even under high-temperature conditions, which contributes to a longer operational lifespan for DSSCs. Through these advancements, polymer electrolytes with enhanced thermal stability offer a pathway toward more durable and reliable DSSCs [50].

Application

Dye-sensitized solar cells (DSSCs) are well-suited for a wide range of applications, particularly in the realm of portable and wearable electronics. Their flexible, lightweight, and semi-transparent nature make them an ideal choice for seamless integration into a variety of products, from smartphones and smartwatches to fitness trackers and smart textiles. The ability of DSSCs to conform to curved surfaces and the possibility of creating customizable, aesthetically pleasing designs make them highly appealing for integration into fashion and lifestyle products, allowing for the provision of on-the-go power generation without compromising the aesthetic appeal or functionality of the devices [51].

Building-Integrated Photovoltaics (BIPV):

Dye-sensitized solar cells (DSSCs) offer a versatile solution for building-integrated photovoltaics (BIPV), seamlessly integrating solar power generation into the built environment. Their ability to be easily incorporated into various building materials, such as windows, facades, and roofing tiles, allows for the seamless integration of renewable energy sources into both new constructions and retrofits. Furthermore, the semi-transparency and diverse color options of DSSCs provide greater architectural design flexibility compared to traditional opaque solar panels, enabling more creative and aesthetically pleasing integration. By harnessing the power-generating capabilities of DSSCs, BIPV applications can help offset building energy consumption and reduce the overall carbon footprint of the built environment, contributing to more sustainable and energy-efficient structures [52].

Automotive and Transportation:

Dye-sensitized solar cells (DSSCs) have a versatile range of applications, particularly in the automotive and transportation sector. These flexible and lightweight solar cells can be seamlessly integrated into the body panels, windows, or sunroofs of vehicles, providing supplementary power generation for on-board electronics, battery charging, or even partial propulsion in electric vehicles. The ability of DSSCs to conform to the curved surfaces of vehicles without adding significant weight or compromising aerodynamics makes them well-suited for this application.Additionally, the potential for customizable colors and designs can enhance the aesthetic appeal of solar-integrated vehicles [53].

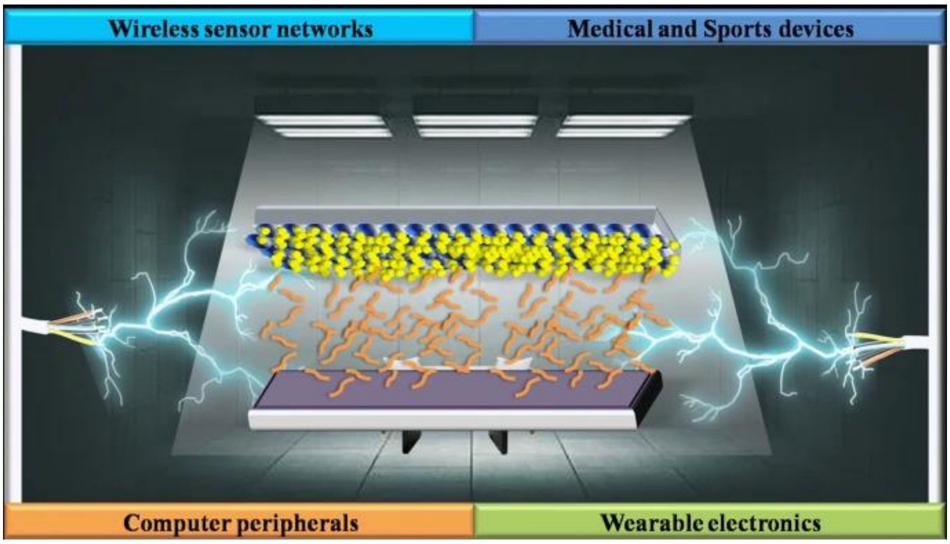

Figure 8. Dye-Sensitized Solar Cell for Indoor Applications

Indoor and Low-Light Environments:

Dye-sensitized solar cells (DSSCs) possess the unique capability to generate power even in low-light conditions, such as under indoor lighting or overcast skies. This feature makes them well-suited for applications in areas with limited access to direct sunlight. By harnessing this ability, DSSCs can power a variety of small electronic devices, sensors, and wireless communication systems in locations where traditional solar cells would be ineffective. For instance, DSSCs can be utilized to power wireless sensors in smart buildings, providing a reliable and sustainable energy source for these monitoring systems [54]. Additionally, they can be employed to power indoor lighting systems, offering an alternative to grid-based electricity in areas with intermittent access to direct sunlight. DSSCs can also be integrated into portable electronics used in industrial or household settings, allowing for the development of self-powered devices that do not rely on disposable batteries. The versatility of DSSCs in low-light environments expands their potential applications beyond traditional outdoor solar installations, enabling the integration of renewable energy solutions in a wide range of indoor and semi-shaded settings where other solar technologies may struggle to perform effectively[55].

Consumer Electronics and Gadgets:

The versatility of dye-sensitized solar cells (DSSCs) enables their seamless integration into a wide range of consumer electronics and gadgets, such as calculators, remote controls, and various portable devices. The ability to customize the size, shape, and color of DSSCs allows for a high degree of design flexibility, enabling their integration to enhance the aesthetics and functionality of these consumer products.By incorporating DSSCs into consumer electronics, manufacturers can provide sustainable, on-board power sources, reducing the reliance on disposable batteries. This not only contributes to a more environmentally-conscious approach but also enhances the convenience and self-sufficiency of these portable devices[56].

Agricultural and Environmental Monitoring:

Dye-sensitized solar cells (DSSCs) offer promising applications in agriculture by powering sensors used in precision farming, irrigation control, and environmental monitoring. Their inherent durability, lightweight design, and resistance to various environmental factors make them ideal for deployment in outdoor, remote, or harsh conditions where reliable energy sources are needed. DSSCs can be integrated with wireless communication systems to create autonomous, self-powered monitoring setups, enabling real-time data collection and control for agriculture, forestry, and conservation. This capability supports sustainable practices by providing continuous power for systems that optimize resource use, track environmental changes, and improve overall management in these sectors[57].

Specialized Applications:

Dye-sensitized solar cells (DSSCs) hold great potential for specialized applications due to their unique properties, such as light weight, flexibility, and resistance to environmental factors. In space exploration, their lightweight and radiation-resistant nature makes them suitable for powering satellites, probes, and other space-based devices. In the medical field, DSSCs can be integrated into wearable health monitors, implants, and portable medical equipment, providing a compact, flexible, and reliable energy source. Additionally, DSSCs are well-suited for building-integrated photovoltaic-thermal (BIPVT) systems, where they can generate solar power while also supporting building heating and cooling needs, thus enhancing energy efficiency[58]. Their versatility makes DSSCs a promising technology for a wide array of applications, from consumer electronics and wearables to energy-efficient buildings and specialized equipment. As ongoing research improves their efficiency and stability, the applications of DSSCs are expected to grow, fostering adoption across diverse sectors and supporting a more sustainable, energy-conscious future [59].

Figure 9. Various application area of DSSC

Challenges and Limitations

One of the key challenges in the development of polymer electrolytes for dye-sensitized solar cells (DSSCs) is the optimization of ion transport within the polymer matrices. The inherent crystalline structure of many polymers can hinder the mobility of ions, leading to reduced ionic conductivity and slower charge transfer kinetics. While strategies such as incorporating plasticizers, ionic liquids, or nanofillers have been explored to increase the amorphous regions and boost ion transport, further advancements are still needed to achieve conductivities on par with liquid electrolytes. Ensuring the long-term durability and stability of polymer electrolytes is another critical challenge for their widespread adoption in DSSC applications. Polymer electrolytes can undergo degradation over time due to factors such as thermal instability, photochemical reactions, and mechanical stress, which can lead to a decline in their performance and integrity. Issues like polymer chain scission, cross-linking, and the formation of byproducts can compromise the electrolyte's ionic conductivity, mechanical properties, and compatibility with the electrodes[60]. Extensive research is focused on developing robust polymer formulations, incorporating stabilizing additives, and optimizing encapsulation strategies to enhance the operational lifetime of DSSC devices. Preventing electrolyte leakage, especially in gel-based polymer electrolytes, is a significant challenge for DSSC design and fabrication. Leakage can occur due to the softness and deformability of polymer-based electrolytes, leading to issues like the loss of active components, environmental contamination, and reduced device performance. Effective encapsulation techniques are crucial to contain the polymer electrolyte within the DSSC structure and maintain the integrity of the device. Developing robust, yet flexible, encapsulation materials and sealing methods that can withstand the operating conditions of DSSC devices is an active area of research. Finally, the cost-effectiveness and scalability of polymer electrolytes for large-scale DSSC applications are important considerations. Many of the high-performance polymer materials, such as specialty copolymers and composites, can be more expensive to produce compared to traditional liquid electrolytes. Scaling up the manufacturing processes for polymer electrolyte-based DSSCs, including material synthesis, device fabrication, and encapsulation, may present economic and technological challenges[61]. Researchers are exploring ways to optimize the material composition, simplify the manufacturing processes, and leverage economies of scale to enhance the cost-competitiveness of polymer electrolyte-based DSSC technologies.

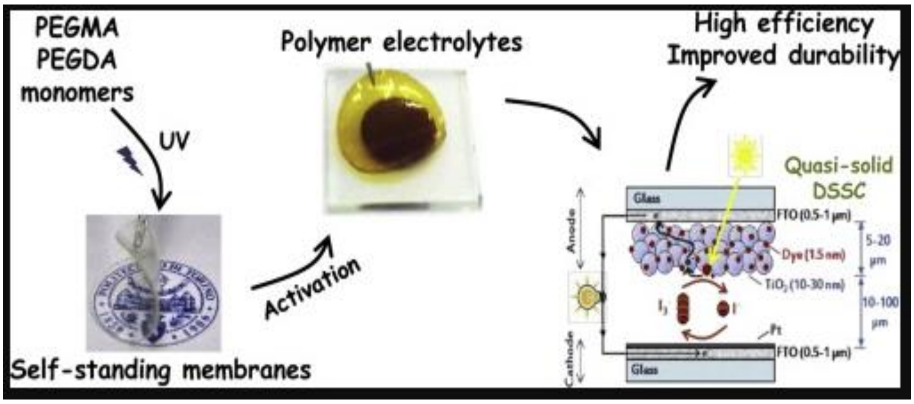

Figure 10. Polymer electrolytes for dye-sensitized solar cells prepared by photopolymerization of PEG-based oligomers

Emerging Trends and Future Directions

The future of polymer electrolytes for dye-sensitized solar cells (DSSCs) is poised to feature a range of innovative advancements across various fronts. In terms of materials and architectures, researchers are likely to push the boundaries of polymer electrolyte design, focusing on developing materials that combine superior ionic conductivity, thermal stability, and mechanical strength. Advanced polymers with self-healing properties or the ability to adapt to varying environmental conditions are being explored to improve DSSC efficiency and longevity. Additionally, the use of ionic liquids, supramolecular structures, and multifunctional copolymers is being investigated, as these materials may offer enhanced ionic mobility, reduced leakage, and improved compatibility with the photoanode. Hybrid electrolytes, which combine organic and inorganic components, could also play a significant role in next-generation DSSCs[62]. These hybrid materials have the potential to offer high thermal stability and enhanced electron transport through carefully designed molecular interfaces, addressing some of the limitations of single-component polymer systems.

The integration of polymer electrolytes with emerging solar cell technologies, such as perovskite solar cells, is an area of growing interest. The high power conversion efficiency and compatibility with flexible, lightweight designs of perovskite solar cells make them an attractive target for integration with polymer electrolytes. Researchers are investigating ways to stabilize perovskite structures using polymer electrolytes, as these materials can help address the issue of perovskite degradation due to environmental factors. Beyond perovskites, polymer electrolytes could also be paired with quantum dot and organic photovoltaics, offering promising pathways to improve the energy conversion efficiency and stability of these emerging technologies [63].

In line with global sustainability goals, there is a growing emphasis on using eco-friendly and biodegradable polymers in DSSCs. Renewable biopolymers derived from sources such as cellulose, chitosan, or polylactic acid (PLA) are gaining attention as they reduce environmental impact and are often easier to process. Research into sustainable polymer electrolytes focuses not only on their functional properties but also on lifecycle analysis, ensuring minimal waste and easier recycling at the end of their usable life. Researchers are also developing eco-compatible solvent systems and avoiding toxic or non-biodegradable components, aiming to make DSSCs more environmentally friendly from production to disposal. Finally, the flexibility and lightness of polymer electrolytes make them well-suited for integration into wearable electronics, such as smart textiles, flexible displays, and sensors[64]. Ongoing advances are focusing on developing thin, lightweight polymer electrolytes that retain high ionic conductivity and durability even when bent or stretched, which are essential for wearable applications. Additionally, the potential for flexible DSSCs could lead to the development of large-area, lightweight solar panels for portable or foldable electronics, electric vehicles, and building-integrated photovoltaics, with researchers exploring self-healing polymers and advanced encapsulation methods to enhance the robustness and reliability of these flexible DSSC system [65].

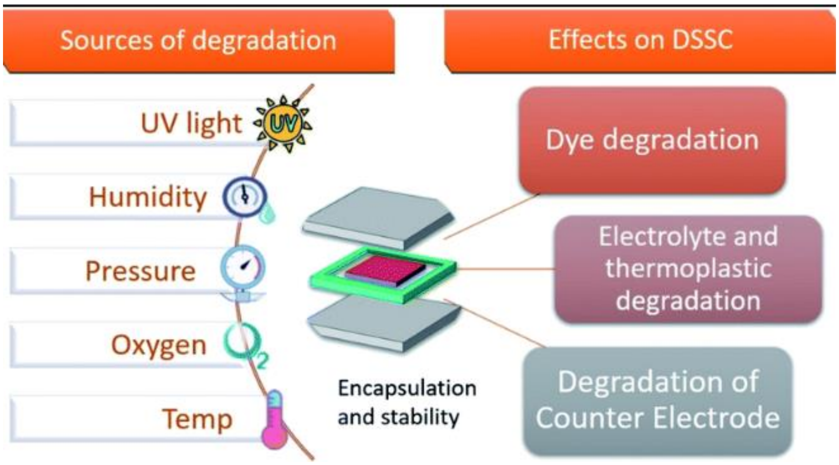

Figure 11. Effect of DSSC

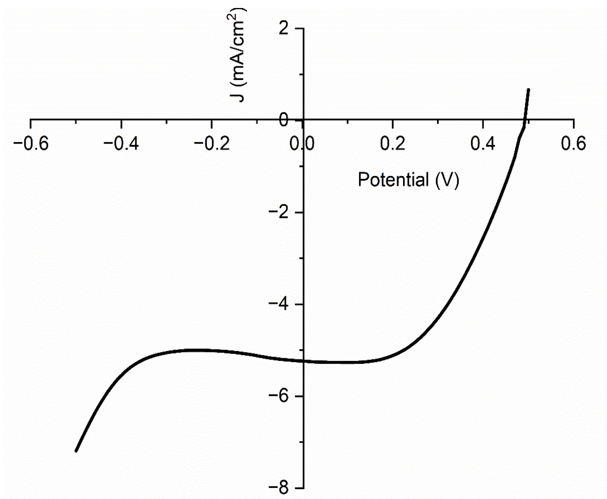

Figure 12. J-V of fabricated DSSC from PEMA based polymer electrolyte

PEMA Based Polymer Electrolyte

Solid polymer electrolyte was successfully synthesized using the solution cast method, employing a complex of PEMA and NaI, infused with IL (1-ethyl-3-Hexyl imidazolium iodide). The incorporation of ionic liquid (IL) into the polymer complex greatly improves the ionic conductivity of the polymer electrolyte, leading to a value of 7.7×10^{-4} Scm−1 at room temperature. This synthesis polymer electrolyte has been utilized in DSSC.

PEMA based Polymer Electrolyte for DSSC performance

The depicted J–V characteristics of the produced solar cells, as illustrated in Fig. 8, correspond to the actual effective area of 1 cm^2 (Fig. 12). The developed dye-sensitized solar cells (DSSCs) demonstrate efficiencies ranging from 1.23% under 1 sun illumination conditions.

CONCLUSION

In conclusion, our study demonstrates that the versatility of ionic liquids facilitates the exploration of different combinations of cations and anions, as well as modifications to their physical and chemical properties, thereby improving the efficiency of dye-sensitized solar cells (DSSCs). It also identifies areas where further research could bridge the gap between laboratory-scale success and commercial feasibility, especially in terms of stability, cost-effectiveness, and environmental sustainability. In conclusion, our study demonstrates that the versatility of polymer electrolyte facilitates the exploration of different combinations of cations and anions, as well as modifications to their physical and chemical properties, thereby improving the efficiency of dye-sensitized solar cells (DSSCs) with the efficient of 1.23%. This research is a valuable resource for researchers aiming to address these gaps and advance the development of efficient, durable, and sustainable DSSCs.

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IZVOD

PRILAGOĐENI POLIMERSKI ELEKTROLIT NA BAZI PEMA ZA VISOKO EFIKASNE I STABILNE BOJOM SINTETIZOVANE SOLARNE ĆELIJE

Ovaj istraživački rad pruža sveobuhvatnu analizu polimernih elektrolita u razvoju solarnih ćelija osetljivih na boju (DSSC), nove fotonaponske tehnologije koja nudi jeftinu i fleksibilnu alternativu konvencionalnim solarnim ćelijama na bazi silicijuma. Polimerni elektroliti se ispituju kao obećavajuće zamene za tradicionalne tečne elektrolite zbog njihove poboljšane stabilnosti, fleksibilnosti i jonske provodljivosti, što je sve ključno za poboljšanje performansi i dugovečnosti DSSC ćelija. Rad kategoriše polimerne elektrolite u čvrste, gel, kompozitne i jonske tečne tipove, razmatrajući jedinstvena svojstva, sastav, prednosti i ograničenja svake kategorije. Ključni materijali, uključujući različite polimerne matrice, jonske provodnike, aditive i nanopunila, detaljno se ispituju kako bi se razumela njihova uloga u postizanju optimalne jonske provodljivosti, termičke stabilnosti i mehaničke čvrstoće. Metrike performansi kao što su provodljivost, stabilnost, fleksibilnost i fotonaponska efikasnost se procenjuju kako bi se pružio uvid u praktičnu primenu ovih materijala u DSSC ćelijama. Nedavna dostignuća, uključujući nove polimerne mešavine, nanokompozitne elektrolite i poboljšanu termičku stabilnost, istaknuta su kako bi se predstavile najnovije inovacije u ovoj oblasti. Pored toga, pregled se bavi značajnim izazovima, kao što su ograničenja transporta jona, izdržljivost, curenje elektrolita i ekonomska skalabilnost, koji trenutno ometaju široko usvajanje DSSC-ova na bazi polimernih elektrolita. Rad se zaključuje identifikovanjem potencijalnih praznina u istraživanju, uključujući potrebu za daljim napretkom u stabilnosti, ekološki prihvatljivim materijalima i skalabilnim metodama proizvodnje. Ovaj pregled služi kao ključni resurs za istraživače koji žele da razviju efikasne, održive i komercijalno isplative DSSC-ove pokretane naprednim tehnologijama polimernih elektrolita.

Ključne reči: *Solarne ćelije osetljive na boje (DSSC), polimerni elektroliti, jonska provodljivost, fotonaponska efikasnost, termička stabilnost, nanokompoziti, gel polimerni elektroliti (GPE), čvrsti polimerni elektroliti (SPE), curenje elektrolita, skalabilnost, ekološki prihvatljivi materijali, fleksibilne solarne ćelije, nanopunila i fotonaponska tehnologija.*

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Ibrahim Zakariya'u	0009-0003-2267-8023
Badiya Tukur	0009-0005-7699-2549
Muhammad Abdullahi Adam	0009-0005-6198-5629
Mamudu Aliyu	0009-0000-2276-3840
Abubakar Tijjani Abu	0009-0009-1445-8489
Pramod K. Singh	0000-0002-3155-6621