



A Review on the Fabrication and Advancements in Dye-Sensitized Solar Cells(DSSCs)

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Abstract: Dye-sensitized solar cells (DSSCs) have gained attention as an efficient and cost-effective alternative to conventional photovoltaic systems, owing to their unique capability to function effectively under diffused light conditions. It is future of green energy technology. The dye-sensitized solar cell (DSSC) is an emerging solar technology that harnesses visible light and transforms it into electricity using a photoelectrochemical system. This review focuses on recent progress in the fabrication and development of DSSCs, emphasizing efforts to enhance their efficiency, durability and environmental compatibility.

Keywords: DSSC, solar, energy, dye, efficiency.

Introduction: -

The global energy landscape is undergoing a substantial upheaval as countries strive to reduce carbon emissions and transition to more sustainable energy sources. Fossil fuels dominate the energy mix, with oil, coal, and natural gas accounting for 80% of global energy use. Nevertheless, the share of renewable energy sources is increasing, with renewable power production growing by 7% in 2020. The increasing availability of renewable energy sources, such as solar and wind power, presents an opportunity. Many countries have set targets for renewable energy adoption, as seen by the European Union's goal of attaining 32% renewable energy by 2030. Some countries have implemented carbon pricing mechanisms to promote the shift away from fossil fuels. However, political instability and policy reversals might threaten sustainable energy growth [1-3]. Solar energy represents the most readily available and plentiful energy source. We have now attained the capability to harness solar energy for many uses. It may be used for heating spaces in cold regions. Solar cookers are used in many homes for culinary purposes [4]. Solar energy may be captured using photovoltaic cells to provide electricity for vehicle operation and lighting. Considering this is a dependable energy source, it would be advantageous to construct economical methods for harnessing solar energy. Many scientists have contributed to the advancement of solar cell technology; nonetheless, Becquerel and Fritts are considered the pioneers of this discovery. The idea, honed over the years, has resulted in the present design of solar panels seen on many home roofs in our area [5]. DSSCs are an intriguing class of third-generation photovoltaic

technologies, characterized by their low toxicity, versatility, lightweight composition, eco-friendly nature and advantageous power conversion efficiencies. Their chemical and physical features require refining to improve efficiency and commercialization [6]. A dye-sensitized solar cell (DSSC) generally comprises of a photoelectrode, a counter electrode, and an electrolyte. DSSCs imitate the energy transformation process of photosynthesis, but are engineered systems that use dyes and semiconductors to generate electrical energy from sunlight. Figure 1 depicts the fundamental structure of a DSSC [7].

Structure and Working Principle of DSSC: -

The main components of a dye-sensitized solar cell (DSSC) include a nanocrystalline semiconductor film, dye sensitizers, an electrolyte medium, a transparent conducting slide and a counter electrode. Typically, nanocrystalline titanium dioxide (TiO_2) films serve as the photoanode, while platinum and graphite used as counter electrode. The system is completed with an electrolyte solution containing the I_3^-/I^- redox couple dissolved in an organic solvent, forming a sandwiched solar cell structure. The functioning of DSSCs is initiated when sunlight excites dye molecules, causing them to inject electrons into the conduction band of the semiconductor electrode. This process restores the dye's original state through electron donation from the electrolyte, which usually contains the I_3^-/I^- redox system in an organic or ionic liquid solvent. The iodide ions in the electrolyte regenerate the dye while preventing the oxidized dye from recapturing the conduction band electron. The circuit is completed through the external load by the reduction of triiodide at the counter electrode. The voltage produced under illumination is determined by the difference between the Fermi level of the electrons in the semiconductor and the redox potential of the electrolyte. In general, electrical power is produced without any permanent chemical changes. These processes also allow for the recombination of conduction band electrons in the semiconductor with the oxidized dye or electron acceptors in the electrolyte solution [7, 8].

In solid-state DSSCs, the electrolyte solution is replaced by a wide band gap p-type inorganic semiconductor, such as copper iodide (CuI) or copper thiocyanate (CuSCN), or a hole-transporting organic solid like amorphous arylamine derivatives [9]. Here, the excited dye injects electrons into the n-type oxide, while hole injection into the p-type material facilitates dye regeneration. Recently, electrolytes containing the I_3^-/I^- redox couple in organic solvents have also been explored as hole-transport materials. The fundamental working principle of liquid-electrolyte DSSCs aligns closely with that of their solid-state counterparts.

The Dye-Sensitized Solar Cell (DSSC) is composed of several crucial parts that collectively convert sunlight into electrical energy. The basic components of a DSSC are as follows [10].

1. Transparent and Conductive Substrate: Dye-Sensitized Solar Cells (DSSCs) typically consist of two transparent conductive glass substrates, which act both as platforms for the semiconductor and catalyst layers and as current collectors. The most commonly used TCO material is Fluorine-doped Tin Oxide (FTO) and indium-doped tin oxide (ITO), which is transparent to light and allows efficient electron flow.

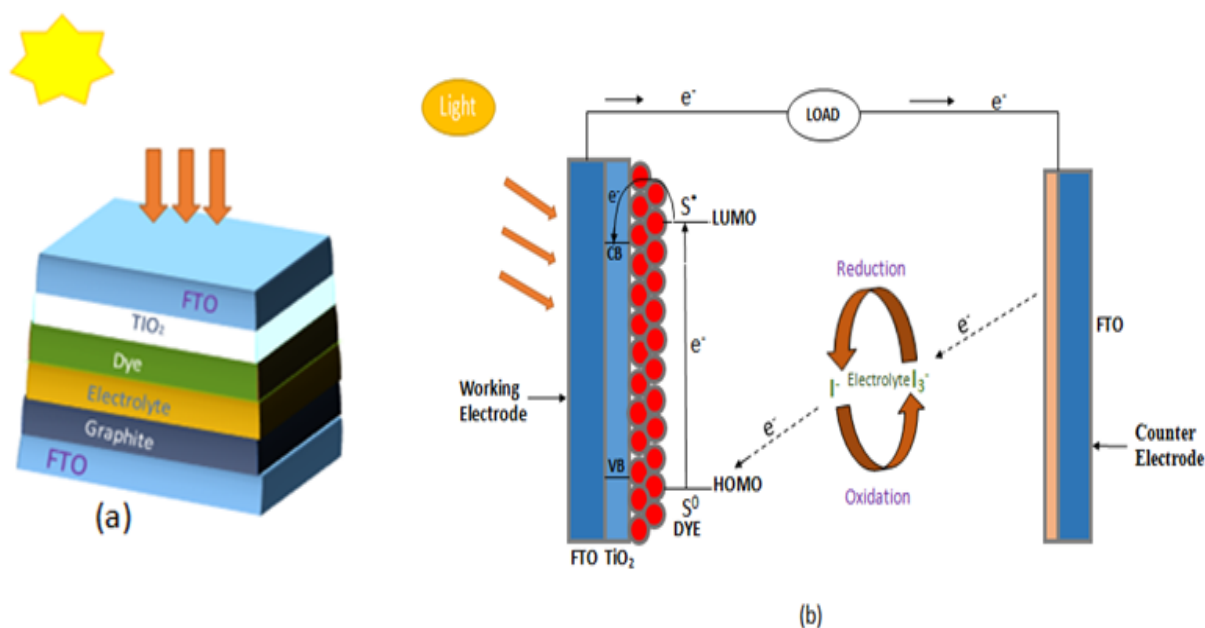
2. Photosensitizers: The next crucial element is the dye, which is a light-sensitive material that absorbs sunlight and undergoes a photoelectric reaction. This reaction excites the dye molecules, causing them to inject electrons into the conduction band of the adjacent Titanium Dioxide (TiO_2) layer. The efficiency of DSSCs is largely determined by the properties of the dye, such as its light absorption characteristics, electron injection proficiency and stability. A wide range of organic and inorganic dyes have been explored, including natural dyes, metal-complex dyes, and porphyrin-based dyes.

3. Working Electrode: The working electrode (WE), which is most often comprised of TiO_2 nanoparticles (anatase), collects electrons excited by the dye and functions as the semiconducting photoanode in dye-sensitized solar cells. Its porous structure enhances the surface area for dye adsorption, maximizing light absorption and electron injection. The anatase form of TiO_2 is more advantageous for DSSCs than the rutile form, as it has a larger energy band gap of 3.2 eV. The working electrode of DSSCs can be fabricated using other semiconductors like Nb_2O_5 , ZnO , and SnO_2 (n-type), as well as NiO (p-type) material.

4. Counter Electrode: This electrode is placed opposite the photoanode and is responsible for completing the circuit. Counter electrodes (CE) in DSSCs are generally composed of platinum (Pt) or carbon material due to their superior catalytic and conductivity properties. The primary function of the counter electrode in DSSCs is to facilitate the reduction of the oxidized dye or triiodide ions in the redox mediator, which is essential for ensuring the ongoing operation of the solar cell. Although research into alternative materials is ongoing, carbon derived materials (graphene and carbon nanotubes), conductive polymers, and metal alloys for counter electrodes have shown promising results.

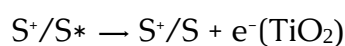
5. Electrolyte: The iodide/triiodide-based electrolyte is fundamental in DSSCs, as it donates electrons to oxidized dye molecules, enabling dye regeneration and the completion of the electrical cycle necessary for ongoing operation. The electrolyte is located between the photoanode and counter electrode, facilitating the electron transfer between them. Generally liquid electrolytes are used, but gel electrolytes and solid-state electrolytes have gained attention to improve stability and prevent leakage. Now alternative redox mediators such as $\text{SCN}^-/\text{SCN}_2$, $\text{Br}^-/\text{Br}_3^-$ and bipyridine cobalt (III/II) complexes are also employed in DSSC designs.

Fig 1: Structure of a DSSC

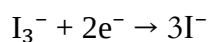


Working Principle: The DSSC mechanism follows four primary steps: light absorption, electron injection, charge carrier transport, and current collection. The process of converting photons into electricity proceeds as follows [10]:

1. **Light Absorption:** The photosensitizer absorbs incoming photons, exciting electrons from the dye's ground state (S^+/S) to its excited state (S^+/S^*). Most dye sensitizers absorb light within the 300-700 nm wavelength range, correlated to energy of approximately 1.71 eV. While sunlight is the primary energy source for DSSCs, artificial light can also be used for excitation. Various artificial light sources, such as LEDs, fluorescent lamps, and halogen bulbs, emit photons capable of exciting the dye molecules, though their spectral distribution and intensity differ from natural sunlight. The efficiency of DSSCs under artificial lighting depends on the match between the emission spectrum of the light source and the absorption spectrum of the sensitizer. Under controlled indoor lighting conditions, DSSCs are capable of producing electricity even under low-light conditions, making them well-suited for low-power uses such as indoor energy harvesting and powering compact electronic devices.
2. **Electron Injection:** The excited electrons, with lifetimes in the nanosecond range, are injected into the conduction band of the semiconductor TiO_2 electrode, which lies at a lower energy level than the dye's excited state. This injection process oxidizes the dye.



3. **Electron Transport:** The injected electrons move through the interconnected TiO₂ nanoparticles and diffuse toward the back contact, which consists of a transparent conducting oxide (TCO). They then travel through the external circuit to the counter electrode.
4. **Regeneration and Charge Balance:** At the counter electrode, the electrons reduce I₃⁻ to I⁻, thereby restoring the dye to its ground state. The I⁻ ions, in turn, undergo oxidation to regenerate I₃⁻, maintaining the redox cycle and sustaining continuous operation.



Each of these components—Transparent Conducting Oxide (FTO), dye, TiO₂, working electrode, counter electrode, and electrolyte—plays a vital role in ensuring the efficient functioning of the DSSC, from light absorption and electron injection to charge collection and regeneration of the dye[11].

The energy conversion in DSSCs is a dynamic process that involving the coordination of both the photoanode and photocathode, which work in tandem to ensure efficient electron flow and charge regeneration.

Electrochemical parameter of DSSC: The performance of the fabricated DSSCs is assessed through I-V characterization techniques. The following parameters are generally analyzed to calculate the efficiency of the DSSCs[12]:

1. **V_{oc} (Open-Circuit Voltage):** V_{oc} represents the maximum voltage a dye-sensitized solar cell can generate when no current flows through the circuit. It is identified from the I-V characteristic curve.
2. **I_{sc} (Short-Circuit Current):** I_{sc} denotes the highest current output of the cell when the voltage across it is zero.
3. **P_{max} (Maximum Power Point):** The peak power output (P_{max}) is determined from the product of voltage and current at a specific point known as the maximum power point. This is expressed as:

$$P_{\max} = V_{pp} \times I_{pp}$$

V_{pp} = voltage at the maximum power point, I_{pp} = current at the maximum power point.

4. **R_{ch} (Series Resistance):** Characteristic resistance (R_{ch}) is the inverse of the slope obtained from the I-V curve and is defined as the ratio of V_{pp} to I_{pp}. It represents the internal resistance of the cell during operation:

$$R_{ch} = V_{pp} / I_{pp}$$

5. **FF (Fill Factor):** The fill factor (FF) is the ratio of the highest power output (V_{pp} × I_{pp}) to the product of open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}). A higher fill factor indicates better energy conversion efficiency and stability. It is given by:

$$FF = (V_{pp} \times I_{pp}) / (V_{oc} \times I_{sc})$$

6. Efficiency (η): The power conversion efficiency (η) is a key performance metric of DSSCs, calculated using the following formula:

$$\eta = \frac{FF \times I_{sc} \times V_{oc}}{P_{in}} \times 100\%$$

Where, η = conversion efficiency of the cell

V_{oc} = open circuit voltage (highest voltage when current is zero)

I_{sc} = short circuit current (highest current when voltage is zero)

FF = Fill Factor

P_{in} = power input

Recent Advances in DSSC: A Review: -

The first dye-sensitized solar cell was developed by Professor Tsubomura and his team in 1976, using porous zinc oxide as the semiconductor material. Later, in 1991, Michael Grätzel and Brian O'Regan introduced an enhanced version of the dye-sensitized solar cell, achieving a conversion efficiency of 7.12% by utilizing a black dye. Although many researchers are actively working in the field of energy sector, making significant strides in solar energy conversion and storage, the efficiency of dye-sensitized solar cells (DSSC) has so far reached a maximum of only 15%. Therefore, this field requires more innovative approaches to enhance performance.

Mishra et al. (2009) investigated current progress in molecular design and the technical aspects of metal-free organic dyes for use in dye-sensitized solar cells (DSSCs). Cosensitization, an innovative approach for expanding the absorption spectrum, was investigated as a means to improve device performance. Additionally, they disclosed results on inverted dyes for photocathodes, signifying an innovative approach to the production of tandem cells [13]. Tian et al. (2009) formulated and synthesized a novel metal-free "black dye" for panchromatic dye-sensitized solar cells (DSSCs). The dye enabled the attainment of broader efficiency over the whole visible spectrum [14]. Miettunen et al. (2010) examined the stability of dye-sensitized solar cells using different metals as the photoelectrode substrate. DSCs with different grades of StS exhibited a rapid decrease in efficacy after a few hours of light exposure. Dye-sensitized solar cells demonstrated robust stability while using Inconel and titanium photoelectrode substrates [15]. Yang et al. (2013) examined the influence of different concentrations of triazoloisoquinoline-based small molecules as coadsorbents on the monolayer of a TiO_2 semiconductor and its effect on the performance of dye-sensitized solar cells (DSSCs). The results exposed that organic small molecules are a potential alternative for boosting the performance of dye-sensitized solar cells (DSSCs) [16].

Pashaei et al. (2015) performed an extensive investigation of unique alternative electrolyte shuttles in dye-sensitized solar cells (DSSCs), emphasizing their numerous advantages, including enhanced conversion efficiency and non-corrosive properties [17]. Soni et al. (2015) investigated the current state and recent developments in photoelectrodes, photosensitizers, and electrolytes for dye-sensitized solar cells (DSSCs) [18]. Rakesh et al. (2015) presented a comprehensive overview of the elements of DSSC, along with an examination of their evolution and related challenges. Researchers have concentrated on different structural alterations in wide band gap nano-crystalline semiconductor materials to enhance electron mobility and

minimize recombination rates. Efforts have been successfully made to create new molecular dyes with broad absorption across the visible spectrum. Moreover, hole transport materials function as a viable substitute for redox couple-based liquid electrolytes, yielding robust solid-state dye-sensitized solar cells (DSSCs). This study also examined the sophisticated technology for the progression of efficient, stable, and adaptable DSSCs [19].

Jinchu (2016) investigated the effects of Lawsone dye and its metal complexes on dye-sensitized solar cells (DSSCs). The absorption spectra of Lawsone changes to longer wavelengths during complex formation. As a result, there is a significant improvement in Jsc and PCE[20].Cakar and Ozacar (2017) synthesized a novel quercetin and Fe-quercetin compound dye for use in dye-sensitized solar cells (DSSCs). Fe-quercetin metal complexes, serving as replacements to natural dyes, provide an innovative method for natural dye-sensitized solar cells (DSSCs), which often have poor conversion efficiency [21].

Murwani et al. (2022) produced a range of dye sensitizers derived from porphyrin and effectively examined the impact of metals on photovoltaic performance. A greater atomic number in metals correlates with an increased effective nuclear charge, resulting in enhanced photovoltaic performance. The maximum efficiency achieved by a solar cell was 4.65% [22].Ozacar et al. (2022) synthesized diphenylcarbazone and tartrazine with various metal complexes and assessed its applicability for DSSCs. UV-Vis spectroscopy was employed for dye characterization, while EIS was utilized to assess the performance of DSSCs [23].Parasuraman (2023) provided a summary of the current development of DSSC prototypes and products from leading companies [24].Kulkarni and Hegde (2024) elucidated the advancement of sensitizers in DSSCs. Efforts are undertaken to thoroughly delineate the diverse tactics pertinent to the molecular design of prospective dye molecules and the methodologies associated with cell construction. Researchers anticipated that this evaluation will act as a catalyst for researchers and stimulate further advancements in this domain [25].Korir et al. (2024) presented a succinct summary of recent advancements in the field of DSSCs, encompassing molecular engineering techniques, effective sensitizers, and improved electrodes. This study examined nanostructured materials utilized as photoelectrodes [26].Asmaa et al. (2024) delineated the components of DSSCs and articulated their primary function. Subsequently, researchers analyzed various approaches employing metal nanoparticles doped onto TiO₂ as a photoanode and assess the impact of this dopant on the efficiency of DSSCs [27].

The continued development of new materials and optimization of DSSC architecture are expected to improve their efficiency, stability, and commercial viability, making them a promising technology for renewable energy generation in the future. As research progresses, DSSCs are expected to play a growing role in the future of green energy, supporting the shift toward cleaner and more sustainable energy options.

Conclusion: DSSCs continue to demonstrate significant potential as a sustainable and cost-effective photovoltaic technology. The advancements in materials, particularly in dye sensitizers, photoanodes and electrolytes, have contributed to notable improvements in efficiency and stability. Innovations such as metal doping, green solvent, natural dye utilization and hybrid material integration have further expanded the applicability and environmental friendliness of DSSCs. However, challenges remain in scaling up production,

mitigating degradation and enhancing long-term performance. Addressing these issues through advanced fabrication techniques and sustainable material choices is critical for the widespread adoption of DSSCs in real-world applications. Dye-sensitized solar cells have recently emerged as a promising and evolving research field, unlocking new potential and shaping the future of solar cell technology.

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