International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 08 Issue: 11 | Nov - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

Dye-Sensitized Solar Cells: Unveiling Barriers to Enhanced Performance

Savita Rambhau Nemade[1], Purnima Swarup Khare[1], Kailash Nemade[2]
[1]Department of School of Nanotechnology, Rajiv Gandhi Prodyogiki Vishwavidyalaya (RGPV) Bhopal, State Technological University, 462033, India.
[2] Department of Physics, Indira Mahavidyalaya, Kalamb Dist. Yavatmal, 445001, India.
Corresponding Author: krnemade@gmail.com

ABSTRACT
Global energy consumption is steadily increasing, and the world's reliance on non-renewable energy sources such as hydroelectric and thermoelectric power is unsustainable due to their diminishing availability. The photovoltaic (PV) devices have been developed through various methods for various applications, and among these, Dye-Sensitized Solar Cells (DSSCs) have emerged as a cost-effective and easily implementable technology. This comprehensive review paper offers an in-depth overview of DSSCs, aiming to provide insights into their construction, working principles, applications, and the significant challenges they face, primarily related to their low efficiency and stability. To fully commercialize DSSCs and compete with existing energy technologies, it is imperative to continue addressing and overcoming the efficiency challenges outlined in this review.

KEYWORDS: TiO_2, Dye Sensitized Solar Cell, Electrolyte, Photoanode, Counter Electrode

1. INTRODUCTION
The global demand for energy is steadily increasing, driven by heavy industrialization and urbanization trends. Developed nations have substantial energy demands, and this demand continues to rise in developing countries as well. According to the International Energy Agency, energy requirements are expected to grow by 55% by the year 2030 [1]. Regrettably, the current global energy demand is predominantly met by non-renewable sources like coal, petroleum, and natural gas. The extraction and use of these non-renewable resources result in a wide array of detrimental consequences, including air and water pollution, adverse public health impacts, global warming, and undesirable alterations in the atmosphere. A viable solution to this pressing issue lies in transitioning to renewable energy sources such as hydropower, geothermal, wind, and solar energy, instead of relying on non-renewable counterparts. Among these renewable alternatives, solar energy stands out as a prime choice due to its exceptional attributes: it is the most abundant, inexhaustible, and environmentally clean of all known renewable energy resources. Considering this discussion, it becomes evident that solar photovoltaic technology represents a pivotal option for clean energy generation. Additionally, it is crucial to raise awareness among the public about the benefits of solar energy.
Recognizing the significance of this shift, the Government of India has taken substantial initiatives, notably through the Jawaharlal Nehru National Solar Mission, which was launched on June 30, 2008, to promote environmentally sustainable growth and address India's energy security challenges [2]. Within the framework of this mission, the Government of India extends subsidies to both photovoltaic cell manufacturers and users, aiming to encourage the widespread adoption of solar energy. The sun, as the primary source of energy for life on Earth, holds immense potential. Harnessing the power of the sun not only diminishes our reliance on fossil fuels but also stimulates economic growth by generating new employment opportunities worldwide. Renewable energy sources have stood the test of time as the most reliable energy source since their discovery in 1673. In contrast, non-renewable energy sources are dwindling at an alarming rate. To address this pressing issue, photovoltaic energy has emerged as a compelling solution. It offers the unique advantage of directly converting solar energy into electricity without causing harm to the environment. Over the past several years, photovoltaic devices, including

organic, inorganic, and hybrid solar cells, have been developed. Among these, Dye-Sensitized Solar Cells (DSSCs) represent a novel and cost-effective class of energy conversion devices with a straightforward manufacturing process. The high light-harvesting efficiency achieved by the best DSSCs is the result of a well-balanced combination: a dye with moderate interaction and a photoanode with a large surface area [3]. Over the past half-century, technological advancements have disrupted the delicate balance between energy production and consumption. Traditional energy sources like coal, oil, and natural gas are proving inadequate to meet future energy demands while simultaneously causing harm to the environment.

Renewable energies offer a promising solution to address these pressing challenges, with photovoltaic solar cells emerging as a standout technology for cost-effective and environmentally friendly energy production. This new wave of photovoltaic technology, known as the third generation (3G), is poised to follow the footsteps of first-generation (1G) silicon wafers and second-generation (2G) thin film technologies. The development of 3G solar cells is driven by the need to overcome the limitations of their predecessors, 1G and 2G solar cells. These limitations include the imperative to enhance power conversion efficiency and reduce production costs. Unlike 1G and 2G devices, which have relatively high production costs, 3G solar cells are engineered to achieve cost reductions through the implementation of economical processing techniques. The photo-physics of photovoltaic devices can be comprehensively divided into four essential stages. First, there is the absorption of light and the generation of excitons. Second, excitons diffuse within the material. Third, excitons dissociate, leading to the generation of charges. Finally, the fourth stage involves the transportation and collection of these charges. This evolving landscape in photovoltaic technology is paving the way for more efficient, affordable, and environmentally sustainable energy production. Table 1 shows the classification of photovoltaic cell technology.

Table 1. Classification of photovoltaic cell technology.

First Generation	**Second Generation**	**Third Generation**
Monocrystalline (Mono c-Si)	Cadmium-Telluride (Cd-Te)	Dye Sensitized Solar Cell (DSSC)
Polycrystalline (Poly c-Si)	Copper-Indium-Selenide (CIS)	Pervoskite PV Cell
Amorphous Silicon Cells	Indium-Gallium-Diselenide (CIGS)	Organic PV Cell

To harness renewable energy, solar cells are essential. Photovoltaic cells have the unique ability to directly transform solar radiation into electricity while leaving no adverse impact on the environment. This feature has prompted researchers to concentrate their efforts on organic DSSC as a promising avenue in solar energy research. Within the realm of DSSC, titanium dioxide (TiO_2) plays a pivotal role. This novel type of solar cell, first conceptualized by Michel Grätzel and Michael O'Regan in 1991, offers distinctive characteristics. Unlike traditional solid-state devices, DSSCs are known for their flexibility, transparency, and the array of vibrant colors they can exhibit, depending on the dye pigments used in their construction. The exploration of DSSCs as an alternative source of electrical energy began in earnest in 1991 [4], and since then, they have garnered significant attention and research interest in the pursuit of sustainable energy solutions.

Over the past three decades, DSSC have emerged as a significant focal point in research. DSSC represents a viable alternative to conventional inorganic semiconductor-based solar cells, such as silicon (Si)-based solar cells. This innovative technology, commonly referred to as the Grätzel solar cell, owes its name to its inventor, Michel Grätzel, who, together with Brian O'Regan, developed it in 1991. DSSC is also known as a photoelectrochemical cell because it generates electricity through a photochemical process, distinct from traditional chemical reactions or advanced-generation solar cells. DSSCs are composed of semiconducting material, typically TiO_2, which acts as the anode. They are coupled with an electrolyte solution and a pure cathode (commonly made of materials like platinum, aluminum, or 3D graphite). DSSCs possess the remarkable ability to generate electricity under varying light intensities, and their fabrication process is cost-effective. At the core of DSSC technology is a nanostructured metal oxide film sensitized by absorbed dye molecules, enabling efficient absorption of visible light. The highest reported power conversion efficiency for DSSCs has reached approximately 11-12%. These characteristics position DSSCs as third-generation solar cells [5], representing a promising avenue for sustainable energy production.

However, the attained power conversion efficiency of approximately 11-12% remains insufficient for widespread commercial application. Solar energy, renowned as a renewable energy source, possesses unparalleled qualities—it is exceptionally versatile, dependable, cost-effective, limitless, and environmentally clean, making it an ideal solution to meet our energy demands. The molecular dye component within DSSC plays a pivotal role, and enhancing efficiency hinges on fine-tuning the optoelectronic properties of these dyes [6]. DSSCs based on TiO_2 have garnered recognition as a promising candidate for the next generation of solar cells. This acclaim is attributed to their low production costs, minimal environmental footprint, and relatively high-power conversion efficiency [7]. In recent years, a diverse range of solar cell technologies has emerged to harness sunlight for electricity generation. Notably, crystalline, polycrystalline, and amorphous silicon solar cells have found widespread utility across various domestic and industrial applications. Multi-junction semiconductor solar cells have even set a remarkable world record with an efficiency of 46%. However, their primary applications are predominantly confined to the space industry, limiting their broader use. In contrast, there exist other types of solar cells that, while less efficient, offer cost-effective alternatives. These cells have achieved the highest reported power conversion efficiency when utilizing Ruthenium complex dyes, specifically [N719], which falls within the range of 11-12% [8].

Global energy consumption continues to rise steadily, leading to an increased dependence on fossil fuels such as coal, petroleum, and natural gas. These finite natural resources, formed over thousands of years, may eventually pose challenges related to resource depletion and storage. Consequently, there is a growing recognition of the need to rely on renewable energy sources. Solar cells have emerged as a promising option in this generation. In DSSC, dyes play a pivotal role as sensitizers, facilitating the absorption of sunlight. Essentially, DSSC functions as a device comprising a nanostructured metal oxide film sensitized by dye molecules to efficiently capture visible light [9]. DSSCs consist of a layer of nanoparticles embedded in a dye, designed to capture photons of light. These dyes can be synthetic, such as Ruthenium complexes or natural dyes. DSSC operates on electrochemical principles, and their efficiency using natural dyes has reached up to 0.89% [10]. Classified as thin-film solar cells, DSSCs have been the subject of extensive research aimed at enhancing their efficiencies. Recent advancements in research techniques have pushed DSSC efficiencies to levels as high as 15% [11]. Dyes not only facilitate light absorption but also play a crucial role in charge transfer within DSSCs. To enable efficient charge transfer, the electrolyte must exhibit robust electrochemical and thermal stability. DSSC functions as a photoelectrochemical cell, with electron movement driven by the combined effects of photon energy and chemical reactions [12]. Prof. G.S. Han and his research group are currently engaged in pioneering work involving nanostructured perovskite solar cells based on reduced graphene oxide/mesoporous-TiO_2 nanocomposites. Their research has yielded significant advancements, particularly in enhancing the electron transport properties within these cells. A notable achievement of their work is the demonstration that graphene/mesoporous-TiO_2 nanocomposites exhibit low interfacial resistance. As a result, a reduced graphene oxide/mesoporous TiO_2 film, featuring an optimal reduced graphene content of 0.4 vol.%, achieves an impressive 18% Power Conversion Efficiency (PCE) when combined with TiO_2 nanoparticles [13]. In the early stages of DSSC development, dyes primarily relied on Ruthenium, which had limited availability and was challenging to produce. To circumvent these issues, researchers turned to natural dyes derived from leaves, flowers, and fruits. Although natural dyes are cost-effective and easier to obtain, they exhibited relatively low efficiency in DSSCs. C. Cari et al. conducted a study using three types of natural dyes: Chlorophyll, anthocyanin, and beta carotene. The synthesis solution consisted of ethanol, methanol, n-hexane, and

acetic acid. Among these natural dyes, spinach dye (chlorophyll) achieved the highest efficiency, reaching 7.2×10^{-2}, as evidenced by absorbance peaks at a wavelength of 2620 Å [chlorophyll] [13]. Furthermore, Dutta et al. embarked on research involving the synthesis of graphene quantum dots through a direct chemical method. These dots were combined with ZnO nanowires to investigate their photovoltaic properties. This composite material exhibited an open-circuit voltage of 0.8 volts, suggesting that graphene quantum dot-based materials represent the next generation of solid-state solar cells [14]. Masudy Panah and colleagues have successfully prepared a thin CuO film overlaid with nanoparticles, creating a highly promising absorber layer for solar cell applications [15]. Prof. Hui Ding and his research group have developed a straightforward method for creating graphene-TiO_2 nanocomposites. They achieved this by exfoliating graphene sheets through a simple liquid-phase sonication process and then combining them with TiO_2 nanoparticles. These nanocomposites exhibited excellent performance in solar cells. Specifically, the graphene-TiO_2 nanocomposite photoanode achieved a remarkable 43% increase in power conversion efficiency compared to TiO_2 alone under identical conditions [16].
Prof. Y. Kusumawati and collaborators have devised an effective technique for preparing a composite porous film that incorporates graphene sheets and anatase TiO_2 nanoparticles. By optimizing the graphene content to 1.2 wt%, they managed to enhance the power conversion efficiency by 12%. This improvement was primarily attributed to the increased short-circuit current density [17]. Prof. Seong-Bum Kim conducted experiments demonstrating the photovoltaic response of graphene integrated into N-doped TiO_2 photoelectrodes. The resulting DSSCs achieved a maximum power conversion efficiency of 9.32% with optimized parameters. This represents a substantial enhancement of approximately 22% over the efficiency of DSSCs with N-doped photoelectrodes [18]. The Khannam research group has developed a highly effective self-assembly method for synthesizing hybrid nanocomposites comprising TiO_2 nanoparticles on graphene oxide sheets. These nanocomposites were specifically designed for use in DSSCs. The graphene oxide TiO_2 nanocomposites, optimized with a graphene oxide content of 2.5 wt.%, exhibited impressive performance characteristics. They achieved a short-circuit current density of 7.67 mA/cm^2, an open-circuit voltage of 0.76 V, and a photoconversion efficiency of 3.97%. These values significantly outperformed those of pure TiO_2 nanoparticles [19]. Harnessing the power of the sun has the potential to reduce our dependence on fossil fuels and stimulate economic growth by creating new employment opportunities. Figure 1 depicts the evaluation of conversion efficiencies of DSSCs in recent years.
DSSCs represent a photovoltaic technology well-suited for powering electronic devices, particularly wireless sensors, using indoor light sources. DSSCs are particularly favored for indoor applications due to their manufacturing as thin, lightweight, and flexible modules. The ability to produce DSSCs as such flexible and lightweight solar modules makes them highly suitable for use in portable devices [20, 21]. This review article spotlights recent advancements in the development of new materials aimed at enhancing the performance of DSSCs [22-24]. Furthermore, it delves into the progress achieved in each functional component of a DSSC through material selection and fabrication process enhancements.

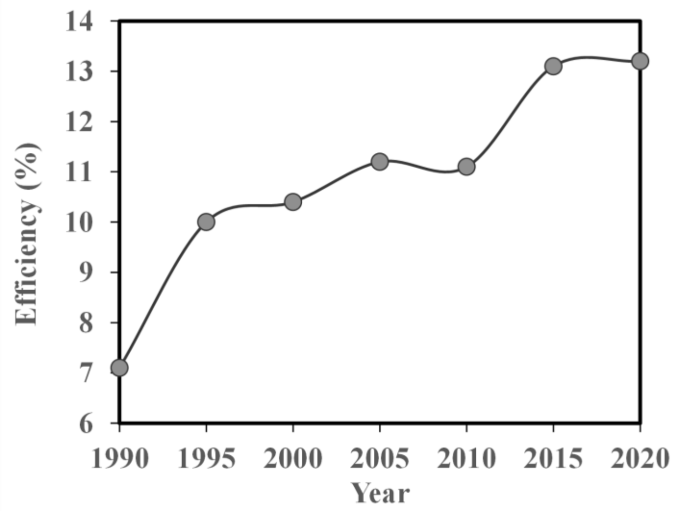


Figure 1. Evaluation of conversion efficiencies of DSSCs in recent years [26].

2. PURPOSE OF REVIEW

The primary aim of this review is to explore the design principles of photoanodes utilizing TiO_2-based nanocomposites, with a specific focus on enhancing the power conversion efficiency (PCE) of DSSCs. TiO_2 is a highly efficient photocatalyst, exhibiting prowess under both UV and visible light, making it a valuable material for solar cell applications. TiO_2 is a metal oxide semiconductor, showcases sensitivity contingent on its mesoporous structure and grain size, rendering it highly responsive and suitable for operation at elevated temperatures. Additionally, TiO_2 is abundant in nature and environmentally friendly.

The review's objectives are outlined as follows:

a) To establish the design principles for photoelectrodes using nanocomposites to elevate the PCE of DSSCs.

b) To enhance efficiency by optimizing the porosity of the photoelectrode, specifically the working electrode, with the overarching goal of boosting the power conversion efficiency of DSSCs.

c) To investigate the V-I characteristics of DSSCs under light illumination, analysing various diode parameters, including open-circuit voltage (Voc), short-circuit current (Isc), fill factor (FF), and power conversion efficiency, all of which are pivotal for photovoltaic applications.

The review also delves into the multifaceted aspects of TiO_2, with its mesoporous nature and structure-dependent characteristics. It highlights the significance of molecular dyes as essential components of DSSCs and underscores how improvements in DSSC efficiency can be achieved through the precise tailoring of the optoelectronic properties of these dyes. Researchers have increasingly turned to natural dyes as cost-effective alternatives to synthetic dyes like Ruthenium. Furthermore, the optimization of the porosity of TiO_2 photoelectrodes is explored as a key avenue for augmenting DSSC performance.

Ultimately, this review seeks to consolidate the wealth of research conducted in recent decades, aiming to provide comprehensive insights into the mechanisms and strategies employed to advance DSSC technology and elevate its overall performance.

3. STRUCTURE OF DYE SENSITIZED SOLAR CELL (DSSC)

This section provides an in-depth examination of the various components of Dye-Sensitized Solar Cells (DSSC), with a particular focus on the photoanode and its versatile applications. Traditionally, DSSCs employ a structural configuration that comprises transparent conducting oxide (TCO) coated glass electrodes, typically utilizing fluorine-doped tin oxide-coated (FTO) glass or Indium-doped tin oxide (ITO). The foundational element of a DSSC is the photoanode, which consists of a monolayer of dye absorbed onto a mesoporous semiconductor oxide, typically TiO_2. In the DSSC, light is absorbed by the dye, leading to a change in separation at the interface through photo-induced electron injection from the dye into the conduction band of the solid. Throughout this review, we delve into the advantages and applications of DSSCs, elucidate their working principles, and explore efficiency enhancements facilitated by the integration of novel materials. The DSSC's fundamental structure encompasses a glass substrate, a transparent conducting layer comprised of TiO_2 nanoparticles, the dye, an electrolyte (I^-/I^{3-}), and a counter or catalytic electrode, as illustrated in Figure 2.

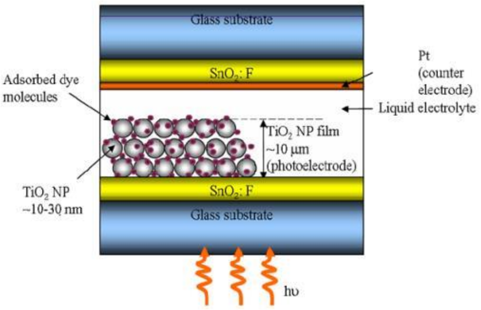


Figure 2. Typical design of a Dye Sensitised Solar Cell [29].

4. COMPONENTS OF DSSC

Dye-Sensitized Solar Cells (DSSCs) are renowned for their utilization of low-cost materials and their ease of fabrication, allowing for diverse and aesthetically appealing designs. The main components of DSSCs include:

- Substrate and Transparent Conducting Layer
- Photoanode
- Dye Sensitizer
- Electrolyte
- Counter Electrode

These components work synergistically to harness sunlight, converting it into electricity through a photovoltaic process within the DSSC.

4.1 Substrate and Transparent Conducting Layer

DSSCs comprise a structural framework involving two sheets of transparent and conductive material that function as a conductive substrate for depositing the TiO_2 semiconductor and catalyst. The selection of substrate materials for DSSCs is governed by specific characteristics. Firstly, the substrate must exhibit over 80% transparency to allow the passage of sunlight to the cell. Secondly, to facilitate charge transfer and minimize energy loss within the DSSC, the substrate should possess high electrical conductivity [25]. Various types of substrates can be employed, including FTO or ITO. These substrates typically consist of soda-lime glass coated with either indium tin oxide or fluorine tin oxide. Additionally, polymers are explored as alternative substrates. The assembly of a DSSC involves a working electrode saturated with a sensitizer and sealed to a counter electrode, which is coated with a thin layer of electrolyte. These components are securely bound using hot metal tape to prevent electrolyte leakage. DSSCs are essentially constructed with two conductive material sheets serving as substrates for the deposition of the TiO_2 semiconductor and catalyst. Among substrate choices, ITO offers greater transmittance compared to FTO.

4.2 Photoanode (Working Electrode)

The photoanode, also known as the working electrode, plays a pivotal role in Dye-Sensitized Solar Cells (DSSCs) and holds significant importance for several key reasons:

- Light Absorption: The photoanode is the primary component responsible for capturing sunlight and converting it into electrical energy. It accomplishes this by absorbing photons from incident light, which excites the dye molecules attached to its surface.

- Electron Generation: When the dye molecules on the photoanode absorb photons, they become excited and release electrons. These electrons are essential for generating an electrical current within the DSSC.
- Electron Transport: The photoanode serves as a pathway for the excited electrons to move through. It possesses a semiconductor material, often titanium dioxide (TiO_2), with a mesoporous structure that facilitates the efficient transport of electrons.
- Chemical Stability: The photoanode material must be chemically stable to endure prolonged exposure to sunlight and harsh environmental conditions. TiO_2, commonly used in DSSCs, is known for its chemical stability.
- Dye Anchoring: The photoanode provides a surface for the attachment of light-absorbing dye molecules. These dyes are crucial for broadening the absorption spectrum of the solar cell and enhancing its overall efficiency.
- Dye Regeneration: After releasing electrons, the dye molecules on the photoanode must be efficiently regenerated by receiving electrons from the electrolyte. This electron transfer process is essential for the continuous operation of the DSSC.
- Porosity: Many photoanodes are intentionally designed with a mesoporous structure to increase their surface area. This allows for a higher density of dye molecules, leading to improved light absorption and, consequently, higher energy conversion efficiency.
- Compatibility with Electrolyte: The photoanode must be compatible with the electrolyte used in the DSSC. This ensures that the redox reactions between the dye, electrolyte, and counter electrode occur smoothly.
- Efficiency Improvement: Researchers continually strive to enhance the performance of the photoanode to increase the overall efficiency of DSSCs. This includes optimizing its morphology, bandgap, and other characteristics.

In summary, the photoanode is a critical component of DSSCs, as it initiates the conversion of solar energy into electricity. Its design, material properties, and compatibility with other cell components significantly influence the efficiency and performance of DSSCs, making it a focal point for research and development in photovoltaic technology.

Wide band gap semiconducting metal oxides were employed as the photoanode material and deposited onto TCO (FTO or ITO) substrates. The working electrode is a mesoporous TiO_2 film, with particles measuring 20 nm in size and a thickness of 10 micrometers. The dye is absorbed onto the surface of the TiO_2, with the TiO_2 serving as both an electron acceptor and a transport medium. In addition, a thin layer of semiconducting oxide was prepared on a conducting glass substrate, such as FTO/ITO. Semiconducting oxides like SnO_2, TiO_2, Nb_2O_5, ZnO and NiO possess wide band gaps typically in the range of 3-3.2 eV.

The anatase allotropic form of TiO_2 finds more favourable application in DSSCs compared to the rutile form, owing to its higher energy band gap of 3.2 eV, while the rutile form has a band gap of approximately 3 eV. However, these semiconducting layers absorb only a limited amount of light in the UV region. Consequently, these working electrodes are immersed in a photosensitive molecular dye. After soaking in the dye solution, the dye becomes bonded to the TiO_2 layer. Nanocrystalline TiO_2 electrodes exhibit a highly porous structure with a large surface area, enabling a greater number of dye molecules to attach to the TiO_2 surface and consequently increasing light absorption on the TiO_2 surface. The interface between the dye and TiO_2 is investigated through impedance spectroscopy. A suitable binder with a high molarity such as Polyethylene Glycol is used for photoanode preparation. The carboxyl groups in Polyethylene Glycol provide chemical binding to the TiO_2 surface. The ideal mesoporous structure for TiO_2 is around 7nm, as it maximizes dye absorption area. Conductivity of the TiO_2 photoelectrode is enhanced through the morphology of TiO_2 and coating TiO_2 with metal oxide. The thickness of the TiO_2 layer and its surface morphology are examined using scanning electron microscopy.

4.2.1 Recent Development in Photoanode

A thin layer of Nb_2O_5 was applied to the FTO substrate. The device exhibited an efficiency of 5.26% without Nb_2O_5, while with Nb_2O_5 (applied in a single dipping cycle), the efficiency increased to 5.94%. Moreover, under 6000 lux illumination, the device with Nb_2O_5 achieved the highest efficiency of 17.40%, whereas the device without Nb_2O_5 displayed an efficiency of 15.53% under the same conditions [26]. In DSSCs, two competing chemical reactions occur simultaneously, involving the oxidation of sensitizing molecules and redox electrolyte species [27]. These reactions take place within a microsecond (10^{-6} s). Photogenerated electrons can recombine with redox species (I^{3-}) or oxidized sensitizers [28, 29]. Chou et al. prepared a photoelectrode containing a composite of TiO_2 reduced graphene oxide-indium gallium zinc oxide using a hydrothermal process, spin coating, and sputtering. In this study, the photoanode exhibited an efficiency of 5.66%, and with TiO_2, a power conversion efficiency (PCE) of 3.46% under 0.63 $mW.cm^{-2}$ illumination. Both devices showed an increase in efficiency: 7.97% (TGI) and 7.70% (TiO_2) [30].

In another study, Hora et al. optimized the TiO_2 photoanode for indoor DSSC applications. They treated the TiO_2 blocking layer and TiO_2 mesoporous layer with $TiCl_4$ to reduce recombination with the electrolyte. After optimization, the device achieved an efficiency of 9.84% under simulated solar light conditions and an impressive 28.7% efficiency under indoor lighting conditions [31]. Liu et al. utilized spray pyrolysis to create a compact blocking layer, preventing electron leakage across a broad spectrum of intensities and allowing the DSSC to function efficiently in low-light conditions. The device with the compact blocking layer exhibited efficiencies of 15.26%, 14.59%, and 15.12% compared to the $TiCl_4$ blocking layer (8.56%, 7.46%, and 6.19%) under illuminations of 1001 lux, 601 lux, and 251 lux, respectively [32]. Sasidharan et al. reported bifacial DSSCs with a templated TiO2 surface formed by fugitive ZnO microflower inclusions. These cells achieved the highest efficiency of 6.82% and 4.71% under front and back side illumination, respectively, in sunny conditions. Furthermore, they demonstrated a remarkable efficiency of 11.8% under 1000 lux illumination [33].

The electron transport layer based on TiO_2 nanoparticles has demonstrated exceptional efficiency as a photoelectrode within the DSSC system, thanks to a multitude of characteristics highlighted in Figure 3. In recent years, intriguing trends and innovative strategies have surfaced, leading to modified designs of conventional TiO_2-based photoelectrodes that can achieve enhanced photovoltaic performance when coupled with advanced molecular dyes.

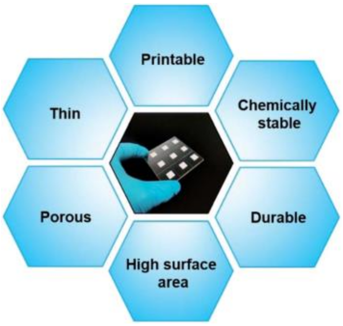


Figure 3. General characteristic of efficient semiconducting oxide layer [34].

4.3 Dye Sensitizer

Several properties of dyes are crucial for their effective use in Dye-Sensitized Solar Cells (DSSC) photovoltaic cells. These properties influence the ability of dyes to absorb light, generate electrons, and enhance the overall efficiency of the DSSC. Some of the key properties of dyes important for DSSC PV cells include:

- Absorption Spectrum: Dyes should have absorption bands that match the solar spectrum to efficiently capture a broad range of sunlight wavelengths, including visible and near-infrared regions.

- High Molar Absorptivity: Dyes with a high molar absorptivity value can absorb more photons per unit volume, increasing the number of electrons generated upon photon absorption.
- Stability: Dyes should be stable under prolonged exposure to light and harsh environmental conditions to ensure the long-term performance of the DSSC.
- Electron Injection Efficiency: Efficient electron injection from the excited dye molecule to the semiconductor (e.g., TiO_2) is crucial for converting absorbed photons into electrical current.
- Cost-Effectiveness: Cost-effective synthesis and availability of dyes are essential for the scalability and commercial viability of DSSCs.
- Environmental Impact: Environmentally friendly dye materials with minimal toxic effects are preferable to align with green energy principles.
- Broadband Absorption: Dyes that absorb a wide range of wavelengths, rather than being limited to a specific color, can enhance the overall efficiency of DSSCs.
- Resistance to Aggregation: Dyes should resist aggregation when adsorbed onto the semiconductor surface to maintain an even distribution.

The selection and design of dyes for DSSCs involve a careful balance of these properties to achieve high-efficiency solar cells capable of converting a significant portion of incident sunlight into electrical energy.

Molecular dyes play a vital role in DSSC and advancements in efficiency have been achieved through the careful customization of their opto-electronic properties [35]. DSSCs rely on dye molecules capable of light absorption and electricity generation. Sensitizers can be categorized into three classes: metal complexes, metal-free organic compounds, and natural sensitizers. The dye's primary function is to maximize the absorption of incident light. An ideal sensitizer should absorb light just below the threshold wavelength of 920 nm and securely anchor itself to the semiconductor oxide surface, facilitating electron injection into the conduction band.

Dyes are chemically bonded to the porous semiconductor surface, and they exhibit excellent light absorption within the visible spectrum, typically ranging from 400 nm to 700 nm. They strongly adhere to the semiconductor's surface. In an ideal dye molecule, the Highest Occupied Molecular Orbital (HOMO) level should be positioned farther from the TiO_2 conduction band's surface, while the Lowest Unoccupied Molecular Orbital (LUMO) level should be situated closer to the TiO_2 surface, with an energy level higher than that of the TiO_2 conduction band. The HOMO level should also be lower than that of the redox electrolyte, and the LUMO level functions as a donor level. Dyes come in two primary categories: Synthetic Dyes and Natural Dyes.

4.3.1 Synthetic Dyes

In the initial stages of DSSC development, stable Ruthenium-based dyes were employed. However, these dyes are challenging to synthesize, toxic, and expensive. Synthetic dyes fall into two subcategories:

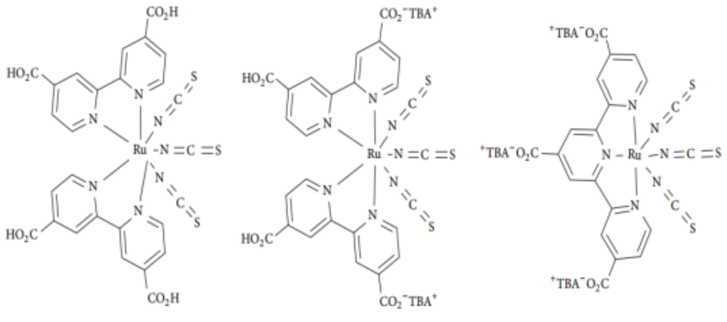
a) Metal Complex Sensitizers - These dyes consist of both Anchoring Ligands (ACLs) and Ancillary Ligands (ALLs). The attachment of the sensitizer to the semiconductor largely relies on the properties of ACLs, while ALLs can be utilized to fine-tune the overall nature of the sensitizer.

b) Metal-Free Photosensitizers - Metal-free organic sensitizers have been employed both as substitutes for expensive Ruthenium-based semiconductors and for enhancing the electronic characteristics of devices. However, the efficiency of these sensitizers remains relatively low.

4.3.2 Natural Dyes

In nature, various parts of plants, such as fruits, flowers, and leaves, exhibit a wide range of colors from red to purple, and these colors are attributed to natural dyes that can be extracted through a simple procedure. Natural dyes have found their way into DSSC applications due to their cost-effectiveness. They are not only more affordable and easier to extract but are also non-toxic and economical.

However, DSSCs using natural dyes often suffer from low efficiency. This can be attributed to the weak binding of natural dyes to TiO_2 and limited charge transfer, especially for absorption in the visible range. The key to enhancing the efficiency of DSSCs with natural dyes lies in effectively incorporating the dye molecules into wide bandgap semiconductors. These dyes have the capability to absorb visible light within a wavelength range of up to 800 nm. Figure 4 illustrates the structure of some efficient Ru-based photosensitizers for DSSCs.



N_3 $\eta = 11.03\%$ N719 $\eta = 11.18\%$ Black dye

Figure 4. Structure of some efficient Ru-based photosensitizers.

To determine the dye absorption characteristics and assess the wavelength absorption values of the dye, UV-VIS testing is employed. Additionally, FT-IR testing is conducted to analyze the chemical bond interactions between TiO_2 and the dye. Dyes play a critical role in the generation of excitons. Various types of natural dyes include Chlorophyll, derived from sources like grass, jelly, and leaves; Anthocyanin, obtained from flowers and red cabbage, with an absorption wavelength ranging from 450 to 580 nm [36]; and Beta carotene, derived from yellow and purple sweet potatoes. Combining different dyes can enhance the absorbance peak. For instance, when Anthocyanin is used alone, the incident photon-to-current conversion efficiency (IPCE) is approximately 0.081% at a wavelength of 430 nm. However, when combined with the synthetic dye N719, the IPCE increases to around 0.092%. DSSCs utilizing Anthocyanin as the dye alone achieve a power conversion efficiency of 0.024%. Yet, when combined with the synthetic dye N719, the power conversion efficiency increases to 0.054%. The highest efficiency reported for DSSCs using natural dye stands at 7.2×10^{-2}. Professor Gratzel's research demonstrated that TiO_2 nanoparticles significantly enhance dye absorption, particularly with Ru-based dyes that exhibit a wide optical absorption range from UV to near-IR. This enhancement led to an overall efficiency of up to 10% in DSSCs.

4.3.3 New Possibilities with Dyes for Co-sensitization

An alternative approach to enhance DSSC performance is co-sensitization, a technique where two or more sensitizing dyes with distinct absorption spectra are combined to expand the range of spectral response. Efforts to improve light harvesting through innovative dye designs represent a prominent area of research in DSSC. Hashmi and colleagues, for instance, have showcased a rapid sensitization method for TiO_2 photoelectrodes involving the application of dye inks through scalable and well-established inkjet printing techniques.

4.4 Electrolyte

The role of the electrolyte in DSSC encompasses regenerating the dye after it injects electrons into the conduction band of TiO_2 while also serving as a conduit for charge transfer. In the realm of organic electrolytes, which include I^- /I^{3-}, Br^- / Br^{2-}, SCN^- /SCN^2 and Co(II)/Co(III), several key components significantly influence DSSC performance: the redox couple, solvent, additives, ionic liquids, and cations. The electrolyte plays a pivotal role in DSSC stability.

Key properties of the electrolyte include:

- Efficient regeneration of oxidized dye by the redox couple.
- Long-term thermal and electrochemical stability.
- Non-corrosiveness with DSSC components.
- Fast charge carrier diffusion, increased conductivity, and strong contact between the working electrode and counter electrode.
- Absorption spectra of the electrolyte should not overlap with the dye's absorption spectra.
- Excellent interfacial contact with nanocrystalline semiconductor/TiO2 and the counter electrode.

I^-/I^{3-} electrolyte is highly efficient but has limitations such as high volatility, which can lead to photo degradation, dye desorption, and reduced stability.

Different types of electrolytes include:

- Quasi-solid-state
- Organic liquid-based
- Room-temperature ionic liquid (RTIL) based solvent
- Solid-state
- Ionic electrolytes (organic salts)

Solid-state electrolytes have been developed to enhance the long-term stability of DSSC by addressing issues related to leakage in liquid electrolytes. Ionic electrolytes are employed to mitigate the higher evaporation rate observed with highly volatile liquid electrolytes.

Organic electrolytes primarily consist of redox couples such as Br^-/Br^3, SCN^-/SCN and $SeCN^-/(SeCN)^2$, with I^{3-}/I^- being considered an ideal couple due to its excellent redox stability, rapid dye regeneration, low absorbance of visible light, suitable redox potential, and slow recombination kinetics between injected electrons into the semiconductor and tri-iodine.

Progress in DSSC technology has been made through the development of electrolyte formulations featuring alternative redox shuttles, resulting in increased efficiency. Traditional tri-iodide electrolytes, known for their corrosive effects on metals, have been replaced by alternative redox couples. Among these alternatives, Co-Cobalt and Cu-Copper redox shuttle-based electrolytes have garnered attention due to their distinctive characteristics. These include rapid dye regeneration with a low driving force and lower absorption in the visible range. Several reports indicate the potential to achieve voltages greater than 1V and to harness light even in low-intensity conditions. The Co-complex, with its tunable redox potential, enables swift adjustment to the highest occupied molecular orbital (HOMO) level of the sensitizer, resulting in a higher open-circuit voltage. Molecular dyes and redox shuttles play crucial roles in light harvesting, while porosity tuning is achieved using porous TiO_2 electrodes. Varying the sizes of TiO_2 nanoparticles in TiO2 films helps avoid the diffusion limitations of redox shuttles. Currently, laboratory-scale DSSCs utilizing [Co(phen)3] 2+/3+-based electrolyte formulations have achieved conversion efficiencies exceeding 14%. These results were obtained when tested with alkoxysilyl-ancor.

4.5 Counter Electrode

The counter electrode serves a crucial role in the regeneration of the electrolyte within a DSSC. When the electrolyte becomes oxidized, it diffuses toward the counter electrode, where it acquires electrons from the external circuit. The presence of a catalyst in DSSCs is essential due to their fundamental differences from conventional Si-based solar cells. In Si-solar cells, light absorption and charge carrier transportation are combined tasks, while in DSSCs, these two functions are separated. Charge separation occurs through photoinduced injection into the conduction band, and the resulting carriers are transported to the charge collector.

Traditionally, counter electrodes have been predominantly made from platinum, but its high cost has led to the development of several alternatives, including carbon, aluminum, and copper. The primary function of the counter electrode is to facilitate the return of electrons generated at the photoelectrode, which are then delivered through the external circuit. Conductive glass coated with platinum, carbon electrode, or conductive polymer offers cost-effective alternatives to using expensive platinum. Typically, the counter electrode is prepared by applying a platinum catalyst to an FTO glass plate. The FTO plate is heated on a hot plate at 250°C for 10 minutes, and a platinum solution is then applied and coated onto the FTO glass. The working electrode and counter electrode are sealed together, and electrolyte is injected using a syringe. The counter electrode catalyzes the reduction of the I-/I3- liquid electrolyte and collects holes from the transport material.

Platinum is the preferred choice for counter electrodes in terms of efficiency, but its high cost and limited natural abundance have driven the development of alternative materials, such as carbon, gold, and FeSe alloys. Figure 5 illustrates the general characteristics of an efficient carbonaceous counter electrode in DSSCs.

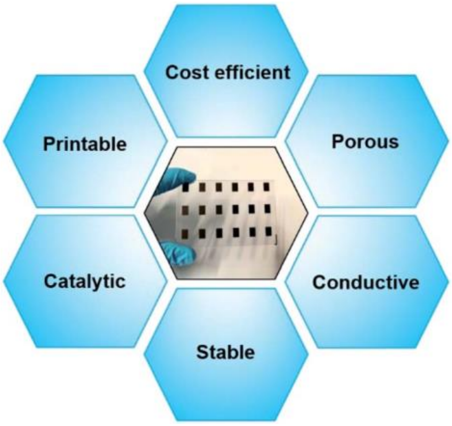


Figure 5. General characteristics of an efficient carbonaceous counter electrode in DSSCs.

Once the working electrode and counter electrode are prepared, they are assembled into a sandwich-type arrangement. The space between the two electrodes is filled with the electrolyte solution. Various characterization techniques are employed to assess the properties of DSSCs, including SEM, TEM, FT-IR, UV-VIS, PL, XRD, Raman spectroscopy. Additionally, the performance of DSSCs is evaluated through current-voltage measurements.

In first-generation DSSCs, platinum (Pt) remains the top choice as a catalyst for achieving high-efficiency DSSCs. Platinum is highly catalytic, exhibits mechanical durability, and demonstrates chemical stability. DSSCs with Pt-based counter electrodes have consistently achieved solar-to-electrical conversion efficiencies exceeding 11.0%. These efficiencies are observed when tested with iodide/tri-iodide redox shuttle-based electrolytes, and they also exhibit long-term stability. However, low-cost carbonaceous materials have emerged as an alternative catalyst material for both cobalt (Co) and copper (Cu) redox shuttle-based electrolytes. Carbonaceous counter electrodes possess several advantageous characteristics, including a high surface area, substantial porosity, and strong catalytic activity, along with the ability for precise printing. Impressive solar-to-electrical conversion efficiencies exceeding 14% are frequently achieved when using carbonaceous counter electrodes. Among carbonaceous materials, graphene nanoplatelets have been widely tested with Co and Cu redox shuttles. To ensure long-term stability and reliability, robust sealing materials and procedures are essential for protecting DSSCs from external factors such as humidity, pressure, temperature, and UV light. The sealing procedure is particularly challenging due to the need to isolate the electrolyte effectively.

5. WORKING MECHANISM AND OPERATIONAL PRINCIPLE OF DSSC

The working mechanism and operational principle of a DSSC involve several key steps:

- Light Absorption: The process begins with the absorption of sunlight by the dye molecules coated on the surface of the semiconductor material, usually titanium dioxide (TiO_2). These dye molecules are responsible for capturing photons from sunlight.
- Electron Excitation: When a photon is absorbed by a dye molecule, it excites an electron within the dye to a higher energy state. This electron is now in a "hot" or excited state.
- Electron Injection: The excited electron in the dye molecule is injected into the conduction band of the TiO_2 semiconductor. This step is critical as it initiates the flow of electrical current.
- Electron Transport: Once injected into the TiO_2 semiconductor, the excited electrons move through the material's conduction band due to an electric field generated within the cell. This movement constitutes an electric current.
- Electrolyte Regeneration: While the electrons are flowing through the TiO_2 semiconductor, the dye molecule left behind is positively charged. The electrolyte, typically consisting of a redox couple like iodide/tri-iodide (I^-/I^{3-}), regenerates the dye by accepting this positive charge and converting it back into its original state.
- Electron Collection: The electrons that have moved through the TiO_2 semiconductor are collected by a transparent conductive electrode, which is usually made of materials like fluorine-doped tin oxide (FTO) or indium tin oxide (ITO). These collected electrons form the electric current that can be harvested for external use.
- Closed Circuit: An external electrical circuit is connected to the conductive electrode, allowing the harvested electrons to flow through the circuit, creating an electric current that can power electronic devices or be stored in a battery.
- Return of Electrons: The electrons that have flowed through the external circuit then return to the dye molecules on the TiO_2 surface by passing through the counter electrode, typically made of materials like platinum or carbon. At the counter electrode, the electrons reduce the oxidized form of the redox couple (e.g., I^{3-}) back to its reduced form (e.g., I^-).
- Electrolyte Regeneration (Again): The redox couple is regenerated at the counter electrode, and the cycle continues.

DSSCs work by using a light-absorbing dye to capture photons, which excite electrons, initiating the flow of electrical current. This current is collected and used as electrical energy, while the dye molecules are regenerated by the redox electrolyte. This unique mechanism allows DSSCs to efficiently convert sunlight into electricity while being relatively inexpensive and easy to manufacture.

In conventional Si-Solar cell light absorption and charge carrier transportation are not separate task. But in DSSC separation done by photo induce injection to condition band of TiO_2 and such created carrier are transported to counter electrode. Working mechanism of DSSC involve four basic steps**.** First is Light absorption, second is Electron injection, third is Transportation of carriers and last is Collection of current as shown in figure given below. Photovoltaic phenomenon in DSSC involves redox reaction and electrolyte in DSSC has redox potential. Firstly, the incident radiation is absorbed by dye and so electrons go from ground state (S+/S) to excited state of dye, where the absorption of most for the dye is in the range of 700 nm which correspond to the photon energy 1.72 eV. Now the excited electrons are injected to the conduction band of nanoporous TiO_2 electrode. The pictorial representation of working principle of DSSC is depicted in Figure 6. Which lies below the excited state of the dye where TiO_2 absorb photons and dye gets oxidized.

General chemical rection in all process

S+ / S + hv ------------------- S+ / S (Dye)

S+ / S ------------------- S+ / S + e- (TiO_2)

These injected electrons are transported between TiO_2 nanoparticles and diffuses to the back contact. And electron reach at counter electrode. The electrons at counter electrode reduce the dye (I^3 to I^-) So dye regeneration takes place due to acceptance of electron from I- ion redox mediator and get oxidized to I^{3-} oxidized state.

$$S^+ / S^\# + e^- \text{ ------------------ } S^+ / S$$

Again the I^{3-} diffuses towards the counter electrode and reduces the ion.

$$I^{3-} + 2e \text{ ------------------- } 3I^-$$

Energy conversion efficiency = J_{sc} x V_{oc} x FF

J_{sc} is photocurrent. From energy band structure and the carrier transfer process in figure 7.

$$V_{oc} = E_{CB} / q + Kt / q \log (n / N_{CB}) E\ redox / q$$

where n is number of electrons in TiO_2

N_{CB} is effective density of state at conduction band;

E redox is HOMO level of the redox couple;

q is unit charge in coulomb.

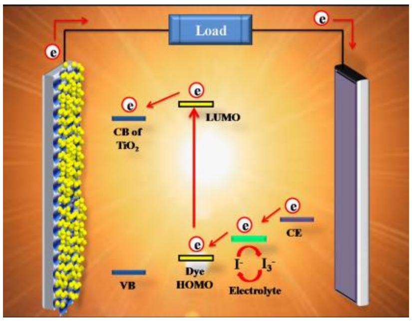


Figure 6. Working principle of DSSC.

6. DIFFERENT WAYS TO ENHANCE POWER CONVERSION EFFICIENCY

Efficiency relies on various variables, including system design, the spectral response of the module, the properties of the active material, the intensity of the light source, as well as factors like illuminance, irradiance, reflection, and temperature. Single junction Dye-Sensitized Solar Cells (DSSCs) have demonstrated an efficiency of up to 13% [44]. Researchers are actively engaged in enhancing this efficiency by modifying electrodes, photosensitizers, and electrolytes. Substantial efforts are being directed towards the development of new materials for photoelectrodes.

The power conversion efficiency (PCE) of DSSCs is closely tied to the thickness of the TiO_2 photoelectrode. PCE is hampered by energy losses during the recombination of electrons within the photoanode in the presence of oxidized dye and electron-accepting species in the electrolyte. Additionally, electron back transfer from TiO_2 to the redox electrolyte contributes to lower efficiency. To address this, vertically aligned ZnO nanorods are applied as a blocking layer.

The highest PCE achieved, utilizing the ruthenium complex dye N719, falls within the range of 11-12%. One avenue for improving PCE involves optimizing the nanostructure of the semiconductor photoanode. This includes experimenting with various nanoparticle shapes, such as nanorods, nanotubes, nanosheets, and mesoporous structures. In the fabrication of the TiO_2 photoanode, Polyethylene Glycol (PEG) is employed as a binder to enhance power conversion efficiency. The presence of PEG ensures the creation of crack-free electrodes.

Significant efforts have been devoted to enhancing light harvesting efficiency. To further boost the energy conversion efficiency of Dye-Sensitized Solar Cells (DSSCs), it is imperative to enhance Voc (open-circuit voltage) by mitigating charge recombination between the electrolyte and injected electrons in the conduction band of TiO_2. This entails reducing charge recombination between the oxidized dye and injected electrons within the TiO_2 conduction band, as well as improving electron injection efficiency.

To curtail charge recombination, it is essential for the dye to establish a compact blocking layer on the TiO_2 surface. Furthermore, it is crucial to prevent desirable complexation between the dye and iodide while ensuring separation of the electron-donor unit from the TiO_2 surface to impede charge recombination between injected electrons and the dye. To enhance electron injection efficiency, alignment of the dye's Lowest Unoccupied Molecular Orbital (LUMO) with TiO_2 is necessary.

To broaden the absorption spectra of the dye, incorporating strong electron donor and acceptor groups proves to be a promising strategy. The rapidly advancing field of organic dye sensitizers holds considerable promise for reinforcing Voc and overall efficiency.

To augment energy conversion efficiency, the following measures are vital:

- Diminish charge recombination between the redox couple and injected electrons in the TiO_2 conduction band.
- Curtail charge recombination between the oxidized sensitizer and injected electrons in the TiO_2 conduction band.
- Enhance electron injection efficiency.

Additionally, the implementation of tandem DSSCs, which combine a p-type photocathode and an n-type photoanode, is being explored to further advance efficiency.

One approach to enhance Dye-Sensitized Solar Cell (DSSC) efficiency involves replacing the single-junction configuration with a multi-junction tandem DSSC. The tandem DSSC has the capability to significantly improve full-spectrum light harvesting by stacking multiple dyes with complementary absorption characteristics. Consequently, the theoretical efficiency limit of a tandem DSSC under standard conditions could reach 43%, surpassing the 30% efficiency of conventional DSSCs equipped with a single photoactive dye-sensitized electrode.

6.1 Types of Tandem DSSCs include:

- Stacking pre-assembled DSSC devices.
- Combining dye-sensitized photocathodes with dye-sensitized photoanodes (DSSC).
- Combining a complete DSSC with another type of solar cell (hybrid).
- The simplest tandem structure comprises a top DSSC stacked on a bottom DSSC. These two cells can be connected either in series or in parallel to form a Tandem DSSC, denoted as ST-DSSC (for series connection) or PT-DSSC (for parallel connection). Figure 7 provides a schematic representation of a tandem pn-DSSC.

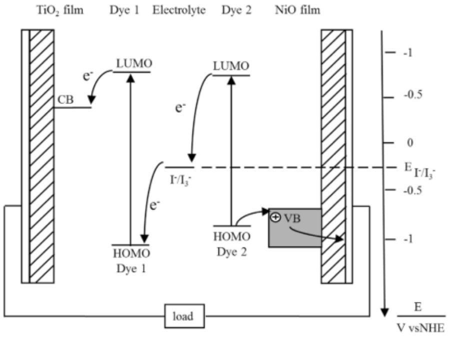


Figure 7. Schematic representation of tandem pn-DSSC.

6.2 Factors Influencing DSSC Efficiency:

Several factors have a significant impact on the performance of Photovoltaic (PV) cells, particularly in the case of Dye-Sensitized Solar Cells (DSSCs):

- Use of volatile liquid electrolyte: DSSCs employ liquid electrolytes that are volatile, limiting their operational lifespan compared to 1st and 2nd generation (1G and 2G) solar cells.
- Sensitivity to sunlight and air: DSSC electrolyte solutions can be dried out by exposure to sunlight and air.

- Requirement for conductive glass and redox electrolyte: DSSCs depend on conductive glass and redox electrolyte solutions for their operation.
- Limited absorption in the IR region: DSSCs exhibit low absorption in IR region due to the requirement for dyes that are volatile in the IR range.
- Dye performance: The effectiveness of the dye used in DSSCs plays a critical role in their performance.
- Electrode contact quality: Poor contact between electrodes can lead to reduced efficiency.
- Electrolyte degradation: The degradation of the electrolyte can impact the long-term performance of DSSCs.

In the DSSC operation, incident radiation is absorbed by a photosensitizer, which results in the promotion of electrons from the Highest Occupied Molecular Orbital (HOMO) to the Lowest Unoccupied Molecular Orbital (LUMO) state of the dye. These excited electrons, with a lifetime on the order of nanoseconds, are then injected into the conduction band of a porous, nanoporous TiO_2 electrode. TiO_2 absorbs a small fraction of solar photons in the UV region, causing the dye to become oxidized. The injected electrons travel between TiO_2 nanoparticles and diffuse through the external circuit toward the back contact, often made of materials like FTO/ITO/TCO. Finally, the electrons reach the counter electrode, where they facilitate the regeneration of the dye. The electrolyte contains a redox mediator, and the counter electrode, typically made of materials like platinum (Pt), is responsible for regenerating the redox mediator [45].

The photoelectrode is constructed using TiO_2 nanoparticles with a porous structure, and to enhance the conductivity of TiO_2 through its morphology, various types of metal oxide nanocomposites with TiO_2 are synthesized to prevent electron leakage from TiO_2 to the electrolyte. The photovoltaic process in DSSCs involves a redox reaction, and the ions involved can be utilized for energy storage in solar cells through artificial photosynthesis. The choice of electrolyte in DSSCs influences the cell's redox potential, with the highest PCE achieved using an electrolyte solution of acetonitrile containing iodine ions and iodine, reaching 10.4%. In contrast, quasi-solid electrolytes composed of non-volatile ionic liquids achieve a PCE of 7%. The original dye used in Grätzel cells was Ruthenium bipyridine with a carboxyl group. This carboxyl group facilitated chemical bonding to the surface of TiO_2 particles, allowing for efficient electron injection from the dye to TiO_2. The dye's ability to absorb visible light extended to a wavelength range of up to 800 nm, and TiO_2 nanoparticles were employed to increase the surface area available for dye absorption.

7. DSSC PERFORMANCE PARAMETER

The performance of DSSCs is also influenced by film morphology. Achieving an optimal balance between the surface area of nanoparticles and light scattering is crucial. This balance is meticulously controlled by adjusting the layers within the multilayer structure. To enhance the scattering of red light, a multilayer structure with progressively increasing particle size from the innermost layer is required.

Evaluating the performance of DSSCs involves various parameters, with the incident photon to current conversion efficiency (IPCE) being a key metric. Other important parameters include the open-circuit voltage (V_{oc}, measured in volts), short-circuit current (J_{sc}, measured in milliamperes per square centimeter), fill factor (FF), maximum power output conversion (P_{max}), and overall efficiency (η), particularly when advanced TiO_2 photoelectrodes are employed. Figure 8 illustrates the I-V curve used for evaluating cell performance, as shown below. These measurement parameters are contingent upon the morphological characteristics of the semiconductor, spectroscopic properties of the dye, and electrical properties of the electrolyte.

The current is generated when the negative and positive electrodes of the DSSC are short-circuited at a voltage of 0 mV. To enhance both efficiency and stability, researchers are concentrating on fundamental fabrication methods and material synthesis. Increasing the porosity of the TiO_2 nanoparticles promotes maximum dye absorption at the working electrode.

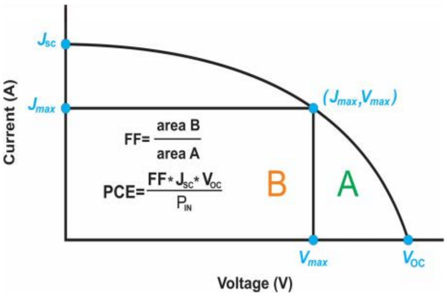


Figure 8. I-V curve to evaluate the cell performance [19].

The current produces when positive and negative electrodes are short circuited at zero mV voltage. V_{oc} is the voltage across positive and negative electrode. Under open circuit condition at 0 mA current. Pmax is maximum efficiency of DSSC to convert sunlight to electricity. Therefore, the fill factor is

$$FF = \text{Area A/Area B} = J_{mp} \text{ x } V_{mp} / J_{sc} \text{ x } V_{sc}$$

Overall efficiency % is the % of solar energy converting to electrical energy.

$$n \% = J_{sc} \text{ x} V_{oc} \text{ x FF/Pin} \quad \text{------------------------------}(1)$$

Incident-Photon-to-Current Efficiency (IPCE) is

$$\text{IPCE \% (y)} = 1240 \text{ x } I_{sc} \text{ /Pin (y)}$$

Where, P_{in} is incident optical power, y is wavelength, n is the global power conversion efficiency to electrical conversion efficiency in IPCE values are also related to light harvesting efficiency (LHE), electro injection quantum efficiency and efficiency of collecting electrons in external circuit.

8. PREVIOUS AND FURTHER IMPROVEMENTS IN DSSCS

Dye-Sensitized Solar Cells (DSSCs) have undergone significant advancements and continue to evolve in pursuit of higher efficiency and practicality.

8.1 Previous Improvements:

- Dye Innovations: The choice of dyes has seen remarkable progress. Early DSSCs primarily used Ruthenium-based dyes, but researchers have developed new organic and metal-free dyes, expanding the spectrum of light they can harness.
- Electrolyte Enhancements: Liquid electrolytes initially posed stability challenges. Researchers have introduced solid-state and quasi-solid-state electrolytes, improving cell longevity and efficiency.
- Nanotechnology: The introduction of nanostructured materials, such as TiO_2 nanoparticles, has increased the surface area for dye absorption and improved charge transport.
- Tandem Structures: Multijunction tandem DSSCs, which stack multiple cells with complementary absorption characteristics, have pushed efficiency beyond traditional single-junction DSSCs.

8.2 Further Improvements:

Advanced Materials: Continued research focuses on finding new materials, including alternative semiconductors and efficient redox mediators, to enhance performance.

- Perovskite Integration: Hybrid DSSCs incorporating perovskite materials show promise for achieving higher efficiency due to their superior light-absorption properties.
- Stability Enhancements: Efforts are ongoing to develop stable and long-lasting DSSCs that can withstand harsh environmental conditions.
- Scaling Up Production: To make DSSCs more commercially viable, scaling up production methods and reducing manufacturing costs are essential steps.
- Tandem Technologies: The exploration of novel tandem structures and combinations with other solar cell types, like silicon solar cells, aims to further boost efficiency.

- Morphology Control: Fine-tuning film morphology through advanced techniques allows for better control of light scattering and electron transport within DSSCs.
- Energy Storage Integration: Research into integrating energy storage systems with DSSCs aims to provide continuous power generation even when sunlight is unavailable.

In conclusion, DSSCs have made significant strides in improving efficiency, stability, and materials. Ongoing research holds the promise of making DSSCs a competitive and sustainable option in the renewable energy landscape [46, 47].

9. LIMITATIONS ASSOCIATED WITH DSSC

DSSCs have gained attention for their unique advantages, but they also come with certain limitations:

- Limited Efficiency: DSSCs typically have lower conversion efficiencies compared to traditional silicon solar cells. While progress has been made, they still lag in achieving high efficiency levels, especially for large-scale applications.
- Shorter Lifespan: The liquid electrolytes used in DSSCs can degrade over time, reducing cell performance and longevity. This limits their reliability and requires periodic maintenance.
- Sensitivity to Environmental Factors: DSSCs are sensitive to environmental conditions. Exposure to moisture and extreme temperatures can lead to degradation, impacting their overall performance.
- Dye Stability: The dyes used in DSSCs can fade or degrade over time due to exposure to light and other environmental factors. This affects the cell's long-term stability and efficiency.
- Complex Manufacturing: The manufacturing process for DSSCs can be complex and may involve expensive materials and equipment, which can hinder mass production and scalability.
- Limited Absorption Range: DSSCs are typically less effective in capturing light from the infrared spectrum, which makes them less efficient in harnessing the full solar spectrum.
- Inherent Voltage Limit: DSSCs have a relatively lower open-circuit voltage (V_{oc}) compared to some other photovoltaic technologies, which can affect their overall energy conversion efficiency.
- Lack of Standardization: Unlike silicon-based solar cells, there is less standardization in DSSC design and manufacturing, making it challenging to compare and reproduce results across different research studies.
- Toxic Materials: Some DSSCs may use toxic materials, such as cadmium, in their construction, which raises environmental and safety concerns.
- Limited Commercial Availability: DSSCs are not as widely available or as commonly used as traditional solar panels, which limits their adoption and accessibility.
- Complex Sealing Requirements: Due to the use of liquid electrolytes, DSSCs require robust sealing to prevent electrolyte leakage and maintain cell integrity, which can add to their manufacturing complexity.

Despite these limitations, ongoing research and development efforts are focused on addressing these challenges and improving the performance, stability, and scalability of DSSCs. These advancements may lead to broader adoption of this technology in the future.

10. RESEARCH AND DEVELOPMENT CHALLENGES IN DSSC

Research and development in Dye-Sensitized Solar Cells (DSSCs) face several significant challenges as scientists work to improve the efficiency, stability, and commercial viability of this promising photovoltaic technology:

- Efficiency Enhancement: Increasing the efficiency of DSSCs remains a major challenge. Researchers are exploring new materials, novel dyes, and innovative device architectures to boost conversion efficiency and narrow the efficiency gap with traditional solar cell technologies.

- Stability and Durability: Enhancing the stability and durability of DSSCs is critical for practical applications. The liquid electrolytes used in many DSSCs can degrade over time due to moisture, temperature variations, and exposure to light. Developing more stable solid-state or quasi-solid-state electrolytes is a priority.
- Scaling Up Production: Transitioning from laboratory-scale prototypes to large-scale production presents challenges in terms of cost-effectiveness and scalability. Developing efficient and cost-competitive manufacturing processes is essential for the widespread adoption of DSSCs.
- Environmental Impact: Addressing the environmental impact of DSSCs, particularly regarding the use of toxic or rare materials in some designs, is crucial. Researchers are actively seeking alternative materials that are eco-friendlier and more sustainable.
- Standardization: Establishing standardized testing procedures, performance metrics, and quality control measures is important to compare and reproduce results across different research studies and manufacturers.
- Tandem Cell Integration: Integrating DSSCs with other solar cell technologies (e.g., silicon solar cells) to create tandem devices is a promising approach to improve overall efficiency. However, achieving optimal compatibility and performance between different cell types is a challenge.
- Improved Redox Mediators: Developing more efficient and stable redox mediators in DSSC electrolytes is vital for better performance and longer lifespan. Researchers are working on finding suitable alternatives to traditional iodide/triiodide redox couples.
- Environmental Exposure: Designing DSSCs that can withstand harsh environmental conditions, including extreme temperatures, humidity, and UV radiation, is essential for outdoor applications.
- Cost Reduction: Reducing the cost of materials and manufacturing processes is essential to make DSSCs more competitive with other solar technologies.
- Market Acceptance: Convincing consumers and industries to adopt DSSC technology requires overcoming skepticism, demonstrating reliability, and showing a clear value proposition.
- Regulatory Challenges: Adapting to evolving regulations and standards in the solar industry, including safety and environmental regulations, is a continuous challenge for DSSC developers.
- Energy Storage Integration: Integrating energy storage solutions with DSSCs to provide consistent power output during nighttime or cloudy conditions presents technical and design challenges.

Despite these challenges, DSSC research and development continue to progress, driven by the potential advantages of this technology, including its flexibility, transparency, and potential for low-cost manufacturing. As researchers address these challenges, DSSCs may become a more competitive and sustainable option in the renewable energy landscape.

11. PROSPECTS OF DSSC

The prospects of DSSCs hold promise as researchers and industry experts continue to work on overcoming challenges and harnessing the unique advantages of this photovoltaic technology. Here are some potential future developments and applications for DSSCs:

- Higher Efficiency: Researchers are focused on improving DSSC efficiency through the development of advanced materials, novel dyes, and innovative device designs. Tandem DSSC configurations and hybrid systems with other solar cell technologies aim to achieve higher conversion efficiencies, making DSSCs more competitive with traditional solar cells.
- Stability and Durability: Enhancing the stability and durability of DSSCs is a priority. Solid-state and quasi-solid-state electrolytes, as well as improved sealing techniques, may extend the lifespan of DSSCs and make them more reliable for long-term use.

- Flexible and Lightweight Solar Panels: DSSCs are inherently flexible and lightweight, making them suitable for applications where rigid silicon panels are impractical. The future may see DSSCs integrated into clothing, wearable devices, and building-integrated solar solutions.
- Energy Harvesting in Low-Light Conditions: DSSCs are known for their ability to operate efficiently in low-light conditions and indirect sunlight. This feature makes them ideal for indoor energy harvesting in smart buildings, IoT devices, and remote sensors.
- Transparent Solar Windows: Integrating DSSCs into windows and glass facades could turn buildings into energy-generating structures without obstructing natural light. Transparent solar windows are an attractive prospect for sustainable architecture.
- Portable and Off-Grid Power: DSSCs can provide portable and off-grid power sources for a variety of applications, including camping, emergency backup power, and remote locations where traditional energy sources are unavailable.
- Environmental Sustainability: Ongoing research aims to develop more sustainable and eco-friendly materials for DSSCs, addressing concerns about the environmental impact of certain components.
- Integration with Energy Storage: Combining DSSCs with energy storage technologies, such as batteries and supercapacitors, allows for continuous power generation even during nighttime or cloudy conditions, increasing the reliability of renewable energy systems.
- Cost Reduction: Streamlining manufacturing processes, reducing material costs, and improving the scalability of DSSC production could lead to cost-competitive solutions.
- Distributed Energy Generation: DSSCs can enable distributed energy generation, allowing homes and businesses to generate their electricity on-site and reduce reliance on centralized power grids.
- Emerging Markets: DSSCs may find applications in emerging markets where access to traditional energy infrastructure is limited, providing clean and affordable energy solutions.
- Educational and Research Tools: DSSCs are excellent educational tools for teaching the principles of photovoltaics and renewable energy. They can be used in schools and universities to promote STEM education.

While DSSCs currently face challenges, ongoing research, technological advancements, and growing environmental concerns make them a technology with significant potential. As these challenges are addressed and innovation continues, DSSCs have the potential to play a more prominent role in the renewable energy landscape.

12. BENEFITS AND APPLICATIONS OF DSSC

This review explores recent advancements in Dye-Sensitized Solar Cell (DSSC) materials and their applications in both outdoor and indoor settings. These applications extend to various fields, such as medical and sports devices, wireless sensor networks, computer peripherals, and wearable electronics. DSSCs have noteworthy implications for indoor use, offering a practical and straightforward production method [48].

DSSCs are characterized by their transparency, flexibility, thin structure, and lightweight nature, making them suitable for integration into building components like windows and doors, as illustrated in Figure 10. This integration allows them to harness daylight for illumination while generating energy. DSSCs are environmentally friendly, and their laboratory fabrication processes are cost-effective compared to conventional 1st and 2nd generation solar cells. Additionally, DSSCs are crafted from non-toxic materials and can be applied to various substrates, including glass and fibers. One of the notable advantages of DSSCs is the freedom to choose from a variety of color pigments, enabling their use for indoor lighting applications in places such as airports.

Furthermore, DSSCs serve as battery chargers for electric vehicles and remain functional under diffuse light conditions, even as low as 0.0205 watt/m^2. They are cost-effective photoelectrochemical cells employed in solar energy harvesting applications. Although natural dyes have demonstrated moderate energy conversion efficiency, molecular engineering techniques are employed to enhance the energetic and kinetic properties of the dyes in order to improve cell performance. DSSCs belong to the category of organic and thin-film solar cells.

12.1 Benefits of DSSCs:

DSSCs utilize easily accessible materials and employ cost-efficient manufacturing methods. They can be processed on flexible substrates and exhibit exceptional performance under diffuse or low-light conditions.

- Lightweight: DSSCs can significantly reduce the weight of solar panels by utilizing plastic substrates.
- Low-Light Performance: DSSCs operate efficiently even under the infrared (IR) spectrum, enabling them to function under cloudy skies with limited sunlight.
- Recyclable and Environmentally Friendly: DSSCs contain non-harmful components that can be easily separated and repurposed, contributing to their environmental friendliness.
- Simple Production Method: DSSC production does not require a vacuum system, reducing manufacturing costs and making them cost-effective.
- Transparency and Color Customization: The use of organic dyes allows for the selection of colored and transparent cells, making them suitable for decorative purposes.
- No Incident Angle Requirement: DSSCs do not require a specific incident angle or sunlight intensity to generate power effectively.
- Effective Performance in Various Lighting Conditions: DSSCs provide effective power output in all lighting conditions, including fluorescent and LED lighting. They perform well even under diffused or dim light, in contrast to traditional solar cells that are less efficient in such conditions [49, 50].

12.2 Indoor and Outdoor Applications of DSSC

DSSCs find diverse applications in both indoor and outdoor settings due to their unique characteristics. Here are examples of applications in each category [51-54]:

Indoor Applications:

- Indoor Lighting: DSSCs are used to harvest ambient indoor lighting, such as fluorescent and LED light, to power lighting systems in homes, offices, and commercial spaces. They offer an eco-friendly and cost-effective alternative for indoor illumination.
- Wearable Electronics: DSSCs can be integrated into wearable devices, like smartwatches, fitness trackers, and clothing. They capture energy from indoor lighting, extending the battery life of wearables and reducing the need for frequent charging.
- Wireless Sensors: DSSCs power wireless sensor networks used in indoor environments for applications like building automation, occupancy sensing, and environmental monitoring. They provide a sustainable energy source for these systems.
- Emergency Lighting: DSSCs serve as backup power sources for emergency lighting systems in indoor spaces. During power outages, they ensure essential areas remain well-lit, enhancing safety.
- IoT Devices: Internet of Things (IoT) devices benefit from DSSCs, particularly in indoor settings. These devices, such as smart thermostats and security cameras, can operate indoors while relying on DSSCs for recharging.

Outdoor Applications:

- Solar Chargers: DSSCs are used in portable solar chargers for outdoor enthusiasts. These chargers harness energy from natural sunlight, allowing users to charge their devices while camping, hiking, or traveling.
- Building-Integrated Photovoltaics (BIPV): DSSCs can be integrated into building structures, including windows, facades, and roofs. They generate renewable energy from outdoor sunlight and contribute to the building's power needs.
- Street Lighting: DSSCs are incorporated into street lamps and lighting fixtures to provide energy-efficient outdoor lighting. They store solar energy during the day and illuminate streets and public areas at night.

- Solar-Powered Gadgets: Outdoor gadgets like solar-powered garden lights, backpacks, and outdoor speakers utilize DSSCs to operate using solar energy, reducing the need for traditional batteries.
- Signage and Displays: DSSCs power outdoor signs, billboards, and electronic displays. They offer a sustainable source of energy for advertising and informational displays.
- Environmental Monitoring: DSSCs are used in remote environmental monitoring systems, such as weather stations and wildlife tracking devices. They provide reliable power for collecting data in outdoor and off-grid locations.
- Maritime Applications: DSSCs can be applied on boats, ships, and maritime installations to generate renewable energy for navigation equipment, communication devices, and lighting.
- Off-Grid Power: In remote and off-grid areas, DSSCs offer independent power sources for various applications, including powering remote telecommunication towers, water pumps, and agricultural equipment.

DSSCs' adaptability, ability to work under low-light conditions, and versatility make them valuable solutions for a wide range of applications in both indoor and outdoor environments.

14. CONCLUSIONS

In conclusion, this review study has provided valuable insights into the world of DSSCs and their ongoing research and development efforts. The primary focus has been on the design of new materials for photoanodes, a crucial component of DSSCs, while also offering a comprehensive understanding of DSSC components and their working principles. DSSC research aims to harness electrical energy through the interaction of organic dyes and semiconductor materials. The attractiveness of DSSCs lies in their environmental friendliness, low production costs, ease of fabrication, availability of raw materials, transparency, lightweight nature, and their ability to operate under low light conditions, including indoor settings. Despite their many advantages, ongoing research is driven by the pursuit of improved efficiency, as DSSCs have traditionally lagged in this aspect.

One of the key challenges in DSSC development is charge carrier mobility and mitigating recombination losses. Unlike traditional silicon solar cells that require intense sunlight exposure, DSSCs can operate efficiently under various light intensities, making them suitable for both outdoor and indoor applications. In DSSCs, mesoporous oxide materials containing TiO_2 nanoparticles act as pathways for electrons to traverse from the photoanode to the working electrode. DSSCs are known for their convenience in fabrication and cost-effectiveness. They have emerged as a promising alternative to conventional inorganic silicon-based solar cells, particularly in harnessing solar energy using organic dyes. Efficiency and stability are two critical factors for DSSCs, and their improvement often involves trade-offs among various parameters. Photo-catalytic reactions on the TiO_2 surface generate electrons and holes known as excitons, contributing to the DSSC's photovoltaic capabilities. DSSCs have found applications in solar energy harvesting devices. However, several challenges must be addressed for the commercial development of DSSCs. These challenges include low stability, low efficiency, dark current, poor dye performance, inadequate electrode contact, and electrolyte degradation. Researchers evaluate DSSC efficiency using tools like solar simulators and characterize synthesized materials before initiating the fabrication of DSSC devices.

In essence, DSSCs hold great promise as a renewable energy technology, and ongoing research endeavors aim to unlock their full potential by addressing efficiency and stability concerns. As advancements continue, DSSCs could become a more prominent player in the renewable energy landscape, offering sustainable and versatile solutions for a variety of applications, both indoor and outdoor.

ACKNOWLEDGMENT

Author is very much thankful to Vice-Chancellor, Rajiv Gandhi Prodyogiki Vishwavidyalaya (RGPV), Bhopal, State Technological University, 462033, India for providing the facility for this work.

REFERENCES

[1] Gielen D., Boshell F., Saygin D., Bazilian M.D., Wagner N., Gorini R., The role of renewable energy in the global energy transformation, Energy Strategy Reviews, 24 (2019) 38-50. doi.org/10.1016/j.esr.2019.01.006

[2] Tyagi H., Chakraborty P.R., Powar S., Agarwal A.K., New Research Directions in Solar Energy Technologies (Edition 1), Springer Singapore, 2021.

[3] Andualem A., Demiss S., Review on Dye-Sensitized Solar Cells (DSSCs), Journal of Heterocyclics, 1 (2018) 29-34. https://doi.org/10.33805/2639-6734.103

[4] Cari C., Khariruddin, Septiawan T. Y., Suciatmoko P. M., Kurniawan D., Supriyanto A. AIP Conference Proceedings (2018) 020106. https://doi.org/10.1063/1.5054510

[5] Mistry V., Patel S., Rao V. Int. J. Innovative Research in Science, Engineering and Technology, 8 (2015) 6823-6823. https://10.15680/ijirset.2015.0408016

[6] Jinchu I., Sreekala C.O., Sreelatha K.S. Material Science Forum, 741 (2014) 39-51 https://doi:10.4028/www.scientifinet/MSF,771.39

[7] Fan Y., Ho C., Chong Y., 56 (2017) 9152973. https://doi.org/10.1155/2017/9152973

[8] Ammar Ahmed M., Mohamed Hemdan S.H., Yousef M.M.K., Abdel-Hafez G.M., HassanienA.S., Khalil A.S.G. Journal of Nanomaterials, (2019) 1867271. https://doi.org/10.1155/2019/18622

[9] Ahliha A.H., Nurosyid F., Supriyanto A., Kusumaningsih T. Journal of Physics: IOP Conference series, 909 (2017) 012013. https://doi:10.1088/1742-6596/909/1/012013

[10] Trihutomo P., Soeparman S., Widhiyawa D., Yuliati L. Hindwi, International Journal of Photoenergy, (2019) 4384728. https://doi.org/10.1155/2019/4384728

[11] Bose S., Soni V., Genwa K.R., Recent Advances and Future Prospects for Dye Sensitized Solar Cells: A Review, International Journal of Scientific and Research Publication, 5 (2015) 1-9.

[12] Sugathan V., Jonhn E., Sudhakar K. Renewable and Sustainable Energy Reviews, 52 (2015) 23-29. http://dx.doi.org/10.1016/j.rser.2015.07.076

[13] Han G.S., Song Y.H., Jin Y.U, Lee J., Park N., Kang B.K., Cho I., Yoon D.H., Jung H.S., Reduced Graphene Oxide/ Mesoporous TiO2 Nanocomposite Based Perovskite Solar Cells, ACS Applied Material Interface 7(2015) 23521-23526. https://doi.org/10.1021/acsami.5b06171

[14] Dutta M., Sarkar S., Ghosh T., Basak D., ZnO/Graphene Quantum Dot Solid-State Solar Cell, J.Phys. Chem. C,116 (2012) 20127-20131. https://doi.org/10.1021/jp302992k

[15] Samikannu S.M., Namani R., Subramaniam S.K., Power enhancement of partially shaded PV arrays through shade dispersion using magic square configuration, Journal of Renewable and Sustainable Energy, 8 (2016) 43507-43512. https://doi.org/10.1063/1.4972285

[16] Ding H., Zhang S., Juan P., Liu T., Du Z., Zhao D., Enhancing the photovoltaic performance of dye-sensitized solar cells by modifying TiO2 photoanodes with exfoliated graphene sheets RSC Advances 6 (2016) 41092-41102. https://doi.org/10.1039/C6RA05639C

[17] Kusumawati Y., Martoprawiro M.A., Pauporte T, Effects of Graphene in Graphene/TiO2 Composite Films Applied to Solar Cell Photoelectrode, Journal of Physical Chemistry C, 118 (2014) 9974–9981. https://doi.org/10.1021/jp502385p

[18] Kim S., Park J., Kim C., Effects of Graphene in Dye-Sensitized Solar Cells Based on Nitrogen-Doped TiO_2 Composite, Journal of Physical Chemistry C, 119 (2015) 16552–16559. https://doi.org/10.1021/acs.jpcc.5b02309

[19] Khannam M., Sharma S., Dolui S., Dolue S.K., A graphene oxide incorporated TiO2 photoanode for high efficiency quasi solid-state dye sensitized solar cells based on a poly-vinyl alcohol gel electrolyte, RSC Advances 6 (2016) 55406-55414. https://doi.org/10.1039/C6RA07577K

[20] Saeed M.A., Yoo K., Kang H.C., Shim J.W., Lee J., Recent developments in dye-sensitized photovoltaic cells under ambient illumination, Dyes and Pigments, 194 (2021) 109626. doi.org/10.1016/j.dyepig.2021.109626

[21] Li G., Sheng L., Li T., Hu J., Li P., Wang K., Engineering flexible dye-sensitized solar cells for portable electronics, Solar Energy, 177 (2019) 80-98. doi.org/10.1016/j.solener.2018.11.017.
[22] B.O'Regan, M. Gratzel, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 film, Nature, 353 (1991) 737 -740. https://doi:10.12691/pmc-3-1-3
[23] Nazeeruddin M.K., Kay A., Rodicio I., Humphry-Baker R., Muller E., Liska P., Vlachopouios N., Gratzel M., Conversion of light to electricity by cis-X2bis(2,2'-bipyridyl-4,4'-dicarboxylate)ruthenium(II) charge-transfer sensitizers (X = Cl-, Br-, I-, CN-, and SCN-) on nanocrystalline titanium dioxide electrodes, J.Am.Chem., 115 (1993) 6382-6390. https://doi:10.1016/j.solener.2011.010018
[24] Cao Y., Liu Y., Zakeeruddin S.M., Hagfeldt A., Gratzel M., Direct Contact of Selective Charge Extraction Layers Enables High-Efficiency Molecular Photovoltaics, Joule, 2 (2018) 1108-1117. https://doi.org/10.1016/j.joule.2018.03.017
[25] Sharma K., Sharma V., Sharma S.S. Nanoscale research letters, 13 (2018) 381. https://doi.org/10.1186/s11671-018-2760-6
[26] Devadiga D., Selvakumar M., Shetty P. Journal of Electronic Materials, 50 (2021) 3187–3206. https://doi.org/10.1007/s1166402-08854-3
[27] Gong J., Sumathy K., QiquanQ., Zhou Z. Renewable and Sustainable Energy Reviews, 68 (2017) 234-246. http://dx.doi.org/10.1016/j.rser.2016.09.097
[28] Hagfeld A., Graetzel M., Light-Induced Redox Reactions in Nanocrystalline Systems, Chem. Rev., 95 (1995) 49-68. https://doi.org/10.1021/cr00033a003
[29] Ruhle S., Cahen D., Electron Tunneling at the TiO2/Substrate Interface Can Determine Dye-Sensitized Solar Cell Performance, J.Phys. Chem. B, 108 (2004) 17946–17951. https://doi.org/10.1021/jp047686s
[30] Chou J.C., Kuo C.H., Kuo P.Y., Lai C.H., Nien Y.H., Liano Y.H., Ko C.C., Yang C.M., Wu C.Y., The Retardation Structure for Improvement of Photovoltaic Performances of Dye-Sensitized Solar Cell Under Low Illumination, IEEE J. Photovolastics, 9 (2019) 926-933. https://doi.org/10.1063/5.0000868
[31] Hora C., Santos F., Sales M.G.F., Ivanou D., Mendes A., Dye-Sensitized Solar Cells for Efficient Solar and Artificial Light Conversion, A.C.S. Sustain, Chem. Eng., 7 (2019) 13464–13470. https://doi.org/10.1021/acssuschemeng.9b02990
[32] Liu I.P., Lin W.H., Tseng-Shan C.M., Lee Y.L., Importance of Compact Blocking Layers to the Performance of Dye-Sensitized Solar Cells under Ambient Light Conditions, A.C.S. Appl. Mater. Interfaces, 10 (2018) 38900-38905. https://doi.org/10.1021/acsami.8b13181
[33] Sasidharan S., Pradhan S.C., Jagadeesh A., Nair B.N., Mohamed A.A.P., Hareesh U.N.S., Bifacial Dye-Sensitized Solar Cells with Enhanced Light Scattering and Improved Power Conversion Efficiency under Full Sun and Indoor Light Conditions, ACS Appl. Energy Mater., 3 (2020) 12584–12595. https://doi.org/10.1021/acsaem.0c02500
[34] Kokkonen M., Talebi P., Zhou J. Journal of Material Chemistry, 9 (2021) 10527-10545. https://doi:10.1039/dlta00690h
[35] Jinchu I. Material Science, 771 (2014) 39-51. https://doi:10.4028/www.scintific.net/MSF.771.39
[36] Pratiwi D.D., Nurosyid F., Spriyanto A., Suryana R. IOP Conference Series Materials Science and Engineering, 176 (2017) 012012. https://doi:10.1088/1757-899X/176/1/012012
[37] Iftikhar H., Sonai G.G., Hashmi S.G., Nogueira A.F., Lund P.D., Progress on Electrolytes Development in Dye-Sensitized Solar Cells, Materials, 12 (2019) 1998. https://doi.org/10.3390/ma12121998
[38] Pradhan S.C., Hagfeldt A., Soman S., Resurgence of DSCs with copper electrolyte: a detailed investigation of interfacial charge dynamics with cobalt and iodine-based electrolytes, J. Mater. Chem. A, 6 (2018) 22204-22214. https://doi.org/10.1039/C8TA06948D
[39] Hamann T.W., Ondersma J.W., Dye-sensitized solar cellredox shuttles, Energy Environ. Sci., 4 (2011) 370-381. https://doi.org/10.1039/C0EE00251H

[40] Michaels H., Rinderle M., Freitag R., Benesperi I., Edvinsson T., Socher R., Gagliardiand A., Freitag M. Dye-sensitized solar cells under ambient light powering machine learning: towards autonomous smart sensors for the internet of things, Chemical Science, 11 (2020) 2895-2906. https://doi.org/10.1039/C9SC06145B
[41] Hashmi S.G., Sonai G.G., Iftikhar H., Lund P.D., Nogueira A.F., Printed single-walled carbon-nanotubes-based counter electrodes for dye-sensitized solar cells with copper-based redox mediators, Semicond . Sci. Technol., 34 (2019) 105001. https://doi10.1088/1361-6641/ab39f
[42] Feldt S.M., Gibson E.A., Gabrielsson E., Sun L., Boschloo G., Hagfeldt A., Design of Organic Dyes and Cobalt Polypyridine Redox Mediators for High-Efficiency Dye-Sensitized Solar Cells, J. Am. Chem. Soc., 132 (2010) 16714-16724. https://doi.org/10.1021/ja1088869
[43] Vlachopoulos N., Hagfeldt A., Benesperi I., Freitag M., Hashmi G., Jia G., Wahyuono R.A., Plentz J., Dietzek B.New approaches in component design for dye-sensitized solar cells, Sustainable Energy Fuels, 5 (2021) 367-383. https://doi.org/10.1039/D0SE00596G
[44] Gong J., Sumathy K., Zhou Q.Q.Z., Review on dye-sensitized solar cells (DSSCs): Advanced techniques and research trends, Renewable and Sustainable Energy Reviews, 68 (2017) 234-246. https://doi:10.1016/j.rser.2016.09.097
[45] Nazeeruddin Md.K., Etienne Baranoff, Michael Grätzel, Science Direct, Solar Energy 85 (2011) 1172-1178. https://doi:10.1016/j.solener.2011.01.018
[46] Nemade K., Dudhe P., Tekade P., Solid State Sciences, 83 (2018) 99-106. https://doi.org/10.1016/j.solidstatesciences.2018.07.009
[47] Zukifili A.N.B., Kento T., Daiki M., Fujiki A. Journal of Clean Energy Technologies, 3 (2015) 382-387. https://doi:10.7763/joce.2015.v3.228
[48] Nemade S.R., Khare P.S. AIP Conference Proceeding, 2220 (2020) 020050. https://doi.org10.1063/5.0002062
[49] Francis O.I., Ikenna A., Review of Dye-Sensitized Solar Cell (DSSCs) Development, Natural Science, 13 (2021) 56-62. https://doi.org/10.4236/ns.2021.1312043
[50] Iwata S., Shibakawa S., Imwaka N., Yoshina K., Stability of the current characteristics of dye-sensitized solar cells in the second quadrant of the current-voltage characteristics, Energy Reports, 4 (2018) 8-14. https://doi.org/10.1016/j.egyr.2017.10.004
[51] Fraas L.M., Partain L.D., Solar cells and their applications (Second Edition) Wiley (2010).
[52] Freitag M., Teuscher J., Saygili Y., Zhang X., Giiiiordano F., Liska P., Hua J., Zakeeruddin S.M., Moser J.E., Gratzel M., Hagfeldt A., Dye-sensitized solar cells for efficient power generation under ambient lighting, Nat. Photonics, 11 (2017) 372-378. https://doi:10.1038/nphoton.2017.60
[53] Ngu A.H., Gutierrez M., Metsis V., Nepal S., Sheng Q.Z. IoT Middleware: A Survey on Issues and Enabling Technologies, IEEE Internet Things, 1 (2017) 1-9. https://doi:10.1109/jiot.2016.2615180
[54] Raj A., Steingart D.Review—Power Sources for the Internet of Things, J. Electrochem. Soc., 165 (2018) 1-8. https://doi:10.1149/2.0181808jes