International Journal of Zoology and Applied Biosciences **ISSN: 2455-9571**
Volume 11, Issue 2, pp: 268-275, 2026
https://doi.org/10.55126/ijzab.2026.v11.i02.034 **http://www.ijzab.com**

Review Article

PROGRESSION OF DYE-SENSITIZED SOLAR CELLS: A REVIEW

[1]Lalitkumar Katre, [1]Chandrakant Bisen, [2*]Manoj Patle, [2]Rajkumar Patle, [3]Gajadhar Bhagat

[1]M. B. Patel College, Sakoli Arjuni, Maharashtra, India
[2*]Dhote Bandhu Science College, Gondia, Maharashtra, India
[3]Jagat College, Goregaon, Maharashtra, India

Article History: Received 5th January 2026; Accepted 19th February 2026; Published 1st March 2026

ABSTRACT

Dye-sensitized solar cells (DSSCs) offer numerous benefits, including a low operating cost relative to performance, minimal processing expenses, the ability to operate at low incident light intensities and wide angles, mechanical resilience, portability, and a transparent design that is visually appealing. Their numerous noteworthy characteristics, such as light weight, transparency, and a wide wavelength range of operation, enable them to be used for a diverse range of functional applications. This study focuses on new developments in creating materials that may be used to fabricate high-performing photovoltaic devices. The power conversion efficiency of the DSSC depends on the optimization and compatibility of each component of solar cell (counter electrode, working electrode, electrolyte, photosensitizers). This paper also outlines developments in related materials and demonstrates how different materials and production techniques have enhanced each functional part of a DSSC.

Keywords: Power conversion efficiency, Photosensitizer, Counter electrode, Working electrode, Photovoltaics.

INTRODUCTION

Dye-sensitized solar cells (DSSCs) might be an alternative to silicon solar cells; unlike Si-based cells, DSSCs disperse both the light absorption and charge transfer processes (Sultana Rahman *et al.,* 2023). Thin film solar cells, which might be appealing substitutes, are produced at a very low cost using either organic or inorganic semiconductors (Andrés Boulett *et al*., 2021). Multilayer thin-film solar cells show a considerable increase in power conversion efficiency over the last few decades, utilizing Chlorophyll dyes (Kofman *et al.,* 2021). DSSCs combine a wide-bandgap semiconductor with nanocrystalline morphology, a light-absorbing material termed the photosensitizer to enable optical absorption and charge separation (Luís Moreira Gonçalves *et al*., 2008), despite competing solar power technologies, the dynamic nature of scientific research, and the critical role of DSSCs in pushing the frontiers of innovation in the field of photovoltaics (Ragu Sasikumar *et al*., 2024). Researchers have begun to utilize QD-sensitized semiconductors to efficiently harness energy from the Sun using conventional QD and green QD photovoltaic solar cells (Sonal Sahai *et al*., 2023). The efficiency of DSSC employing double-layered SPD-type TiO2 photoelectrodes was (1.31∼2.64%) more than that of single-layered SP-type (1.31∼2.50%) and D-type (0.90∼1.54%) TiO2 photoelectrodes using organic photosensitizer (Mi-Ra Kim *et al.,* 2023). The chemically stable photoelectrode of the biohybrid PEC was created by combining organic and inorganic layers on FTO substrate (Shiyani *et al*., 2022). Energy used by the globe today is 10,000 times less than what the sun produces (S. Arul *et al*., 2016). Optimizing the photovoltaic performance of DSSC by adjusting the working area of the mesoporous TiO2 photoanode (Nasikhudin *et al*., 2022). DSSCs are known for low cost, high transparency, sustainability, and simple construction procedure, high efficiency, and flexibility than silicon-based solar cells (Ragu Sasikumar et al., 2024, Mohammad Dehghanimadvar *et al*., 2022). The I^-/I_3^- redox electrolyte has been used extensively in DSSCs, but it restricts Voc to 0.7-0.8 V; a redox shuttle with higher positive redox potential is necessary to increase Voc (Nazeeruddin *et al*., 2011, Masud *et al*., 2023). Creating new photoanode structures that utilize light more efficiently and developing new sensitizers that span a wider

*Corresponding Author: Manoj Patle, Dhote Bandhu Science College, Gondia, India Email: manojpatle14@gmail.com

range of the solar spectrum, such as use of three-dimensional metal oxide nanostructures or panchromatic sensitizers (Babak Pashaei *et al*., 2020). To improve optoelectrical properties, greater interactions between metal oxide semiconductor/dye, semiconductor/dye/electrolyte, and electrolyte/CE are required (Prem Singh Saud et al. 2024). DSSCs employing extract from petals of male flowers as a natural sensitizer (Ishwar Chandra Maurya *et al*., 2016).

It is necessary to establish a link between the photosensitizer structure, interfacial charge transfer processes, and device performance (Kakiage *et al*., 2014). By employing indoor illumination, DSSCs effectively provide the energy needed for electronic applications such as wireless sensors (Kokkonen *et al*., 2021). Figure 1 illustrate the Latest advancements in developing novel materials for high-performance DSSCs. Single-junction cells now account for more than 18% of all organic photovoltaics (OPVs), a significant increase in efficiency due to new non-fullerene acceptors and meticulous modification of their molecular structures (Joel Luke *et al*. 2023).

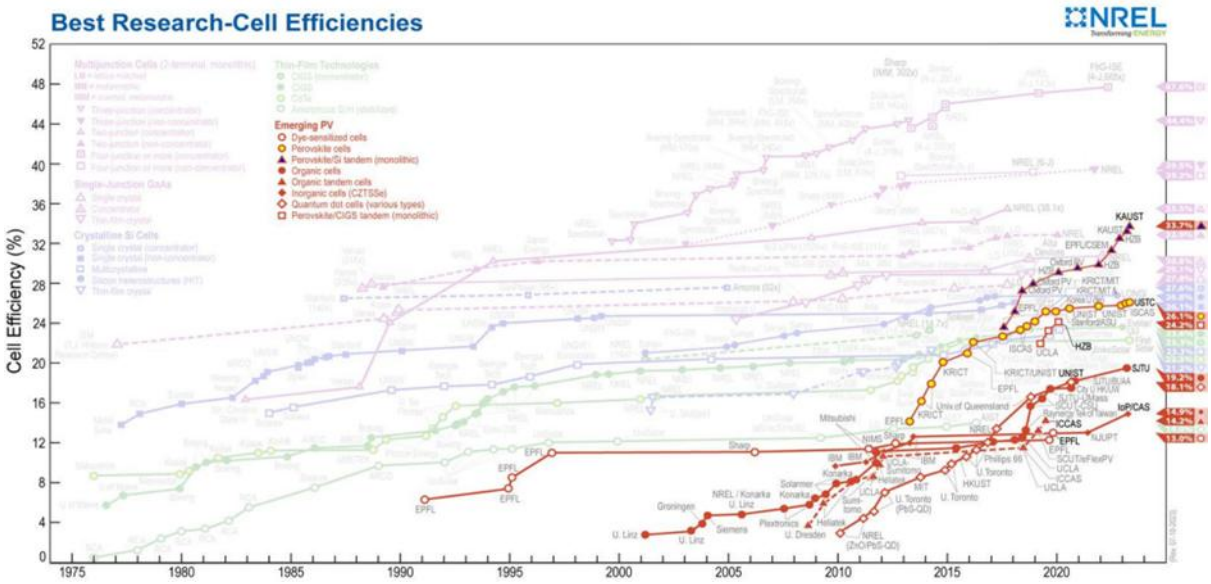

Figure 1. Latest advancements in high-performance photovoltaic devices based on DSSCs.

The cell's monolithic design structure (M-DSSCs) simplifies and reduces the cost of the devices; the most effective DSSCs described thus far are Co (III/II)-mediated liquid junction cells with acetonitrile electrolytes (Fátima Santos *et al*., 2022, B. Oregan *et al*., 1991). The rate of electron injection at the interface between CB of the GaAs semiconductor and the cis-bis-(4,4'-dicarboxy-2,2'-bipyridine) thiocyanate N3 dye was investigated using quantum transient theory (Hadi Jabbar Alagealy *et al*., 2023). Natural dyes are a viable substitute for costly and scarce ruthenium dyes due to their low cost, ease of use, plentiful resources, and eco-friendliness (Sultana Rahman *et al*., 2023).

The applications of DSSC in conjunction with ionic liquids enhance the ionic/transport characteristics of polymer electrolytes by various salts, plasticizers, and filler groups (Nidhi Asthana *et al*., 2020). The most recent technique, which uses UV-O_3 treatment or titanium (IV) tetraisopropoxide to create flexible DSSC, involves a variety of photoanode materials, including graphene, ZnO, and TiO_2, using peel-and-stick techniques, hydrothermal, electrophoretic deposition, doctor blades, and pulse laser deposition (Noorasid *et al*., 2022). By adding several kinds of chemicals to electrolytes to improve DSSCs' performance and transport characteristics (N.K. Farhana *et al*.,2021), organic (Regan *et al*., 1997), and inorganic hole conductors (Jiao *et al*., 2011; Halls *et al*. 1995). By filling the gaps between nanowires, photoanode's branching structure raises the dye loading (Brishty Deb Choudhury *et al*., 2021), combinations of organic materials like polymer or molecular semiconductors (Peumans *et al*., 2001; Brabec *et al*., 2003). The DSSC, with its amazing shape, colour, and transparency adaptability, is one of the most promising technologies for solar applications (Noorasid *et al*., 2022, Jung-Min Ji *et al*., 2020). With the use of cobalt electrolytes and porphyrin dye, DSSC efficiency has now been reached in the lab at 14.2% (Jeongmin Ji *et al*., 2020). The most recent studies on novel electrodes, electrolytes, and dyes, as well as present and prospective applications of bifacial dye sensitized solar cells (BFDSCs) for renewable energy sources, both indoors and outdoors (Jessica Barichello *et al.*, 2024).

MATERIALS AND METHODS

By fabricating the cell using an Mg2+-doped anatase-TiO2 electrode with negatively shifted $E_{C.B.}$ compared to the

anatase-TiO_2 electrode, a coumarin dye of SFD-5 with an alkoxy silyl group as an anchor moiety for chemisorption to the TiO_2 electrode, and electrolyte with the Br3−/Br− redox mediator has a higher positive redox potential than the typical I3−/I− redox mediator and Co3+/Co2+ complexes (Kenji Kakiage *et al*., 2016). Adding Mg2+ by substitution, TiO_2's band gap increased, and upward shift in CB. At around 6.6% Mg-La co-doped TiO2-based DSSC had maximum efficiency (Doaa M Atia *et al*., 2024). A decrease in the energy factor (EF) and CB is shown by a positive shift in the flat band potential (VFB). JSC significantly increased as a result of the quicker transport and the greater electron injection brought about by the CB shift (Farzam *et al*., 2025).

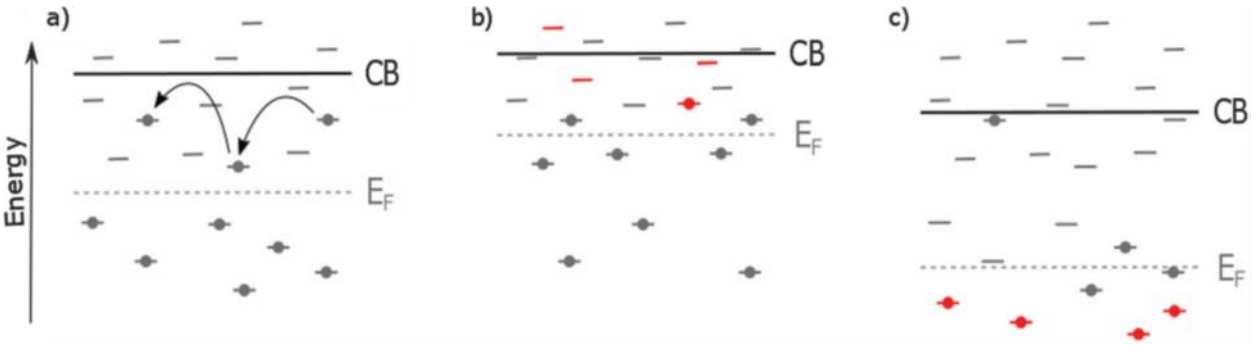

Figure 2. The effect of TiO2 doping on the CB and EF. The doping-induced states are shown in red (Roose *et al*., 2015).

Figure 2a illustrates how electrons in pure TiO2 go from a shallow trap to the electrode by hopping. Since VOC is defined as the difference between the EF of TiO2 and the hole transport material (HTM), doping can lower the density of deep traps, which raises EF and VOC (Figure 2b). JSC decreases when the CB shifts toward the absorber's LUMO, resulting in a lower trap density and related electron transit. Doping plays a role in creating deep traps by shifting the EF and conduction band lower, as seen in Figure 2c (Roose *et al*., 2015).

Synthesis of TiO2 Substrate

Hydrothermal Method

Take 15 mL of Conc. HCl and 15 mL deionized water in a 100 mL beaker, stir for 15 min using magnetic stirrer, add 0.5 mL of Titanium tetraisopropoxide (TTIP) and stir again for 15 min. Pour this mixture into a Teflon-lined autoclave preloaded with FTO substrate, seal it, and place it into a furnace for 4 hrs at 170 o C. Cool and wash the TiO2 nanoparticles with deionized water 2-3 times, and dry overnight (Hui Huang *et al*., 2013).

Sol-gel Method

11.5 mL of titanium (IV) isopropoxide was dissolved in 100 mL of distilled water in a beaker. After three hours of stirring, it was centrifuged for five minutes at 3700 rpm, cleaned three times with ethanol and once with distilled water, and then dried for 24 hours at 80 °C. TiO2 Nanoparticles were then produced by high-temperature treatments at 600 °C, 800 °C, and 1000 °C for six hours. These were gathered and stored (Jean Flores-Gómez *et al*., 2024).

Construction of DSSC

Working Electrode (WE)

The working electrodes (WE) are created by depositing a thin layer of oxide semiconducting materials such as TiO2, Nb2O5, ZnO, SnO2 (n-type), and NiO (p-type) on FTO or ITO glass. The allotropic anatase form of TiO2 has a greater energy band gap of 3.2 eV than the rutile form(3eV) (Tennakone *et al.*, 1999). Broadband gap oxides like ZnO and Nb2O5 have also shown encouraging outcomes (Sayama *et al*., 1998 and Richhariya *et al*., 2017). Important factors affecting DSSC's effectiveness are photoanode's layer thickness and dye's ideal adsorption time (Kaiswariah Magiswaran *et al*., 2022).

Photosensitizer or Dye

Variations in the absorption of available light by photosensitizers lead to variations in their efficiency and cost (Hamadanian *et al*., 2014, Wuryanti *et al*., 2021). Anthocyanin-sensitized ZnO shows a greater increase in nanoparticle diameter than chlorophyll-sensitized ZnO (Wan Almaz Dhafina *et al*. 2020), Ruthenium-based inorganic dyes are exceedingly poisonous and costly photosensitizers (Gao *et al*., 2008; Sasanka Peiris *et al*., 2021). Natural dyes have high light-harvesting efficiency, large absorption coefficients, low cost (Carlos Diaz-Uribe *et al.,* 2020), simplicity of manufacture, and environmental friendliness (Rajaramanan, *et al*., 2023). Syafnar *et al.* explain that natural dyes are extracted from flowers and plants (Syafnar *et al*., 2015), spinach, aloe vera, and the cladode of cactus (Ganta *et al*., 2017). Turmeric (TM), Black glutinous rice (BGR), and Ivy gourd leaves (IGL). IGL-dye was the most efficient, followed by the TM-dye

and BGR-dye, with 0.12% and 0.04% respectively (Seithtanabutara *et al*., 2023). Co-absorbers such as chenodeoxycholic acid (CDCA) and anchor groups like alkoxy silyl, phosphoric acid, and carboxylic acid groups (Hagberg *et al*., 2008, Elmorsy *et al*., 2023) placed between the dye and TiO2 to restrict the recombination process between the electrons in TiO2 nanolayer and redox electrolyte (Suzanne Ferrere *et al*., 2010). Important photophysical and electrochemical properties of the dyes (Shiling Liu *et al*., 2024) To begin with, the dye has to be luminous. Dye's absorption spectrum needs to encompass both near-infrared (NIR) and ultraviolet-visible (UV-vis) areas. The LUMO should be higher than the TiO2 conduction band potential. HOMO should lie lower than that of redox electrolytes. The dye's perimeter should be hydrophobic to improve the long-term stability of cells.

Electrolyte

An electrolyte should have characteristics such as, (i) The redox pair must be able to renew oxidized dye easily. (ii) Long-term stability in terms of chemicals, heat, and electrochemistry. (iii) Must not corrode DSSC components. (iv) Must provide efficient contact between the working and counter electrodes, enhance conductivity, and permit quick diffusion of charge carriers. An electrolyte, such as I/I3, Br/Br2, SCN/SCN2, and Co (II)/ Co (III), has five primary components: redox pair, solvents, additives, ionic liquids, and cations (Djamel Ghernaout *et al*., 2020). Angulakshmi *et. al*., created innovative new opportunities and paradigms for the production of solar photovoltaic systems at a reduced cost (Angulakshmi *et al*., 2015). Solid-state electrolytes overcome the leakage problem of ionic liquid electrolytes (IL) (Fakharuddin *et al*., 2014, Layla Haythoor Kharboot *et al*., 2023). Throughout the years, long-term light soaking studies on sealed cells have also been developed considerably to assess the failure of the redox electrolyte under prolonged illumination (Michael Grätzel *et al*., 2001).

Counter Electrode (CE)

Platinum (Pt) or carbon (C) is primarily used in the manufacturing of CE in DSSCs (Cai H. *et al*., 2014). The reduction of the liquid I/I_3 electrolyte is catalysed by CE, which also gathers holes from the hole transport materials (HTMs) (Kamal Prajapat *et al*., 2024). Pt is most utilized counter-electrode. Novel Polythiophenes (PT) with deep HOMO levels to achieve large values for Voc. Intense and broad visible absorption with high carrier mobility to increase Jsc, which made significant advancements in PT-based perovskite solar cells (PSCs) possible (Wang *et al*., 2014). Pt in DSSCs has been replaced with several substituents, like carbon (Gratzel 2005), cobalt sulphide (CoS), Au/GNP (K. Kakiage et al., 2014), and alloy CEs such as FeSe and CoNi0.25 (Liu J. *et al*., 2015)

Transparent and Conductive Substrate

DSSCs are frequently made up of two transparent, conductive layers that function as both current collectors and substrates for the catalyst and semiconductor to be deposited (Andualem *et al*., 2018). Two glass electrodes covered with transparent conducting oxides (TCO), typically glass substrates coated with FTO (Halme *et al*., 2010). The substrate must have a transparency >80%. Indium- and fluorine-doped tin oxides (ITO, In2O3: Sn) and (FTO, SnO2: F) are often utilized as conductive substrates in DSSCs. FTO films have a sheet resistance of 8.5 Ω/cm2 and a transmittance around 75% in the visible range, ITO films have a transmittance of > 80% and a sheet resistance of 18 Ω/cm2 (Umer Mehmood *et al*., 2014).

According to Hashmi et al., charges are transferred between PE and CE via redox mediators that diffuse via bulk phase of liquid electrolyte, porous spacer, and porous TiO2 electrode (Hashmi *et al*., 2019). DSSCs with poly (3,4-ethylene-dioxythiophene; PEDOT) catalyst-based CE and TiO2-based mesoporous PE were in physical contact without need for a spacer in between (Sultana Rahman *et al*., 2023; Suruthi Priya Nagalingam *et al*., 2022). The only ways to minimize diffusion resistance (RD) are thermoplastic customization, porous insulator thickness adjustments (Hashmi *et al*., 2011), or the use of low-viscosity solvent-based electrolytes to create high-efficiency DSSCs (Yella *et al*., 2017).

Working Principle of DSSC

Four steps are involved in the working principle of DSSC (Figure 3) Absorption: A photosensitizer absorbs incident photons, causing electrons to be promoted from the dye's ground state (S+/S) to excited state (S+/S*). For majority of dyes, absorption occurs in the 700 nm range (1.72 eV). Excited electrons with a nanosecond lifespan are introduced into CB of the nanoporous TiO_2 electrode, which is located underneath the dye's excited state, and TiO2 absorbs a small percentage of the UV photons from the sun (Kusama H. *et al*., 2008). This causes oxidation of dye.

$$S_+/S + h\nu \rightarrow S_+/S^*$$

$$S_+/S^* \rightarrow S_+/S + e^- (TiO2)$$

These injected electrons spread toward transparent conducting oxide (TCO). Electrons arrive at the counter electrode via external circuit. The counter electrode's electrons convert I− 3 to I−; as a result, the dye or its ground state regenerates because electrons from I− ion are accepted, and I− is oxidized to I− 3.

$$S_+/S^* + e— \rightarrow S_+/S$$

The oxidized mediator (I−3) diffuses in the direction of the counter electrode and transforms into an I— once $I^-3 + 2e^- \rightarrow 3I^-$

Evaluation of Dye-Sensitized Solar Cell Performance

Incident photon to current conversion efficiency (IPCE, %), short circuit current (JSC, mAcm−2), open circuit voltage (VOC, V), maximum power output [Pmax], overall efficiency [η %], and fill factor [FF] (as shown in Figure 4) can all be used to assess a dye-sensitized solar cell's

performance at a constant light level exposure, as indicated by Eq. 1 (Murakami *et al*., 2008). Voc (V) is simply potential difference between electrolyte's redox potential and semiconductor material's conduction band energy. The DSSC's greatest efficiency in turning sunlight into energy is known as Pmax. FF is obtained by dividing the highest power output (Jmp × Vmp) by the product (VOC×JSC).

$$FF = \frac{\text{Area A}}{\text{Area B}}$$

$$FF = \frac{(Jmp \times Vmp)}{(Voc \times Jsc)}$$

$$\eta\ \% = \frac{(V\,oc \times Jsc \times FF)}{Pin} \quad \text{----------(1)}$$

The ratio of electrons passing via the external circuit to photons striking the cell surface at any wavelength λ is called external quantum efficiency, or IPCE (Eq.2)

$$IPCE\ \% = \frac{1240 \times Jsc}{Pin\ \lambda} \quad \text{----------(2)}$$

IPCE values are also related to LHE, φE1, and ηEC. As shown in Eq. 3 (Khushboo Sharma et al., 2018)

IPCE (λ, nm) = LHEφE1ηEC ----------(3)

Where, IPCE is Incident Photon to Current Conversion Efficiency

LHE is the light-harvesting efficiency

φE1 is electron injection quantum efficiency

ηEC is the efficiency of collecting electrons in the external circuit.

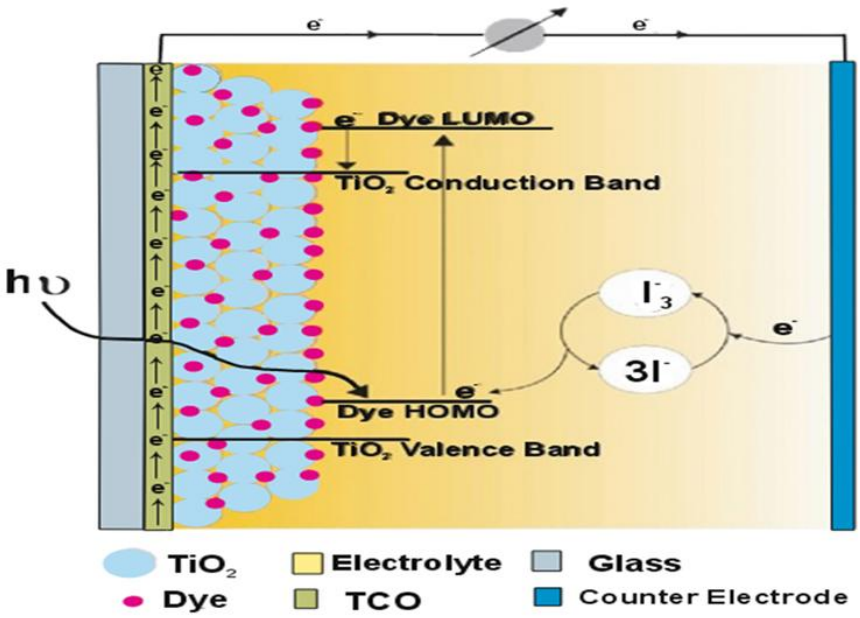

Figure 3. Construction and Working principle of DSSC.

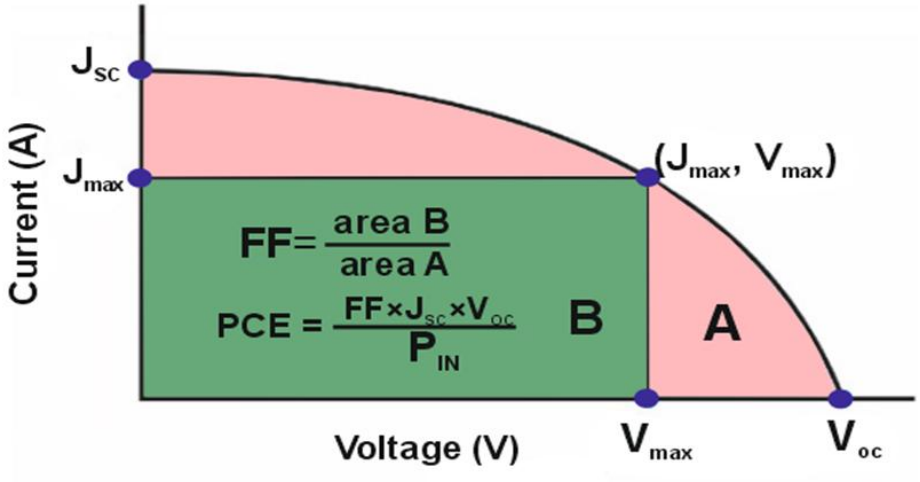

Figure 4. Current-Voltage curve for evaluation of DSSC performance.

Limitations of the Device

Limitation towards extrinsic stability: DSSCs are sealed using sealant materials like Surlyn® and Bynel®, hot-melt foils lose their capacity to seal when pressure builds up inside the cell (Ambika Prasad Jena *et al*., 2022), and when frequent temperature changes (Sommeling *et al*., 2004). Alternative sealants based on low-melting glass frits provide more durability than hot-melted foils, but they are not appropriate for fabricating large-area modules (Hinsch *et al*., 2001). Limitation towards intrinsic stability: 1000-hour accelerated aging tests demonstrate the thermal stability of the dye, electrolyte, and Pt-counter electrode at 80 °C, with efficiencies were 7.65% and 8% (Wang *et al*., 2003, Klein *et al*., 2005). The device remained stable for 1000 hours at moderate temperatures of 55 to 60 °C and AM 1.5. However, a quick deterioration in the cell's function was noted around 80 °C (Sommeling *et al*., 2004). Lower conversion efficiency of flexible plastic-based DSSC compared to stiff high-temperature DSSC (Hazim Khir *et al*., 2022).

Ways to Improve Efficiency of Dye-Sensitized Solar Cells

Maximize the ratio of natural red and yellow dye sensitizers for TiO2 (Kabir *et al*., 2019). After electron injection, the oxidized dye must be regenerated (Cristina Martín *et al*., 2016). Increase the porosity of the TiO2 nanoparticles, Co-sensitization (Khalid Zouhri *et al*., 2022; Hardin *et al*.,2009). By employing various kinds of CEs, creating hydrophobic sensitizers, and advancements in DSSC CEs (Kamal Prajapat *et al*., 2024). Use of phosphorescence or luminescent chromophores, like rare-earth-doped oxides (Palvinder Singh *et al*., 2024) coating of a luminescent layer on the photoanode glass (Chander *et al.*, 2015). Energy relay dyes (ERDs) applied to electrolyte (Rahman *et al*., 2015).

CONCLUSION

DSSCs have been intensively studied for more than five decades due to their low cost, simple fabrication method, low toxicity, and ease of fabrication. The efficiency of existing DSSCs reaches up to 14.2%. Thus, there is great scope for improving DSSC efficiency by adjusting the type of electrolytes, such as ionic liquids, polymer electrolytes, and organic and inorganic hole conductors. Modified dye molecules with steric groups can be introduced to slow recombination reactions with optimal dye packing. The power conversion efficiency of DSSC can be improved using a nanostructured porous material with a wide bandgap to construct photoanode. Therefore, the efficiency of the DSSC depends on optimization and compatibility of each solar cell component.

ACKNOWLEDGMENT

The authors express sincere thanks to the Head of the Dhote Bandhu Science College for the facilities provided to carry out this research work.

CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

FUNDING

This study received no specific funding from public, commercial, or not-for-profit funding agencies.

AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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