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REVIEW ARTICLE

Review on fabrication methodologies and its impacts on performance of dye-sensitized solar cells

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Abstract
This review highlights and summarizes the impact of different fabrication processes on the efficiency of dye-sensitized solar cells (DSSCs). Energy conversion efficiency of cell depends upon semiconductor, sensitizer, electrolyte, and counter electrode. Efficiency of DSSCs can be enhanced by properly selecting the optimum significance of various parameters of fabrications process. Major challenges of these solar cells are non-vegetal, noxious, extreme sensitizers. Application of natural dyes in this field plays a significant role. An optimized CdSe-TiO_2 photoanode showed a power conversion efficiency (PCE) of 13.29% and short circuit current density of 15.30 mA cm^{-2} for the DSSC. Power conversion efficiency of 3.26% was achieved by using TTO electrode for DSSC device that is ascribed to the improved electrical and optical properties due to doping with Ta element. Absorbance of betalain was shown in the visible range of 530–535 nm for betanin while 450–559 nm for anthocyanin pigment. The natural dyes are economical, readily available, and environmentally friendly. This compilation would be beneficial for researchers working on dye solar cell.

Keywords Dye-sensitized solar cell · Working electrode · Natural dye · Electrolyte · Counter electrode

Introduction

All over the world, non-renewable energy based power plants such as thermal power plants, nuclear power plants, diesel and gas turbine power plants, etc. are used to generate electricity. These fossil fuels pollute the environment due to carbon emissions (Polo et al. 2004). On the other hand, the application of renewable energy sources results in clean surroundings (Awasthi et al. 2020) and a healthy environment across the universe (Sharma et al. 2015). There are various renewable energy sources such as wind energy, solar energy, and hydro energy (Fukurozaki et al. 2013). Solar energy is the more convenient renewable energy source due to simple principles and easy construction of conversion devices. Photovoltaic is a device that converts solar energy into electricity (Kumar et al. 2015). There are three generations of solar cells: (i) crystalline solar cell, (ii) thin-film solar cell, and (iii) dye-sensitized solar cell (Ludin et al. 2014). A dye-sensitized solar cell (DSSC) is particularly interested in research and industries due to the novel and emerging solar cell generation. These solar cells have different parts, photosensitizer, photoelectrode, liquid electrolyte, and counter electrode, as shown in Fig. 1.

Highlights
•Different fabrication methodologies of dye-sensitized solar cells are described.
• Ideal features of fabrication parameters of DSSCs are explained.
• Various natural sensitizers for a healthy environment are discussed.
• Performance evaluation between natural and synthetic dye is described.

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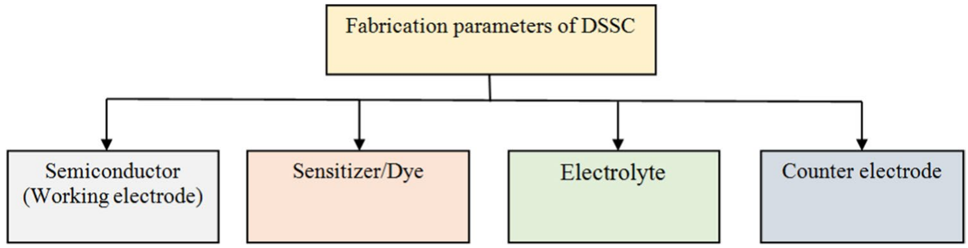

Fig. 1 Fabrication parameters of DSSC

Photosensitizer converts incident solar radiation into electric voltage. Photoelectrode is made up of a nanocrystalline semiconductor that absorbs solar radiation. During illumination, electrons move from sensitizer to the working electrode (semiconductor). Liquid electrolyte consists of a redox couple that regenerates the dye. Some researchers have been examined the factors that influence DSSC performance, resulting in good alternatives. The porphyrin-dyed ZnPorph-L-H2Porph(ZnP-H2P) and metal-free organic dye solar cell were used to make co-sensitized DSSC (Sharma et al. 2014). Co-sensitized (mixed) dye solar cells C (Zn{Porph}-L-H_2{Porph}/DC) and D (Zn{Porph}-L-H_2{Porph}) were obtained by immersing the working electrode in separate solutions of sensitizers in varying sequences. Power conversion efficiency of C and D was observed as 6.16% and 4.80%, respectively. Three different types of dye solar cells were prepared by treating titanium dioxide electrodes in three different ways, untreated, post-treated, and pre- and post-treated, through titanium tetrachloride ($TiCl_4$) solution. Pre- and post-treated working electrodes showed the best results and gave 5.1% conversion efficiency. This novel working electrode raises the thickness of TiO_2, thus increasing the current density of the solar cell. Therefore, the thickness of TiO_2 raises cell performance (Sedghi and Miankushki 2013). Nitrogen-doped TiO_2 (NSND-TiO_2) nanoparticle was prepared using modified flame spray pyrolysis (FSP) equipment. NSND-TiO_2 was formed by spraying ammonia water above the flame in which TiO_2 particles were made. Addition of nitrogen elements to TiO_2 showed a decreased energy band gap to 2.90eV and recorded 6.03% power conversion efficiency (Huo et al. 2014). Naturally occurring dyes available in various kinds of roots, leaves, fruits, and flowers show a viable environmentally friendly alternative and can be employed in DSSCs. Various natural dyes named *Anethum graveolens*, parsley, arugula, *Spinacia oleracea*, and green algae to fabricate DSSCs were treated using two different methods, i.e., before and after drying raw materials. It has been found that some DSSCs using after drying method showed better performance and others revealed better results using before drying method. The *Spinacia oleracea* extract gave the highest efficiency after the drying method was recorded as 0.29% (Taya et al. 2013). Benzonitrile-based electrolytes have low vapor pressure, thus causing more extended stability to the solar cells using N179 dye (Latini et al. 2014). Five aldimine derivatives were prepared by condensing the suitable amine with salicylaldehyde (m1–m4) and 4-aminobenzoic acid with 2-thiophene carboxaldehyde (m5). Highest efficiency of 0.575% was obtained with 2-(2-hydroxybenzylideneamino) benzoic acid-based dye solar cell (Batniji et al. 2014).

The objectives of this review are (i) to describe different fabrication methodologies of dye-sensitized solar cell while analyzing the impact of various technical procedures on the photovoltaic performance of DSSC; (ii) to discuss various ideal features of performance parameters for DSSCs; (iii) to discuss the detailed description of various natural sensitizers for the healthy environment; and (iv) to discuss performance evaluation between natural and synthetic DSSC. This study will be fruitful for the researcher to understand the construction and functioning of natural DSSC. Also, it provides knowledge in the field of natural dyes in the environment.

Performance parameters of DSSCs

Open-circuit voltage, short circuit current, fill factor, maximum voltage, and maximum current are the various distinct performance parameters of dye solar cell. All the parameters of DSSC discussed are as follows (Fig. 2):

Open-circuit voltage

Open-circuit voltage is the difference in potential between the two terminals in the cell under light illumination when the circuit is open. It is influenced by the fermi level

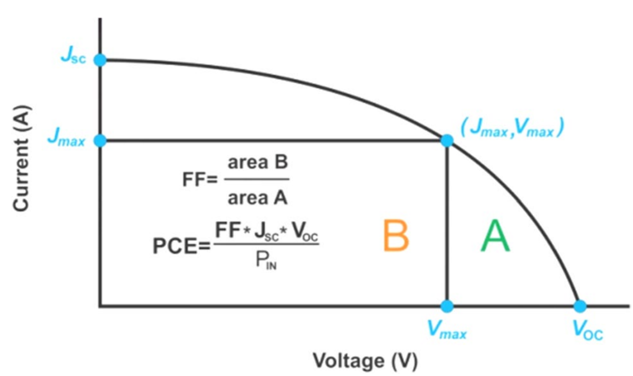

Fig. 2 Performance parameters of DSSC (Sharma et al. 2020)

(semiconductor) and the level of dark current. It is calculated when the current through the DSSC is zero (open circuit). Open-circuit voltage is dependent on the cell temperature. At the open terminals of DSSC, the voltage is mentioned as open-circuit voltage. The following is the expression for open-circuit voltage (Takagi et al. 2013):

$$V_{OC} = V_t \ln\left\{\left(\frac{I_{SC}}{I_O}\right) + 1\right\} \tag{1}$$

Short circuit current

Short circuit current density (I_{sc}) is the photocurrent per unit area (mA/cm^2) when an illuminated DSSC is short-circuited. It relies on various factors such as light absorption, light intensity, regeneration of the oxidized dye, and injection efficiency. It is strongly associated with incident photon conversion efficiency and theoretical values of the current density can be determined from the IPCE spectrum. At the short circuit terminals of DSSC, the current is mentioned as short circuit current. When the cell temperature rises, short circuit current also rises (Takagi et al. 2013). The expression for short circuit current is as follows (Lee et al. 2005):

$$I_{SC} = I + I_O\left\{\exp\left(\frac{V}{V_t}\right) - 1\right\} \tag{2}$$

Fill factor

Fill factor measures the ideality of the DSSC and is defined as the ratio of the maximum power output per unit area to the product of open-circuit voltage and current density. Several factors can affect the fill factor, such as a high internal resistance value that will offer a low fill factor and a reduced overall efficiency. It is expressed as follows (Zhou et al. 2007):

$$FF = \frac{V_m I_m}{V_{OC}\, I_{SC}} \tag{3}$$

Efficiency

Overall solar energy to the electrical conversion efficiency of a dye solar cell is defined as the maximum value of the cell output divided by the incident light power. It is estimated by measuring photocurrent density at short circuit (J_{sc}), the open-circuit photovoltage (V_{oc}) at open-circuit terminals, and intensity of the incident light and fill factor of the cell (FF), as shown in Eq. 4. Since it is reliant on all the three factors under standard conditions (Mbonyiryivuze et al. 2015), it is of great significance to optimize each one of them for high overall efficiency (Nan et al. 2017):

$$\eta = FF\left(\frac{V_{oc}\, I_{SC}}{Incident\ Solar\ Power}\right) \tag{4}$$

Fabrication elements

Structure of DSSC is shown in Fig. 3, displaying all components of the cell. Structure of DSSC is varied from the first and second generations of the solar cell. DSSC consists of specially four parts: (i) working electrode (WE); (ii) sensitizer; (iii) electrolyte; (iv) counter electrode (Gratzel 2003). Optimization of all the components is of immense meaning to enhance the overall efficiency of the cell. Working substrate is made up of semiconductor material deposited on the transparent conductive oxide. In general, metal oxides with wide band gaps are used as materials for working electrodes. Titanium dioxide, zinc oxide, and tin oxide have been extensively used in dye-sensitized solar cells (Hagfeldt et al. 2010). Semiconductor metal oxides nanoparticles form nanoporous and semi-transparent working electrodes. To sensitize working electrode, sensitizer is used that enhances semiconductor conductivity. On the surface of the working electrode, a layer of dye molecules is liable for electron harvest. Ruthenium-based dyes such as N719 (known as black dye) (Nazeeruddin et al. 1999) and N3 have been extensively employed as synthetic dyes for DSSCs (Nazeeruddin et al. 1993). N719 or N3 based DSSCs have been shown the highest efficiency of the cell. Electrolyte is filled between the working and counter electrode to complete the flow of electrons. Iodide/triiodide (I^-/I_3^-) redox couple has been widely preferred because of its appropriate

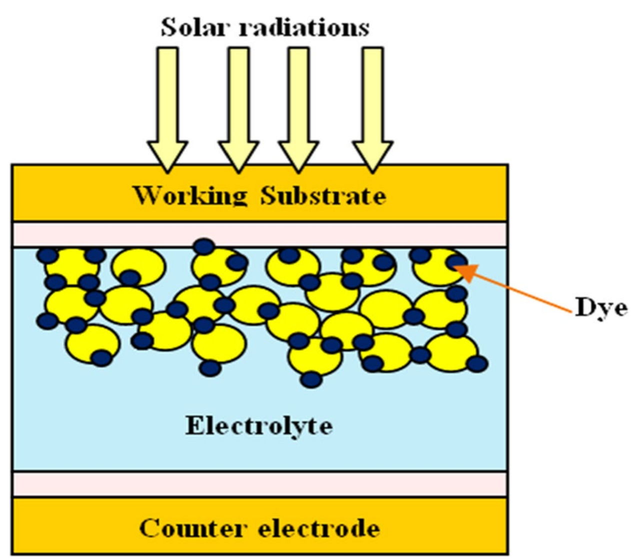

Fig. 3 Constructional parts of a dye-sensitized solar cell (Rawal et al. 2015)

redox potential (Daeneke et al. 2011). Other redox couples such as Br^-/Br_3^- (Wang et al. 2005), $SCN^-/(SCN)_3^-$, and $SeCN^-/(SeCN)_3^-$ (Oskam et al. 2001) have been striking due to their redox potentials closer to the ground state of the dyes, which provide a higher output voltage. Counter electrode is used to catalyze the regeneration of I^-. Platinum is mostly used as a counter electrode due to its better performance. Efficient regeneration of iodide enhances the diffusion rate of iodide and thus increases the reduction rate of the oxidized dye.

Working substrate

Working electrode (anode) consists of a mesoporous extensive bandgap semiconductor layer. Titanium dioxide is the most common material used as a semiconductor for DSSC. Nanoparticle layer of titanium dioxide is sintered on the working electrode to enhance electronic conduction. Mesoporous layer is deposited on a transparent conducting oxide (TCO). The fluorine-doped tin oxide (FTO) and indium-doped tin oxide are mainly transparent conducting oxide. Plastic foils (Richhariya and Kumar 2016) and metal sheets (Heo et al. 2009) are also used as materials for the working substrate of DSSC (Jun et al. 2007). Merits and failures of different substrates are shown in Table 1.

DSSC efficiency can be increased by using suitable functionalized semiconducting metal oxides having quantum dots, organic conjugated polymers, etc. Photoanodes are fabricated using semiconductor oxides having wide bandgap. Such metal oxides can absorb almost all the incident sunlight and have stability against photo-corrosion (Kumar et al. 2020). An optimized CdSe-TiO_2 photoanode showed a power conversion efficiency (PCE) of 13.29% and short circuit current density of 15.30 mA cm^{-2} for the DSSC, as shown in Fig. 4 (Bhattacharya and Datta 2020).

A facile spray pyrolysis method was used to deposit a thin film of Ta-doped SnO_2 (TTO). Resistance stability of sheet resistance was relatively better up to 400°C representing the appropriateness of TTO electrode to provide as conducting photoanode electrode in DSSC. XRD study showed the crystallinity, phase purity, and texture properties of the thin film (Fig. 5). Power conversion efficiency of 3.26% was achieved using the TTO electrode for DSSC device ascribed to the improved electrical and optical properties due to doping with Ta element (Ramarajan et al. 2020).

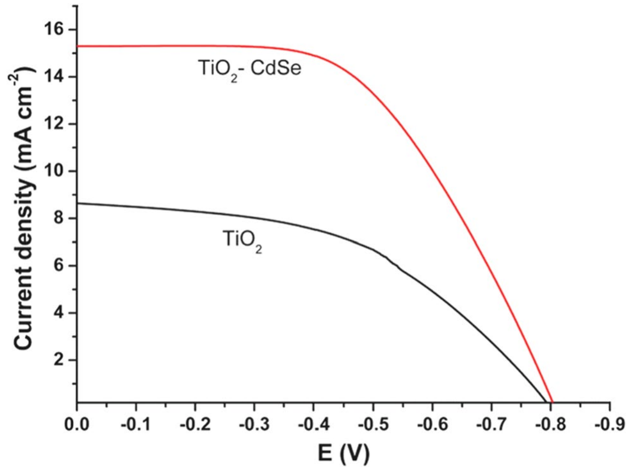

Fig. 4 J-V curve for CdSe-TiO_2-based DSSC (Bhattacharya and Datta 2020)

Materials of working substrate

Titanium dioxide is the best semiconductor for DSSC due to its suitable properties that match the solar cell requirement. Conversion efficiency of 2.61% was achieved by employing two-step hydrothermal method for synthesizing TiO_2 materials. Paste was prepared by grinding 6.0g of TiO_2 with ethanol and water, and then mixed with terpineol and ethyl cellulose after sonication (40). Photoanode with 23μm thickness was prepared using shear-exfoliated graphene, causing less electron recombination and giving cell efficiency of 8.9%. Nanofiber-based photoanode causes a higher electron diffusion coefficient (Lo and Leung 2019). Two grams of

Table 1 Merits and failures of working electrodes

Working electrode	Merits	Failures	Reference
TCO	-Transparent in nature -Greater conductivity	-Uneconomical -Breakable -Hard construction	(Weerasinghe et al. 2013) (Hashmi et al. 2011) (Narayan 2012)
Polymers-based substrate	-Flexibility of cell -Suitable for roll to roll fabrication technique	-Less efficiency -Less temperature tolerance	(Han et al. 2015)
Metallic substrate	-Very high electrical conductivity	-Rusty in nature -Uneconomical	(Yugis et al. 2015) (Law et al. 2005) (Yune et al. 2013)

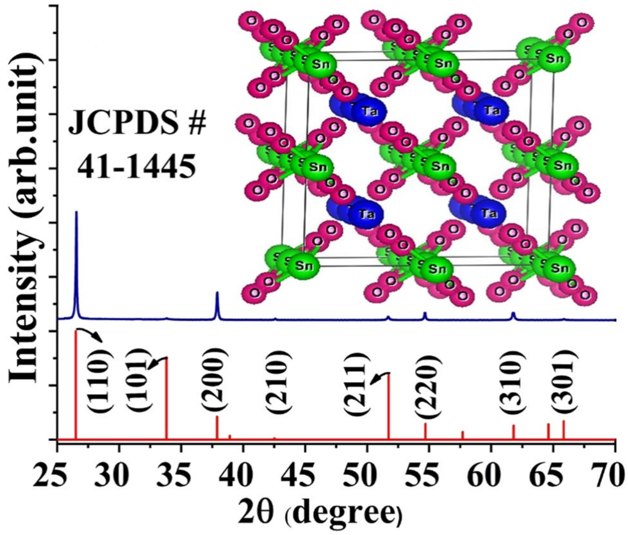

Fig. 5 XRD pattern of the TTO thin film (Ramarajan et al. 2020)

titania powder was placed in a beaker and 6mL citric acid of 0.1M, 0.2mL polyethylene glycol, 0.2mL titanium (IV) isopropoxide, and 0.1mL non-ionic surfactant Triton X-100 were added to prepare the solution. Table 2 reveals that dyes extracted using acetone acquired every parameter of DSSC superior to the other four solvents. Therefore, that experiment verified the need for solvent effect and showed that the solvent having less polarity, being as acetone, was more able to extract an effective fraction of red amaranth dye than the other four solvents (Uddin et al. 2015).

TiO_2 working substrate was synthesized using a hydrothermal gel method employing polyvinylpyrrolidone (PVP) by adding 100mL of deionized water in 10mL of titanium tetrabutanolate under vigorous agitation at room temperature. Colloid was mixed with 0.8g of polyethylene glycol, 1ml of OP emulsifier, and stoichiometric PVP (0.0270, 0.0405, 0.0540, 0.0810, 0.108, and 0.135) and subsequently concentrated at 80°C. The resultant titanium dioxide nanocrystallites were calculated as TiO_2-1 wt%, TiO_2-1.5 wt%, TiO_2-2 wt%, TiO_2-3 wt%, TiO_2-4 wt%, and TiO_2-5 wt%, respectively. The TiO_2-0 wt% was considered zero PVP. Compared with dense titanium dioxide working substrate, the power conversion efficiency was reported as 9.86%, as shown in Table 3 (Hu et al. 2014).

Table 3 Performance parameters of resultant dye solar cell (Hu et al. 2014)

Working substrate	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)
TiO_2-0 wt%	0.729	12.82	0.686	6.41
TiO_2-1 wt%	0.740	11.92	0.729	3.43
TiO_2-1.5 wt%	0.779	17.99	0.704	9.86
TiO_2-2 wt%	0.746	17.63	0.728	9.57
TiO_2-3 wt%	0.743	15.18	0.671	7.57
TiO_2-4 wt%	0.750	11.35	0.724	7.30
TiO_2-5 wt%	0.763	11.76	0.720	6.46

Table 4 Performance parameters of silver-coated DSSCs (Peng et al. 2013)

Working electrode	Deposition time (min)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)
Silver-coated TiO_2	0	0.720	12.44	0.66	5.97
	5	0.724	12.98	0.68	6.46
	10	0.735	13.55	0.69	6.86
	15	0.730	12.76	0.66	6.18
	30	0.730	12.22	0.57	5.15

TiO_2 colloidal dispersions synthesize hydrothermally at 200°C by using titanium isopropoxide gels and acetic acid under non-ionic surfactant. Particle size varying from 15 to 20nm showed the cell's average efficiency as 5.2% (Muniz et al. 2011). TiO_2-based working electrode was fabricated using silver coating photo-deposition with distinct light durations. In a solution of 5×10^{-4} mol/L $AgNO_3$, TiO_2 working electrode was dipped in distinct durations of 5, 10, 15, and 30 min, and ultraviolet radiations irradiated the solutions. This novel fabrication enhanced the conversion efficiency of the DSSC 6.86% in deposition time of 10 min with fill factor of 69.4% (Table 4). IPCE spectra of dye solar cell using TiO_2 and TiO_2-Ag-coated electrode are shown in Fig. 6. There is higher IPCE in the case of the silver-coated electrode (Peng et al. 2013). Anatase TiO_2 was synthesized using a hydrothermal process in two steps using amine ligands and achieved a conversion efficiency of 2.61% for the smallest nanoparticles (Phonkhokkong et al. 2016).

Table 2 Performance parameters of DSSC using different solvents (Uddin et al. 2015)

Working electrode	Solvent	V_{oc} (V)	J_{sc} (mA/cm^2)	P_{max} (mW)	FF	η (%)
TiO_2	Water (room temp)	0.452	0.17	0.043	0.56	0.04
	Boiling water	0.450	0.47	0.117	0.55	0.12
	Ethanol	0.390	0.27	0.066	0.63	0.07
	Methanol	0.435	0.42	0.107	0.59	0.11
	Acetone	0.475	0.65	0.213	0.69	0.21

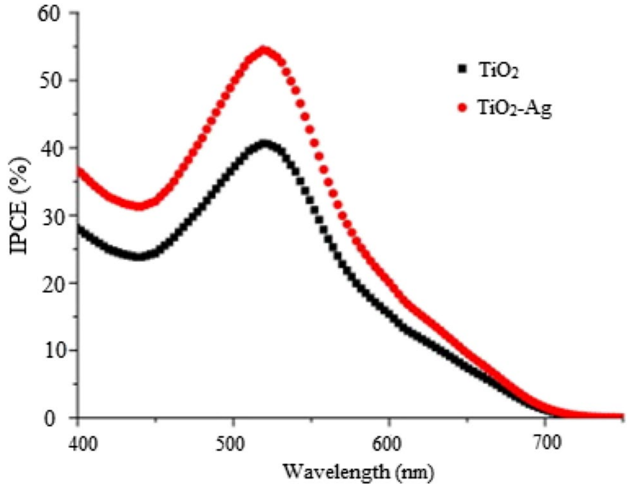

Fig. 6 IPCE spectra of dye solar cell using TiO_2 and TiO_2-Ag-coated electrode (Peng et al. 2013)

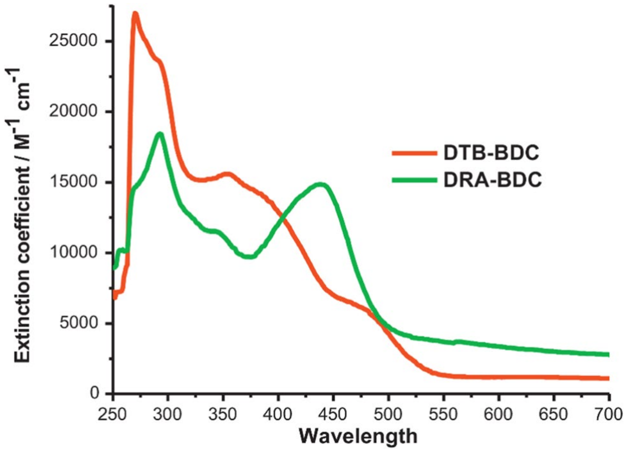

Fig. 7 Absorption spectra of organic dyes (Moustafa et al. 2021)

Sensitizer

A layer of the sensitizer is adsorbed onto the surface of the semiconductor by chemical bonding. The primary role of the sensitizer is to absorb the incident light, infuse the excited electron into the semiconductor, and turn it into regenerated by the redox couple in the electrolyte. Dye (sensitizer) is the heart of dye-sensitized solar cells, making the DSSC different from other solar cells. Metal complex sensitizers, metal-free organic sensitizers, and natural sensitizers are the most common varieties of sensitizers in DSSC. Natural sensitizers are environmentally friendly and easily extractable using a simple extraction process (Calogero et al. 2012). Two new organic dyes were DRA-BDC and DTB-BDC, with electron acceptors as rhodanine-3-acetic acid/thiobarbituric acid while electron donor as N,N-butyldicarbazole, which have been used as dye for DSSC. DRA-BDC and DTB-BDC revealed higher absorption peaks at 440 and 370 nm, respectively, in UV-visible spectra of dyes (Fig. 7). Novel sensitizer has a larger energy gap between its LUMO and conduction band of TiO_2, leading to increased current density ($2.46 mA/cm^2$), thus contributing to the enhancement of the PCE (1.16%) (Moustafa et al. 2021).

Two novel compounds derived from the phenyltetrazole system, 5-(4-decyloxyphenyl)tetrazole (LTz-4) and N,N-diethyl-4-{((2′-nitro-4′-tetrazoyl)phenyl)diazenyl}aniline (SD - 6), were used as co-adsorbents for DSSC. Highest open-circuit voltage (0.71V) and PCE (9.20%) were observed in the case of dye HD-14 (ruthenium complex) with co-adsorbent DCA (Fig. 8). High value of photocurrent density can be due to the co-adsorbent, favoring the capture of photons and encouraging the introduction of electrons into semiconductors (Silva et al. 2020).

Natural dye was extracted from the daisy flowers family (*Leucanthemum vulgare*), namely yellow daisy, purple daisy, and wine daisy, containing luteolin flavonoid used to fabricate DSSCs. The yellow daisy-, wine daisy-, and purple daisy-based DSSC revealed PCE of 0.6%, 0.4%, and 0.8%, respectively (Fig. 9) (Ferreira et al. 2020).

Materials of sensitizer

There are various methods used for the fabrication of dye for DSSC using different natural dyes. Extracts from *Dianthus barbatus*, *Lepidium sativum*, and *Raphanus raphanistrum* were employed as dyes in titanium dioxide nano-powder-based dye solar cell. Highest efficiency and fill factor of 0.15% and 0.48 were observed from *Dianthus barbatus* (Researcher et al. 2016). One gram of rosella and blue pea flower was taken in 100mL of two different solvents at various temperatures (25, 50, 50, 70, and 100°C). The observed conversion efficiency of DSSCs using extracts of rosella, blue pea, and mixed dye extracted at 100°C was 0.37%, 0.05%, and 0.15%, respectively (Table 5) (Hamadanian et al. 2014).

Anthocyanin was extracted from maqui berry by drying 0.5g of maqui berries at 45°C and dipped in 5mL of distilled water. At 750 and 1500mg of anthocyanin/L, the extracted concentration of maqui was examined and power conversion efficiency was obtained as 0.14 % and 0.19%, respectively (Table 6) (Ozuomba et al. 2013).

Natural dyes from *Reseda luteola*, *Berberis integerrima*, *Panica granatum*, Pleniflora, *Consolida orientalis*, *Reseda gredensis*, *Clematis orientalis*, *Adonis flammea*, *Salvia sclarea*, and *Consolida ajacis* plants were extracted using Soxhlet extractor. Identifying suitable natural dyes for improving V_{OC} without resulting dye degradation may result in additional improvement of cell performance. The

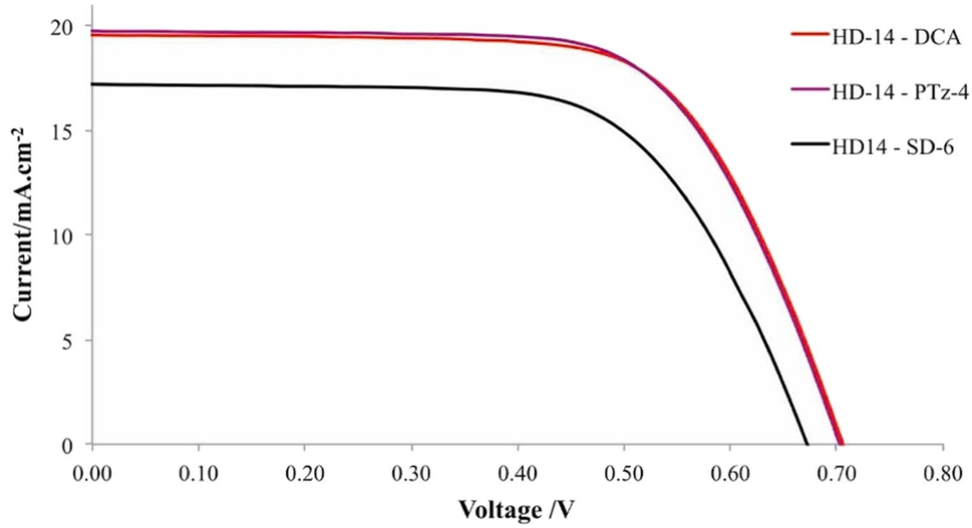

Fig. 8 J-V characteristics for HD-14 (ruthenium complex) with co-adsorbent DCA (Silva et al. 2020)

maximum energy conversion of DSSC using Reseda luteola extract is 0.22%. (Table 7) (Phinjaturus et al. 2016).

Two dye solar cells were fabricated using anthocyanin extracted from *Hibiscus sabdariffa* and plain (un-dyed) cells, which reported an energy conversion efficiency of 0.58% for dyed cells while 0.03% for un-dyed solar cell. Husk, cob, and silk of purple corn were extracted in acetone, ethanol, and DI waters. Maximum conversion efficiency of 1.06% was obtained from husk extracted from acetone, as given in Table 8 (Ananth et al. 2015).

TiO_2-based DSSC was sensitized using natural dye formed by *Pterocarpus marsupium* stem bark. One hundred milliliters of distilled water was added in 250g of *Pterocarpus marsupium* stem bark (cut pieces) for a duration of 14 h, and filtered out. In this concentrated solution, distilled water of 250mL and isopropanol of 15mL were added. Initial pH value was recorded as 8.75. Nitric acid was added drop wise to raise the pH value up to 2, and the solution was vigorously stirred. After that, the titanium isopropoxide solution of 5mL was mixed drop wise until white precipitation was formed. Solution was then heated up to 80°C for 2–3 h. At room temperature, the solution was going to foraging for 1 h. The resultant white precipitate was left to dry at 150°C for 15–20 h to form fine particles of pure titanium dioxide. Table 9 displays the conversion efficiency of DSSC using pre-dyed titanium nanoparticles as 0.49% (Jia et al. 2018).

Novel X type D-$(\pi\text{-A})_2$ organic dyes JX1 and JX2 were developed and co-sensitized with porphyrin dyes JP1 and JP3 for dye solar cells. JX1-based DSSC showed photo-conversion efficiency (PCE) of 3.67%, while JX2-based DSSC showed PCE of 4.63%. Co-sensitized dye solar cell (JP3+JX2) showed the highest efficiency of 8.08% (Zeng et al. 2010).

Electrolyte

Electrolyte regenerates the sensitizer of dye solar cells. Redox couple present in the electrolyte is an essential feature of the electrolyte for better cell performance. The function of electrolytes is to transfer the electron between two electrodes. Active transport of electrons within the dye solar cell is essential, and many different redox systems have been explored. Iodide triiodide is the most common liquid electrolyte. However, severe problems such as electrolyte volatility can lead to long-term stability concerns because of complications in sealing the device. Transform of the volatile electrolyte into a nonvolatile ionic liquid (Choi et al. 2008) has been recognized to be victorious (Gorlov and Kloo 2008), and high efficiencies and excellent stabilities have been reported (Tian et al. 2000). Numerous other iodine-free redox mediators have been experienced. Both complexes (Wang et al. 2010) and organic redox couples have been verified to be potential alternatives (Ayalew and Ayele 2016). Electrolyte configuration can be further changed to enhance the performance of the cell. DSSC has been fabricated using gel polymer electrolytes (GPEs) with polyacrylonitrile (PAN)-based polymer with variant number of tetrabutylammonium iodide (TBAI) salt and iodine. The S3 electrolyte-based DSSC showed the highest PCE of 3.45%, with V_{oc} of 582 mV and J_{sc} of 12.9 mA cm^{-2} (Fig. 10). High PCE of DSSC (S3 electrolyte) over a visible wavelength range shows superior photon harvesting efficiency (Chowdhury et al. 2020).

Gel polymer electrolyte (GPE) has been prepared using different lithium iodide concentrations (LiI). Solution was contained PEO and PVA in same quantity, ethylene carbonate (EC), tetrabutylammonium iodide (TBAI), dimethyl sulfoxide (DMSO), and iodine crystals (I_2). DSSC fabricated

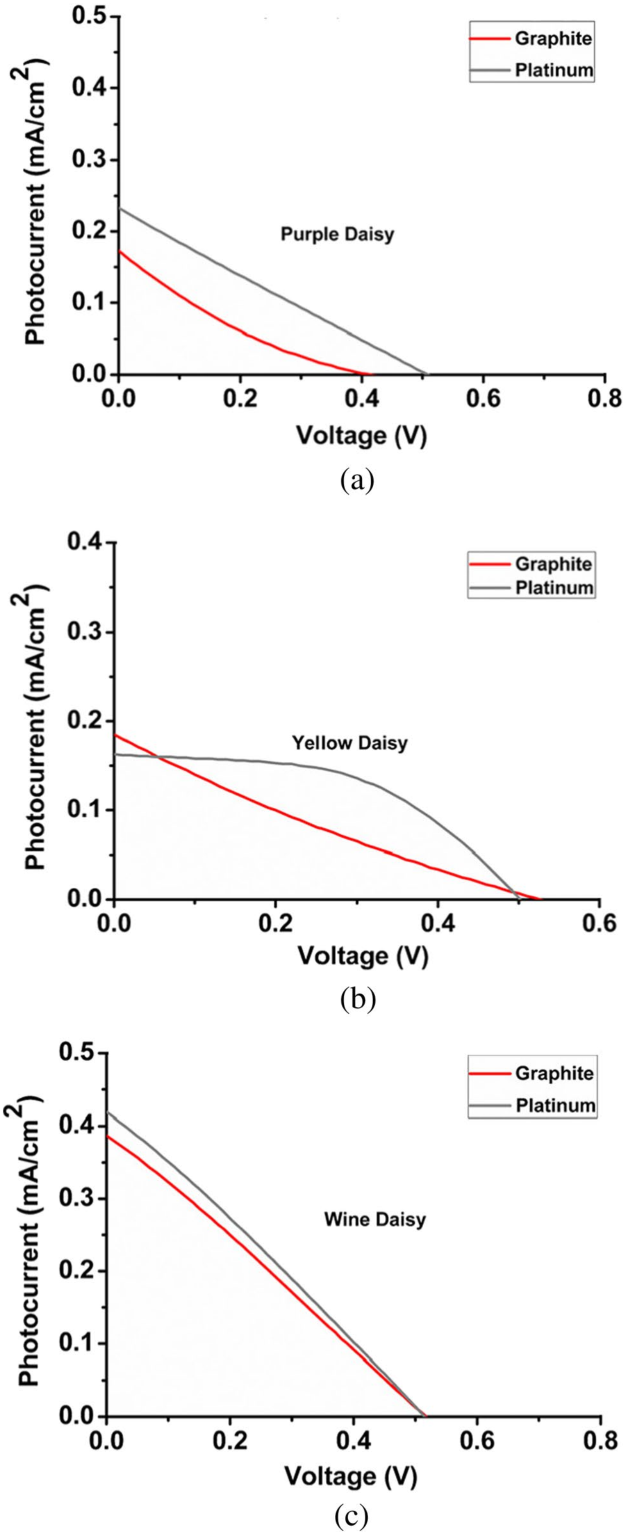

Fig. 9 J-V curves for dyes: **a** purple; **b** yellow; **c** wine (Ferreira et al. 2020)

Table 5 Performance parameters of DSSCs using natural extracts (Hamadanian et al. 2014)

Dye	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF	*η* (%)
Mixed dye	382	0.82	0.47	0.15
Rosella	404	1.63	0.57	0.37
Blue pea	372	0.37	0.33	0.05

Table 6 Performance parameters of the DSSCs using maqui berries at concentrations of 750mg/L and 1500mg/L (Ozuomba et al. 2013)

Anthocyanin concentration (mg/L)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	*η* (%)
Maqui (1500mg/L)	0.44	0.44	0.54	0.19
Maqui (750mg/L)	0.43	0.37	0.49	0.14

Table 7 Performance parameters of natural dyes extracts of various plants (Phinjaturus et al. 2016)

Natural dye	V_{oc} (mV)	I_{sc} (mA)	FF	η (%)
Reseda luteola	0.64	0.54	0.63	0.22
Berberis integerrima	0.56	0.004	0.53	0.01
Panica granatum Pleniflora	0.62	0.40	0.61	0.15
Consolida orientalis	0.60	0.56	0.53	0.18
Reseda gredensis	0.53	0.14	0.71	0.07
Consolida ajacis	0.55	1.68	0.65	0.60
Adonis flammea	0.59	0.40	0.66	0.16
Salvia sclarea	037	0.10	0.54	0.02
Clematis orientalis	0.42	0.22	0.49	0.05

Table 8 Performance parameters using different solvents (Ananth et al. 2015)

Solvent	Natural dye	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	*η* (%)
Acetone	Husk	0.46	3.57	0.64	1.06
Acetone	Cob	0.48	3.42	0.62	1.01
Acetone	Silk	0.48	3.25	0.62	0.96
Ethanol	Husk	0.43	2.91	0.61	0.76
Ethanol	Cob	0.45	3.21	0.61	0.89
Ethanol	Silk	0.47	2.19	0.64	0.65
DI water	Husk	0.40	2.13	0.59	0.50
DI water	Cob	0.42	2.29	0.56	0.53
DI water	Silk	0.47	1.46	0.61	0.43

from GPE with 1.34 wt% LiI gave the highest efficiency of 6.26%, as shown in Fig. 11 (Teo et al. 2018).

Table 9 Performance parameters using *Euphorbia cotinifolia* leaves and *Acanthus sennii* chiov flower-based dye solar cell (Jia et al. 2018)

Natural dye	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	*η (%)*
Euphorbia cotinifolia leaves	0.436	0.642	0.48	0.136
Acanthus sennii chiov flower	0.507	0.491	0.60	0.150

Materials of electrolyte

Usually, iodide triiodide redox couple is generally used in the fabrication of dye solar cells. Evaporation and long-term stability are the main issues in front of liquid electrolytes. Gel polymer electrolytes were synthesized using distinguished weights (0%, 2%, 4%, 5%, 6%, and 8%) of acetamide in poly(ethylene oxide) (PEO) with LiI/I_2. Gel electrolyte was formed by mixing 0.53g of polyethylene oxide with acetonitrile and propylene carbonate (20:1) stirred for 2h continuously. After that, 0.2g of LiI, 0.04g of I_2, and different wt% of acetamide (0%, 2%, 4%, 5%, 6%, and 8%) were added and dropping was continued for 2 h; homogeneous sol was evaporated at 80°C to get gel polymer electrolyte. The highest cell efficiency 9.01% was observed with 5%wt of acetamide, as discussed in Table 10 (Pavithra et al. 2015).

Single-step methodology was employed for preparing counter electrodes using copper sulfide nanoparticle that was treated with two distinct electrolytes, Co(II)/(III) bipyridine and Fe(II)/(III) ferrocene-based liquid electrolyte. Ferrocene electrolyte was prepared by mixing 0.1M of ferrocene and 0.05M of ferrocenium tetrafluoroborate in propylene carbonate. The sol was kept

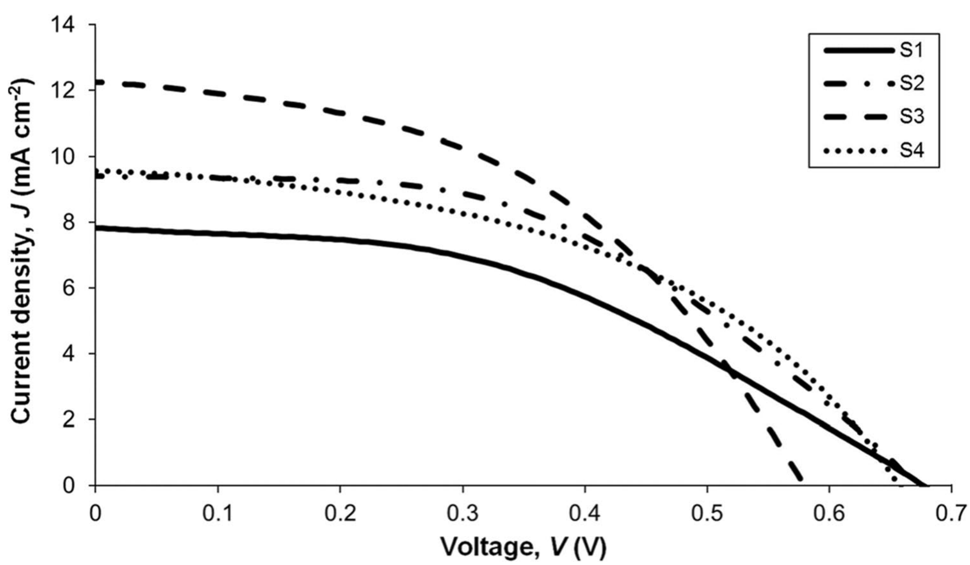

Fig. 10 J-V characteristics of DSSCs using different electrolytes (Chowdhury et al. 2020)

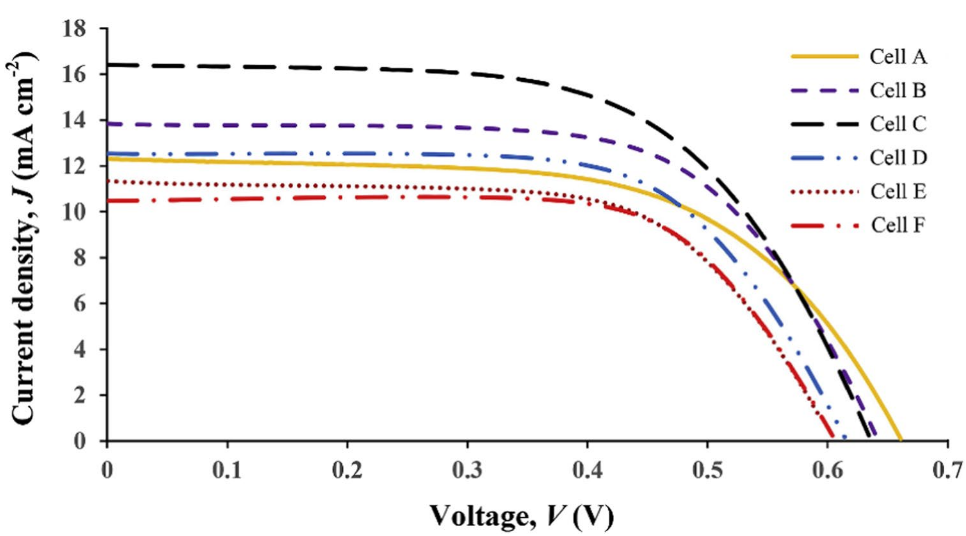

Fig. 11 J-V characteristics of DSSCs using PVA-PEO-based GPEs consisting of different ratios of TBAI and LiI salts (Teo et al. 2018)

Table 10 Performance parameters using acetamide with different weights (Pavithra et al. 2015)

Acetamide (wt%)	Electrolyte	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)
-	Liquid	0.68	5.87	0.62	2.93
0	A	0.74	12.04	0.54	5.70
2	B	0.74	16.78	0.44	6.40
4	C	0.75	18.59	0.48	7.89
5	D	0.74	19.81	0.52	9.01
6	E	0.76	15.08	0.45	6.04
8	F	0.76	11.38	0.56	5.74

Table 11 Performance parameters using biopolymer electrolyte (Singh et al. 2014)

Electrolyte	V_{oc} (V)	J_{sc} (mA/cm^2)	η (%)
Biopolymer electrolyte	0.56	5.68×10^{-4}	0.63

under the nitrogen atmosphere, thus avoiding degradation of ferrocenium ion in contact with air. A high limiting current (11.8mAcm^{-2}) was observed by the ferrocene/ferrocenium redox couple (Congiu et al. 2016). Ionic liquid electrolyte enhances the thermal durability of DSSC with an energy conversion efficiency of 2.06% and a fill factor of 0.49 (Ito and Takahashi 2012). An electrolyte was developed by adding 0.172g of arrowroot powder in 20 mL of double-distilled water (D2) and stirred for 30 min at 70°C. On the other hand, potassium iodide was taken in D2. Finally, two solutions were mixed drop-by-drop and stirred continuously to produce biopolymer electrolyte, and 0.63% efficiency observed in this was observed in Table 11 (Singh et al. 2014).

Different electrolytes, liquid, solid-state, and quasi-solid-state electrolytes used in DSSC and concluded quasi-solid-state electrolytes, were more suitable for providing the best performance of the cell. Table 12 shows the performance parameters of different electrolytes (Wu et al. 2008). Photoconversion efficiency of 2.06% was achieved using heteroleptic copper(I) dyes and homoleptic copper(I)/(II) redox shuttles. It shows the potential for all copper-based dye solar cells (Karpacheva et al. 2018).

Counter electrode

The function of the counter electrode in dye solar cells is to regenerate the electrolyte. Counter electrode consists of a conducting layer on a glass (TCO) or a plastic substrate. Catalytic material is used for resulting fast chemical reactions in the DSSC, thus reducing transition time. A layer of platinum is commonly coated on the substrate for the effective regeneration of the redox couple. High catalytic activity towards the iodide/triiodide redox reaction (Pettersson et al. 2007) is the most significant advantage of using platinum as a counter electrode. In electrolytes, platinum is also chemically stable (Kay and Gratzel 1996). Various catalytic materials have been tested in dye solar cells, such as carbon (Saito et al. 2002), platinum (Bay et al. 2006), and graphene (Kay and Gratzel 1996). Increasing an extremely efficient double-featured electrode material is imperative to the identity charged integrated electronics that unite the energy conversion unit of the dye-sensitized solar cell (DSC) and the energy storage unit of the supercapacitor. Nitrogen-doped carbon sphere (NCS) was incorporated to encourage electrode activity. A power energy conversion efficiency of 8.64% was recorded, much higher than the conventional solid carbon sphere (SCS), as shown in Fig. 12 (Wang et al. 2020).

A structured configuration (n-MWCNT-TiO_2/N_3/MWCNT) was used for DSSC. In this configuration, expensive Pt was replaced by economical MWCNT that ensures less costly DSSC. Absorbance spectrum of dye is shown in Fig. 13. Presence of MWCNT in n-MWCNT-TiO_2 nanocomposite encourages the introduction of electron initiated because of dye to conduction band MWCNT-TiO_2 nanocomposite semiconductor (Younas et al. 2019a).

Pristine perfect and defective graphene nanosheets (GNSs) were formed and applied as substrates for catalytic activity against the reduction reaction of T_2 to T^-. It was observed that pristine GNSs could accomplish high reactivity to T_2/T^- through an exothermic adsorption reaction (Tontapha et al. 2019). Admirable electrocatalytic properties and economics are major necessities for the appropriate counter electrodes of dye-sensitized solar cells. DSSCs with the optimal PEDOT-Ni_2P-3 electrode and PEDOT-CO_2P-3 electrode displayed the power conversion efficiency of 7.14% and 6.85%, respectively (Table 13) (Di et al. 2019).

DSSC using tungsten oxide/titanium oxide nanocomposites (nWO_3-TiO_2) with three dissimilar WO_3-TiO_2 (1%WO_3-TiO_2/N719/MWCNT) displayed an efficiency improvement of about

Table 12 Performance parameters of DSSC using various electrolytes (Wu et al. 2008)

Electrolyte	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)
0.5 M NaI, 0.05 M I_2 in 30 vol % NMP, and 70 vol % GBL mixed solvents (liquid A)	0.632	14.78	0.61	5.73
Liquid b: adding 0.4 M pyridine into liquid A (liquid B)	0.705	13.34	0.71	6.70

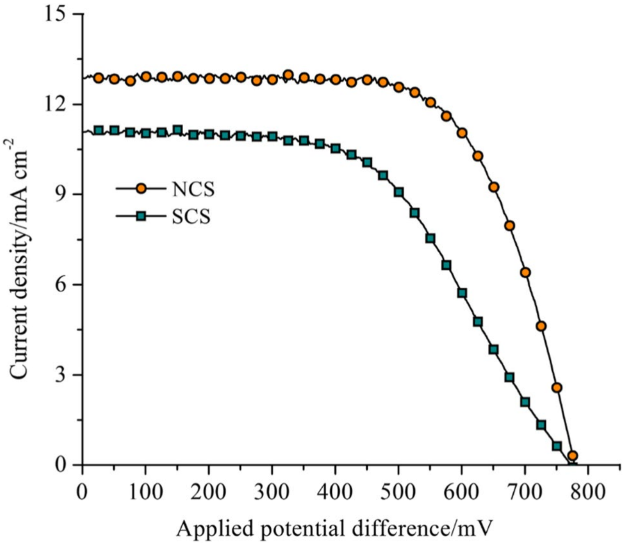

Fig. 12 J-V characteristics of nitrogen-doped carbon sphere-based DSSC (Wang et al. 2020)

40% as corresponding to the conventional TiO_2/dye/Pt solar cell as shown in Fig. 14 (Younas et al. 2019a).

Due to its remarkably low price, polyaniline (PANI) is a striking option to platinum counter electrode for dye-sensitized solar cell. Though, deposition of PANI film up to fluorine-doped tin oxide glass surface is too complicated. DSSC using Gr/PANI and Pt counter electrode displayed photoconversion efficiency of 3.58% and 3.97%, respectively (Fig. 15) (Shahid et al. 2019).

Materials of counter electrode

Counter electrode can be fabricated by using different fabrication methods. One-step hydrothermal method was used to prepare nickel sulfide hollow spheres as a counter electrode using 0.1g nickel sulfide (NiS) and 0.025 g polyethylene glycol powder in 1mL absolute ethanol solution stirred in an agate mortar to make a paste. NiS counter electrode-based DSSC showed power conversion efficiency of 6.90% (Chen et al. 2009). Novel platinum-free counter electrode named poly-3-methylthiophene (P3MT) was fabricated using an electrochemical deposition method. At room temperature, the P3MT electro-deposition was taken out in acetonitrile solution containing 0.1 M 3-methylthiophene (3MT) and 0.1M tetrabutylammonium tetrafluoroborate. An efficiency of 2.76% with a fill factor of 0.50 was reported for P3MT counter electrode-based DSSC (Yang et al. 2014). Carbon was generated in the presence of argon from the graphitization of glucose at high temperatures. Counter electrode was prepared using 1g of carbon and 0.12g of PVP solution in a mortar pestle and the mixture was carried on pot mill for 2 days for homogenous slurry. Conversion efficiency was observed as 3.63% for carbon cathode (Table 14) (Torabi et al. 2014).

Table 13 Performance parameters of PEDOT-Ni_2P-3- and PEDOT-CO_2P-3-based DSSC (Di et al. 2019)

Counter electrode	V_{oc} (V)	J_{sc} ($mAcm^{-2}$)	FF	PCE (%)
PEDOT-CO_2P-3	0.75	13.61	0.68	6.85
PEDOT-Ni_2P-3	0.75	13.91	0.68	7.14

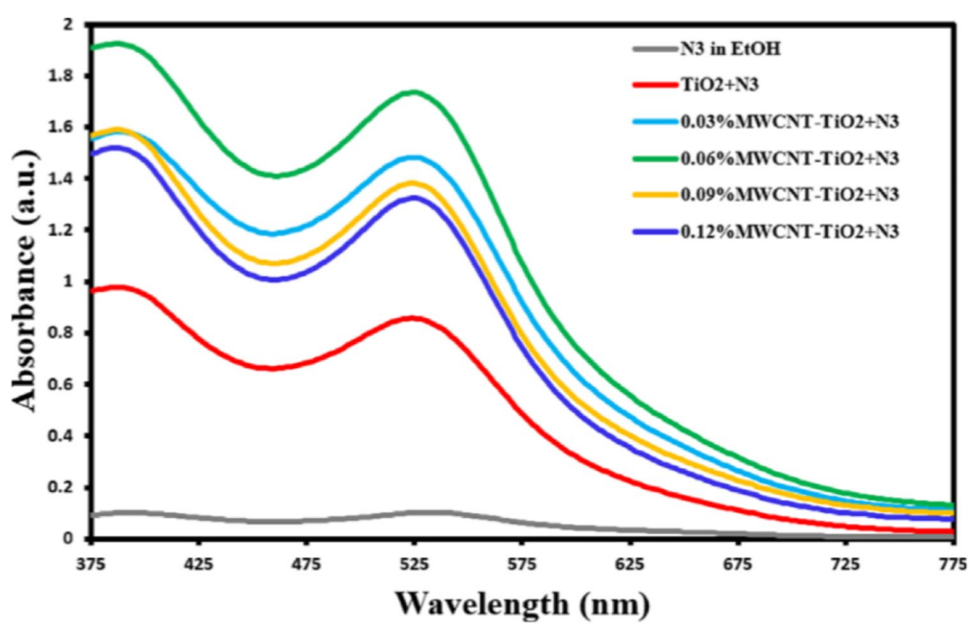

Fig. 13 UV-Vis spectra of N3 dye in n-MWCNT-TiO_2/N3, TiO_2/N3, and EtOH films (Younas et al. 2019b)

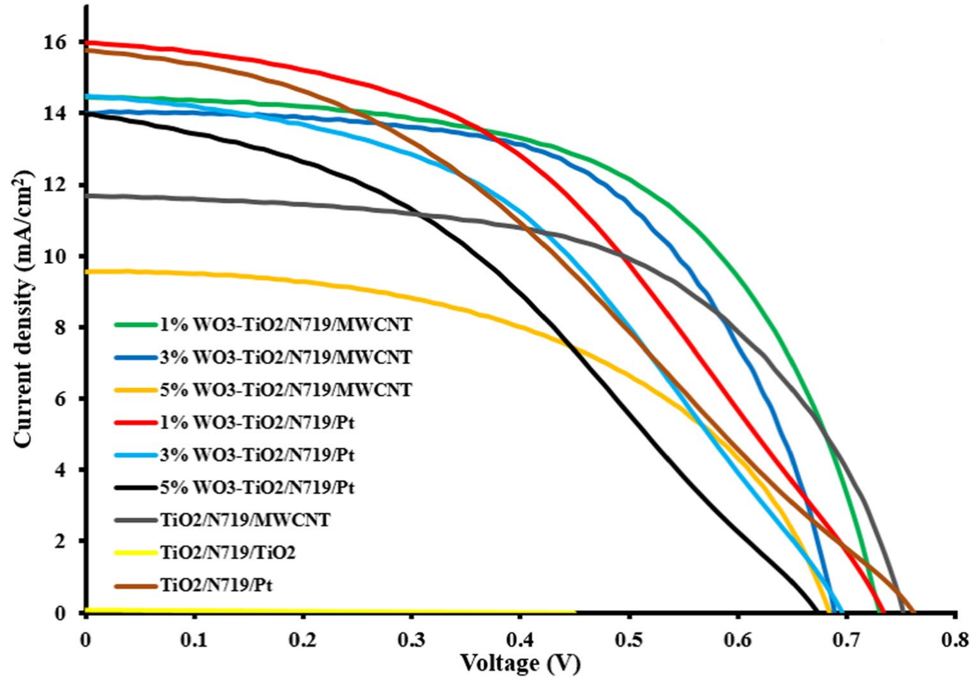

Fig. 14 J-V curves for nWO_3-TiO_2-based DSSC (Younas et al. 2019b)

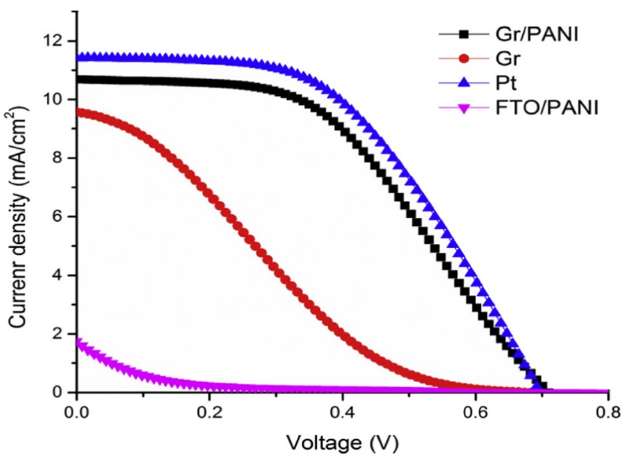

Fig. 15 J-V curves of Gr/PANI, Gr, FTO/PANI, and Pt counter electrode-based DSSCs (Shahid et al. 2019)

H_2-reduced carbon counter electrode showed the best performance of DSSC as compared to the conventional cell. Counter electrode was prepared using H_2 reduction technique. In this process, carbon was heated in a mixture of H_2-Ar gas at 450°C for half an hour. The highest power conversion efficiency was found 7.7%, with a fill factor of 0.69% and an open-circuit voltage of 0.65V, as shown in Table 15 (Kumar and Bharg 2015).

Hummers methodology was used to synthesize graphene oxide (GO) and obtained solar-reduced graphene oxide (SRGO) by reducing GO under focused sunlight. Before spraying substrate, 1mg of GO (or SRGO) was scattered in 1mL of isopropanol and then the solution was ultrasonicated for half an hour. SRGO-DSSC has shown better results (Table 16) (Takada et al. 2015).

4. Natural vs synthetic dye

Recent development in natural photosensitizer

Natural dye solar cells have tremendous advantages over synthetic dyes-based solar cells. Environmental friendly, economic, and facile synthesis chooses fabrication of dye

Table 14 Performance parameters comparison of DSSC using nickel sulfide and platinum counter electrode

Counter electrode	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)	Ref.
Nickel sulfide	0.71	15.26	0.63	6.90	(Chen et al. 2009)
Platinum	0.72	15.11	0.62	6.75	
Platinum	0.7	15.29	0.47	5.06	(Yang et al. 2014)
P3MT	0.63	8.88	0.50	2.76	
Carbon	0.77	8.30	0.50	3.63	(Torabi et al. 2014)
Platinum	0.72	12.07	0.60	5.82	

Table 15 Performance parameters of DSSC under initial and after durability test (Kumar and Bharg 2015)

Counter electrode	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	*η (%)*
After 1000 h; carbon A	0.64	17.0	0.62	6.8
After 1000 h; carbon B	0.65	17.0	0.69	7.7
Initial carbon A	0.71	15.1	0.72	7.4
Initial carbon B	0.71	14.6	0.72	7.5

Table 16 Performance parameters of DSSC using GO and SRGO (Takada et al. 2015)

Counter elec-trode—DSSC	V_{OC} (V)	J_{SC} (mA/cm^2)	FF	*η* (%)
GO-DSSC	0.69	10.83	0.45	3.38
SRGO-DSSC	0.72	12.20	0.44	3.96

solar cells using natural dyes. Performance of dye solar cell can be understood by evaluating open-circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and efficiency of the cell (η). Various photoelectrochemical parameters of dye solar cell with different natural sensitizers are given in Table 17.

Natural resources like *Crocus sativus* (Saffron), *Allium cepa* L (red onion), Malva sylvestris (Mallow), and oregano (Origanum vulgare) were used to prepare natural dye for DSSC. The efficiency of 0.54% was observed by red onion L. Existence of carbonyl and hydroxyl groups enables these dyes to bind to semiconductor layer (Jalali et al. 2020). Betalain and anthocyanin pigments were extracted from prickly pear and mulberry, respectively. UV-Vis spectroscopy (Fig. 16) shows absorbance in the visible range of 530–535 nm for betanin while 450–559 nm for anthocyanin pigment (Obi et al. 2020).

The effect of different organic solvents, temperatures, and pH levels for the extraction of dye from *Areca catechu was studied*. The most favorable state of dye extraction was recorded at 80°C, pH 10, and ethanol as extraction solvent, as shown in Fig. 17 (Al-Alwania et al. 2020).

Natural and synthetic dyes

The most important field of the DSSC compared to the other types of solar cells is applying the dye. It is well determined that the energy gap size of the semiconductors examines the absorption frequency of light in the solar cells. A vital purpose for using the dyes in the DSSC is to explore the absorption spectra on the visible light because the visible light has about 96% energy of the sunlight (Phonkhokkong et al. 2016). Absorption spectra of dye solar cells are determined by grouping the photoelectrode's nanoparticles, e.g., titanium dioxide and sensitizer, where dyes can assist dye solar cell in exploring their absorption spectra. Synthetic dyes synthesized from a complex methodology. On the other hand, natural dyes are extracted from natural resources which results in economic feasibility. Natural and synthetic dyes are evaluated based on economics, environmental aspects, the methodology used, performance, stability, and absorbance, as given in Table 18.

Performance evaluation between natural and synthetic

Natural and synthetic dyes are compared based on performance and fabrication parameters, as shown in Table 19.

Table 17 Recent development in natural photosensitizer

Year	Author	Sensitizer	V_{oc} (V)	I_{sc} (mA/cm^2)	FF	*Ŋ (%)*	Reference
2016	Maurya et al.	C. haematocephala	0.37	0.25	0.70	0.06	(Nagavolu et al. 2016)
2016	Cerda et al.	Maqui	0.06	0.00002	0.47	0.006	(Maurya et al. 2016)
2015	Lim et al.	*Canarium odontophyllu*m	0.419	3.54	0.59	0.68	(Cerda et al. 2016)
2015	Latif et al.	Olive leaves	0.59	0.85	0.33	0.17	(Lim et al. 2015)
2015	Godibo et al.	*Bougainvillea spectabilis*	0.5	1.11	0.58	0.325	(Latif et al. 2015)
2014	Hug et al.	*Bixa orellana* L.	0.57	1.1	0.59	0.37	(Godibo et al. 2015)
2014	Reddy et al.	Mangosteen	0.67	2.69	0.63	1.17	(Hug et al. 2013)
2014	Reddy et al.	Shisonin	0.53	4.80	0.51	1.13	(Mehmood et al. 2014)
2014	Chien et al.	Crude anthocyanin	0.612	2.25	0.70	0.965	(Chien and Hsu 2014)
2013	Chien et al.		0.572	3.027	0.67	1.162	(Chien and Hsu 2013)
2013	Park et al.	Gardenia yellow	0.55	0.43	0.64	0.16	(Park et al. 2012)
2013	Susanti et al.	Tamarillo	0.513	0.321	-	0.037	(Susanti et al. 2014)
2013	Esteban et al.	1A2G		1.47	0.47	0.423	(Esteban and Enriquez 2013)
2013	Kumara et al.	*Canarium odontophyllum* (CMB)	0.385	9.8	0.46	0.59	(Kumara et al. 2013)

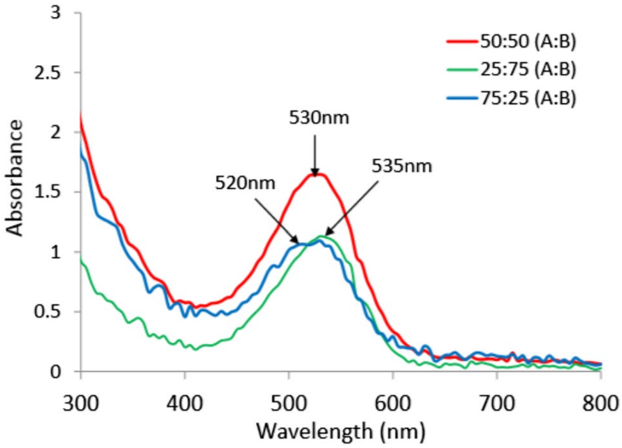

Fig. 16 Absorbance spectra of different mix concentrations of anthocyanin (**a**) and betalain (**b**) (Obi et al. 2020)

Conclusion and recommendations

This article summarizes various factors affecting performance of the DSSC with critical review. The various fabrication parameters (semiconductor, sensitizer, electrolyte, and counter electrode) affect the performance of the DSSC.

The following concluding remarks are drawn based on the above review:

- There are various fabrication methods employed for DSSC. The use of titanium dioxide showed the best results in semiconductor material, while mangosteen used as natural dye gave the highest power conversion efficiency. Also, the quasi-solid-state electrolyte used in DSSC was more suitable for DSSC performance. Conversion efficiency of 7.5% was achieved by carbon as a counter electrode.
- Shear-exfoliated graphene-based photoanode with 23μm thickness gave conversion efficiency of 8.9%, resulting in lesser electron recombination.
- Extracts of *Dianthus barbatus* gave an efficiency of 0.05%, with a fill factor of 0.48 showing progress in dye solar cells using natural dyes.
- Porphyrin dyes co-sensitized with new X organic dyes showed excellent enhancement in conversion efficiency (8.08%) compared to individual dye (4.63%).
- Dye-sensitized solar cells with copper(I) dyes and copper(I)/(II) redox shuttles achieved an efficiency of 2.06%, showing the potential of all copper-based DSSCs.
- An optimized CdSe-TiO_2 photoanode showed a power conversion efficiency (PCE) of 13.29% and short circuit current density of 15.30 mA cm^{-2} for the DSSC.
- TTO electrode-based DSSC gave power conversion efficiency of 3.26% ascribed to the improved electrical and optical properties due to doping with Ta element.

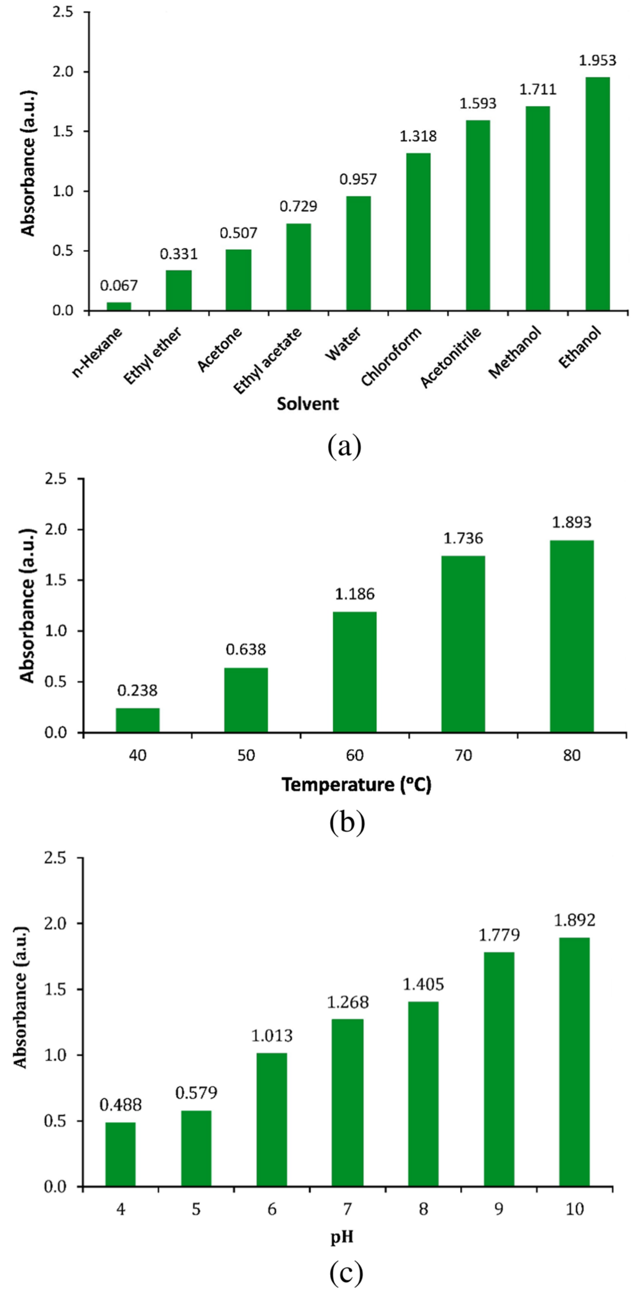

Fig. 17 Effect of **a** solvent, **b** temperature, and **c** pH on the absorbance of the dye (Al-Alwania et al. 2020)

- Absorbance of betalain was shown in the visible range of 530–535 nm for betanin while 450–559 nm for anthocyanin pigment.

Significant issues in the progress of dye solar cells are less efficient and have poor stability. The following are the various issues regarding the efficiency and stability of dye solar cell:

- Viscous nature of electrolyte used in DSSC.

Table 18 Synthetic and natural dyes

Constraint	Dyes	
	Natural dye	Synthetic dye
Ecological effects	Environmentally friendly due to natural availability and entire biodegradation (104)	Toxicity results in harmful effects on the environment. Ruthenium complexes consist of heavy metal that is dangerous to the atmosphere
Economic feasibility	These dyes extracted from natural resources are economically feasible (Oskam et al. 2001)	Nobel metal complex dyes need chemical synthesis which causes uneconomical (Nazeeruddin et al. 1999)
Methodology and performance	Simple extraction procedure makes it less costly. Siahkooti fruit extract gave an efficiency of 0.32% (Adel et al. 2015)	Complicated and costly synthesis. DSSC based on synthetic dyes reveals higher efficiency and favorable photoelectrochemical characteristics. Y123 gave an efficiency of 6.9% (Kavan et al. 2016)
Stability	Degradation of dye in the presence of sunlight radiation results poor stability	Excellent chemical stability, therefore long life of such cells (Mehmood et al. 2017)
Absorption in solar spectrum	*Erythrina variegata* showed maximum absorption at 451–492 (Hao et al. 2005)	Strong charge transfer absorption in the broad range of the visible spectrum. Porphyrin dye revealed absorption (400–650 nm) (Campbell et al. 2007)

Table 19 Performance evaluation of various DSSCs using different fabrication parameters

Dye	Performance parameter				Fabrication parameters			Ref.
	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)	Semiconductor	Electrolyte	Counter electrode	
				Natural dyes				
Turmeric	0.568	0.65	0.44	0.16	TiO_2	Potassium iodide and iodine	Carbon	(Ruhane et al. 2017)
Hemigraphis colorata	0.279	0.18	0.13	0.0065	TiO_2	15.9672g of 1-butyl-3-methylimidazolium iodide, 1.3385g of lithium iodide, 6.7605g of 4-tert-butyl 1 pyridine, 1.269g of iodine and 1.1816g of guanidine thiocyanate in 100 mL acetonitrile	Platinum	(Nandakumar et al. 2017)
Henna	0.40	4.9	-	1.08	TiO_2	0.8 g KI, 10 mL acetonitrile and added by 0.127 g I_2	Graphite	(Sathyajothi et al. 2017)
				Synthetic dye				
(Ru (bpy)$_3$$^{2+}$	0.534	0.76	0.55	0.22	TiO_2	A mixture of 0.6M 1-propyl-3-methylimidazolium iodide (Aldrich), 0.03M iodine (Aldrich), 0.1M guanidine thiocyanate and 0.5M 4-tert-butylpyridine in acetonitrile	Platinum	(Zalas et al. 2017)
(Ru(dcbH$_2$)(bpy)(9AA)Cl)$^{2+}$	0.58	3.54	0.46	0.95	TiO_2	0.05molL^{-1} I$_2$/0.5molL^{-1}LiI/0.5molL^{-1} pyridine in acetonitrile and 3-methyl-2-oxazolidinone (9:1 v/v)	Platinum	(Silva et al., 2016)
N3	0.71	12.59	0.64	5.65				
N719	0.69	10.83	0.45	3.38	TiO_2	0.1 M lithium iodide and 0.05 M iodine in acetonitrile	Graphene oxide	(Teo et al. 2018)
N3	0.687	1.53	0.67	2.366	TiO_2	0.1 M lithium iodide and 0.05 M iodine in acetonitrile	Platinum	(Mali et al. 2012)

- Weak performance of sensitizers in the near to infra-red region (NIR) of solar spectrum.
- Fast degradation of sensitizer resulting in less life of DSSC.
- The following recommendations can improve the efficiency and stability of dye solar cell:
- Structure of sensitizer—enhancement in dye structure to provide high efficiency in NIR region of the solar spectrum.
- Viscosity of electrolyte—electron mobility can be improved by a less viscous electrolyte that enhances the stability of the DSSC.

- Morphology of working substrate—dark current can be decreased by the proper morphology of the working substrate.
- Expensive platinum-based counter electrode can be replaced by numerous materials such as conducting polymers, carbonaceous materials, sulfides, and oxides.
- Flexible working electrode is very useful for curved surfaces. The lesser weight and low cost promote the application of flexible electrodes rather than transparent conducting oxide glasses.

Nomenclature *DSSC*: dye-sensitized solar cell; *FF*: fill factor; *FSP*: flame spray pyrolysis; I_{sc}: short circuit photocurrent (mA); P_{max}: maximum value power (mW); J_{sc}: photocurrent current density (mA/cm^2); *PCE*: power conversion efficiency (%); *PVP*: polyvinylpyrrolidone; V_{oc}: open-circuit voltage of DSSC (V); V_m: maximum value of voltage corresponds to maximum power (mV or V); η: efficiency (%)

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Author contribution Geetam Richhariya: methodology, writing (original draft), and investigation. Bhim Charan Meikap: conceptualization and supervision. Anil Kumar: conceptualization, writing (review and editing), visualization, and supervision.

Availability of data and materials Here, critical analysis has been done with reference to earlier research work. This is a kind of comprehensive review. Hence, there is no data used.

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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