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REVIEW PAPER

A Review on Dye-Sensitized Solar Cells (DSSCs), Materials and Applications

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Abstract: *Fossil fuels served as the main source of energy throughout the 1800s, when the industrial revolution got underway. Countries started aiming for carbon-neutral footprints and lowered emissions as environmental degradation became more apparent. Numerous research projects have been undertaken to discover a photovoltaic device that can replace conventional silicon-based solar cells. Dye-sensitized solar cells (DSSCs) have undergone extensive research during the past three decades. Due to their straightforward preparation process, low cost, ease of production, and low toxicity, DSSCs have seen extensive use. The reader will be able to comprehend the numerous types of TCO layers, physical methods for depositing metal oxide on TCO thin films, materials for fabricating the various DSSC layers, and the various types of dyes included in DSSC, as well as their components and structures. The reader's ability to construct the DSSC, gain a general understanding of how it operates, and increase the effectiveness of these devices' potential growth and development paths are all aided by this review. For these technologies to be debated and shown to be appropriate for a breakthrough in consumer electronics on the market, manufacturing, stability, and efficiency improvements must also be addressed in the future. An overview of current DSSC prototype development and products from major firms is presented.*

Keywords: *Organic Solar Cells, Dye-Sensitized Solar Cells, Perovskite Solar Cells, Efficiency, Commercialization.*

1. INTRODUCTION

The Sun continuously, unrestrictedly, and indefinitely provides solar energy to the entire planet. Solar radiation offers the advantages of being ecologically friendly, renewable, and sustainable. Solar energy can also be used to generate other sorts of power. To mention a few applications, it is used to create electric power for microscopic things such as computers and watches, as well as thermal radiation for homes and businesses [1–3].

Solar energy, on the other hand, is a cyclical resource because it is not produced during the cloudy or rainy seasons. As a result, numerous devices are built with power storage capabilities or an alternative power supply, such as the electric grid. O'Regan and Grätzel's solar cells from 1991 are a noteworthy leap in solar cell revolutionary technologies today [4]. They pioneered a novel type of photocatalytic solar cell, the dye-sensitised solar cell (DSSC), which is a type of photovoltaic cell in an excited state. The construction of a dye-sensitized solar cell is low-cost and environmentally friendly, and the coating framework is light enough for automated manufacturing [5].

From Figure 1, it is observed that the research based on DSSC's is worldwide increasing from the year 1990-2023. Nearly 63,137 Academic Journals, 3535 Conference Materials, 4089 Magazines published from year 1990-2023.

Dyes utilised in investigational cells in 1995 were mainly responsive to the elevated intensity section of the optical spectral region, such as visible light and ultraviolet light. Latest variants with a greater frequency sensitivity that is competitive especially at reddish and infrared regions were launched in 1999 [6]. The dye utilised in these cells is dark dye, which has a strong brown appearance and a total efficacy of nearly 90%- regrettably, it preferred to deteriorate during extreme luminous exposures. Various pigments with specialised features have been created, such as copper-diselenium (Cu (In, GA) Se_2), that improves transition performances and 1-ethyl-3-methylimidazolium tetrocyanoborate ($EMIB(CN)_4$), which is thermally resistant. Scientists want to exploit quantum dots to transform strong light into various electrons, utilize solid-state electrolytes for better thermal sensitivity, and change the electro deposition of TiO_2 to complement the electrolyte applied [7]. Dye-sensitized solar cells relying on TiO_2 nanoparticles are an intriguing technique, with performances above 10%.

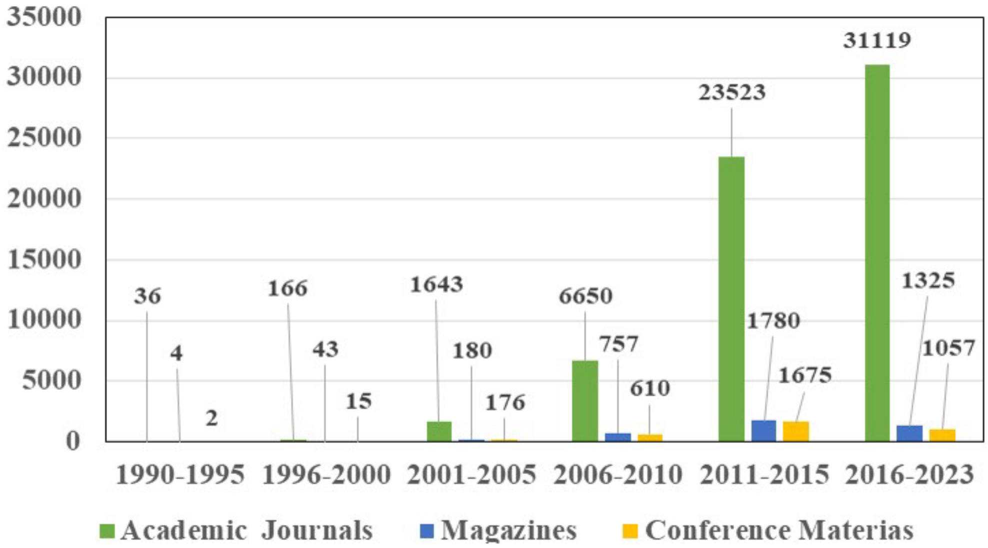

Fig. 1. List of DSSC Papers published in various years from Scopus Indexed Database

The pigment compounds are deposited onto laminated TiO_2 nanoscale surfaces. According to Figure 2, which shows the quantity of Scopus-indexed documents by nation, it is noteworthy that Indian academics have contributed significantly to DSSC research during the past 23 years. The dye collects the occurrence light and injects an electron into TiO_2, where it is transferred across the TiO_2 nanostructures to an electrode. The result and features of a zinc oxide nanostructured dye-sensitized solar cell were revealed by scientists from the University of California in Santa Barbara in 2004 [9]. When contrasted to crystalline nanoscale films, nanomaterials allow for a decisive electron transmission route across the conductive material medium and the region of light production, potentially improving transfer of electrons. The systems have a light capturing rate of less than 10%, demonstrating that increasing the nanoscale substrate region increases current performance and concentrations by a sequence of proportion [10]. The majority of current DSSC studies focuses on increasing spectroscopic absorption coefficient by modifying the dye, getting better hole transmission by replacing the fluid electrolyte with executing polymers or ionic solid particles, and trying to improve transfer of electrons by utilising innovative core-shell formations or large band gap semiconducting components.

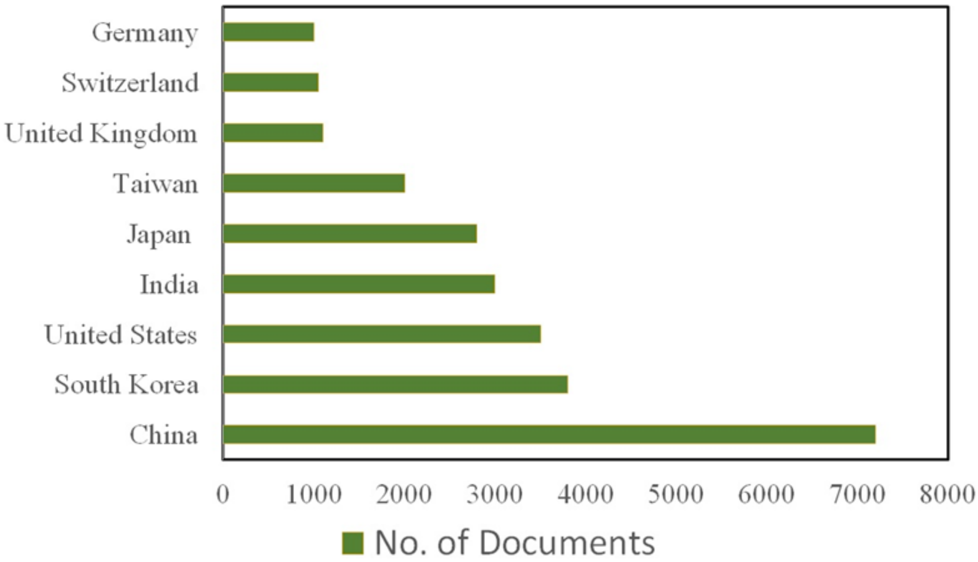

Fig. 2. List of DSSC Papers published in various countries from Scopus Indexed Database (Reprinted with permission from -8)

1.1. Recent Advances in DSSC

To build more robust, potent, and affordable photovoltaic systems, scientists from the University of Pennsylvania and Drexel Institute are using computational models and nanomaterials [11]. To investigate if they can quicken the electron exchange process inside the solar screen and more efficiently convert photons to energy, the team is experimenting with dye-sensitized photovoltaic solar cells. Currently, 11–12% of the sunlight that strikes dye-sensitized photovoltaic arrays is converted into electricity. In order to compete with silicon-based solar arrays, engineers are empting to increase the quality of the panels [12]. The total charge carrier capability of the solar cell would be greatly enhanced by carbon nanostructures, according to researchers. The next step in the process is to replace the electrolyte solution that separates the electrodes in the solar panel with a more suitable polymer compound. The effectiveness of the solar cell should also be enhanced, according to the researchers. Researchers from North-western University have created a revolutionary way to get rid of the DSSC's harmful and leak-prone fluid electrolyte [13]. A solid iodine-based semiconductor was substituted for the liquid electrolyte of the dye cells by two graduate students, nanomaterial researcher Robert Chang, and chemist Mercouri Kanatzidis [14]. This configuration significantly enhances functioning because the caesium-tin-iodine semiconductor that replaces the electrolytes also aids in the device's ability to absorb energy. A massive transition to renewable power sources will be necessary to reduce the negative effects on the environment. Solar energy is a very quick sustainable power source that has the potential to provide most of the world's future power needs. Solar cells made of silicon (Si) presently dominate the photovoltaic (PV) industry. This technology has become significantly less expensive over the past ten years, which has led to rapid commercial growth.

Although crystalline silicon (c-Si) solar panels have a promising future, issues with their intricate manufacturing processes, protracted resource recovery times, and use of hazardous chemicals may cause other Photovoltaic systems to develop in the coming years [15]. Since third-generation PV innovations can be produced using scalable manufacturing processes like screen coating, inkjet printing, or slot die spraying, they have a lot of potential for commercial process manufacture. These innovations include dye-sensitized solar cells or perovskite photovoltaic cells.

The standard n-type dye-sensitized solar cells, also referred to as "DSSCs," as well as a number of current third-generation PV advances, have both been thoroughly studied in the years since Grätzel and O'Reagan published their ground-breaking paper in 1991 [16]. The advantages of DSSCs include low manufacturing costs, concise design and production processes, the use of inexpensive and easily accessible materials (such as TiO2 and carbon-based components), the ability to use customizable resource crystallisation methodologies in their dispersion over conventional fluorine-doped tin oxide (FTO)-Glass precursors, and the ability to convert this conventional rigid configuration over versatile configurations. DSSCs also operate better in low- and indoor light environments than other solar systems. Additional qualities enable applications with enormous potential, like photovoltaic screens and fabric products, as well as the capacity to construct devices employing a variety of materials, as well as structure, colour, and notably transparency adaptability.

The lab-sized DSSC's energy transformation ratio has progressively increased from 7% in 1991 to the most recent benchmark of 14.3%, reached in 2015 [17]. The use of transformative metallic oxidation couples in conjunction with suitable dyes and less viscous solutions like acetonitrile have all helped to significantly boost the conversion of solar energy into electricity. By co-sensitizing photo electrochemical (PEs) with an alkoxysilyl-anchor dye (ADEKA-1) and a carboxy-anchor natural dye (LEG4) in conjunction with a cobalt-based electrolyte, Kakiage et al. [18] developed equipment and achieved a yield of =14.3% at 100 mW cm^{-2} transmittance.

Recent research by Cao et al. [19] suggested a modified DSSC design with a copper-based electrolyte that produced an impressive energy transition yield (=32%) under conditions of moderate light strength (1000 lux). Recent considerable improvements in the efficiency of solar-to-electrical conversion have rekindled plans to produce DSSC on a variety of scales, including large components for commercial energy production and also small devices for compact gadgets. On the other hand, the highly productive DSSCs often use a liquid electrolyte, which is now a limiting limitation for significant production. Due to worries about long-term implementation sustainability and scaling complexity, a significant amount of industrial accomplishment has yet to be realised regarding the existence of a limited number of industrial purposes [20]. One of the main reasons for the DSSCs' limited term dependability is the electrolyte solution, which serves as a moderator between the photoelectrodes (PE) and the counter electrode (CE) and has problems with leakage and ultraviolet radiation. This paper outlines important developments in the development of DSSC electrolytes for different components as well as the current state of knowledge about system operation and temporary resilience when these electrolytes are used. Also reviewed are a few freshly produced electrolyte compounds. Additionally, electrolytes' significance in possible DSSC research and development is emphasised [21].

2. DYE-SENSITIZED SOLAR CELL

These solar cells, often referred to as dye-sensitized solar cells, consist of a thin layer of nanostructures embedded in a pigment that absorbs photoelectron radiation and contains electrodes, conductor glass, and electrolyte sensors (DSSCs).

A photodiode that relies on the electrical and chemical mechanism of dye absorption on the TiO_2 photo electrode surface is called a Dye-Sensitized Solar Cell (DSSC). This dye will absorb the quantity of photons that illumination emits, and through a series of electron exchanges on its surface, will convert that quantity of photons into electrical energy. The varieties of solar cells are depicted in Figure 3.

2.1. The Concept of Sensitisation

A DSSC is made up of TiO_2 nanoparticles that are supported by an electrolyte and connected to the cell's anode and cathode by light-sensitive dye. Since the anode is transparent, like glass, sunlight may enter the solar cell's interior and power its internal processes [22]. As a route for the electrons (power generation) moving within the cell, a grid of TiO_2 nanostructures spans the anode to the cathode. On the TiO_2 nanostructures, which convert electrons (light) into power, are layers of light-absorbing pigments [23].

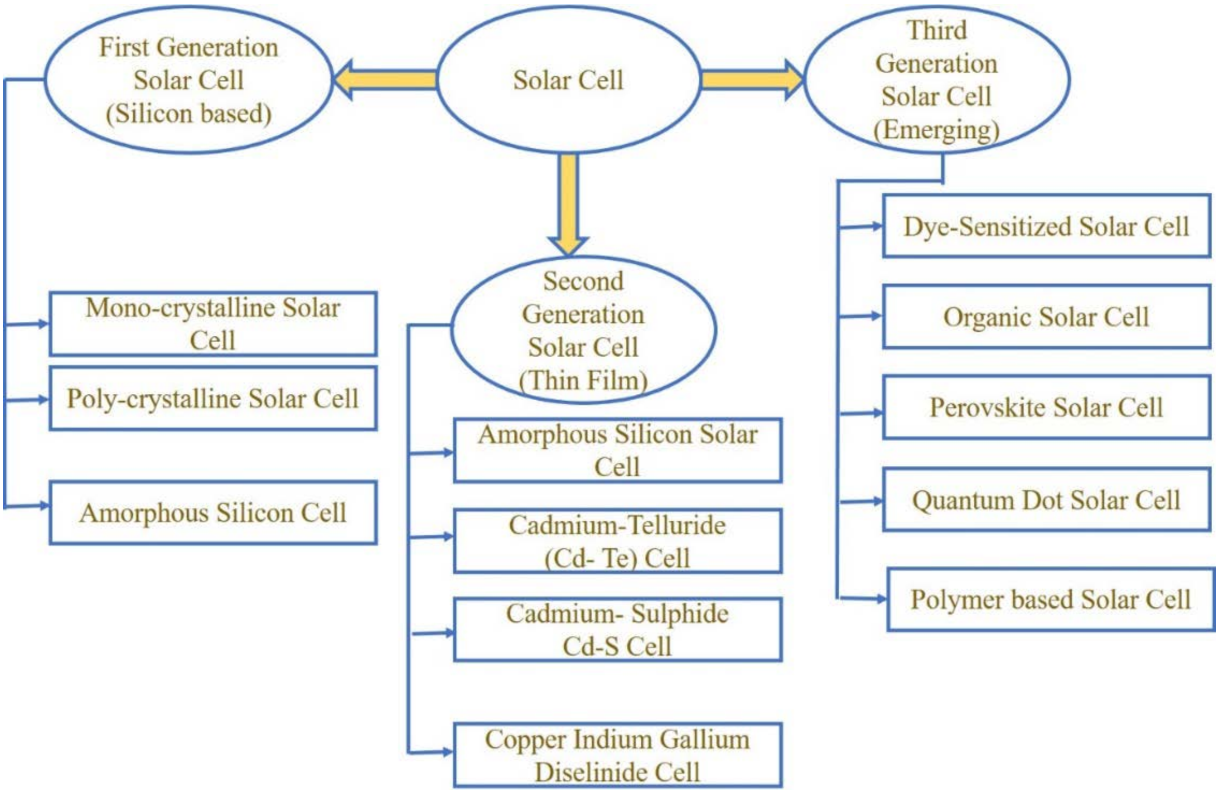

Fig. 3. Structure of different types of Solar Cell

In a DSSC, the electrons have to move from one side of the column to the other (from the cathode to the anode). TiO_2 nanoparticles are frequently used as conductors because of their extraordinary ability to "bond" with one another and form a vast matrix for electrons to travel through. Electrons are released when light strikes the dye compounds encasing the TiO_2 nanomaterial (photons). Different colour pigments absorb photons with different wavelengths, which causes radiation to be emitted in different amounts. An electron is released by the dye receptor after it is triggered [24]. The liberated electron travels through the TiO_2 nanoparticles until it hits the anode as a result of defects in the TiO_2 nanoparticles.

The conventional DSSC system is seen in Figure 4. When a dye particle loses one electron, it starts to disintegrate until it can get another electron to replace the one that has been used up. In this state, the dye molecule is no longer capable of producing electrons. To do this, the dye-coated TiO_2 particles are infused with I solution (the I-ion can replenish the electrons that the dye molecules have lost). Once it touches the cathode, the I- ion is oxidised to I3-, which floats throughout. Every I3- ion received two electrons from the cathode, resulting in three I ions. In the beginning (about 1995), experimental cells used dyes that were only active to the higher frequency end of the sun's spectral region (UV and blue). The more dependable DSSCs up to this point have all been constructed using ruthenium dyes discovered by Grätzel, including N3, N719, and "dark dyes." Suyoung Hwang et al. [25] reported that the electrolytic bandgaps of N3 and N719 were 2.4 eV and 2.6 eV, respectively. A more recent addition was the "black dye," precisely "triscarboxy-ruthenium terpyridine" [Ru (4, 4’, 4"- (COOH) 3-terpy) (NCS) 3]. It operated well in the low-frequency band of reddish and infrared light and had a much larger frequency reaction. The dye's broad spectrum reactivity gives it a deep dark black colour. The likelihood of converting a photon into an electron is high thanks to the dyes, with substitution rates ranging from about 80% in the most prominent dyes to about 100% in others. The "lost" 10% was primarily made up for by propagation loss from the main electrode, bringing performance up to about 90%.

2.2. Constituents and DSSCs Operating Principles

The schematic view of a typical DSSC is shown in Figure 5. The four essential components of a DSSC are an electrolyte, a base electrode, a photocatalyst (dye), and a photographic anode. Understanding the DSSC's component properties is necessary for understanding and enhancing its performance [26]. The basic traits of these elements are covered in the following sections.

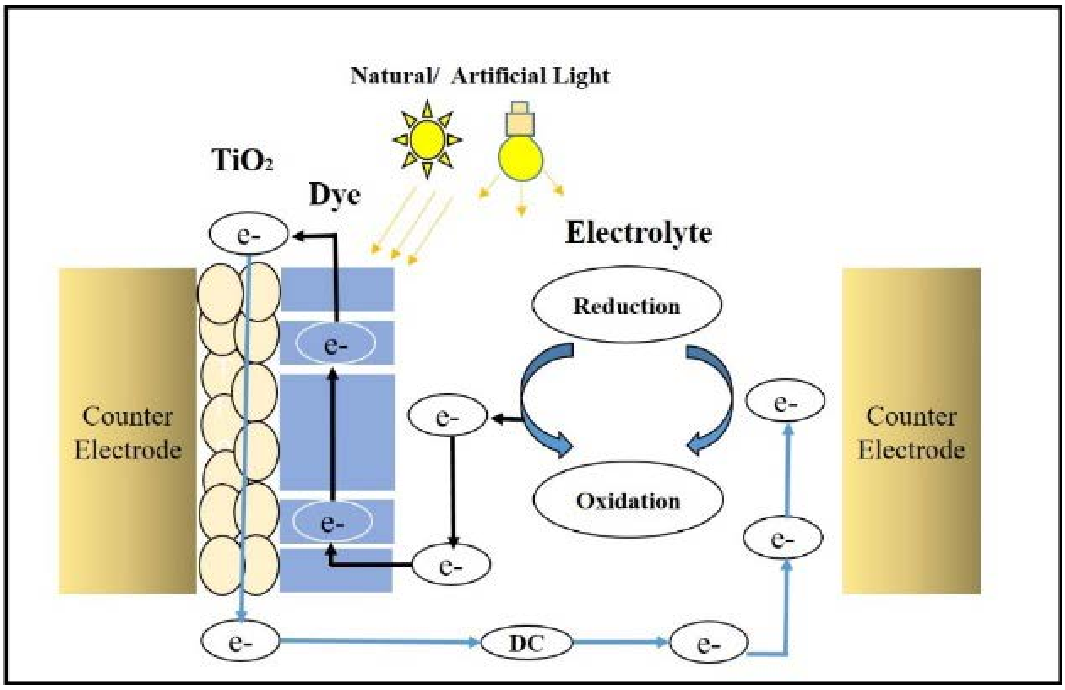

Fig. 4. DSSC system (Reprinted with permission from - 25)

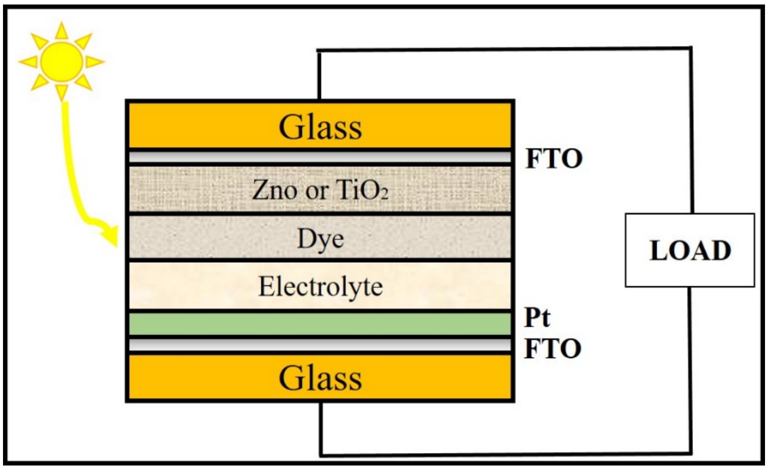

Fig. 5. Schematic view of a dye-sensitized solar cell

2.3. Operating Principles

The publications provide thorough documentation of the DSSCs' operational methods. The operational concepts of DSSC are thoroughly addressed here with reference to Figure 6, which was first published earlier [27-30], for the sake of clarity. The dyes placed to the SMO surface in DSSCs initially capture illumination. The dye particles' photo-induced electrons next move towards the CB of the SMO before being carried to the semiconducting interface of the operational electrode.

When the active electrode is connected to the electrochemical cell by an external source, photogenerated electrons enter the cell. Table 1 describes a different layers of fabrication of DSSC and its materials accordingly. The redox electrolyte maintains its aggressiveness for the rejuvenation of the oxidised dye by absorbing electrons from the reference electrode. For the DSSC to function properly, the electrolyte's reconstruction of the dye must be faster than the photoinduced electrons' replication [33]. Figure 6 illustrates the envisioned processes, which include dye photoexcitation (path a), photoexcited electron absorption and transit (paths b–d), redox pair recycling (path f) and dye reproduction (path g). The efficient but unwanted reproduction of photogenerated electrons with oxidised dyes or tri-iodides (path h).

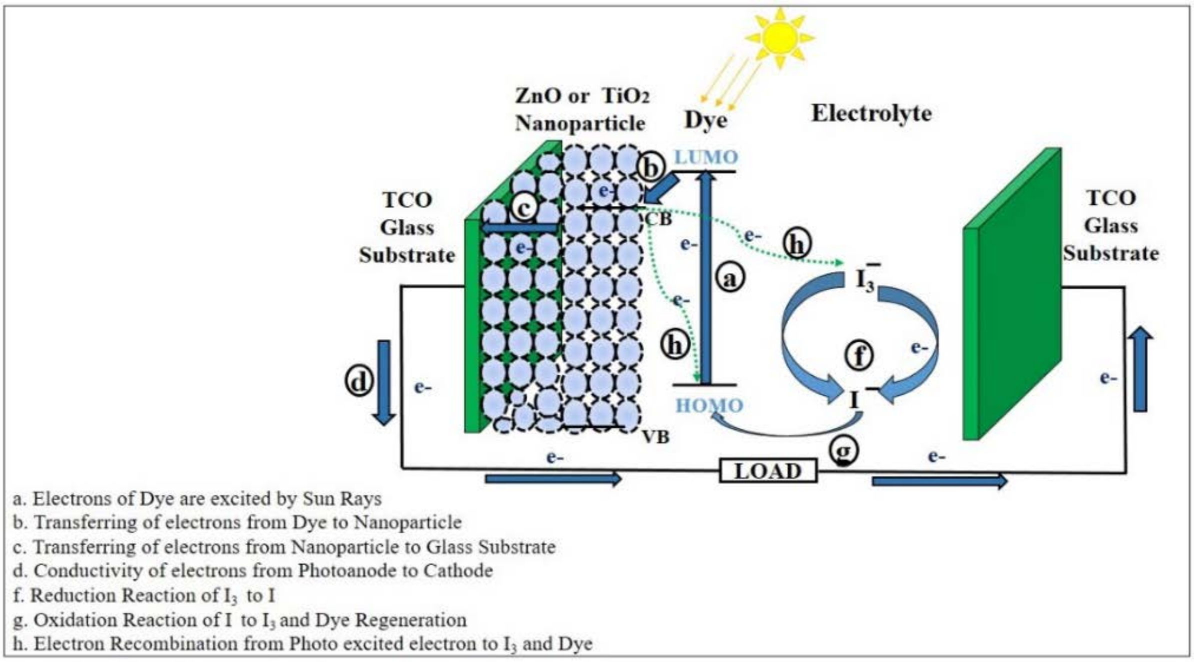

Fig. 6. A graphical view of the dye-sensitized solar cell's operating principle (Reprinted with permission from -31)

Table 1. Different layers of fabrication of DSSC and its materials [32]

Photoanode	**Electrolyte**			**Solvents**	**Dye**	**Counter Electrode**
	Liquid Electrolyte	**Solid Electrolyte**	**Quasi-Solid State**			
TiO_2	I^-/I_3	CuI	Composite of liquid and polymer	Acetone	Organo-metallic Dyes	Platinum
ZnO	Br^-/Br_3	CuBr		Ethanol	Metal- Free Organic Dyes	Carbon Nanotube
SnO_2	$SCN^-/(SCN)_2^-$	CuSCN		Dimethyl formamide	Natural Dyes	Conductive Polymer
Niobium Oxide	$SeCN^-/(SeCN)^3$	2-2'-7-7' terakis		Dimethyl Sulfoxide	Mordant Dyes	Graphite
	$(FeCN)_6{}^{3/4}$	N,N-di-p-methoxy phenylamine			Quantum-Dot dyes	
	Co(II/III complex)	9-9'-spirobifluorine			Perovskite based Dyes	

2.4. Routes to High Efficiency DSSCs

The levelized charge of energy (LCOE), which is guided by the essential pyramid notion and covers light-to-electric energy transition productivity, sustainability, and expense, is the primary emphasis of DSSC advancement priorities, like those of other Photovoltaic devices. System performance has always been a focus because any issue might be said to be more important than another [34]. Therefore, it's critical to show how effective electrical activation is using DSSCs with more advanced silicon technology. The method for accomplishing this involves increasing light absorption while reducing electron losses. The major innovations are examined in this section [35].

3. LIGHT SCATTERING

The development of photo catalysts with higher spectral sensitivity at the lower portion of the solar radiation has not been as successful, despite dye compounds with strong reddish absorbance having less excited-state overabundance free energy, which lowers the quantum efficiency for electron infusion. One way to increase reddish absorption is to widen the surface area above 10 metres. However, this will result in a greater likelihood of replication, a longer electron traveling duration, and a marginally smaller photo detector. Another way to boost yield is to increase light scattering in TiO_2 layers, which will expand the cross-sectional area of the light path. A novel definition of "haze" was created by Chiba et al. [36] to assess the optical pathway distance in TiO_2 electrodes. To control haze, which is defined as the ratio of dispersed absorbance to overall light transmission, micro particles (400 nm size) were added to the TiO_2 electrodes. It was found that raising the TiO_2 haze significantly boosted the incidence photon to current efficacy (IPCE) of DSSCs in the along infrared wavelength range, with a changeover productivity of 11.1%. A different method to increase light scattering besides adding larger particles is to layer a scattering surface on top of the functional surface. Hore et al [37] investigation examined the impact of scattering surfaces on dye-sensitized solar cells' performance. Cell performance increased from 3.8 to 6.8% with the addition of a light scattering surface made up of TiO_2-rutile and ZrO_2 in a 1:3 ratio.

Three-dimensional (3D) TiO_2 nanoparticles like hollow spheres, nanofiber networks, nanotube arrangements (TNAs), and subgroups have recently been created in order to improve optical scattering. These nanostructures may be able to assist solar cells with a variety of functions, such as creating a large structural surface area for appropriate dye injection or creating an internally attached core-shell framework in DSSCs to slow the recombination process [38]. ZnO or SnO_2 dye-sensitized solar cells can be manufactured using a similar technique. The first multi-layered SnO_2 hollow nanoparticles with a TiO_2-coated surface were created by Sigdel et al. [39] and had a photon absorption rate of 5.65%, a 34% improvement over the TiO_2-nano-SnO_2 surface

4. SURFACE ENGINEERING

4.1. Compact Layer

Intriguing intercellular charge exchange mechanisms combine to power dye-sensitized solar cells (DSSCs) throughout their operation. In contrast to conventional solar cells, DSSCs have a much larger interior substrate region of the nanostructured TiO_2 anode with electrolyte penetration, making interfacial redox reactions and dynamics more important. Two functions, the FTO precursor and the photographic anode/electrolyte TiO_2 have an impact on the rate of electron replication [40]. The latter is the main mechanism for tri-iodide in electrolyte electron absorption at low light concentrations, when the energy level is optimal or when there is an open circuit. One common technique for reducing electron coupling at the FTO interfacial region is to apply a thin TiO_2 portable layer to reduce the accessible FTO region that is not coated by the Nano porous TiO_2 nanoparticles. On fluorine-doped tin oxide (FTO) glassware, a fine TiO_2 packed layer (about 100 nm) can be covered by dip coating. The monolayer significantly enhanced TiO_2 adherence to the FTO surface, provided a greater TiO_2/FTO interaction zone and minimised electron regeneration by limiting physical interaction between the redox electrolyte and the semiconducting FTO substrate. Pulsed laser deposition is another method for creating a practical monolayer of Nb-doped TiO_2 (NTO) on a regular FTO surface.

The NTO surface in the anatase state, with an electrical resistivity of 2.1×10^{-2} Ω-cm and a width of 80 nm, decreased the interlayer impedance by generating an ohmic contact across the FTO and TiO_2 Nanoparticles layer. A considerable difference in the commencement of the dark current and a sluggish Voc decreasing were indicators that reverse electron transport had been prevented.

Dye-sensitized solar cells made of ZnO can also benefit from the idea of using a condensed layer to enhance the conductive contact between the semiconductor and the FTO surface. As a photographic electrode, Guan et al. [41] created a compressed layer of ZnO at the interface of a fluorine-doped tin oxide (FTO) medium and a mesoporous ZnO surface. Table 2 and Table 3 lists the different precursors and the approaches that can be used to apply them to TCO. When compared to bare FTO substrates, the intercellular impedance of the ZnO (0.1 M)/FTO cell specimen was found to be substantially lower (6.77 Ω). Huang et al. [42] found synergistic effects between ZnO portable surface and $TiCl_4$ post-treatment on TiO_2 oriented DSSCs.

In addition to preventing back electron transport from the FTO to the electrochemical cell and decreasing the FTO/TiO_2 intercellular response, the $TiCl_4$ post-treatment transformed the ZnO portable surface into a bi-functional thin sheet and dispersed significant Zn component into the TiO_2 protective layer, facilitating electron transmission at the TiO_2 interface. It has been discovered that the interfacial replication kinetics at the TiO_2 photo anode/electrolyte functionality are slowed by a homogeneous deposition of insulating coatings (such as SiO_2, Al_2O_3 and ZrO_2) on TiO_2 particles. These metal oxides' conductance band boundaries must be more negative than those of TiO_2 and the dye excitement stage oxidative possibilities (ESOP). As a result, all electron insertion and charge electron exchange activities may be mechanically barred by the metal oxide across layers. The performance of DSSCs is significantly improved from 8.78% to 9.65% when vanadium pentoxide (V_2O_5) is encapsulated, as previously shown by Elbohy et al. [43]. Furthermore, the results of the cyclic voltammetry analysis showed that TiO_2/V_2O_5 has a larger impedance than undoped TiO_2. It was assumed that the increase in impedance represented a large Fermi-level transition

Table 2. Physical Methods to deposit the material on FTO according to their medium [44-45]

Liquid Phase Precursors	Gas Phase Precursors
Dip Coating	Sputtering (a) DC Magnetron Sputtering (b)Radio Frequency (RF) Magnetron Sputtering
Spin Coating	Electron Beam evaporation
Doctor blade Method	Pulsed Laser Deposition
Screen Printing	Cathodic Arc Deposition
Electro Spray Deposition	Thermal Spraying
Sol-gel Method	Nanoparticle Deposition

Table 3. Various TCO thin films and its Precursors used for synthesis [46-48]

Transparent Conducting oxides	**Preparation of Thin films**	**Transmittance**	**Band Gap**	**Sheet resistance**
Antimony doped tin oxide (ATO)	$SnCl_2.2H_2O$ and $SbCl_3$ in ethanol	80%	4.08eV	56
Fluorine doped tin oxide (FTO)	$SnCl_2.2H_2O$ and NH_4F in methanol	76%	4.09eV	32
Indium-tin oxide (ITO) thin films	$InCl_3.4H_2O$ and $SnCl_2.2H_2O$ dissolved in propanol and methanol respectively.	70%	4.09eV	23
Aluminum doped ZnO films(AZO)	Indium Gallium Zinc Oxide as buffer layer between glass and AZO TCO. AZO-Al_2O_3 and ZnO	63%	More than 3.05eV	9.4×10^{-4} Ω·cm
AZO/Ag/AZO (AAA) TCO layers	AZO (top layer), Ag, AZO (bottom layer)	70%	4eV	2.1×10^{-4} Ω·cm

In contrast to SnO_2 dependent DSSCs, where the dielectric covering surface is essential, mesoporous TiO_2 directed devices may even experience a slight yield improvement. SnO_2 has an advantage over TiO_2 in terms of electronic conductivity because of the mild conduction band. The photo generated electrons in the redox electrolyte are nevertheless susceptible to interaction with holes in the redox electrolyte despite the smaller conduction band. One option to get over this constraint [49] is to incorporate the dielectric covering surface to make a core-shell configuration with SnO_2 as the core and a metal oxide semiconductor with a better CB like TiO_2, MgO, or $CaCO_3$ as the shell.

4.2. DSSC Research in India

Increased commercialization and a rapid rise in global power consumption have created a critical demand for alternative resources in India's energy sector. More than half of India's energy needs are still met by coal, which continues to be the country's primary energy source [50]. Alternative energy sources are viewed as clean since they reduce global CO_2 emissions.

The most widely used clean energy source on the planet is still solar radiation. The increased interest in renewable energy sources has motivated many Indian academics to begin or focus their research on the production of clean energy. Over the past ten years, there have been numerous discussions and disagreements on the inventive sustainability of solar energy, with the Indian government eventually supporting the growth of photovoltaic (PV) technology. First-generation, second-generation, and third-generation solar cells can be used in photovoltaic systems. The first and second generations of cells, respectively, are crystalline Si-based and thin film-based. Examples of third-generation solar cells include perovskite solar cells, dye-sensitized solar cells (DSSCs).

5. DESCRIPTION OF INDIAN RESEARCH INTO SENSITIZERS USED IN DSSCS

5.1. Organometallic Dyes

Transition elements such as Ru, Os, and Ir, as well as organic material, make up organometallic colours. For the accompanying considerations, Ru (II) metal is generally a good choice for DSSC.

a) Its octahedral geometrical arrangement facilitates the incorporation of compounds in a seamless manner.
b) Ru (II) combinations appealing photoluminescence, photochemical, and electrochemical features can be modified to create the desired attribute.
c) It has oxidation levels ranging from I to IV that are sustainable and inexpensive.
d) It is resilient in a wide range of solutions.

The excitation source selected as a dye has a general pattern of ML2(X)2. M stands for metal, L for the ligand 2, 2'-bipyridyl-4, 4'-dicarboxylic acid, and X stands for halide, cyanide, thiocyanate, acetylacetonate, thiocarbamate, or water. Praveen Naik et al. [51] created a dye by combining traditional aniline-based dyes A1-4 with a N3 dye in order to co-sensitize a DSSC. An N, N-dimethylaniline ring serves as the co-sensitizers' donor scaffold, and it is connected to compounds with electron-withdrawing properties including barbituric acid (A1), N, N-dimethyl barbituric acid (A2), thiobarbituric acid (A3), and N, N-diethyl thiobarbituric acid (A4). A solar panel with a PCE of 7.02% was produced by them. Figure 7 illustrates schematic diagram of various dyes used in DSSC. Using a 4-nitro-phenylenediamine (NPD-PC) Schiff molecule as a ligand, Subramaniam, K., et al. [52] produced a new heteroleptic dual-anchored Ru (II) complex (RNPDA). Schiff-based metal combinations have been shown to be potential sensitizers because of their photocatalytic properties. The dye consists of a nitro compound-binding subunit and an electron-withdrawing pyridine component. As a photocatalyst for DSSCs, it has an overall PCE of 3.42%.

5.2. Metal-free Dyes

In DSSCs, metal-free natural dyes are also used, and in some cases, the PCEs produced by the cells have been found to be comparable to those produced by Ru-based photosensitizer.

Natural dyes devoid of metals have incredibly high proportionate extinction factors, easily programmable absorption frequencies, and a slightly lower cost than Ru-, Os-, and Ir-based groups. They are also not dependent on the dangerous and expensive Ru metal. These chemicals can be used as both sensitizers and co-sensitizers to produce a wide range of absorption [53-54]. A-conjugation abutment, an electron acceptor (A), and an electron donor (D) are present in the majority of metal-free natural pigments, with a push-pull D—A pattern. The -electron barrier accelerates photo-induced interatomic electron transference between donor and acceptor, which has a strong polarisation impact and can lead to a considerable PCE. The HOMO proportion is linked to the donor and -conjugate, but the LUMO scale depends on the electron acceptor and may therefore be precisely controlled to enhance performance as a whole.

Electron-rich substances utilised as donor organisations include phenylamine, aminocoumarin, indoline, (di-fluorenyl) TPA, TPAs, and carbazoles. As conjugated compounds, thiophenes, polyenes, and benzothiadiazole are employed. Rhodamines, pyridines, and cyanoacrylic acid are among acceptors. Tetrathiafulvalene (TTF), a chemical that contains sulphur, serves as a potent electron donor and has a variety of applications. Donors based on TTF are easy to control and effective at sensitising solar cells. In addition to TTF, dithiafulvalene (DTF) is recognised as a possible electron donor due to its unique charge-transporting properties. DTFs are extremely effective electron donors with a proven track record.

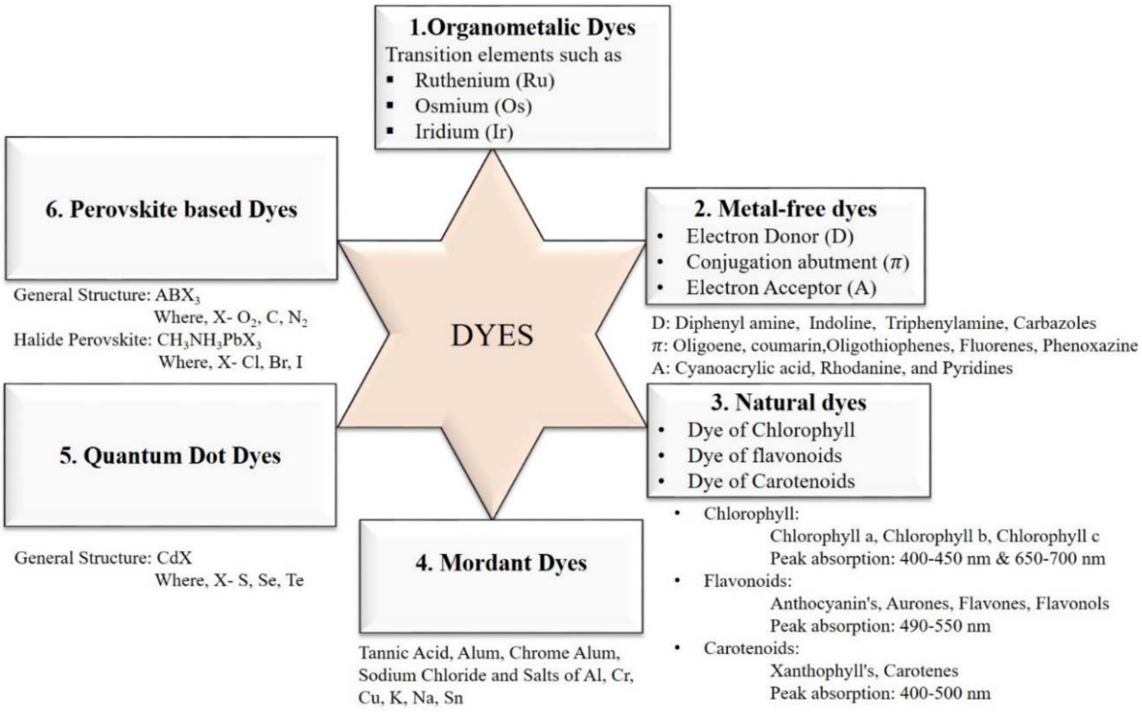

Fig. 7. Schematic Diagram of Various Dyes used in DSSC

The findings of Duvva N et al overview of TTF- and DTF-based donor dyes are promising [54]. More research has been done with D-π-A patterned photosensitizer built on N-annulated perylene (NP). TPA compounds are used as electron donors, functionalized substituents, and acceptors in these pigments, which are coupled to NP, thiophene, and 2-cyanoacetic acid, correspondingly. It has been discovered that (E)-2-cyano-3-(10-(4-(diphenyl amino) phenyl)-1-(4-(diphenyl amino) phenyl)-1-(4-(diphenyl amino) phenyl)-1-(4-(dipheny (2-ethylhexyl) the finest between them is -1H-phenanthro carbazol-3-yl) acrylic acid (NPS-4) [55]. Besides from the D-π-A design, investigators in India have looked at the D-D-π-A and D-A-π-A configurations, with promising outcomes for increased DSSC PCEs. As efficient photosensitizer for nanostructured TiO_2-based DSSCs, metal-free D-A-π-A pattern dyes (E1–3) with diverse acceptor/anchoring compounds have been devised and produced. Every one of these dyes have an electron-donating methoxy family as an auxiliary and an indole as the primary donor, cyanovinylene as a supplemental acceptor, and thiophene as a π-spacer, so although cyanoacetic acid, rhodanine-3-acetic acid, and 4-aminobenzoic acid, correspondingly, operate as acceptor/anchoring substituents. During conventional worldwide AM 1.5G, an E3-based DSSC obtained an aggregate PCE of 4.12%. [56].

Naik et al employed N, N'-para-aminobenzoic acid (PABA) built on N, N-dimethyl-4-vinyl aniline with 4-amino benzoic acid as an acceptor as photosensitizer for a TiO_2 photo electrode. In sensitizers, the N, N-dimethylaniline ring serves as an electron donor, whereas para-aminobenzoic acid serves as an electron acceptor or anchoring component. The PCE of DSSC systems manufactured with this dye at AM 1.5G emulated radiation from the sun was 1%. [57]

Porphyrin sensitizers with geometric changes have been demonstrated to have a considerable impact on the PCE of DSSCs. Duvva et al. [58] revealed that numerous geographical variations of donors and anchoring organisations improved IPCE and PCE results. SPSGOD3 and SPSGOD4 are two D-π-A natural sensitizers created by Chandrasekharan et al. [59]. They contrast in their anchoring sites (cyan acrylic acid and rhodanine-3-acetic acid) on a conventional donor (N-(9, 9-dihexyl-9H-fluoren-2-yl)-9, 9-dihexyl-N-phenyl-9H-fluoren-2-amine) and π-spacer (furan). At 485 nm, SPSGOD3 had an optimum IPCE of 79% and a PCE of 6.21%, whereas at 536 nm, SPSGOD4 had a highest PCE of 67% and a PCE of 3.78%.

5.3. Natural Dyes

For instance, there are numerous colour schemes and pigments present in fruits, flowers, leaves, and microbes that can be extracted and used in DSSCs. The advantages of using these organic dyes are their great visual absorption coefficients, abundant occurrence, straightforward synthesis methods, and ecological friendliness. Even though natural dyes have a much lower performance than Ru-based dyes due to their limited photon absorption, a blend of natural dyes has been investigated to greatly increase their potential. The explanations of a few of the natural dyes hat Indian scientists have studied are given in the following sections [60].

5.3.1. Chlorophyll

All photosynthetic crops, algae, and cyanobacteria contain chlorophyll, which is one of the main significant environmentally friendly natural pigments. Carbon, hydrogen, oxygen, nitrogen, and magnesium ions make up this chelate complex. Chlorophyll is classified into four stages: chlorophyll a, chlorophyll b, chlorophyll c, and chlorophyll d. The terminal chains of chlorophyll a and chlorophyll b vary considerably in constituents, with $C_{55}H_{72}O_5N_4Mg$ and $C_{55}H_{70}O_6N_4Mg$ accordingly. The much more effective is chlorophyll 'a' variant (methyl trans-32-carboxy-pyropheophorbide) [61-63].

6. COMMERCIALIZATION OF DYE SENSITIZED SOLAR CELLS

DSSCs have quickly gained notoriety as a cutting-edge method for overcoming the issue of excessive electricity consumption in small electronics. DSSCs provide a variety of advantages over other cell types, including simplicity in production, lower cost, and adaptability with diverse materials. However, from a commercial standpoint, the issues of the so-called "Golden Triangle," namely poor photoelectrochemical performance, extended durability, and the need to reduce manufacturing costs, are worth taking into account [64-66]. Figure 8 displays the most current efficiency reports.

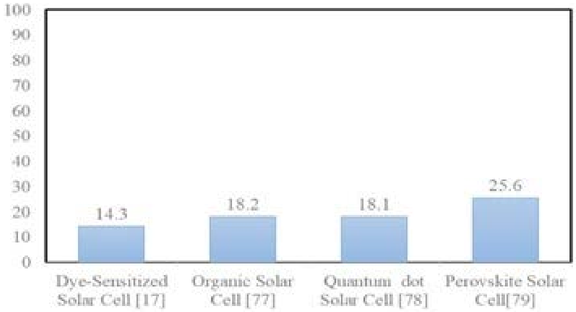

Fig. 8. Efficiency of Solar Cell [66]

7. FROM THE LABORATORY TO THE MARKET

Given the aforementioned limitations and the paucity of revolutionary advancements in cell efficiency over the previous 25 years, some companies are developing prototypes and solutions that incorporate DSSCs. Any product with commercial uses must go through an important stage of improvement. For all photovoltaic systems, experimental experiments with tiny surface region cells have shown the best solar energy conversion performances. As the operational (charge production and collecting) cell surface increases, the efficiency per square centimetre decreases, which results in a reduction of some photo-induced charge carriers via replication and/or capture mechanisms. Almost all photovoltaic devices, including those made of solitary crystal Si, unstructured Si, CdTe, CIGS, and other materials, exhibit this impact. The cell must have the required productivity of 10-12% for DSSC to be applicable with different PV systems.

Consumer technology applications are substantially more advantageous with the device because the cell runs at room temperature and the illumination flow is significantly less than the total solar energy. Because of this, the thermodynamic stabilisation requirements for this use are less stringent than those for modules that are accessible outside, where they must withstand temperatures between -10 and 60 degrees Celsius and moisture contents above 75%.

These frames must be well-organized and durable if they are to be effective. It's also important to note that a long usable lifespan of the cell is not necessary because other components have shorter lifetimes than the cell due to the quick technological improvements in commercial gadgets and the expiration of some parts.

Fig. 9. G24 Power Limited dye-sensitized module (left) and Power Curve charger (right) (Reprinted with permission from -66)

Number of sectors are researching DSSCs for a range of applications. Working on integrated bus shield prototypes, Solaronix (Switzerland) and Dyesol (Australia) are building veneers, terraces, and partially transparent window frames. The G24 Generation Company (UK) is developing prototypes that integrate solar panels into a variety of commercial goods, including as e-readers, wireless keypads, TV virtual devices, wearable technologies, and more.

A DSSC is included in the Power Concave Worldwide Solar Energy Charger as shown in Figure 9, which may be attached to any external outfit. They work with African enterprises to distribute portable photovoltaic adapters to underprivileged populations across Africa as one of their initiatives. In October 2009, G24 Generation Corporation, in partnership with Mascotte Industries Associations (MIA), a Hong Kong-based manufacturer, became the first company to commercialise a product with the ability to generate 0.5 W of electricity when exposed to direct sunlight in Figure 10. 3G Solar (Israel) specialised on remote off-grid industries, like wireless agricultural pump operation, photovoltaic panel’s lights, and so on. Their prototypes were made of glass, and they focused on merging tiny DSSCs to make a bigger component. They've subsequently converted their invention to cordless electronics for interior uses, using incandescent and LED illumination to charge the cells. EXEGER Sweden, a Swedish firm situated in Stockholm, recently released the initial device driven by a variable DSSC in the shape of a cycle helmet and self-charging earphones in Figure 11. With the launch of noise dampening in 1989 and Bluetooth incorporation in 2004, the newest has been dubbed as a truly ground-breaking actual breakthrough in headsets technology. Based on IDTechEx, the dye sensitised solar cells (DSSCs) business would expand to more than $130 million by 2022, with a consistent annualized growth ratio (CAGR) of 12.4% from 2014 to 2022.

Fig. 10. Backpack and duffel bag with an integrated DSSC, (Reprinted with permission from –66)

Fig. 11. Urbanista Los Angeles solar powered headphones using Exeger Powerfoyle technology, (Reprinted with permission from –66)

7.1. Future Prospects

Due of their cost-effectiveness and improving converter performance standards, DSSCs are considered the power of the future. The features of DSSC are their ease of fabrication and manipulation. In comparison to conventional solar cell techniques, they also operate well in scattered light and at increased temperatures. With single major interface DSSC, transformation rates of above 13% have previously been achieved. To fulfil with present technology, however, production standards must approach 15% to hit maximum commercialisation. Aside from productivity, other issues involve improving system reliability and lowering component and production expenditures. Dyes, as the photosensitive element, have a significant impact on DSSC optical absorption and illumination transformation. Despite the fact that much effort has gone into generating multispectral dye photosensitizer over the last two decades, additional advances in the affordability and functionality of artificial ruthenium-based dyes are becoming highly improbable. Inorganic-organic hybrid halogen perovskite has greater absorbance efficiency than standard N719 dyes, allowing it to be used as a photo-catalyst in DSSCs. Perovskite $(CH+NH_3PbI_3)$ nanostructures were initially used as a sensitizer in DSSC in 2009. Owing to the quick dissolving of the perovskite in a liquid electrolyte, the performance is low (4%), but it has emerged clear that the perovskite can operate as both hole and electron conductors, and that the main crystalline perovskite layer can even maintain charge creation and transportation. Etgar et al. [87] then established a $CH_3NH_3PbI_3/TiO_2$ heterostructure system in which $CH_3NH_3PbI_3$ may operate as a photon generator as well as a hole transportation substance. The power of solid-state perovskite photovoltaic cells has increased from 3% to 22% in the last six years, according to the United States National Rechargeable Energy Laboratories (NREL), ushering in an innovative phase of solar cell development. Aside from boosting efficiency, other major topic that requires to be handled in forthcoming study is how to increase cellular durability over a lengthy operational period. The loss of electrolyte solution and deteriorated Pt catalyst are the major causes of destabilisation in DSSCs.

To avoid spillage, solid state hole transportation material (HTM) should be used instead of electrolyte solution. Graphene compounds, which have better electrochemical endurance with extended prospective switching, can also be used to substitute Pt catalyst. Milic JV et al., [88] calculated a lifecycle of 20 years for DSSC components by tackling these difficulties. Perovskite photovoltaic cells, on the other hand, can merely be active for a mere 100 hrs without functionalization.

The combination of environmental humidity and perovskite substances under sunshine, which causes perovskite crystalline disintegration, could be one of the explanations for quick disintegration.

Table 4. Some of the high efficiency DSSCs with TiO2 PEs combined with various sensitizers, as well as Co and Cu redox shuttle-based alternative electrolytes [67-68]

Photelectrode (PE)	**Thickness (µm), TiO$_2$ (nanocrystalline 20–40 nm)**	**Dye**	**PCE (%)**	**Stability**	**Ref.**
TiO$_2$	3.5	SM315	13.0 @1000 W m^{-2}	500 h @ full sun @298 K ~25°C no significant loss detected	67
TiO$_2$	5	YD2-o-C8/Y123	12.3 @ 99.5 mW cm^{-2}	DSSC (unknown number of cells) were soaked in full sunlight at 30°C for a period of 220 h, which led to 10–15% decrease in the overall efficiency	67
TiO$_2$	3.5	SM342: Y123	12.76 @100% sun	Not reported	68
TiO$_2$	5	Y123	8.6 @ 100 mW cm^{-2}	Not reported	68

Table 5. Comparison of various Types of photoanode, Precursors, Sensitizer with Efficiency

	Author	**Anode and Preparatory Methods**	**Sensitizer**	**Precursors Used**	**Counter Electrode**	**Sealant**	**Efficiency**
DSSC based Organometallic Dyes	Alessandra Imbrogo et al.,[69]	Graphene based Tio$_2$ (G- TiO$_2$) By Spin Coating Method	N719 Dye(Di-terta methyl ammonium cis-Bis (isothiocyanto) Bis (2, 2’-bipyridyl-4-4’-dicarboxyato) ruthenium(II))	Acetyl Acetone, Poly-ethylene Glycol, Triton-X 100	Co-Ni decorated Multi walled Carbon Nanotube	Surlyn Poymer Foil	9.8%
	Sanchayan Mahato et al.,[70]	Sn-doped MoS$_2$ by Doctor Blade Method	N719 Dye (Di-tertamethylammonium cis-Bis(isothiocyanto) Bis (2, 2’-bipyridyl-4-4’-dicarboxyato) ruthenium(II))	SnCl$_4$, MoO$_3$, thiourea, ethanol	Isophylised Sn doped MoS$_2$	Hot melt parafilm	7.4%
	Aseena et.al.,[71]	ZnO/CNT	N719 Dye	Zncl$_2$ salts, oxalic acid, CuSo$_4$ Salts	Platinum	Binding Clips	2.6%
DSSC based metal free organic Dyes	Nagarajan et al..,[72]	TiO$_2$ by Doctor Blade Method	(E)-2-cyano-3-(10-hexy-7-(pyren-1-ylenthynyl-10H-phenothaiazin-3-yl) acrylic acid	Phenothiazine, pyrene, 2-cyano-acetic acid	Platinum	Hot melt Sheet (MS004610-10)	11.9%
	Zhencao Wang et al.,[73]	TiO$_2$ by Doctor Blade Method	Di thieno pyrrolo benzothiadiazole (DTPBT) and N719	Toluene, tetra hydro furan, 1, 2-dichloroethane, N-di methyl form ammide	Platinum	Surlyn film	7.9%
DSSC based Quantum dot	Mahalingam et al.,[74]	TiO$_2$ by Doctor Blade Method	Graphene Quantum dots+N719 dye	Hydrogen Peroxide, Sodium hydroxide, Polyethylene gycol	Platinum	Binding Clips	3.01%

	Kiran P.Shejale et al.,[75]	TiO_2 by screen printing method	Nitrogen doped Quantum dots + N719 dye	Citric acid,urea used as Carbon core precursor, ethanol	Platisol-T	Silver conducting paste	8.75%
	Rabia Riaz et al.,[76]	TiO_2 by Doctor Blade	Energy down shift (EDS) of nitrogen doped carbon quantum dots + N719 and Indoline based organic dye	1-butyl-3-methylimidazolium iodide(BMII), 4-tert-buty-pyridine, iodine, citric acid	Platinised FTO	Ionomer surlyn	10%
	Norhaffis Mustafa et al.[77],	TiO_2 (EDOT-NCC) by Doctor Blade	N719 dye	Potassium chloride, Sodium hydroxide, acetonitrile, butanol	Platinum	Binding Clips	5.01%
	Prabhakar Rai et al.,[78]	FTO by squeeze printing	Cerium Oxide quantum dots with zinc oxide nanorods +N719	1-butyl-3-methylimidazolium iodide (BMII), Guanidinium thiocyanate (GUSCN)	Platinum	Surlyn (Dyesol) spacer	2.65%
DSSC based Natural dyes	K.B. Erande et al.,[79]	TiO_2 coated ITO	Pomegranate juice as dye	Potassium Iodide, ethylene glycol, iodine	Carbon with candle flame	Binding clips	0.2%
	Shalini Singh et al., [80]	TiO_2	Tropaeolum majus flower	Acetonitrile, Ethanol, Distilled water	Graphite	Sx1170-60	0.28%
	F.C.Ferreira et al.,[81]	TiO_2	Leucanthemum vulgare flower (yellow daisy, purple daisy, wine daisy)	Polyethylene Glycol, Triton X-100, Hexa chloro platinic acid	Graphite and Platinum	Binding Clips	0.8% for purple daisy
	IChandra Maurya et al., [82]	TiO_2 by Doctor blade Method	Male flowers of Luffa cylindrica L.	Acetone, Ethanol, Water	Platinum	Sx1170-60	0.13%
	Almaz Dhafina et al..,[83],	ZnO by doctor blade method	Ardisia elliptica	Acetone, Ethanol, Distilled Water	Graphite	Binding Clips	0.04%

Dssc based perovskite Dyes	Kim HS et al.,[84]	TiO_2	$(CH_3NH_3)PbI_3$	CH_3NH_3I and PbI_2 γ - Butylacetone,	Platinum	Binding Clips	4%
	Im JH et al.,[85]	TiO_2 by Doctor blade Method	$(CH_3NH_3)PbI_3$	CH_3NH_3I and PbI_2 γ - Butylacetone,	Platinum	Surlyn hot-melt gasket	9.7%
	Kojima Al et al.,[86]	TiO_2 by Doctor blade Method	$(CH_3NH_3)PbI_3$	CH_3NH_3I and PbI_2 γ - Butylacetone,	Platinized FTO	Hot melt films	3.8%

As a result, it's vital to figure out how to encapsulate perovskite solar modules properly to avoid atmospheric ageing, particularly when they're driven to high temperatures and humidity. It is also critical to lower component and production expenses in addition to enhancing equipment functionality. The artificial dye, which employs poisonous raw ingredients and needs intricate, manufacturing, is one of the very extensive aspects in DSSC. Organic enhancers can be harvested readily through organic products such as fruits, flowers, and leaves and used as DSSC photosensitizer. Natural colours, contrary artificial dyes, are readily obtainable, simple to create, inexpensive, non-toxic, ecologically beneficial, and completely recyclable. There are many different organic dyes and stabilisers available; the performance can be increased even further by selecting the right organic dyes and co-sensitizing them with a stabiliser. The second biggest significant element of a DSSC nowadays is the conductive material, such as FTO or ITO. Since they have been shown to have a moderate layer impedance (30/sq.) and a strong optical properties (>90%) through dosing, grapheme based translucent conductors (TCs) are an enticing replacement to ITO and FTO. They can function as both a reagent and a promoter. The substitution of platinum, which is commonly employed as an electrochemical catalyst in DSSCs, might yield in an expense decrease of over four parts of scale. The effective application of DSSC technique is on the horizon, thanks to the huge component price decline. DSSC innovation is expected to be employed to fulfil three prospective power requirements: economic growth, energy sustainability, and environmental conservation. Furthermore, DSSC is one of the most prominent renewable technologies that help to alleviate the effects of environmental disruption. Greijer et al. [89] conducted a statistical analysis to evaluate the CO_2 emissions produced by a DSSC technology with an organic gas process power plant. When contrasted to a gas power plant (450 g CO_2/KWh), DSSC emissions were determined to be much lesser (9–47 g CO_2/KWh). The CO_2 removal benefit of DSSC is equivalent to that of imperfect silicon photovoltaic devices. Furthermore, life-cycle evaluations have revealed that DSSC has an extremely low unfavourable atmospheric influence, with improvements in power generation performance and the use of vegetable dyes predicted to have a beneficial influence.

8. CONCLUSIONS

Since nearly three decades ago, dye-sensitized solar cells have been the subject of intensive research all over the world as a potential replacement for conventional p-n junction-based Si solar cells. The photoanode, the dye, the electrolyte, and the counter electrode are the major parts of a conventional DSSC. Stability will be overcome by incorporating the DSSC with Photo-Voltaic Thermal collectors in order to neglect the degradation of Dye. To increase the PCEs and long-term stability of each component of DSSCs, research activities have been carried out separately for each one of them. Significant efforts have also been made in India to keep up with the global research on DSSC. Researchers from various Indian academic and research institutions have done studies on all the DSSC components. After extensive research on DSSCs, it is believed that their lack of long-term stability makes it difficult for these solar devices to be commercially viable. In regulated laboratory settings, the photoconversion efficiency of DSSCs is about 12%–15%, which is not very promising [90]. Additionally, pricey Ru-based organometallic dyes were used to achieve the highest efficiency in DSSCs. Researchers started looking for other substitutes, and they discovered that PSCs, a modified form of DSSCs, were promising solar devices. However, it is crucial to remember that the discovery of PSCs was really made possible by the broad study of DSSCs. India-based researchers have made a substantial contribution to the long-term study of dye-sensitizer-based solar cells. An effort has been made to condense the research on the various DSSC components conducted in India into this review paper. Researchers and institutions from India who have made major contributions to DSSCs were also named. The following section of this article then addressed recent developments in international study into the various DSSC components. The article's final and primary section then covered the work done in India to investigate the photoanode, electrolyte, counter electrode, and photosensitizers for DSSC applications independently. DSSCs are intended to be efficient and inexpensive solar devices, but they have faced unique difficulties that have limited their commercial viability. For solar cells to remain viable in the commercial sector, they need to have a respectable PCE as well as long-term stability. The PCEs acquired from DSSCs under ambient circumstances, however, are not encouraging as of yet. Long-term stability in DSSCs is still difficult to achieve. The excitation of dye molecules exposed to sunlight is the main procedure in DSSCs [91-95].

Due to the dyes' typical inability to absorb the entire solar light spectrum, there is insufficient production of photoexcited electrons. The priciest and most hazardous sensitizers known to date are Ru-based synthetic organometallic dyes. Natural colours are plentiful and simple to extract from plants and vegetables, but they are not promising for making decent PCEs. The primary objective for this innovation is to develop materials, designs, and production methods that integrate excellent performance, long-term dependability, and cheap prices.

FUTURE SCOPE

Nobel Laureate Richard E. Smalley stated that fixing the resource issue is critical to addressing essential requirements like freshwater resources, food, and health. Although the assumption that the implementation of DSSCs in consumer electronics including such earphones, smartphones, tablet devices, and wearable technology does not appear to be relevant to solving worldwide fundamental requirements at initial look, it is. The majority of commercial electrical gadgets are transportable and require an energy source to operate. Much medicinal equipment has these properties as well. In the on-going covid-19 outbreak, that has afflicted the globe for the past couple years, millions of PCRs have been performed, necessitating the use of a thermo cycler. There are compact thermo cyclers on the marketplace with minimal energy utilization (7.3Wh for 30 PCR cycles), but their usage in distant or impoverished places is limited due to the requirement for a power supply. The inclusion of DSSCs in these types of gadgets would be a huge step forward in the detection of viral infections like tuberculosis, dengue fever, and malaria, as well as the prompt prescription of the appropriate medicine, potentially saving millions of individuals each year. When the priority is on electrifying rural regions or satisfying the demands of emerging nations, the value of DSSCs gets very apparent [96-100]. Similarly, using DSSCs to generate farming equipment's in remote regions, such as freshwater pumps, would encourage farming in locations where there is no immediate exposure to freshwater, lowering famine and misery for whole communities [101-103]. An incorporated DSSC would help comparable technologies with a real effect on environmental sustainability. Whereas the current availability of contemporary devices with incorporated DSSCs appears to be mainly concentrated on meeting first-world demands, the commercialization of the DSSC principle as a device is a significant milestone toward its future implementation for sustainable objectives.

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