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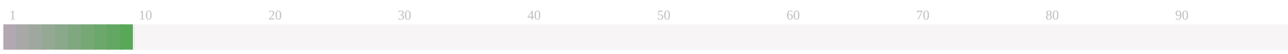


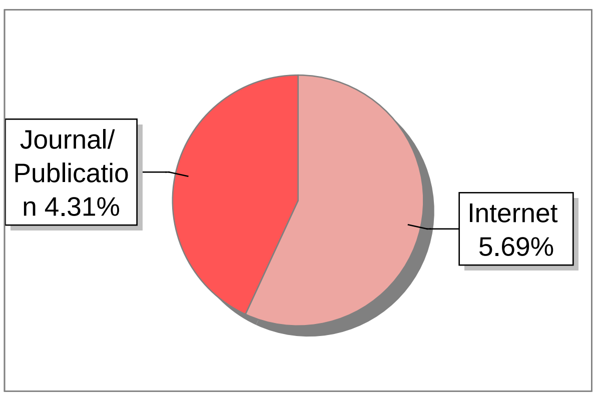


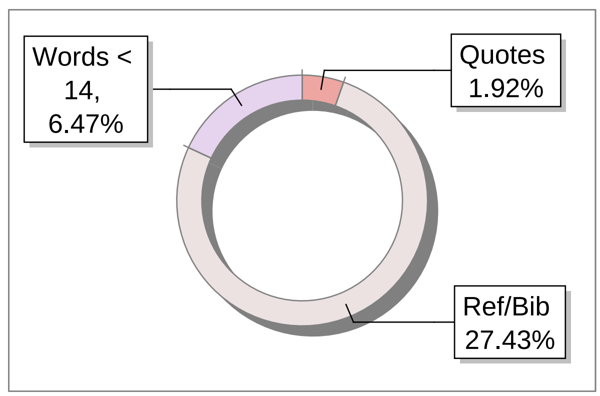


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# Advancement in Dye-Sensitized Solar Cells: A Comprehensive Review on materials, Efficiency Enhancement Strategies

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## Abstract:

The use of renewable energy sources is becoming increasingly important in the current global energy scenario. Among various renewable energy options, solar energy is considered a crucial solution to energy and environmental challenges. Dye-sensitized solar cells (DSSCs) are a promising technology that has drawn significant attention from the scientific community due to their high efficiency, low cost, and ease of fabrication. This article provides an overview of DSSC technology, including the architecture, materials used, fabrication and characterization techniques, major challenges, and current research efforts. Additionally, discuss the applications and prospects of DSSCs as a clean and sustainable energy source.

**Keywords:** Renewable energy, photovoltaic cells, dye-sensitized solar cell, photoanode, photosensitizer.

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## 1. Introduction

### 1.1. Global Energy Scenario and Renewable Energy

Our world is facing an unprecedented surge in global energy demand, currently standing at 13 terawatts (TW) and projected to skyrocket to approximately 23 TW by 2050[1]. This surge is fueled by our increasing reliance on energy, but the concerning reality is that the rate at which we are burning fossil fuels to meet this demand is simply unsustainable. Currently, these fossil fuels cover about 80% of our global energy needs, but they are depleting rapidly and contribute significantly to the rising levels of atmospheric carbon dioxide, intensifying the challenges of global warming [2].

Given these alarming facts and the pressing challenges they present, it is evident that we urgently need cleaner and renewable energy technologies. One compelling option on the renewable energy horizon is photovoltaic technology, which taps into the vast potential of solar energy. Recognized as one of the most efficient sustainable energy technologies, alongside alternatives like tidal power, solar thermal, hydropower, and biomass [3], harnessing such technologies becomes not just a technological pursuit but a critical scientific imperative.

In many regions around the world, the availability of energy sources and water supply is severely restricted, emphasizing the crucial importance of incorporating renewable energy sources such as solar, wind, hydropower, and others [4]. These renewable sources not only offer a path to sustainable energy but also address the broader challenges of resource scarcity, making them integral to a more resilient and equitable future.

The term "renewable energy" encompasses a diverse range of resources relying on self-renewing sources like sunlight, wind, flowing water, Earth's internal heat, biomass, agricultural and industrial waste, and municipal trash [5]. These sources have the potential to generate electricity for various sectors, power transportation, and provide heating for buildings and industrial processes. The interconnected nature of power energy and water accessibility underscores the urgency of addressing global energy demands while simultaneously reducing greenhouse gas emissions to mitigate climate change [6].

The energy sector has undergone significant transformations since the Industrial Revolution, as illustrated in Fig. 1 [7]. The Fig depicts the changing landscape of world energy use from the 1800s onwards, based on historical primary energy consumption projections and current data. Considering population growth and power generation, the projected global power demand in 2050 is estimated to be 28 terawatts (TW) **[3]**. Solar power emerges as a leading contender to meet renewable power needs globally, with a potential estimate of about 600 TW based on solar energy striking the Earth's surface [5]. Harnessing just 10% of this potential could provide around 60 TW of energy. Notably, solar cell production has grown at approximately 30% per year over the last 15 years, indicating significant progress in the adoption of solar technology **[8]**.

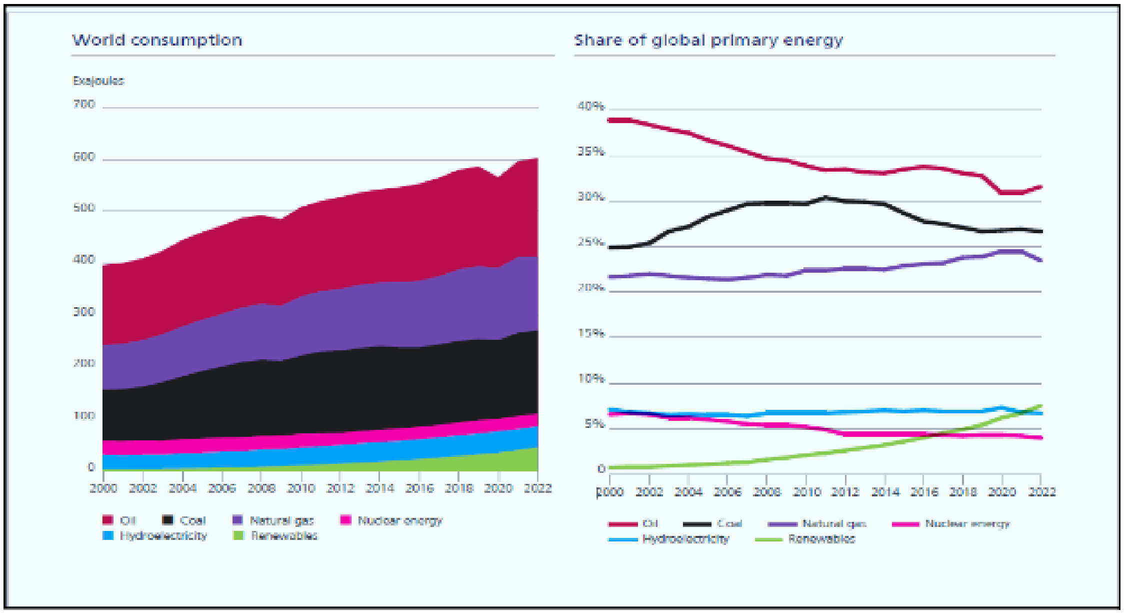


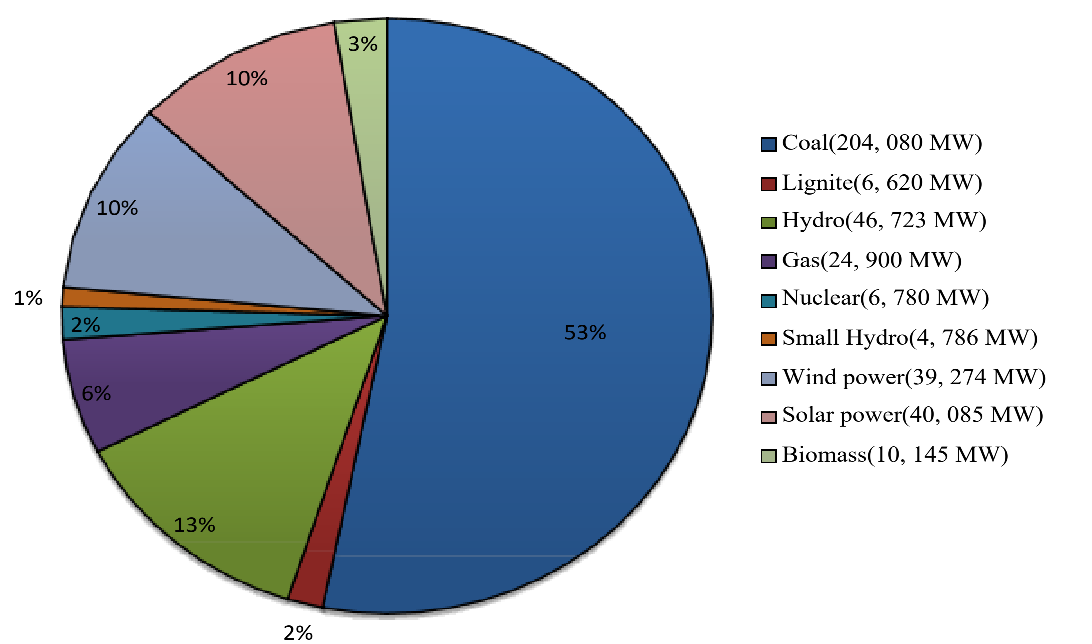

Fig1.Source: 72nd Energy Institute Statistical Review o of World Energy 2023

### 1.2. Indian Energy Scenario and Renewable Energy

Renewable energy sources are those naturally replenishing energy reservoirs that outpace their consumption rate [9]. With India experiencing a surge in energy demands, it becomes imperative for the nation to explore renewable energy alternatives to ensure energy security and achieve sustainable development objectives. To this end, the government is actively promoting the adoption of various renewable energy resources, including solar, wind, biomass, small-hydro, hydrogen energy, and waste-to-energy [9].

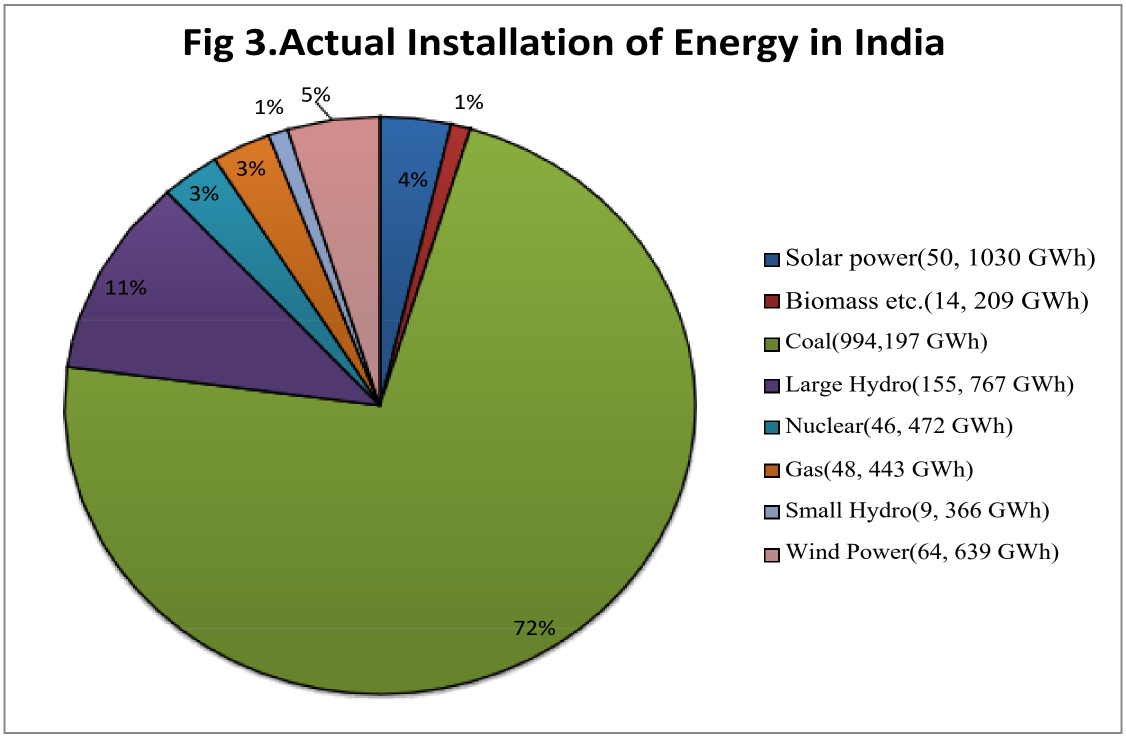
India secured the third global position for renewable energy installations in 2021, as reported by the Renewable 2022 Global Status Report from REN21[9]. Remarkably, about 42% of India's total installed power capacity is now sourced from renewable energy [9].

**Fig 2. Installed Energy Generation Capacity in India**




In the specific realm of solar energy, India achieved the fourth position globally in 2021, boasting an impressive 60.4 GW, surpassing even Germany [10]. According to the Ministry of New and Renewable Energy's December 2022 report, India has operationalized 41.8 GW of wind energy and 61.9 GW of solar energy [11]. Noteworthy projects valued at $200 billion are currently underway in India's renewable energy sector, as highlighted by the International Energy Agency [10].

Despite having nearly 40% of installed renewable capacity, the actual utilization hovers around 25%, factoring in large hydro and nuclear energy [9]. Addressing and surmounting these challenges is crucial to unlocking the full efficiency and impact of renewable energy in India, fostering a more sustainable and resilient energy landscape [9].




**1.3. Solar Energy: A Crucial Solution to Energy and Environmental Challenges**

The next 50 years pose significant challenges for humanity, particularly in the realms of energy and the environment. Our current dependence on fossil fuels, despite advancements in battery technology, remains the primary source of energy [12]. The relentless consumption of fossil fuels not only depletes Earth's oil reserves but also contributes to the greenhouse effect and environmental pollution [13]. Projections indicate that the depletion of these non-renewable resources is inevitable in the 21st century, necessitating a global shift towards clean and sustainable energy alternatives [14].

Amidst various sustainable energy resources like tidal, hydro, geothermal, wind, and biomass, solar energy emerges as a prominent and compelling solution [15]. The Earth receives an astounding 3.8 million petajoules of energy annually from the Sun—almost ten thousand times more than humanity consumes daily [16]. Harnessing just 0.1% of the Earth's surface with solar cells boasting 10% efficiency could meet all current energy needs [17]. This underscores the immense potential of solar power for both the present and future generations. Solar energy can be captured and converted into electricity through two primary methods:

a. **Photovoltaic Cells:**
   Solar energy is directed onto photovoltaic cells, generating electricity for immediate use.
b. **Solar Thermal Technology:**
   Focused sunlight is directed onto collectors, generating heat that can be utilized for various purposes. This heat can be channelled through a conventional generator to produce electricity.

India's target of generating 500 GW of renewable energy by 2030 has been widely reported [18]. Interestingly, a study suggests that using only 3% of wasteland for solar units could result in a whopping 768 GW of power [20]. This emphasizes the immense potential and scalability of solar energy in meeting the rising energy demands sustainably.

Solar energy's storability as electrical energy and its versatility in various applications, including chemical processes, has been highlighted in many sources [21]. Experts suggest that due to its abundance, cleanliness, and versatility, solar energy could play a crucial role in building a sustainable and resilient energy future for the entire planet [22-23].

**1.4. Evaluation of Photovoltaic devices:**

Researchers have long been engaged in harnessing sunlight for chemical reactions or electricity generation. Photovoltaic (PV) devices play a pivotal role in this process, generating direct current or power by absorbing solar radiation through semiconductor materials. The "photovoltaic effect" is the underlying physical process wherein the PV cell converts incident sunlight into electricity. The term "photovoltaic" itself denotes the combination of "photo" meaning light and "voltaic" meaning electricity. PV cells are commonly referred to as "solar cells." Solar photovoltaics stand out as the cleanest, most viable, and sustainable technology among various renewable harvesting technologies [24].

Electricity generation through solar photovoltaics is considered environmentally friendly, emitting no hazardous or toxic gases into the environment. The "photovoltaic effect" was first discovered by the renowned French scientist Edmond Becquerel in 1839. He demonstrated the effect by exposing solid electrodes in an electrolyte solution to sunlight. The first solar cell, built by Charles Fritts in 1883, utilized selenium and gold to form p-n junctions and reported an efficiency of 1% conversion of absorbed solar light [25].

Albert Einstein's theoretical explanation of the "photoelectric effect" in 1905 laid the foundation for understanding how electrons are emitted from a metal surface by absorbing discrete amounts of light, now known as photons. In 1954, the first silicon photovoltaic cell, employing diffused silicon p-n junction technology, was developed, boasting a 6% conversion efficiency. The space industry adopted this technology in the 1960s for powering spacecraft [25].

Over time, intense competition among manufacturers has driven significant advancements in photovoltaic technology, improving efficiency and reducing costs. The energy crisis of the 1970s propelled photovoltaic technology into the spotlight across various non-space and domestic sectors [24].

A photovoltaic cell generates electricity through the following key steps:

• Absorption of solar radiation, creating electron-hole pairs (or excitons in specific solar cells).

• Separation of charge carriers, involving exciton ionization and/or carriers' separation in specific solar cells [25].

**1.5. Classification of Photovoltaics**

Photovoltaic cells, also known as solar cells, have been categorized into three primary groups by Martin A. Green. This classification revolves around the material composition of the solar cell, the highest attainable solar-to-power conversion efficiency, and the production cost

Solar cells come in three main generations. The first, known as conventional or wafer-based cells, are the oldest and most widely used [26]. Despite being made of crystalline silicon (mono or poly), they have high production costs and modest efficiency, reaching 26.6%. The expense of making single-crystalline Si solar cells hinders the idea of low-cost production.

In contrast, second-generation solar cells, called thin-film solar cells, were developed as an alternative to silicon [27]. These cells are made by depositing thin semiconductor layers on substrates like glass or plastic. Although cheaper than traditional silicon cells, they are less efficient, with challenges in complex deposition, stoichiometry control, and structural defects.

The third generation, often called emerging photovoltaics, includes Dye-Sensitized Solar Cells (DSSCs), Organic Solar Cells (OSCs), Perovskite Solar Cells (PSCs), and Quantum Dot Solar Cells (QDSCs). These aim for low-cost production and increased efficiency by overcoming energy loss issues. They use a "tandem cell" or "multi-junction" approach, stacking layers with varying band gaps.

All third-generation cells operate on the same principle but differ in the light-harvesting layer. Dyes in DSSCs, conductive organic polymers in OSCs, perovskite structured compounds in PSCs, and inorganic/organic quantum dots in QDSCs serve this role. Each type faces unique challenges, like low efficiency in OSCs, film quality issues in PSCs, and difficulty controlling particle size in QDSCs [28].

Despite challenges, DSSCs stand out as a promising alternative due to their performance in various conditions, long life, eco-friendliness, low toxicity and production cost, and simple manufacturing techniques. To boost their efficiency and quicken commercialization, researchers should reconsider the materials used in different components.

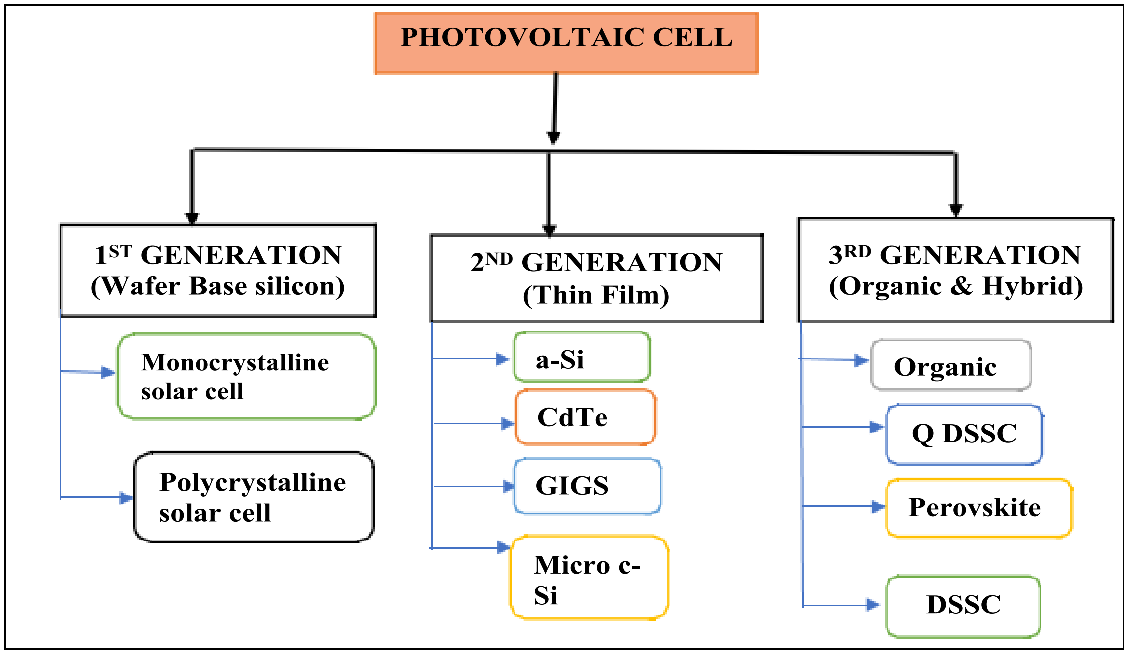



**Figure 4. Classification of photovoltaic cell**

## 2. INTRODUCTION TO DYE-SENSITISED SOLAR CELL:

Dye-sensitized solar cells (DSSCs) have emerged as a viable alternative to traditional p-n junction photovoltaic devices, presenting both technical and economic advantages. The concept of generating electricity through illuminated organic dyes in electrochemical cells was initially explored in the late 1960s [29]. However, the efficiency of these dye-sensitized solar cells was initially limited, absorbing only up to 1% of incident light due to the monolayer of dye molecules. Subsequent improvements were achieved by optimizing the porosity of the electrode using fine oxide powder, enhancing dye absorption, and consequently, light harvesting efficiency (LHE) [30]. This led to the discovery of nanoporous titanium dioxide ($TiO_2$) electrodes with a roughness factor of approximately 1000, resulting in the invention of DSSCs in 1991 with 7% efficiency [29].

Gratzel cells, developed by Brian O'Regan and Michael Gratzel, exhibited exceptional efficiency, with over 80% incident photon to current conversion efficiency (IPCE) in simulated solar light [29]. The corresponding reactions involve photoexcitation, electron injection, electron transport, reduction regeneration, and dye regeneration, ultimately leading to electricity generation [35]. Subsequent advancements led to 9.6% efficiency in 1993 and 10% efficiency at the National Renewable Energy Laboratory (NREL) in 1997 [31-32].

The construction of DSSCs involved a transparent conductive oxide (TCO) layer on two glass sheets—one coated with a sensitized photoanode and the other with a counter electrode [33]. DSSCs mimic natural photosynthesis, with dye molecules absorbing sunlight and injecting electrons into the semiconductor [34]. The review by Anandan until 2007 focused on aspects such as light-harvesting inorganic dye molecules, p-CuO nanorod counter electrodes, and the self-organization of electroactive polymers [30]. Another review by Bose et al. (2015)

highlighted developments in photoelectrode, photosensitizer, and electrolyte components, underscoring DSSC's superior performance compared to Si-based modules [35]. Shalini et al. (2018) delved into sensitizers, while Jihuai Wu et al. (2012) concentrated on counter electrodes.

The review offers a detailed examination of diverse components and their applications within DSSCs. Furthermore, it provides insights into the construction and operational principles of these cells. The overarching goal of the article is to cultivate a thorough understanding of DSSC components and applications, elucidating the development and operational principles underlying these innovative solar cells.

### 2.1. History and Development of Dye-Sensitized Solar Cells

The development of DSSCs has evolved over the years, marked by significant milestones and breakthroughs:

- **Initial Investigations (1839)**: Alexandre-Edmond Becquerel initiated the investigations of solar-to-electric devices [36].
- **First Efficient Solar Cell (1883)**: Charles Fritts developed a 1% efficient solar cell [36].
- **First Solar Cell Patent (1888)**: Edward Weston received the first solar cell patent.
- **Photoelectric Effect (1921)**: Albert Einstein was awarded the Nobel Prize in Physics for his work on the photoelectric effect.
- **First Practical Silicon Solar Cell (1954)**: Bell Labs announced the first practical silicon solar cell with about 6% efficiency.
- **Alternatives to Silicon Solar Cells (~1950s)**: Gallium arsenide (GaAs), copper gallium indium diselenide (CIGS), cadmium telluride (CdTe), and amorphous silicon alternatives emerged.
- **Dye-Sensitized Solar Cells (DSCs, 1991)**: The modern version of a dye solar cell, also known as the Grätzel cell, was co-invented by Brian O'Regan and Michael Grätzel at UC Berkeley and later developed at the École Polytechnique Fédérale de Lausanne (EPFL).
- **Organic Photovoltaics (OPVs, 2001)**: More recently, the processability approach has been the focus of multiple modern advances in dye-sensitized solar cells (DSCs).
- **Perovskite Solar Cells (PSCs, ~2009)**: All of these technologies can be processed via solution-based techniques which dramatically lowers pricing.
- **Current Developments (2022)**: Scientists at EPFL have increased the power conversion efficiency of dye-sensitized solar cells beyond 15% in direct sunlight and 30% in ambient light conditions.

The field of DSSCs continues to progress, with efforts directed toward enhancing their performance, reducing production costs, and expanding their applications in renewable energy technologies. As an intriguing and sustainable photovoltaic option, DSSCs hold promise for the future of solar energy.

## 3. ARCHITECTURE OF DSSC

The architecture of a Dye-Sensitized Solar Cell (DSSC) comprises several key components, each playing a crucial role in the conversion of sunlight into electrical energy. The schematic representation of a standard Dye-Sensitized Solar Cell (DSSC) is depicted in the figure 5. Here is an overview of the architecture of a typical DSSC:

### 3.1. Photoanode:

The photoanode is a critical component responsible for capturing sunlight and initiating the conversion process in Dye-Sensitized Solar Cells (DSSCs) [29]. Typically composed of semiconducting metal oxides (SMOs) with wide bandgaps, such as titanium dioxide (TiO2) or zinc oxide (ZnO), these metal oxides are coated onto transparent conducting glass substrates. The photoanode also contains a layer of photosensitizer (dye) anchored to the metal-oxide layer, making it the backbone of the DSSC [29].

Key characteristics of an ideal photoanode can be succinctly summarized:

- **High Surface Area:** To enhance the capacity for picking up and adsorbing dye molecules, the photoanode should possess a high surface area [37].
- **Facilitation of Fast Electron Transfer:** It should facilitate rapid electron transfer from the dye to the external circuit and ensure fast electron injection from the dye into the semiconductor [37].
- **Optimized Pore Size:** The pore size of the photoanode should be carefully engineered to enable the optimum diffusion of both dye molecules and electrolyte, promoting efficient charge transport.
- **High Resistance to Photo-corrosion:** The photoanode should exhibit resistance to photo-corrosion, ensuring stability and longevity under prolonged exposure to light.
- **Light Absorption/Scattering Capability:** The photoanode should efficiently absorb or scatter sunlight, contributing to the effective functioning of the dye and the overall energy conversion process.
- **Effective Electron Acceptor:** Acting as a good electron acceptor, the photoanode should efficiently accept electrons from the dye molecules [38] .
- **Optimal Interface Contact:** Establishing an optimum interface contact with both the dye molecules and the conductive layer on the substrate is crucial for facilitating efficient electron transfer throughout the cell [37].

### 3.2. Photosensitizer (Dye):

The dye in a Dye-Sensitized Solar Cell (DSSC) plays a crucial role in absorbing incident light. For optimal performance, the dye should possess specific photophysical and electrochemical properties:

- **Luminescence:** The dye should exhibit luminescent properties.
- **Absorption Spectra:** The absorption spectra of the dye should cover both ultraviolet-visible (UV-vis) and near-infrared (NIR) regions.
- **HOMO and LUMO Placement:** The Highest Occupied Molecular Orbital (HOMO) should be situated far from the surface of the TiO2 conduction band, while the Lowest Unoccupied Molecular Orbital (LUMO) should be positioned close to

the TiO2 surface. The LUMO should also be higher than the TiO2 conduction band potential [39].

- **HOMO Energy Level:** The HOMO energy level should be lower than that of redox electrolytes.
- **Hydrophobic Periphery:** The periphery of the dye should be hydrophobic to enhance long-term stability. This property minimizes direct contact between the electrolyte and the anode, preventing water-induced distortion of the dye from the TiO2 surface, which could compromise cell stability [40].
- **Preventing Aggregation:** To avoid dye aggregation on the TiO2 surface, co-absorbents like chenodeoxycholic acid (CDCA) and anchoring groups such as alkoxy-silyl, phosphoric acid, and carboxylic acid groups are introduced between the dye and TiO2. This insertion prevents dye aggregation, limits recombination reactions between the redox electrolyte and electrons in the TiO2 nanolayer, and promotes the formation of stable linkages. [41].

### 3.3. Electrolyte:

Electrolytes in Dye-Sensitized Solar Cells (DSSCs), such as $I^-/I_3^-$, $Br^-/Br_2^-$, $SCN^-/SCN_2$, and Co (II)/Co (III), consist of redox couples, solvents, additives, ionic liquids, and cations. Key properties expected in an electrolyte include:

- **Efficient Redox Regeneration:** The redox couple should effectively regenerate the oxidized dye.
- **Stability:** The electrolyte should exhibit long-term chemical, thermal, and electrochemical stability.
- **Non-Corrosiveness:** It should not corrode DSSC components.
- **Facilitate Charge Carrier Diffusion:** The electrolyte should enable fast diffusion of charge carriers, enhance conductivity, and establish effective contact between working and counter electrodes.
- **Non-overlapping Absorption Spectra:** The absorption spectra of the electrolyte should not overlap with that of the dye.

While $I^-/I^-_3$ has shown high efficiency, it has limitations, including corrosion, volatility, photodegradation, and poor long-term stability. Solvents like acetonitrile (ACN), N-methylpyrrolidine (NMP), and solvent mixtures (e.g., ACN/valeronitrile) are used, with 4-tert-butylpyridine (TBP) as an additive to shift the conduction band of TiO2 upwards. However, TBP has drawbacks like reduced photocurrent and injection driving force. Ionic liquids (ILs) face challenges like leakage, leading to the development of solid-state electrolytes as alternatives. To address issues like redox electrolyte failure or sealing under prolonged illumination, extensive long-term light soaking tests on sealed cells have been advanced over the years [42].

### 3.4. Counter Electrode:

The counter electrode plays an important role in catalyzing the reduction of the electrolyte and collecting holes from HTMs[43]. Platinum is often preferred due to its high efficiency [43]. However, more cost-effective and abundant alternatives such as carbon, CoS, FeSe, and CoNi0.25 are being explored [43-44].

Working in conjunction with the redox electrolyte, the counter electrode gathers electrons from the external circuit [45]. The creation of the counter electrode often involves applying thin layers of noble metals onto transparent glass substrates [44]. In a bid to find more cost-effective solutions, conductive carbonaceous materials are being investigated as potential substitutes for the counter electrode [45].

### 3.5. Transparent Conductive Substrates:

conductive materials, which serve both as a substrate for depositing semiconductors and catalysts and as collectors for electric current [46]. The chosen substrate for DSSCs should possess two key characteristics. Firstly, it needs to have a transparency level exceeding 80% to allow optimal sunlight to reach the cell's effective area [47]. Secondly, to ensure efficient charge transfer and minimize energy loss in DSSCs, the substrate should exhibit high electrical conductivity.

Fluorine-doped tin oxide (FTO, $SnO_2$: F) and indium-doped tin oxide (ITO, $In_2O_3$: Sn) are commonly employed as conductive substrates in DSSCs [29]. These substrates consist of soda lime glass layered with indium-doped tin oxide and fluorine-doped tin oxide. Specifically, ITO films demonstrate a transmittance greater than 80% and a sheet resistance of 18 Ω/cm2, whereas FTO films exhibit a slightly lower transmittance of approximately 75% in the visible region, coupled with a sheet resistance of 8.5 Ω/cm2[25].

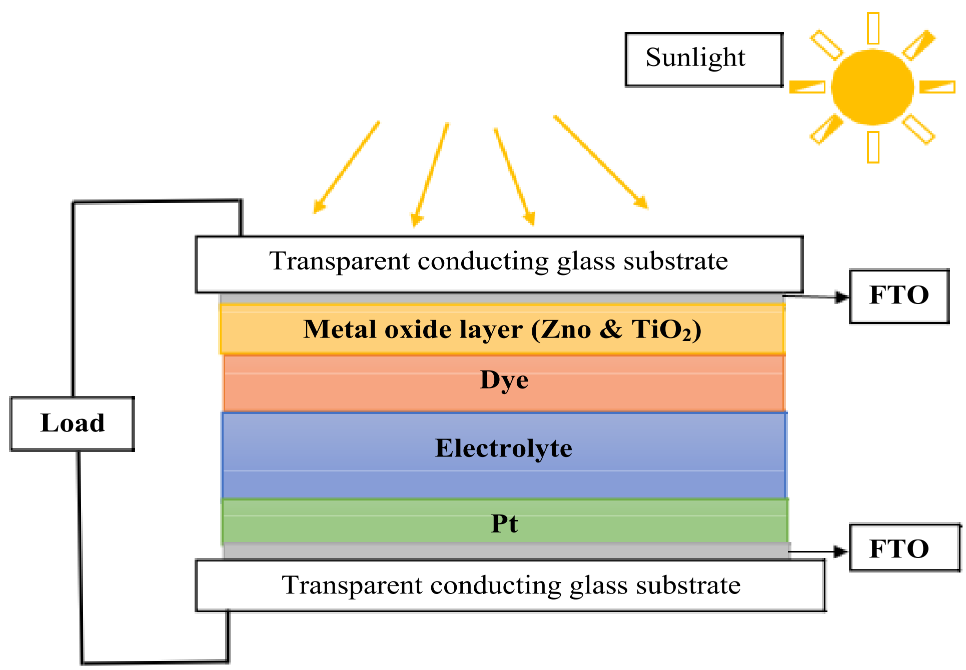



Fig 5. Schematic View of a dye-sensitized solar cell

## 4. WORKING OF DSSC

The operation of a Dye-Sensitized Solar Cell (DSSC) involves a sequence of steps that convert sunlight into electrical energy. The following steps are involved in the conversion of photons into current [48]. (as shown in Fig. 6):

- **Photon Absorption:**
  Incident light (photon) is absorbed by a photosensitizer (dye), causing electrons to be promoted from the ground state ($S^{+}/S$) to the excited state ($S^{+}/S^{*}$):
  $$S^{+} + h\nu \rightarrow S^{*} + e^{-}$$
- **Electron Injection:**
  Excited electrons are injected into the conduction band of a nanoporous $TiO_2$ electrode, leading to the oxidation of the dye:
  $$S^{*} \rightarrow S^{+} + e^{-} (TiO_2 \text{ absorption})$$
- **Electron Transport:**
  Injected electrons move through the $TiO_2$ nanoparticles, diffusing towards the back contact (transparent conducting oxide, TCO). Through the external circuit, electrons reach the counter electrode.
- **Redox Reaction and Electrolyte:**
  Electrons reaching the counter electrode reduce $I_3^{-}$ to $I^{-}$, regenerating the ground state of the dye:
  $$S^{*} + e^{-} \longrightarrow S^{+} + I_3^{-}$$
  $$I_3^{-} + 2e^{-} \longrightarrow 3I^{-}$$
- **Counter Electrode:**
  The oxidized mediator ($I_3^{-}$ diffuses back toward the counter electrode and is reduced to $I^{-}$)

This cyclic process allows DSSCs to continuously convert sunlight into electricity, with equations illustrating the photon absorption, electron injection, transport, redox reaction, and regeneration steps.

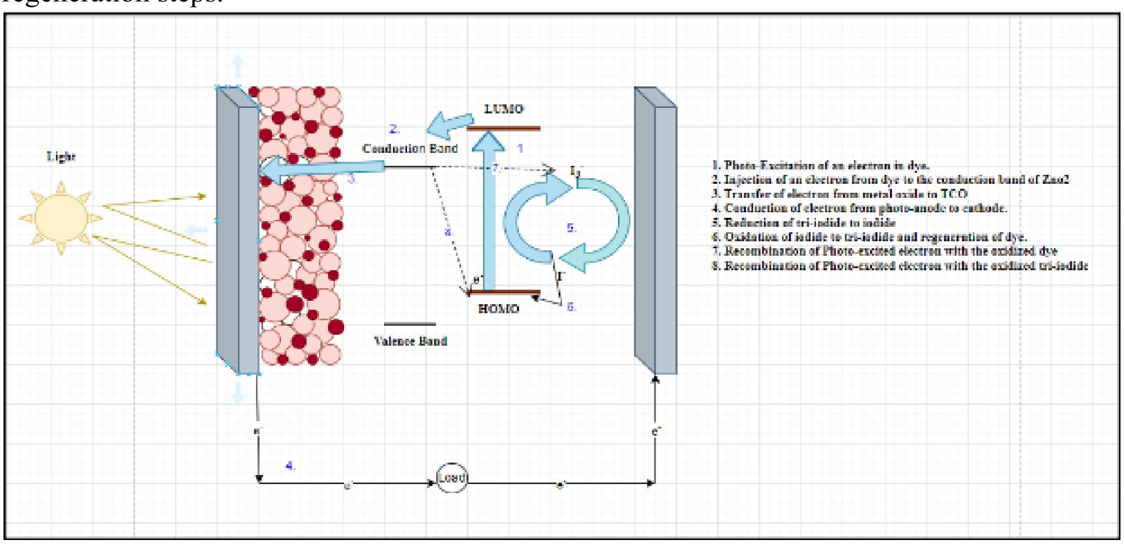



**Fig 6. Working principle of DSSCs**

## 5. MATERIALS USED IN DYE-SENSITIZED SOLAR CELLS

Dye-Sensitized Solar Cells (DSSCs) involve the use of various materials to construct the different components of the cell. The key materials used in DSSCs include:

### 5.1. Photosensitizer (Dye):

Photosensitizers, crucial components responsible for light absorption and electron generation, are pivotal in DSSCs [49]. They encompass both organometallic and organic dyes, with examples such as ruthenium-based N719 and N3, as well as organic compounds like coumarins and porphyrins. These dyes play a vital role in capturing sunlight, initiating the electron injection process, and contributing to the overall efficiency of the solar cell. Researchers continually strive to develop novel photosensitizer materials to improve DSSC performance and sustainability [50].

Indian researchers have made significant strides in the exploration of sensitizers utilized in dye-sensitized solar cells (DSSCs), with a specific focus on three main categories: organometallic dyes, metal-free dyes, and natural dyes [51] (fig.7)

- **Organometallic Dyes:** In the realm of DSSCs, organometallic dyes stand out as promising candidates, incorporating transition elements such as Ru, Os, and Ir along with organic materials. Ru (II) is particularly favoured due to its advantageous octahedral geometry, appealing photoluminescence, electrochemical features, sustainability, and resilience in various solutions. Noteworthy contributions from researchers like Praveen Naik et al. involve the development of dyes by combining aniline-based dyes with an N3 dye, achieving a commendable solar panel with a PCE of 7.02%. Another study by Subramaniam, K., et al. introduced a heteroleptic dual-anchored Ru (II) complex (RNPDA) with a PCE of 3.42% [50].

- **Metal-Free Dyes:** Metal-free natural dyes have emerged as an alternative for DSSCs, showcasing PCEs comparable to Ru-based sensitizers (Singh et al., 2021). These dyes offer high extinction factors, programmable absorption frequencies, and cost advantages. Most metal-free natural pigments follow a D—A pattern, incorporating electron-rich substances like phenylamine, aminocoumarin, and indoline as donors, and thiophenes, polyenes, and benzothiadiazole as conjugated compounds [52]. Novel metal-free D-A-π-A pattern dyes, such as (E)-2-cyano-3-(10-(4-(diphenyl amino) phenyl)-1-(4-(diphenylamino)phenyl)-1-(4-(diphenylamino)phenyl)-1-(4-(diphenylamine)phenyl)(2-ethylhexyl)-1H-phenanthrocarbazol-3-yl) acrylic acid (NPS-4), have been developed, exhibiting an aggregate PCE of 4.12% [50],[52].
- **Natural Dyes:** Natural dyes extracted from various sources, including fruits, flowers, leaves, and microbes, have garnered attention for their potential use in DSSCs [53]. These organic dyes offer advantages such as high visual absorption coefficients, abundant availability, straightforward synthesis methods, and environmental friendliness. For instance, chlorophyll, - a significant natural pigment found in photosynthetic organisms, has been studied. Despite generally lower performance compared to Ru-based dyes, researchers have explored combining natural dyes to enhance their potential [50][53].

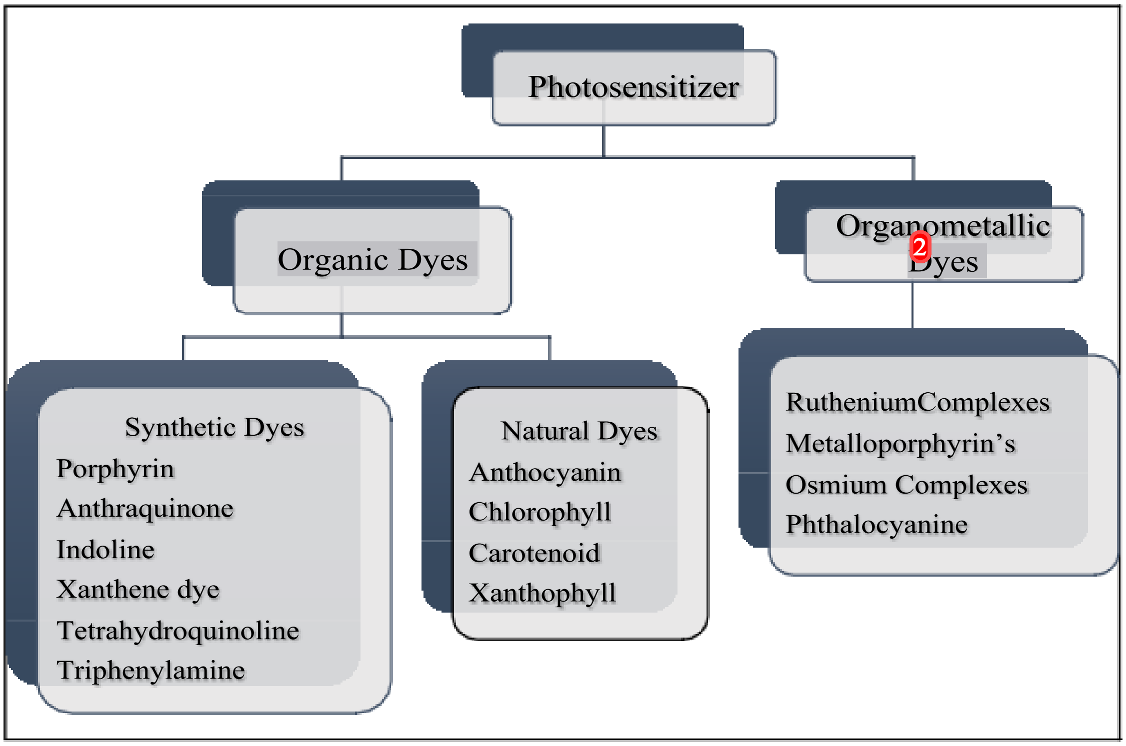



**Fig 7. Overview of Different Photosensitizers or Dyes.**

**5.2. Metal oxide-based photoanodes:**

The metal oxide semiconductor is a crucial component of the photoanode in Dye-Sensitized Solar Cells (DSSCs) [54]. These wide bandgap metal oxides serve as electron carriers and provide a surface for dye adsorption. Various metal oxides, such as TiO2, ZnO, SnO2, Nb2O5, WO3, In2O3, SrTiO3, Zn2SnO4, BaSnO3, and CoTiO3, have been investigated for their suitability in DSSCs [55]. The selection of a particular metal oxide depends on the energy levels of the valence band and conduction band, aiming to achieve effective charge separation and reduced recombination [50][56].

TiO2 photoanodes are extensively explored due to TiO2 being relatively cost-effective, abundant, biocompatible, and non-toxic, making it a stable n-type semiconductor material [57]. Three crystalline polymorphs of TiO2 are designed for DSSCs: anatase (bandgap 3.2 eV), rutile (bandgap 3.0 eV), and brookite (bandgap 3.4 eV). Among these, anatase TiO2 is widely considered superior in TiO2-based DSSCs.58[56].

Another metal oxide explored as a photoanode is WO3, a transition metal oxide with a bandgap ranging from 2.6 to 3.1 eV in the blue-UV region [58]. Porous WO3 nanoparticle films in DSSCs achieved an initial efficiency of 0.75%, which was later improved to 1.46% through treatment with TiCl4.

$In_2O_3$, a wide bandgap material with an energy level of 3.6 eV, is less commonly used but has been studied. Nanostructures of $In_2O_3$, such as spheres, nanotubes, nanocubes, pyramids, and inverse opals, have been investigated, influencing the overall photovoltaic performance [55].

$SnO_2$ is another alternative semiconductor with high electron mobility and a sizable bandgap of about 3.6 eV. Nanostructured $SnO_2$ materials, including nanowires, nanocrystallites, and coral-like porous hollow architectures, have been explored as efficient photoanodes [55].

The reported efficiencies for different metal oxides based on their energy band gaps are summarized and the advantages and disadvantages of various metal oxides are presented in Table 1. These comparative tables offer insights into the performance characteristics of different metal oxides in DSSCs.

**Table 1. Efficiencies of different metal oxides in Dye-Sensitized Solar Cells, and a comparative analysis of the advantages and disadvantages associated with their use as photoanodes.**

| Metal Oxides | Band Gap (eV) | Best Efficiency (%) | Advantages | Disadvantages | Ref |
|---|---|---|---|---|---|
| $TiO_2$ – Anatase<br>Rutile<br>Brookite | 3.2<br>3.0<br>3.4 | 8.75<br>6.23<br>4.1 | Cost-effective, abundant, biocompatible & non-toxic, Stable n-type semiconductor, Better photostability, Fast electron injection rate. | Limited electron mobility. | [57] |
| ZnO | 3.37 | 7.5 | Heterogeneity in ZnO nanostructures., High electron mobility. | Complexation with dyes, Dyes dependent performance. | [55] |
| $SnO_2$ | 3.6 | 8.23 | High electron Mobility, Sizeable bandgap. | Lower electron injection, Faster electron,recombination, Less adsorption of dye. | [55] |
| $Nb_2O_5$ | 3.4 | 4.1 | Wider bandgap. Reduced electron scattering, Greater surface area. | Reduction in the dye loading sites. | [54] |

| | | | | | |
|---|---|---|---|---|---|
| WO3 | 2.6-3.1 | 1.46 | Extremely stable material. Good carrier mobility. | Acidic surface, More positive conduction band edge. | [58] |
| In2O3 | 3.6 | <2 | Higher electron lifetime. Large surface area with hollow porous structure. | Wide bandgap, More positive potentials of bands. | [55] |
| SrTiO3(Strontium Titanate) | 4.15 | 0.58 | High dielectric constant, good thermal stability | Low electrical conductivity | [55] |
| Zn2SnO4(Zinc Stannate) | 3.6 | 3.8 | High transparency in the visible light range, good stability | Lower electrical conductivity compared to other TCOs | [55] |
| BaSnO3(Barium Stannate) | 2.9-4.0 | 5.2 | High electron mobility, transparency in the visible light range | Requires high-temperature processing | [55] |
| CoTiO3 (Cobalt Titanate) | 2.25 | 7.67 | High thermal, stability, good chemical resistance | Not a good conductor of electricity | [55] |

### 5.3 Electrolyte:

The utilization of liquid electrolytes in dye-sensitized solar cells (DSSCs) presents practical challenges, including leakages, volatilization, corrosion of the platinum secondary electrode, desorption, and photodegradation of the dye. Additionally, issues such as the precipitation of salts at low temperatures and ineffective sealing limit the long-term applications of DSSCs in solar modules. To overcome these disadvantages, considerable efforts have been directed toward replacing liquid electrolytes with alternatives such as ionic liquids (ILs), polymer gels, and solid-state electrolytes [58].

**5.3.1. Role of Redox Couples:** Redox couples are crucial in DSSCs as they facilitate electron transfer from the counter electrode to the oxidized dye (Chen et al., 2017). Commonly used redox couples include $I^-/I_3^-$, $Br^-/Br_2$, $SCN^-/SCN_2$, and Co (II)/Co (III) [59].

**5.3.2. Solvents and Additives:** These redox couples are dissolved in solvents such as acetonitrile (ACN) or N-methylpyrrolidine (NMP). Additives like 4-tert-butylpyridine (TBP) are often included to enhance cell performance [59].

**5.3.3. Effectiveness of Redox Electrolytes:** The efficiency of redox electrolytes is influenced by factors like solubility, ionic mobility, the driving force for dye regeneration, and fast electron transfer kinetics with minimal overpotential at the counter electrode [59].

**5.3.4. Types of Electrolytes:** Electrolytes can be categorized into liquid, quasi-solid, and solid-state. Each type has its advantages and disadvantages, impacting the efficiency and stability of DSSCs.

- **Ionic Liquids:** Ionic liquids have emerged as promising alternatives for electrolyte solvents in DSSCs. These organic salts, with melting points near room temperature, consist of organic cations paired with various anions. Their unique properties, including good ionic conductivity, high chemical and thermal stability, non-flammability, and negligible vapor pressure, make them attractive for DSSCs [60]. Numerous imidazolium-based ILs with different anions have been synthesized and investigated for their application in DSSCs. Despite their promising properties, the high viscosities of ILs result in low ion mobility, leading to lower DSSC device efficiencies compared to organic solvent-based electrolytes [60].

- **Polymer Gel Electrolyte:** Polymer gel electrolytes, a combination of polymers and redox couples, are commonly employed in DSSCs. Various types of gel electrolytes have been reported, utilizing polymers such as polyacrylonitrile, poly(vinyl chloride) (PVC), poly(methylmethacrylate), polyvinyl pyrrolidone, and polyethylene glycol. The conductivity of these electrolytes depends on the morphology and molecular weight of the polymers. Introducing disorder in the structure, achieved through blends of different polymers or the addition of plasticizers, can enhance ionic conductivity [61]. Despite achieving efficiencies of 8–9%, polymer gel electrolytes suffer from thermodynamic instability under high temperatures, necessitating careful sealing treatments [61].

- **Solid-State Electrolytes:** Solid-state electrolytes, involving inorganic p-type semiconductors or various hole-transporting materials (HTMs), have been explored as hole acceptors to replace liquid electrolytes. Inorganic materials like copper compounds (CuI, CuSCN), CsSnI3, $Cs_2SnI_3Br_3$, and organic polymers ($P_3HT$, PEDOT, spiroMeOTAD) have been successfully utilized in solid-state DSSCs. Challenges include issues with crystallization rates and control, with inhibitors like triethylaminehydrothiocyanate showing some improvement. SpiroMeOTAD, despite its effectiveness, faces hurdles due to high production costs and low hole mobility. Achieving high conductivity for effective hole transfer and good HTM diffusion into the photoanode electrode remains crucial for the success of solid-state electrolytes in DSSCs [62].

**Table 2. concise overview of the advantages and disadvantages of each electrolyte type in DSSCs.**

| Electrolyte Type | Examples | Advantages | Disadvantages | Ref. |
|---|---|---|---|---|
| Liquid | Iodide–triiodide ($I3^-/I^-$) system | Satisfactory kinetic properties | Absorption of visible light, potential leakage, volatility | [60] |
| Polymer Gel | Polyacrylonitrile, PVC, etc. | Enhanced ionic conductivity, flexibility | Thermodynamic instability under high temperatures | [61] |
| Solid-State | Copper compounds, organic polymers | Improved stability, reduced leakage, potential for scale-up | Challenges in achieving high conductivity and cost concerns | [62] |
| Quasi-solid | Ionic liquids or polymer gels with redox couples | Addresses sealing and durability issues | Thermodynamic instability under high temperature | [62] |

### 5.4. Counter Electrode Catalyst:

Dye-sensitized solar cells (DSSCs) stand out among various photovoltaic devices due to their cost-effectiveness, ease of fabrication, and environmentally friendly characteristics. The fundamental components of DSSCs, including the photoanode, sensitizer, electrolyte, and counter electrode (CE), collectively influence their performance. The choice of CE materials is particularly crucial in determining the overall efficiency of DSSCs [63].

To enhance the cost-effectiveness of photovoltaic applications, there is a growing emphasis on developing alternative CE catalysts. While platinum-based CEs are effective, they are expensive. Several economical and highly stable materials, such as conducting polymers, sulfides, oxides, and carbonaceous substances like N-doped core–shell structures, have emerged as promising alternatives. Remarkably, N-doped core–shell-based DSSCs have demonstrated a power conversion efficiency of 7.89%, surpassing that of platinum-based cells (7.48%) [63].

In the pursuit of efficient CE catalysts, researchers have explored various materials. For instance, Cr-doped SiC exhibited superior activity in triiodide splitting but demonstrated limitations in further iodine splitting into mono-iodides compared to Pt-doped SiC slabs. Additionally, graphene nanoplatelet-based CEs showed a charge transfer resistance of 3.36 Ω, slightly higher than platinum (1.18 Ω), resulting in slightly elevated oxidation [63].

- The role of the Counter Electrode (CE) in Dye-Sensitized Solar Cells (DSSCs) is to collect electrons from the external circuit and catalyze the reduction of the redox electrolyte, or transport holes in solid-state electrolyte. It requires high conductivity, excellent electrocatalytic activity, and overall stability [63].
- Noble metals like Platinum (Pt), Gold (Au), and Silver (Ag) have traditionally been used as CE materials due to their high electrocatalytic activity. However, their high cost and susceptibility to corrosion have led to the exploration of alternative materials [64].

- Carbon materials, including porous carbon, carbon nanotubes (CNTs), and graphene, are favored for their low cost, good electrocatalytic activity, high electrical conductivity, thermal stability, and corrosion resistance. Enhancements in electrocatalytic activity have been achieved by combining different carbon materials [65-66].
- Inorganic compounds like sulfides, carbides, nitrides, phosphides, tellurides, and metal oxides have potential applications in low-cost and large-scale DSSCs. However, they require further improvements in performance and stability [67].
- Conductive polymers, such as polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT), and polypyrrole (PPy), are used as CE materials, especially for transparent and flexible DSSCs. PEDOT is commonly used, and its solubility and electrical conductivity are enhanced through doping [68-69].
- Composite CEs, composed of two or more materials, combine the merits of each component. They have been extensively investigated, with examples including composites of carbon materials with other organic/inorganic materials.

**Table 3. Summary table for the types of CE materials:**

| CE Material Type | Examples | Advantages | Disadvantages | Ref |
|---|---|---|---|---|
| Noble Metals | Pt, Au, Ag | High electrocatalytic activity | High cost, susceptibility to corrosion | [64] |
| Carbon Materials | Porous carbon, CNTs, Graphene | Low cost, good electrocatalytic activity, high electrical conductivity, thermal stability, corrosion resistance | Requires combination for enhanced activity | [65-66] |
| Inorganic Compounds | Sulfides, Carbides, Nitrides, Phosphides, Tellurides, Metal Oxides | Potential for low-cost and large-scale DSSCs | Requires further improvements in performance and stability | [67] |
| Conductive Polymers | PANI, PEDOT, PPy | Used for transparent and flexible DSSCs, solubility and electrical conductivity can be enhanced through doping | Specific to certain types of DSSCs | [68-69] |
| Composite CEs | Composites of carbon materials with other organic/inorganic materials | Combines the merits of each component | Performance depends on the combination of materials | [67] |

### 5.5 Back Contact (Transparent Conducting Oxide - TCO):

In Dye-Sensitized Solar Cells (DSSCs), the back contact, also known as the Transparent Conducting Oxide (TCO), plays a crucial role. It allows light to pass through to the semiconductor layer while also serving as an electrical contact. The most commonly used materials for this purpose are Fluorine-doped Tin Oxide (FTO) and Indium Tin Oxide (ITO).

**5.5.1.Fluorine-doped Tin Oxide (FTO)**: FTO is a transparent conducting oxide that is well-suited for use in DSSCs due to its transparent and conductive nature[70]. It is composed of abundant elements, making it a cost-effective alternative to ITO. FTO has high thermal stability and is resistant to corrosion, making it suitable for high-temperature processes [70]. However, FTO has a higher surface roughness compared to ITO, which can be reduced by introducing an additional SnO2 coating[71].

**5.5.2. Indium Tin Oxide (ITO)**: ITO is another transparent conducting oxide commonly used in DSSCs. It is popular due to its lower surface roughness and excellent optical and electrical properties. However, the cost of ITO is relatively high due to the scarcity of indium. Moreover, indium migration from ITO can cause stability issues in DSSCs[70].

**5.5.3. Antimony-doped Tin Oxide (ATO):** ATO is an excellent candidate for transparent conducting oxides (TCOs) due to its high transparency with a large band gap (>3.6 eV), an inexpensive source, and good electrical conductivity. The doping of Sb in the SnO2 lattice without structural change leads to an improvement in the properties and performance of DSSCs. However, it is limited by its opto-electrical properties. The surface of the ATO conductive electrode increases the hydrophilicity due to high surface roughness compared to that of the undoped tin oxide (TO) electrode [72-73].

**5.5.4. Aluminium-doped ZnO Film (AZO):** AZO is another transparent conducting oxide used in DSSCs. Both zinc oxide (ZnO) nanorods and aluminium-doped zinc oxide (AZO) nanosheets were deposited by hydrothermal growth on fluorine-doped tin oxide (FTO) glass. After a photoanode was added to ZnO nanorods or AZO nanosheets, the photovoltaic conversion efficiency (PCE) increased due to improved electron transport and enhanced dye absorption. The addition of the ZnO nanorods increased the short-circuit current density (Jsc) from 9.07 mA/cm2 to 10.91 mA/cm2, the open circuit voltage (Voc) from 0.68 V to 0.70 V, and the PCE from 3.70% to 4.73%, respectively [74-76].

### Table 4. FTO and ITO:

| Material | Advantages | Disadvantages | Ref. |
|---|---|---|---|
| FTO | High thermal stability, corrosion resistance, cost-effective | Higher surface roughness | [70-71] |
| ITO | Lower surface roughness, excellent optical and electrical properties | High cost, potential stability issues due to indium migration | [70-71] |
| Antimony doped tin oxide (ATO) | Excellent candidate for transparent conducting oxides (TCOs), shows | Limited by its opto-electrical properties | [72-73] |

| | | | |
|---|---|---|---|
| | excellent electrical properties | | |
| Aluminium doped ZnO Film (AZO) | Transparent and electrically conductive, high transmission in the visible region | Low electrical conductivity and charge concentration | [74-76] |

**5.6. Substrates:**

In Dye-Sensitized Solar Cells (DSSCs), the substrate plays a vital role by providing the necessary structural support. The substrate, whether it's glass or plastic, provides crucial structural support and influences the efficiency, stability, and potential applications of the solar cell [65][77].

The choice between glass and plastic substrates indeed depends on the specific requirements of the solar cell. Glass substrates offer excellent durability and resistance to high temperatures, but they are heavier and more fragile compared to plastic substrates [78-79].

On the other hand, plastic substrates are lightweight and flexible, making them suitable for portable and flexible solar applications [80].

The substrate must be carefully prepared and treated to ensure good adhesion of the subsequent layers and overall performance of the DSSC. This often involves processes such as cleaning, etching, and the application of various coatings to enhance light absorption and reduce reflection [65].

Researchers continually explore new materials to improve the performance and sustainability of DSSCs [81]. The specific choice of materials can vary based on the design, efficiency requirements, and cost considerations of the DSSC [82].

## 6. Fabrication and Characterization of Dye-Sensitized Solar Cells (DSSCs)

Dye-sensitized solar cells (DSSCs) are a type of thin-film solar cell that convert sunlight into electricity. They consist of a semiconductor photoanode, a sensitizing dye, an electrolyte, and a counter electrode. The fabrication and characterization of DSSCs involve several key steps:

**6.1. Fabrication Process:**

- **Substrate Preparation**: The substrate, usually a transparent conducting material like fluorine-doped tin oxide (FTO) or indium tin oxide (ITO), is thoroughly cleaned to remove any contaminants [65][77].
- **Photoanode Preparation**: A layer of a semiconductor, typically titanium dioxide (TiO2), is deposited onto the substrate. The TiO2 layer is often nanoparticulate to provide a large surface area for dye adsorption [83].
- **Dye Adsorption**: A photosensitizing dye, often a metal complex like ruthenium-based dyes (e.g., N719 or N3), is adsorbed onto the TiO2 layer. The dye absorbs photons and generates electron-hole pairs [84-85].
- **Electrolyte Filling**: A liquid electrolyte containing a redox couple (e.g., $I^-/I_3^-$) is introduced into the cell to facilitate electron transport. Alternatively, solid-state or quasi-solid-state electrolytes can be used [81][86].

- **Counter Electrode Preparation**: A counter electrode, often composed of platinum-coated FTO or a conductive carbon material, is prepared. This electrode facilitates the reduction of the redox couple [87-89].
- **Sealing**: The DSSC is sealed to prevent the leakage of the electrolyte and protect the components. Sealing methods include thermoplastic seals or epoxy resins [81][90].

**6.2. Characterization Techniques:**

**6.2.1. Current-Voltage (I-V) Characteristics**: To understand how well a dye-sensitized solar cell (DSSC) performs, we look at several key parameters that act as indicators of its effectiveness. These parameters include the incident photon to current conversion efficiency (IPCE, %), short circuit current (JSC, $mAcm^{-2}$), open circuit voltage (VOC, V), maximum power output (Pmax), overall efficiency (η, %), and fill factor (FF). These metrics play a crucial role in evaluating the cell's performance under consistent exposure to light [77]

- **Power Conversion Efficiency (PCE):** PCE is a measure of how efficiently a solar cell converts incident light energy into usable electrical power. It is determined by three properties of the solar cell and one property of the incident spectrum.
- **Open-Circuit Voltage (Voc):** Voc is the maximum voltage achievable from a solar cell when no current is flowing. It corresponds to the forward bias on the solar cell due to the junction bias with light-generated current.
- **Short-Circuit Current (Jsc):** Jsc is the current through the solar cell when the voltage across it is zero, typically occurring when the cell is short-circuited. The short-circuit current is identical to the light-generated current.
- **Fill Factor (FF):** When the negative and positive electrodes of the cell are short-circuited at zero mV voltage, a current is generated. VOC represents the voltage across these electrodes under open circuit conditions at zero milliampere (mA) current. It essentially signifies the potential difference between the conduction band energy of the semiconducting material and the redox potential of the electrolyte. Pmax reflects the maximum efficiency of the DSSC in converting sunlight into electricity. The ratio of the maximum power output (Jmp × Vmp) to the product (VOC × JSC) gives the FF.

$$FF = \frac{(Jmp \times Vmp)}{(VOC \times JSC)}$$

The overall efficiency (η) indicates the percentage of solar energy converted into electrical energy on a photovoltaic (PV) device. η increases with a decrease in JSC and an increase in VOC, FF, and the molar coefficient of the dye.
External quantum efficiency, or IPCE, is the ratio of electrons flowing through the external circuit to photons incident on the cell's surface at any wavelength λ. The IPCE values are linked to light harvesting efficiency (LHE), electron injection quantum efficiency (φE1), and the efficiency of collecting electrons in the external circuit (ηEC).
Equations for these parameters are provided as follows:

**Overall Efficiency:** $\eta\% = \frac{JSC \times VOC \times FF}{Pin}$

**External Quantum Efficiency (IPC (%)** $= 1240 \times \frac{JSC}{\lambda Pin}$

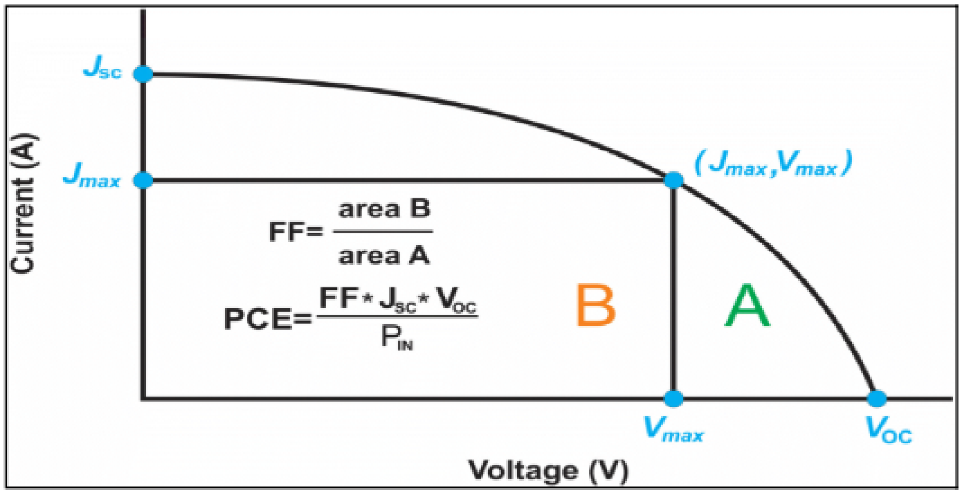



**Fig 8. I–V curve to evaluate the cells performance (taken from [Sharma et al., 2018])**

**6.2.2. Electrochemical Impedance Spectroscopy (EIS)**: Electrochemical Impedance Spectroscopy (EIS) is a technique utilized to investigate the charge transfer and transport mechanisms within a Dye-Sensitized Solar Cell (DSSC). It offers insights into electron recombination, dye regeneration, and the properties of the electrolyte. This method has become an essential tool for characterizing DSSCs. By analyzing the impedance spectrum with its equivalent circuit model, EIS can provide a comprehensive understanding of the electron transport processes and performance of DSSCs [91-93].

**6.2.3. UV-Visible Absorption Spectroscopy**: UV-Visible Absorption Spectroscopy emerges as a pivotal technique for examining the absorption characteristics of the dye on the TiO2 layer within Dye-Sensitized Solar Cells (DSSCs). This method plays a crucial role in understanding the efficiency of dye absorption of light. The absorption occurring in the visible range directly influences the perceived color of the involved chemical. This technique holds significance in the study of DSSCs, providing valuable information on the interaction between the dye and the TiO2 layer [94].

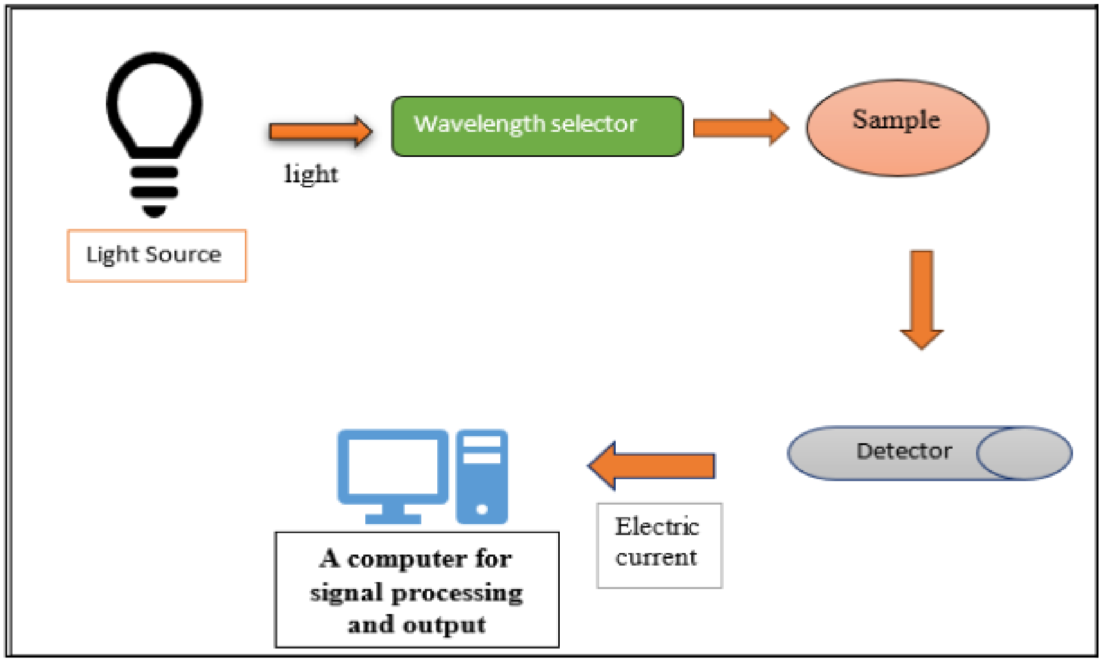



**Fig 9. A simplified schematic of the main components in a UV-Vis spectrophotometer.**

**6.2.4. Scanning Electron Microscopy (SEM)**: SEM is used for morphological analysis of the TiO2 layer, dye coverage, and overall cell structure. It provides insights into the surface properties of the photoanode [95-96]. Scanning Electron Microscopy (SEM) is a powerful tool used in the analysis of the TiO2 layer, dye coverage, and overall cell structure. Here's a simplified explanation of how it's used:

- **Morphological Analysis of the TiO2 Layer**: SEM helps in understanding the structure and form of the TiO2 layer. For instance, in the field of dye-sensitized solar cells (DSSCs), SEM has been used to analyze the effect of multidimensional TiO2 nanostructures on the performance of the cells. The hydrothermal method was used to synthesize TiO2 nanoparticles (TNPs), TiO2 nanorods (TNRs), and TiO2 nanotubes (TNTs) for photoanodes. The crystallinity, surface, and internal morphological changes were analyzed with SEM.
- **Dye Coverage**: SEM can provide insights into how well the dye covers the TiO2 layer. This is crucial in applications like DSSCs where the dye plays a key role in light absorption and the transfer of excited electrons.
- **Overall Cell Structure**: SEM is used to study the overall structure of cells. For example, in DSSCs, SEM images showed the formation of TiO2 film nanocoral with morphologies due to the effect of increasing the reaction times.

**6.2.5. X-ray Diffraction (XRD):** XRD is used to analyze the crystal structure of the TiO2 layer. It helps in understanding the crystallinity and phase composition of the semiconductor. X-ray Diffraction (XRD) is indeed a powerful technique used to analyze the crystal structure of the TiO2 layer. Here's a simplified explanation:

- **Crystal Structure Analysis**: XRD can provide insights into the crystal structure of the $TiO_2$ layer. For instance, it can help identify whether the $TiO_2$ is in the anatase or rutile phase [97]. These phases have different properties and are used in different applications.
- **Crystallinity**: XRD can determine the degree of crystallinity in the $TiO_2$ layer. This is important because the crystallinity can affect the properties of the material.
- **Phase Composition**: XRD can also be used to understand the phase composition of the $TiO_2$ layer. This can provide information about the presence of different phases (like anatase or rutile) in the material.

**6.2.6. Photocurrent Spectroscopy**: This technique involves illuminating the DSSC with monochromatic light and measuring the resulting photocurrent. It provides information about the action spectrum and efficiency of the dye [98-100]. Photocurrent Spectroscopy is indeed a valuable technique used in the study of Dye-Sensitized Solar Cells (DSSCs). Here's a simplified explanation:

- **Illumination and Measurement**: In this technique, the DSSC is illuminated with monochromatic light, and the resulting photocurrent is measured. This process is similar to Electrochemical Impedance Spectroscopy (EIS), but in this case, light is used instead of an electrical signal.
- **Action Spectrum Information**: The action spectrum refers to the relative effectiveness of different wavelengths of light at producing a response. In the case of DSSCs, this response is the generation of photocurrent. Photocurrent Spectroscopy can provide information about the action spectrum of the dye used in the DSSC.
- **Efficiency of the Dye**: The efficiency of the dye refers to how effectively it can absorb light and generate photocurrent. Photocurrent Spectroscopy can provide insights into the efficiency of the dye.

**6.2.7. Stability Testing**: DSSCs are subjected to stability tests under different conditions (e.g., prolonged light exposure, temperature variations) to assess their long-term performance and durability [101-104]. Stability Testing is indeed a critical aspect of Dye-Sensitized Solar Cells (DSSCs) research. Here's a simplified explanation:

- **Prolonged Light Exposure**: DSSCs are often subjected to long-term light exposure to assess their stability. This is because in real-world applications, these cells will be exposed to sunlight for extended periods. The performance of DSSCs can degrade over time due to factors like dye degradation, electrolyte evaporation, etc.
- **Temperature Variations**: DSSCs are also tested under different temperature conditions. High temperatures can affect the performance of DSSCs. For instance, exposure to sunlight increases the temperature of the internal component of DSSC and consequently degradation in device performance.
- **Long-term Performance and Durability**: The long-term stability of DSSCs is a crucial factor for their practical application. Studies have shown that with the right choice of materials and protective measures like plastic covers, long-term stability can be achieved.

**6.2.8. Optimization and Improvement**: Based on the characterization results, researchers aim to optimize DSSCs by improving various parameters such as the choice of dye, semiconductor materials, electrolyte composition, and overall cell design. Continuous research efforts focus on enhancing efficiency, stability, and cost-effectiveness for practical applications [81][85] [105-106]. Optimization and improvement of Dye-Sensitized Solar Cells (DSSCs) are indeed crucial areas of research. Here's a simplified explanation:

- **Choice of Dye**: The choice of dye is a significant factor in the performance of DSSCs. Researchers are exploring both organic (natural and synthetic) and inorganic (ruthenium) dyes. Natural dyes are considered a viable alternative due to their low cost, easy utility, abundant supply of resources, and no environmental threat.
- **Semiconductor Materials**: The type of semiconductor material used can greatly affect the efficiency of DSSCs. For instance, TiO2 is commonly used, but researchers are exploring other materials as well.
- **Electrolyte Composition**: The composition of the electrolyte can also impact the performance of DSSCs. Researchers are investigating different electrolyte compositions to enhance the efficiency of DSSCs.
- **Overall Cell Design**: The design of the cell, including factors like the thickness of the film, the nature of FTO/ITO glasses, and the anode and cathode electrodes, plays a crucial role in the performance of DSSCs.
- **Efficiency, Stability, and Cost-effectiveness**: Continuous research efforts are focused on enhancing the efficiency, stability, and cost-effectiveness of DSSCs for practical applications. For instance, six different optimization algorithms are used for DSSC parameter extraction, including the genetic algorithm, grey wolf algorithm, dragonfly algorithm, moth flame algorithm, ant-lion algorithm, and whale algorithm.

## 7. Major challenges and limitations faced by dye-sensitized solar cells

Dye-sensitized solar cells (DSSCs) have shown promise in various applications, but they face several challenges and limitations that impact their widespread adoption. Here's a discussion on some of the major challenges:

### 7.1. Degradation Mechanisms:

- **Dye Degradation:** Organic dyes used as sensitizers can degrade over time due to exposure to light, temperature, and other environmental factors, leading to reduced light absorption and cell efficiency[107-108].
- **Electrolyte Decomposition:** The liquid electrolyte in traditional DSSCs may undergo decomposition over extended periods, impacting cell performance and stability [109-110] .

### 7.2. Long-Term Stability:

- **Sensitivity to Moisture:** DSSCs are sensitive to moisture, which can lead to corrosion of electrodes and degradation of the electrolyte [77][111].
- **Encapsulation Challenges:** Ensuring effective encapsulation to protect the cell components from environmental factors is a challenge, especially for flexible and lightweight DSSCs [111].

### 7.3. Scalability for Large-Scale Production:

- **Complex Fabrication Processes:** The traditional fabrication processes involve multiple steps, such as sensitization, electrode deposition, and electrolyte filling, which can be complex and time-consuming [85].
- **Material Costs:** While some materials used in DSSCs are cost-effective, the reliance on expensive counter electrodes (platinum or gold) can impact overall production costs.
- **Limited Scalability:** Scalability for large-scale production remains a challenge, especially when compared to well-established technologies like silicon solar cells.

### 7.4. Efficiency and Performance Variability:

- **Sensitivity to Fabrication Conditions:** DSSC performance can vary based on the fabrication conditions, making reproducibility and quality control challenging [113-114].
- Spectral Sensitivity: DSSCs may have a limited spectral sensitivity, especially in the infrared region, which can affect overall energy conversion efficiency [85][115].

### 7.5. Electrolyte Volatility:

- **Liquid Electrolyte Issues:** Liquid electrolytes used in traditional DSSCs can be volatile and susceptible to leakage or evaporation, leading to long-term stability concerns [109][116].

### 7.6. Toxicity and Environmental Impact:

- **Heavy Metal Usage:** Some DSSCs may use heavy metals in components like counter electrodes, posing environmental concerns and limiting their sustainability [86][117].

### 7.7. Competition with Emerging Solar Cell Technologies:

- **Rapid Advancements in Perovskite Cells:** Perovskite solar cells have emerged as a strong competitor with rapid advancements in efficiency and stability, posing a challenge to the adoption of DSSCs [109][118].

### 7.8. Temperature Sensitivity:

- **Performance in Extreme Temperatures:** DSSCs may exhibit performance degradation in extreme temperature conditions, affecting their suitability for certain environments [119].

While DSSCs have unique advantages, including flexibility and ease of fabrication, addressing the challenges related to degradation mechanisms, long-term stability, and scalability for large-scale production is crucial for their continued development and commercial viability. Ongoing research focuses on mitigating these challenges through the exploration of new materials, fabrication techniques, and encapsulation strategies. As advancements in materials science and engineering continue, DSSCs may become more competitive and find niche applications in the broader landscape of solar energy technologies.

## 8. Current Research Efforts and Technological Advancements in Dye-Sensitized Solar Cells (DSSCs):

### 8.1. Novel Materials for Sensitizers and Electrolytes:

- **Perovskite Sensitizers:** Research focuses on incorporating perovskite materials as sensitizers to enhance light absorption and improve stability [120].
- **Metal-Free Organic Dyes:** Exploration of metal-free organic dyes with improved stability and absorption characteristics [121-123].

### 8.2. Stability-Enhancing Strategies:

- **Molecular Design:** Tailoring the molecular structure of sensitizers and electrolytes to improve chemical stability and reduce degradation [124-125].
- **Inorganic Electrolytes:** Investigation of inorganic electrolytes to address the volatility and stability issues associated with liquid electrolytes [126-129].

### 8.3. Advanced Device Engineering:

- **Tandem and Multiple Cells:** Implementing tandem and multiple-cell configurations to maximize light absorption and minimize recombination losses [130].
- **Transparent Conductive Oxides (TCOs):** Utilizing TCOs with enhanced conductivity and stability as alternatives to traditional counter electrodes [65][131-133].

### 8.4. Surface Passivation Techniques:

- **Advanced Passivation Layers:** Employing advanced passivation layers, such as ALD-deposited materials, to reduce recombination and improve long-term stability [81]
- **Functional Coatings:** Developing functional coatings to protect the semiconductor surface from environmental factors [134] .

### 8.5. Innovative Manufacturing Techniques:

- **Printing Technologies:** Exploring printing techniques, such as inkjet and screen printing, for cost-effective and scalable production [135-137].
- **Roll-to-Roll Processing:** Implementing continuous roll-to-roll processing for large-scale manufacturing, enhancing scalability and reducing production costs [138-139].

### 8.6. Dye and Material Engineering:

- **Quantum Dot Sensitizers:** Investigating the use of quantum dots as sensitizers to enhance electron injection and reduce recombination [120].
- **Conductive Polymers:** Incorporating conductive polymers as charge transport materials to improve overall cell performance [120].

### 8.7. Advanced Encapsulation Techniques:

- **Nanostructured Encapsulation:** Developing nanostructured encapsulation materials to enhance barrier properties and protect against moisture and environmental degradation [81].
- **Flexible Encapsulation:** Designing flexible encapsulation methods for use in lightweight and flexible DSSCs [81].

**8.8. Machine Learning and Optimization Algorithms:**

- **Computational Modeling:** Employing machine learning and computational modeling to optimize device parameters, sensitizers, and electrolytes for enhanced performance.
- **Data-Driven Design:** Utilizing data-driven design approaches to predict and optimize material properties for improved stability and efficiency [120].

8.9. **Environmental Sustainability:**

- **Green Synthesis:** Exploring environmentally friendly and sustainable synthesis methods for materials to minimize the environmental impact of DSSC production [120].

## 9. Applications and Future Prospects of Dye-Sensitized Solar Cells

Dye-Sensitized Solar Cells (DSSCs) are a promising technology in the field of renewable energy. Here are some applications and future prospects of DSSC technology:

### 9.1. Applications:

- **Powering Electronic Applications**: DSSCs are an efficient photovoltaic technology for powering electronic applications such as wireless sensors with indoor light [81].
- **Flexible Solar Modules**: Their capability to be manufactured as thin and lightweight flexible solar modules highlights their potential for economic indoor photovoltaics [81].
- **Portable Electronics and IoT Devices**: There is a need to design new stability testing protocols to assess the probable deployment of DSSCs in portable electronics and internet-of-things devices [81].

**9.2. Future Prospects**:

- **Use of Organic and Inorganic Dyes**: Currently, DSSCs utilize organic (natural and synthetic) dye and inorganic (ruthenium) as a sensitizer [85] . The nature of these dyes, combined with different variables, has brought about a change in their use [85].
- **Alternative to Expensive Dyes**: Natural dyes are being seen as a viable alternative to expensive and rare ruthenium dye due to their low cost, easy utility, abundant supply of resources, and no environmental threat [85].
- **Advancements in DSSC Components**: There has been significant progress in the development of new device structures, alternative redox shuttles, solid-state hole conductors, TiO2 photoelectrodes, catalyst materials, and sealing techniques [81].
- **Sustainability and Safety**: The focus is also on the sustainability of materials and processes in DSSC fabrication [81].
- **Use of Renewable Materials**: There is interest in bio- or waste-derived renewable materials for DSSCs [81].
- **Flexible and Wearable DSSCs**: DSSCs are being developed for flexible and wearable applications [81].
- **Integrated Devices**: Efforts are being made to integrate DSSCs with an energy storage unit, like batteries or supercapacitors [81].

These advancements are expected to enhance the efficiency, sustainability, and applicability of DSSCs in the future. However, more research and development are needed to overcome the challenges and realize the full potential of this technology.

## 10. CONCLUSION

In closing, dye-sensitized solar cells (DSSCs) present an exciting prospect for reshaping the energy paradigm, given their unique advantages, such as affordability, ease of fabrication, and adaptability across a wide spectrum of light wavelengths [29]. The lightweight and flexible characteristics of DSSCs further amplify their potential applications, extending to portable electronics, building-integrated photovoltaics, and wearable technology.

Despite these promising attributes, challenges persist in the realm of DSSCs, notably their lower efficiency when compared to conventional silicon-based solar cells, acting as a hurdle to widespread adoption [140]. To unlock their full potential, it is imperative to sustain research and development endeavors. Resolving efficiency, stability, and scalability issues stands paramount to transforming DSSCs into a commercially viable and competitive option for sustainable energy generation.

In summary, while DSSCs offer a compelling avenue for clean energy production, their journey into mainstream energy usage necessitates ongoing dedication to surmount existing limitations. Through unwavering research and development efforts [29][140], DSSCs could emerge as a pivotal and influential player in realizing a more sustainable and renewable energy future.

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