

Review

Current Status and Prospects for the Development of Emerging Photovoltaic Technologies

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Abstract

Third-generation photovoltaic (PV) technologies, such as dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), quantum-dot solar cells (QDSSCs), and perovskite solar cells (PSCs), are characterized by properties that enable applications beyond conventional silicon-based devices. However, despite remarkable progress in third-generation solar cells, significant challenges related to efficiency, stability, scalability, and commercialization remain significant. The purpose of this review work was to summarize recent developments in third-generation photovoltaic technologies, including component materials design, configurations, performance data, limitations, and future research directions. The reported studies demonstrated crucial improvements in power conversion efficiency, which exceeded 15% for DSSC, 20% for OSC, 12% for QDSSC, and 26% for PSC. The key challenges to commercialization include further improvements in efficiency, better stability, and meeting the environmental requirements. Although important technological and environmental challenges remain, third-generation solar cells are expected to contribute to future sustainable energy systems due to their high efficiency potential, low-cost fabrication, and possible incorporation of environmentally friendly materials in the structure of the cells. The photovoltaic performance under indoor conditions and the aspect of a sustainable approach were identified as recent research trends.

Keywords: photovoltaics; third-generation solar cell; perovskite cell; organic cell; dye-sensitized solar cell; quantum dot-sensitized solar cell

1. Introduction

The development of photovoltaics is crucial for addressing global energy demand, as well as environmental and economic challenges. According to forecasts by the International Energy Agency, annual photovoltaic capacity additions will increase for the next five years [1]. Photovoltaic technologies enable the direct conversion of solar radiation into electricity, thereby contributing to the reduction in air pollution accompanying combustion of traditional fuels. The energy of solar radiation is abundant and widely distributed; thus, photovoltaics enhance energy security and reduce dependence on fossil resources as well as geopolitical constraints.

Solar cell development is commonly divided into three generations based on materials and operating principles. First-generation solar cells are based on crystalline silicon, including monocrystalline and polycrystalline wafers. They dominate the market due to

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high efficiency, long-term stability, and well-established manufacturing processes but require relatively high material and energy input. Second-generation solar cells are thin-film technologies such as amorphous silicon, CdTe, and CIGS. These cells use less material and allow flexible substrates, reducing costs, although their efficiencies are generally lower than crystalline silicon. Third-generation solar cells include novel concepts, such as dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), quantum dot-sensitized solar cells (QDSSCs), perovskite solar cells (PSCs), and hybrid tandem photocells which integrate different classes of materials [2,3].

Conventional photovoltaic technologies, particularly silicon-based cells, are approaching theoretical efficiency limits and require complex energy-intensive manufacturing processes. Emerging technologies, which are not based on traditional semiconductor p-n junctions, offer the potential for lower production costs, reduced material consumption, and compatibility with lightweight or flexible substrates. These advantages enable new applications, including building-integrated photovoltaics, portable or wearable electronics, and the development of the Internet of Things (IoT) based on performance under low light conditions [4,5]. Continued development of emerging photovoltaic technologies is therefore essential for expanding solar energy deployment and achieving long-term energy sustainability.

A comprehensive review of third-generation solar cells is necessary to critically summarize recent advances, compare photovoltaic performance, identify existing limitations, and outline future research directions for the development of efficient as well as commercially promising next-generation solar technologies. This work provides an updated review of the progress in component innovations, architectures, and performance of emerging solar cells. Modifications in the area of photoactive materials, electron transport layer, hole transport layer, and electrodes were described, and the novel innovations of the structure of the photocells were also presented.

The overview of the current status of third-generation solar cells indicates promising strategies and provides insights into the current challenges in terms of commercialization. Furthermore, this work indicates the recent trends in research on emerging photovoltaics, including the impact on sustainable solutions and environmental responsibility, as well as the growing interest in the investigations of novel photocells under artificial lighting conditions. Moreover, contrary to the vast majority of reviews in this field, all technologies belonging to the third generation are presented in a single review.

This work can help in understanding differences in technologies, the role of particular components of the photocells and their configurations, as well as obstacles in the widespread adoption of emerging photovoltaics. This review indicates the most promising technologies, the prospective pathways of investigations in the near future, and new application fields.

The article is divided into sections devoted to specific emerging photovoltaic technologies. Section 3 introduces DSSCs, including recent progress in material components, with particular emphasis on advances in sensitizers and electrolytes, which are key elements of the DSSC technology. Section 4 discusses OSCs, focusing on novel acceptor materials and various device configurations. Section 5 presents the characteristic properties of quantum dots and their limitations when used as sensitizers in QDSSCs. PSCs are discussed in Section 6, including recent achievements in perovskite absorber development and the remaining technological challenges. Section 7 is devoted to hybrid photovoltaic technologies, particularly tandem perovskite/silicon structures, the operating principle, and recent achievements in device performance. Finally, Section 8 presents the future perspectives for third-generation photovoltaics, and the subsections address indoor applications of third-generation solar cells, the challenges related to commercialization, and the

environmental concerns associated with the large-scale deployment of emerging photovoltaic technologies.

2. Methods

The presented review was conducted through a comprehensive analysis of the recently published literature related to third-generation solar cells, with particular emphasis on material development, device architecture, photovoltaic performance, and stability enhancement strategies. Relevant research articles and review papers were collected from scientific databases (e.g., Scopus, Science Direct, Web of Science) using the keywords associated with dye-sensitized, organic, quantum dot-sensitized, perovskite, and hybrid solar cells. The selected literature was evaluated according to the significance of the reported data and the year of publication.

3. Dye-Sensitized Solar Cells

The development of dye-sensitized solar cells (DSSCs) is based on the sensitization process, well-known in photoelectrochemistry. The modern advancement of DSSCs began in 1991, when Brian O'Regan and Michael Grätzel reported a highly efficient dye-sensitized solar cell using a nanocrystalline TiO_2 electrode and a ruthenium-based dye [6]. For over a decade, a DSSC was the only technically feasible alternative to conventional solid-state photovoltaic devices. The application of spectrally selective dye extended the light absorption range and improved charge separation, establishing the operating concept of contemporary DSSCs and stimulating extensive research on other low-cost, solution-processed photovoltaic technologies.

3.1. DSSC Structure and Operation Principle

A dye-sensitized solar cell is a photoelectrochemical device that converts solar energy into electrical energy. The photoanode, which consists of glass with a transparent conductive fluorine-doped tin layer (FTO), is an illuminated electrode. A layer of titanium dioxide nanoparticles forms a mesoporous coating of the photoanode, onto which dye molecules are adsorbed. As a result of photon absorption, the dye molecule becomes excited, and it injects an electron into the conduction band of TiO_2 . Then, nanostructural TiO_2 accepts electrons and enables electron transport through the porous layer of TiO_2 to the conductive coating of the glass electrode and to the external circuit. When the electrons reach the counter electrode, they reduce oxidized species of the electrolyte in a reaction, which is catalyzed by a platinum coating. The electrolyte completes the electric circuit by transporting charge (redox species) from the counter electrode. The dye molecule is restored to the ground state as a result of electron donation from iodide ions in the electrolyte. The components of a DSSC and the scheme of operation cycle involving a sequence of photo-physical and photoelectrochemical steps are presented in Figure 1.

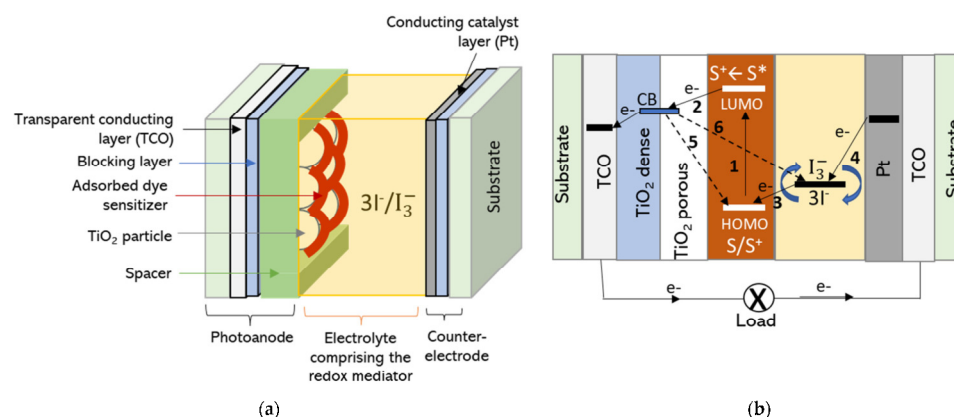


Figure 1. Structure of the DSSC (a) and charge transfer processes numbered 1 to 6 (b). S^* is an excited state of sensitizer. Copied with no changes under Creative Commons Attribution 4.0 International License from: [7].

3.2. Materials

3.2.1. Electron Transport Layer

In a dye-sensitized solar cell, titanium dioxide acts as the electron-accepting material and the electron transport layer (ETL). The nanostructured form of TiO_2 provides a high internal surface area for the adsorption of sensitizer molecules, leading to enhancement of light absorption and photocurrent generation. The mesoporous TiO_2 coating is typically deposited in the form of a paste of P25 nanoparticles by the doctor blade method and then sintered at a high temperature of 450 °C. The bottom of the conduction band of TiO_2 lies lower than the excited state of many commonly used dyes, ensuring favorable alignment of energy levels for efficient and fast transfer of electrons, which limits recombination losses. The advantage of titanium dioxide is its chemical stability, resistance to photocorrosion, abundance, and low cost.

Numerous modifications of TiO_2 photoelectrodes have been introduced in recent years to improve the overall photovoltaic performance of DSSCs. Due to deposition of double-layer microspheres/P25, the photoelectric conversion efficiency increased to 5.61%, compared with 2.67% for a traditional P25 single layer of TiO_2 and 2.14% for a TiO_2 microspheres layer [8]. Conventional P25 TiO_2 is characterized by high transparency but limited light scattering ability, resulting in an incident photon to current efficiency (IPCE) value of approximately 30–40%. However, the introduction of a double-layer architecture increases the IPCE to 70–80%. The additional layer consists of TiO_2 microspheres with anatase crystalline structure, which forms a mesoporous network with a pore size in the range of 2–9 nm. Electrochemical impedance spectroscopy analysis indicates that the double layer exhibits the lowest charge transfer resistance compared with each studied single layer of TiO_2 .

Improvement of photovoltaic performance was also reported for the photoanodes featuring a double-layer structure composed of transparent TiO_2 , deposited by a solution-processed spin-coating, and dispersed TiO_2 , deposited by the doctor blade method [9]. A similar approach, based on enhanced light scattering by popcorn-like TiO_2 aggregates, enabled the achievement of a power conversion efficiency of 7.56% [10]. The photoanode covered with the commercial P90 TiO_2 layer coated by sensitizer and popcorn-like layer exhibited a large surface area, anatase structure, and excellent light scattering ability. Moreover, the popcorn-like aggregates, which were synthesized with an easy solution method, present beneficial charge transfer resistance and extended electron lifetime. Morphological improvements of TiO_2 resulted in an increase in efficiency from 1.4% to 3.5%,

also for a dye cell with nanorods instead of traditional nanoparticles. In this case, TiO₂ nanorods were grown on an ultrathin TiO₂ prepared using the sol–gel method [11].

In addition to TiO₂, zinc oxide (ZnO) was investigated in a variety of nanostructured forms as an alternative electron transport material in DSSCs. Figure 2 shows images of TiO₂ nanoparticles and, for comparison, a ZnO nanorod layer deposited on the photoanode. ZnO in forms such as nanostars or nanoplates, synthesized using hydrothermal methods, served as the photoanode material in DSSCs, which achieved efficiency exceeding 7% for both nanostructures [12]. The relatively high value of efficiencies obtained with N719 sensitization of those cells was an effect of improved interfacial contact facilitated by the addition of electrolyte containing 1-ethyl-3-methylimidazolium iodide, which enhances electron transfer from the dye molecule to ZnO with a broadened energy bandgap.

Another approach, in which TiO₂ was substituted by gadolinium ruthenate pyrochlore oxide Gd₂Ru₂O₇ (GRO) as a novel semiconductor material for photoanode fabrication, successfully yielded a PCE of 9.65% and an open circuit voltage of 3.82 V, when a natural sensitizing dye extracted from *Hibiscus sabdariffa* was employed [13].

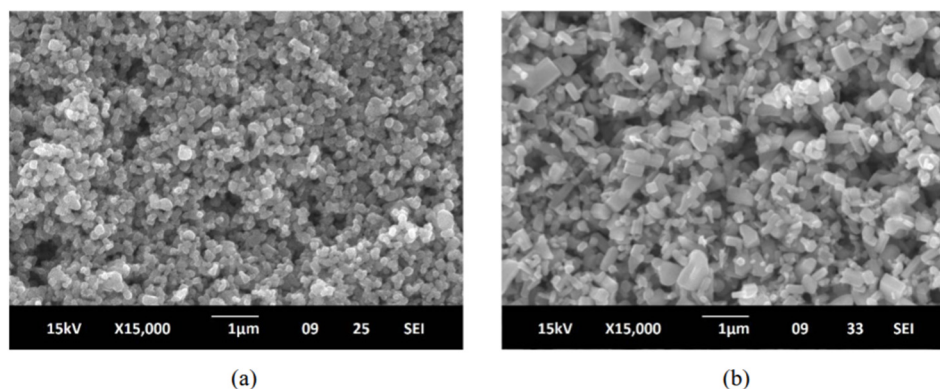


Figure 2. SEM image of photoanode covered with TiO₂ nanoparticles of a 19 nm size (a) and ZnO nanorods of a 41.6 nm size (b). Copied with no changes under Creative Commons Attribution 3.0 International License from: [14].

3.2.2. Sensitizers

Since the pioneering research on DSSCs published in 1991 [6], organometallic sensitizers based on ruthenium have remained among the most efficient single dyes for DSSCs employing a liquid electrolyte. Among these sensitizers, N3 dye (cis-Ru(II) polypyridyl with thiocyanates), N719 dye (tetrabutylammonium salt of a Ru(II) complex), and N749 black dye (terpyridine ruthenium complex with broad visible absorption) achieved power conversion efficiencies of approximately 10–11% that represented benchmarks in the development of the DSSC technology. The mentioned N719 dye is widely used as a reference standard dye in the majority of studies on DSSCs, against which newly developed sensitizers are compared and evaluated [15,16]. The sensitizing dye is deposited during the immersion of the photoanode in a dye solution. A common feature of the ruthenium dyes is their broad absorption in the visible region up to 500 nm for N3 dye and 750 nm for N719 dye, extending to near-infrared (around 860 nm) for the black dye [17,18]. These leading ruthenium dyes also offer favorable energy alignment between the dye LUMO level and the bottom of the TiO₂ conduction band, leading to high electron injection efficiencies. These characteristics led to a very high IPCE value of dye cells, with the peak of around 80–85% [19]. Ruthenium dyes have numerous advantages, but ruthenium is considered a critical element, known for extreme scarcity, which motivates the ongoing efforts to develop alternative synthetic sensitizers as well as natural dyes for application in DSSCs.

Other metal-based complexes applied as sensitizers in DSSCs include porphyrins, the molecules of which contain a central metal ion coordinated by pyrrole units. This type of dye can rival or even outperform traditional ruthenium complexes, reaching a PCE of 12–13%. For example, DSSCs sensitized with SM315 porphyrin dye achieved an efficiency of 13% using a cobalt-based electrolyte [20], and an efficiency of 11.9% was obtained by YD2-o-C8 push–pull zinc porphyrin [21]. The strategy focused on optimization of the structure of porphyrin dyes, which limits dye aggregation and charge recombination, improving the overall photovoltaic performance of DSSCs. Through molecular engineering and the introduction of alternative electrolytes, porphyrin dyes are among the leading sensitizers for DSSCs.

Moreover, synthetic metal-containing derivatives of phthalocyanines, such as Zn-Pc-dg, Co-Pc-dg, Zn-Pc-dp, and Co-Pc-dp, were investigated as sensitizers. A PCE of 2.45% was obtained by the dyes with shorter glycolic acid chains (dg) [22]. The improved performance is attributed to the shorter electron transport path in diglycolic acid-substituted complexes.

Another class of sensitizers employed in DSSCs consists of purely organic, metal-free compounds considered as more environmentally friendly [23]. Among them, the molecules following a donor- π -acceptor (D- π -A) structure facilitate light absorption, electron transfer from the dye molecule to the semiconductor, and regeneration of the dye [24–26]. Above all, an advantage of metal-free dye is that it is lower cost and has better environmental compatibility linked to the absence of rare or expensive metals such as ruthenium. Additional benefits include high molar extinction coefficients and tunable optoelectronic and electrochemical properties, which can be optimized during molecular synthesis [27,28]. An example is a recently developed dye, MRS-3, which incorporates pyrene units serving as a donor, furan moieties as a π -spacer to extend light absorption, and dicyanovinyl as an electron acceptor. The MRS-3 dye co-sensitized with SA-10 dye provided a PCE of 10.15% [29].

A widely available group of sensitizers consists of plant-derived pigments, which can be easily extracted directly from various parts of plants and are environmentally benign. Specific classes of natural dyes occur in various plants, for example, anthocyanins in berries, red cabbage, fruits, and flowers; flavonoids in grapes, citrus fruits, and berries; chlorophyll in spinach and broccoli; betalains in beetroot; and carotenoids in carrots, tomatoes, and fruits [30]. Functional groups present in molecules of natural dyes, such as –OH or –COOH, act as anchoring sites for adsorption onto TiO₂ [31–33]. When applied to photoelectrodes, natural dyes exhibit absorption of light in a broad spectral range. Common solvents for these pigments include ethanol or methanol, and the adsorption process of a dye onto the semiconductor can be enhanced by increasing the temperature.

Although valued for their environmental compatibility, natural dyes generally suffer from poor photostability and exhibit lower conversion efficiencies compared with synthetic dyes. Table 1 presents photovoltaic parameters obtained by DSSCs sensitized with different synthetic and natural sensitizers.

In addition to the dyes extracted from plants, the natural bacterial pigment prodigiosin was also investigated. The absorption range of the pigment can be tuned by adjusting pH; however, the resulting DSSCs exhibited a very low PCE, reaching only 0.047% [34].

Another significantly more successful approach is co-sensitization, which involves two or more dyes with complementary spectral absorption to improve light harvesting, particularly in the near-infrared region. Co-sensitization improves the PCE by reducing dye aggregation, suppressing charge recombination, and increasing electron lifetime. Common strategies include combining ruthenium-based dyes (e.g., N719) with organic or natural dyes. An example is a mixture of two dyes, N719 and 3,7'-bis(2-cyano-1-acrylic acid)-10-ethyl-phenothiazine (AC-9), together with a co-adsorbent additive to limit the

formation of aggregates, which achieves an efficiency of 6.97% [35]. The studies focusing on co-sensitization with a ruthenium-based N3 dye and novel, synthetic acidic dyes (ME-1 and ME-2) also showed promising improvements in light absorption and electron transport. In particular, the N3 dye combined with novel organic ME-2 dye, derived from thiazole compounds, achieved a PCE of 10.11%, attributed to excellent charge transfer properties confirmed by electrochemical impedance spectroscopy [36].

Carbazole and indoline dyes were also extensively investigated as co-sensitizers in DSSCs, providing an efficiency exceeding 9%. Representative dyes from these two classes, carbazole MK-2 dye and indoline D205 dye, were employed in a co-sensitization strategy to extend the light absorption range. Figure 3 presents the absorption spectra of two dyes before and after adsorption on the photoanode. Individually, MK-2 and D205 provided a PCE of 4.82% and 4.24%, respectively; however, their mixture improved efficiency to 5.41% [37]. A recent study on a mix of novel push–pull phthalocyanines and YD2 porphyrin also reported highly promising results. Among the tested combinations, the mixture of YD2 and TiOPc2 was the most effective, extending the solar absorption range and achieving a DSSC efficiency of 12.28% [38].

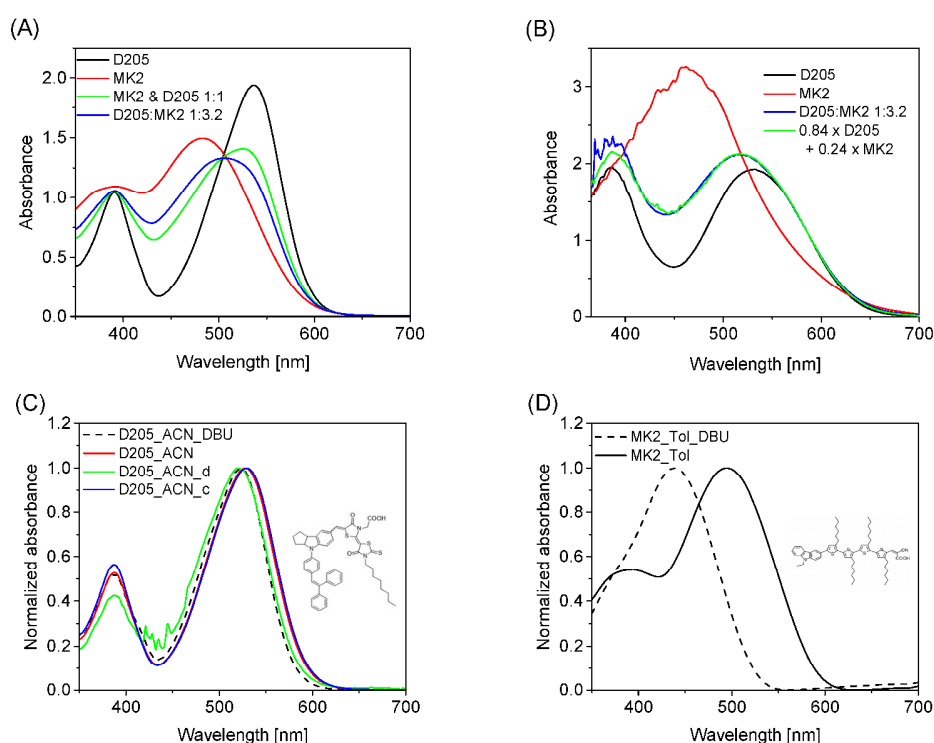


Figure 3. Absorption spectra of the dyes (A), co-sensitized photoanodes (B), absorption of D205 dye in ACN (C), and absorption of MK-2 dye in Tol and Tol with DBU (D). Copied with no changes under Creative Commons Attribution 4.0 International License from: [37].

Table 1. Photovoltaic parameters of dye-sensitized solar cells: J_{sc} —density of short circuit current, V_{oc} —open circuit voltage, FF —fill factor, and η —efficiency. Photovoltaic parameters of the cells are determined under standard test conditions (STCs) (temperature of 25 °C, irradiance 1000 W/m², air mass AM1.5G).

Year	Dye	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)	Ref.
2020	Ruthenium sensitizers	1.43–5.13	0.254–0.620	0.45–0.7	0.54–2.25	[39]
2020	Ruthenium dye RhB	3.91	0.54	0.67	1.42	[40]
2020	Ruthenium dye D149	13.33	0.72	0.69	6.67	[40]
2020	Porphyrin TH-2F	16.07	0.68	0.63	6.98	[41]

2020	Synthetic SGT-149 + SGT021, Co electrolyte	20.86	0.912	0.73	13.9	[42]
2020	Synthetic SGT-149 + SGT021, iodide electrolyte		0.722	0.70	11.6	[42]
2021	Phthalocyanine Zn metal complex	4.70	0.63	0.69	2.04	[43]
2022	Blueberry/TiO ₂	0.82	1.18	0.4	0.39	[44]
	Anthocyanin					
2022	Pomegranate/TiO ₂	5.86	0.35	0.45	0.93	[44]
2022	Black grape/TiO ₂	6.69	0.52	0.3	1.05	[44]
2022	Blueberry/ZnO	7.12	0.79	0.5	2.81	[44]
2022	Pomegranate/ZnO	7.12	0.71	0.6	3.03	[44]
2022	Black grape/ZnO	9.72	0.73	0.51	3.63	[44]
2023	MK-2	3.45–19	0.63–0.74	0.33–0.62	0.72–6.72	[45]
2023	N3	16.92	0.59	0.62	6.28	[46]
2025	Anthocyanins + chlorophyll	0.276	0.512	0.313	0.0197	[47]
2025	Anthocyanins, pomegranate	1.063	0.4	0.312	0.132	[34]
2025	Anthocyanins, hibiscus	1.701	0.361	0.322	0.2	[34]
2025	Crude extract from Lonchocarpus cyanescens	4.25	0.44	0.626	0.116	[48]
2025	Semi-pure extract from Lonchocarpus cyanescens	2.48	0.44	0.523	0.057	[48]
2025	Black dye	16.68	0.665	0.67	7.49	[49]
2025	phenylfluorone	0.73	0.465	0.436	0.17	[50]

The photovoltaic parameters of co-sensitized dye cells are presented in Table 2. The highest laboratory scale-certified efficiency of 15.2% was exhibited by DSSCs co-sensitized with newly designed SL9 and SL10 dyes [51]. This record efficiency is ascribed to absorption of the entire visible spectrum and improvement in electron collection by the pre-adsorption of a monolayer of a hydroxamic acid on TiO₂ before the adsorption of dye molecules.

Table 2. Photovoltaic parameters of co-sensitized dye cells determined under STCs.

Year	Dyes	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)	Ref.
2018	Betain + chlorophyll	1.25	0.53	0.68	0.6	[52]
2021	Coomassie R-250 + N719	15.86	0.89	0.759	10.92	[53]
2022	D205 + MK-2	11.32	0.72	0.66	5.41	[37]
2023	Beetroot + cranberry	0.36	0.42	0.51	0.076	[54]
2023	Pomegranate + cranberry	0.359	0.45	0.55	0.09	[54]
2023	Pomegranate + beetroot	0.167	0.45	0.55	0.041	[54]
2023	SL9 + SL10/BPHA/EL1	17.5	1.04	0.82	15.2 (certified)	[51]
2023	5a + N3	18.14	0.676	0.60	7.42	[46]
2024	MSW-3 + N719	21.96	0.791	0.58	10.2	[55]

3.2.3. Counter Electrode

The typical coverage of the counter electrode in DSSCs is a thin layer of nanosized platinum, which exhibits excellent photocatalytic and electrical properties, as well as high corrosion resistance. Platinum is deposited from chloroplatinic acid solution, which is drop-cast and spin-coated and then annealed at a temperature of 350 °C to 450 °C. However, the high cost of platinum motivates the search for more abundant alternative materials. Potential, valuable substitutes for platinum include carbon nanomaterials, which attract significant attention due to high catalytic activity enhanced by a large surface area and a superior electrical and thermal conductivity, which promotes charge transport and reduces charge transfer resistance [56]. For example, the graphene fabricated via a laser-induced process on a polyimide demonstrated lower charge transfer resistance than a

platinum electrode. When comparing graphene with PEDOT-coated ITO/PET, both flexible materials showed that DSSCs with graphene counter electrodes achieved approximately 60% higher photoconversion efficiency [57]. Furthermore, laser-induced graphene is thermally and chemically stable and compatible with both iodide- and copper-based electrolytes.

The attention is also focused on multiwall carbon nanotubes, which, in addition, can improve the properties of metal oxides because they offer high surface area, good conductivity, and chemical stability. The example is a counter electrode coated with the unique structure of MoWO_4 , with the ZnO nanoflowers grown on multi-walled carbon nanotubes by a hydrothermal method [58]. Due to the synergistic advantages of the components, the obtained nanocomposite outperformed the platinum electrode, reaching a PCE of 9.96%. Another novel low-cost nanocomposite consisting of graphene oxide- $\text{La}_2\text{CrFeW}_6$ mixed with urea, gallic, or sodium dodecyl sulfate was deposited via the hydrothermal method to serve as a counter electrode. The achieved DSSC efficiency of 10.4% overcame the efficiency of 7.49% obtained with a typical platinum counter electrode [59].

3.2.4. Electrolyte

Electrolytes used in dye cells should provide high ionic conductivity and be injected between the two electrodes to ensure efficient contact with both the photoelectrode and the counter electrode. Typically, electrolytes contain a redox couple, such as iodide (I^-)/triiodide (I_3^-) in acetonitrile, methoxyacetonitrile, bromide ($\text{Br}^-/\text{Br}_3^-$), cobalt ($\text{Co}^{2+}/\text{Co}^{3+}$), or copper ($\text{Cu}^{2+}/\text{Co}^{3+}$ or $\text{Cu}^{2+}/\text{Cu}^{1+}$) dissolved in an organic solvent. The commonly used iodide/triiodide redox couple is notable for rapid and reliable dye regeneration, resistance to contact with oxygen, moisture, and light, and simple preparation. It has contributed to record DSSC efficiencies, such as certified values of 11.1% [60] and 12.4% [19]. However, an iodide-based redox shuttle also has disadvantages: it can corrode metal contacts, e.g., silver, and at higher concentrations, it can limit open-circuit voltage by increasing the recombination [61]. Among alternative redox couples, the most suitable one is the cobalt-based electrolyte. DSSCs employing a cobalt redox shuttle with co-sensitization of YD2-o-C8 and Y123 dyes achieved a PCE of 12.3% [62]. Further optimization of co-sensitization with ADEKA-1 and LEG4 dye led to a milestone efficiency of 14.3% [63].

In liquid electrolytes, two types of solvents are commonly used: organic solvents and ionic liquids. Organic solvents (e.g., acetonitrile, valeronitrile, MPN) efficiently dissolve salts and promote fast ion transport, which enhances the photocurrent. Many high-efficiency DSSCs were based on organic solvent electrolytes [64,65]. However, the limitations of organic solvents include leakage risk and low boiling points, which promote evaporation of the electrolyte solution. Ionic liquids represent a promising alternative because they enhance the long-term operational stability of DSSCs. Their low volatility and limited leakage, coupled with thermal robustness and resistance to degradation, make them highly stable. However, their higher viscosity compared with organic solvents can reduce charge transport [66]. Therefore, the mixing of organic solvents with ionic liquids or developing low-viscosity ionic liquids appears to be a favorable approach for both conductivity and stability [67].

Numerous studies addressing the issue of leakage, volatility, and poor long-term stability aim at the development of quasi-solid-state or solid-state electrolytes for DSSC applications [68]. Quasi-solid-state electrolytes, also referred to as polymer gel electrolytes or gel polymer electrolytes, consist of a liquid electrolyte embedded within a solid polymer network, resulting in a mechanically stable material with sufficient ionic conductivity [7,69–71]. Depending on the preparation method and physical properties, quasi-solid-state electrolytes include composite, thermosetting, thermoplastic, ionic liquid, and poly-

ionic liquid electrolytes. Composite electrolytes incorporate different fillers, such as carbon derivatives, TiO_2 , or ZnO [72–74]. Thermosetting electrolytes are produced by polymerizing a copolymer soaked in liquid electrolyte [75,76], while thermoplastic electrolytes consist of a polymeric matrix mixed with liquid electrolyte that can transit from liquid to solid, depending on temperature [77–80]. Ionic liquids, typically used as solvents, can be transformed into gels or solids through the addition of polymers or organic fillers [81,82]. Recent developments combining ionic liquids and polymers provide materials with high ionic conductivity and tunable electrochemical properties [83,84].

An example of the electrolyte containing an organic solvent within a polymer matrix is a system composed of polyacrylonitrile, propylene carbonate, and tetrabutylammonium iodide, which exhibits an ionic conductivity of 5.14 mS/cm due to the high density of charge carriers. The application of this electrolyte in DSSCs resulted in a power conversion efficiency of 3.45%, a short circuit current density of 12.9 mA/cm², an open circuit voltage of 582 mV, and a fill factor of 46% [85]. Intensity modulated photocurrent/photo-voltage spectroscopy enabled the determination of relatively short electron transfer times, ranging from 34.14 ms to 55.6 ms, and longer electron recombination times, ranging from 53.7 ms to 90.41 ms for this electrolyte system. Electrochemical impedance spectroscopy (EIS) analysis revealed a charge-transfer resistance of 15 Ω at the TiO_2 /dye/electrolyte interface.

Solid electrolytes are entirely solid materials capable of conducting ions; however, their ionic conductivity is generally lower than that of liquid or quasi-solid-gel electrolytes, which may result in reduced photocurrent and overall device efficiency [86]. In flexible DSSCs, which are subject to mechanical deformation such as bending, solid electrolytes represent a promising alternative due to their ability to prevent leakage. An efficiency of 6.16% was obtained in a fiber shape DSSC employing a solid electrolyte containing lithium bis(trifluoromethanesulfonyl)imide and TEMPOL derivatives (Figure 4a). The advantageous electrical and optical characteristics of the TEMPOL derivatives, particularly enhanced ionic conductivity and low light absorption, are illustrated in Figure 4b,c.

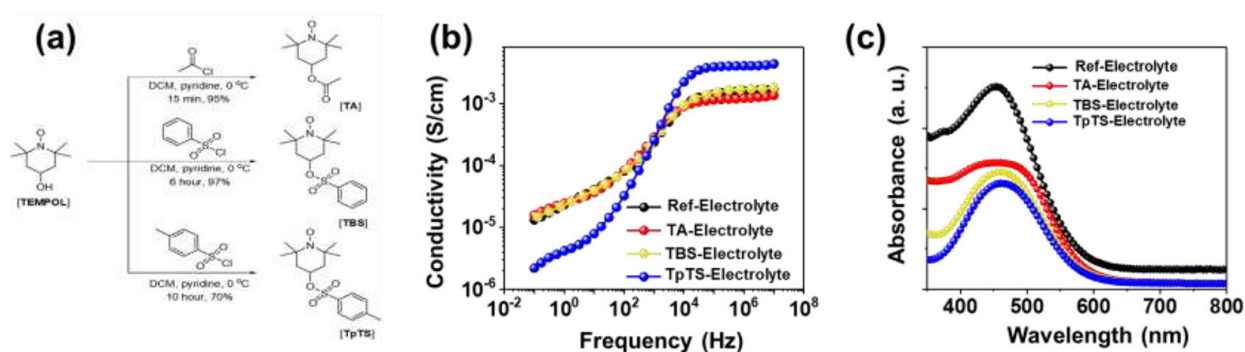


Figure 4. Molecular structures of TEMPOL derivatives (a), ion conductivities after adsorption onto LiTFSI film (b), absorption spectrum after adsorption onto LiTFSI film (c). Copied with no changes from [87], permission granted under the terms of the ACS AuthorChoice License.

Solid-state polymer electrolytes were also fabricated in the form of thin films deposited between two electrodes using heat and pressure. Iodide-based PEO/PEG/ TiO_2 solid-state electrolyte films provided a PCE of 8.13% along with very good stability over 700 h [88]. Another interesting approach showed that a conventional DSSC utilizing a liquid iodide redox mediator can be converted into a solid-state device through controlled evaporation of the electrolyte. This process increased the concentration of the ionic liquid, leading to enhanced short circuit current and stability for over 1000 h [45]. Furthermore, a

composite solid-state electrolyte containing iodide–triiodide redox species within a poly-aniline/thiourea matrix resulted in a 73% improvement in efficiency compared to a standard electrolyte [89].

3.3. Summary

In the presented studies on DSSCs, the remarkable diversity of sensitizers is particularly noteworthy. These include not only ruthenium-based dyes but also porphyrins and metal-free dyes, including a broad range of natural compounds. However, the power conversion efficiencies achieved with natural dyes remain relatively low. In contrast, a successful trend has been the co-sensitization approach, in which the mixing of dyes has resulted in the highest reported efficiencies exceeding 15%. Numerous studies have also focused on the search for alternatives to iodide-based electrolytes. In this regard, ionic liquids have attracted considerable attention due to their ability to reduce evaporation and leakage; however, they still do not provide sufficiently efficient charge transport.

The major strength of DSSCs undoubtedly is the use of inexpensive TiO_2 as the electron transport layer (ETL), as well as promising results obtained with carbon-based counter electrodes instead of platinum. Nevertheless, the liquid electrolyte remains a significant weakness, as it negatively affects the operational lifetime of the devices.

4. Organic Solar Cells

The development of organic photovoltaics began alongside early research on organic semiconductors and conductive polymers. Initial studies focused on understanding photoconductivity in organic materials; however, device efficiencies were extremely low. Subsequent advances, particularly the introduction of conjugated polymers and bulk heterojunction architectures, significantly improved power conversion efficiencies and stimulated rapid progress in organic photovoltaic technologies. The first efficiency values recorded by certified laboratories and reported in the literature after 2000 were then approximately two times lower than those achieved for DSSCs.

4.1. Structure and Operation Principle of OSC

The fundamental materials used in organic solar cells are organic semiconductors, which include small molecules (discrete molecules) and conjugated polymers (repeating molecular chains). A typical organic solar cell consists of a transparent electrode, a hole transport layer, a donor–acceptor active layer, an electron transport layer, and a metal electrode. Figure 5 depicts the structure of OSC fabricated on a glass substrate, along with an image of actual devices. The active layer typically comprises a conjugated polymer as the electron donor and either a fullerene or non-fullerene compound as the electron acceptor. In contrast to inorganic semiconductors, photoexcitation in organic materials leads to the formation of Frenkel excitons, characterized by a radius of approximately 1–2 nm and a binding energy of 0.3–0.5 eV [90], rather than free charge carriers. To avoid recombination, these excitons must diffuse to a donor–acceptor interface where charge separation can occur. The typical value of exciton diffusion length is in the range of 5–20 nm; therefore, the bulk heterojunction architecture, where donor and acceptor phases form an interpenetrating nanoscale network, provides an effective solution. Studies demonstrated that the exciton diffusion length plays a pivotal role in charge generation and separation. A longer diffusion length, combined with an extended exciton lifetime, facilitates exciton migration to the interface and reduces the rate of back transfer and recombination of charge carriers [91].

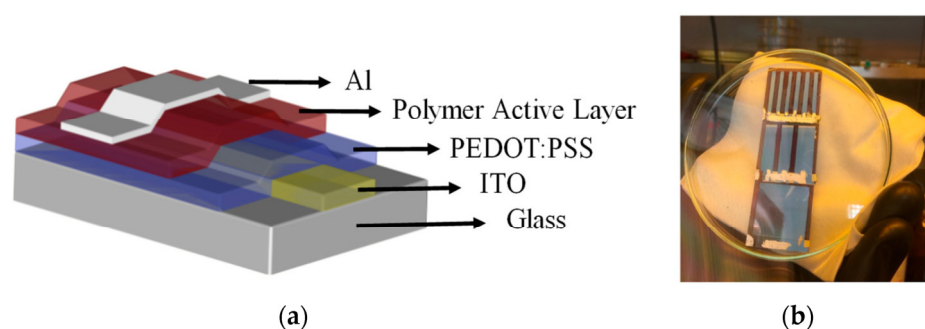


Figure 5. Scheme of an organic solar cell structure (a) and a photo of the prepared devices (b). Copied with no changes under Creative Commons Attribution 4.0 International License from: [92].

4.2. Optimization of Donor–Acceptor Materials

Bulk heterojunctions formed from donor–acceptor blends based on fullerene acceptors have dominated organic photocells for many years. However, the essential drawbacks, such as photochemical degradation under prolonged illumination and thermal instability associated with fullerene aggregation and diffusion, lead to performance losses over time [93]. A bulk heterojunction, deposited from solution by the doctor blade method or co-evaporation, comprising a polythiophene derivative PT12OH and the fullerene derivative PC₆₁BM, exhibited a PCE of 4.83% [94]. A promising alternative to PC₆₁BM is a fuller-ylene hybrid, consisting of a planar ylene molecule linked to a spherical fullerene, which enabled an efficiency of 8.01% [95].

However, in 2018, the record efficiencies achieved using the best fullerene acceptors in OSCs were surpassed by non-fullerene acceptors, leading to efficiency exceeding 13% [96]. Non-fullerene acceptor materials proved to be an advantageous alternative due to several key benefits, including broader light absorption, reduced energy loss, and improved morphological stability. Moreover, non-fullerene acceptors offer exceptional tunability in molecular design, enabling precise control over their electronic and optical properties [97]. Their structural features directly influence the absorption range, the mobility of excitons and charge carriers, as well as charge separation efficiency at the donor–acceptor interface. A critical advantage of non-fullerene acceptors is their relatively long exciton diffusion length, typically in the range of 20–45 nm, e.g., in materials such as ITIC, Y6, IT-4F, as demonstrated by both experimental and theoretical studies [98].

One of the most extensively investigated non-fullerene acceptors is Y6, which, when blended with the copolymer donor D18 containing a fused-ring acceptor unit DTBT, provided efficiency exceeding 18% [99]. Copolymers such as D18 are characterized by a strong electron-withdrawing ability and a high hole mobility, which, in consequence, contribute to improved values of V_{OC} , J_{SC} , and FF . Y6 is a prominent non-fullerene acceptor whose absorption is extended up to approximately 1100 nm. When blended with a suitable polymer donor, it can effectively harvest both visible and near-infrared light. Furthermore, studies showed that a Y6 derivative named BTP-eC9 exhibited improved morphology and suppressed charge recombination, resulting in a PCE of 17.3% [100]. Among the highest reported efficiencies, a value of 19.31% was provided by OSC based on a PM6:BTP-eC9 blend, primarily attributed to reduced non-radiative recombination losses [97]. The corresponding devices also demonstrate enhanced stability, which is associated with high crystallinity, uniform molecular aggregation, and the absence of residual solvent in the active layer.

The strategy of enriching a conventional donor–acceptor blend with a third component broadened the spectral range of light absorption and improved charge transfer by the formation of cascade alignment of energy levels, thereby enabling higher power conversion efficiencies. Extensive research in this area showed that the incorporation of the

fullerene derivative PC₆₁BM into a combination of a polymer donor PBDB-TF and the fused-ring non-fullerene Y6 resulted in a high efficiency of 16.5%, primarily due to improved charge transport and reduced non-radiative recombination losses [101].

Recently, an outstanding efficiency of 21% was reported for an OPV device based on a ternary blend, in which polymer donors L8-BO and C5-16 featuring an A-D-A architecture, and the polymer acceptor PY-IT were employed to dilute the donor D18 [102]. As a result, a device based on the D18 (PY-IT diluted)/L8-BO:C5-16 (D18 diluted) system exhibited enhanced light absorption and significant suppression of charge recombination.

Another important class of photoactive materials used in organic solar cells is porphyrins, which are widely found in naturally occurring organic molecules. Their characteristic feature is an exceptionally high molar extinction coefficient, typically in the range of 10^5 – 10^6 M^{−1}cm^{−1} [103]. Porphyrins are most commonly employed as electron-donating molecules, e.g., in dye-sensitized solar cells; however, appropriate functionalization and pairing with wide band gap semiconductors, e.g., zinc-based systems, can enable their use as electron acceptors as well.

A ternary blend based on the porphyrin ZnP-TSEH: 6TIC, enriched with a crystalline low band gap non-fullerene acceptor (4TIC), provided efficiency over 15.5% [104]. The highly ordered crystalline structure of the obtained ternary system is advantageous for charge generation and contributes to reduced charge recombination. The devices incorporating PC₆₁BM and Y6 as the acceptors, together with a dimeric porphyrin small molecule (m-ph-ZnP₂), exhibited a PCE of 8.34 %, which was attributed to enhanced charge generation and charge transfer arising from improved blend miscibility [105]. Furthermore, newly synthesized porphyrin-based materials with an optimized A- π -D- π -A architecture incorporating Pd or Pt metal ions were applied in OPVs. A device with C19-PdP as the donor and PC₇₁BM as the electron acceptor provided an efficiency of 8.09% [106]. The results were attributed to improved charge collection, optimized phase separation, enhanced charge carrier mobility, and reduced recombination losses.

Modern synthesis methods enable the preparation of porphyrin derivatives that differ in the number of porphyrin structure units and their molecular architecture. The most commonly applied molecular architectures include: the donor–acceptor system (D-A) composed of a single porphyrin and a single acceptor unit, the A-D-A system with an additional acceptor unit, which provides a PCE up to 17.7%, the D-A-D built by two porphyrins connected by a π -conjugated molecule, and the A-D-A-D-A system offering extended light absorption but involving more complicated synthesis [107]. The simplest D-A push–pull systems are characterized by a relatively narrow absorption band; however, coordination with a metal atom, such as zinc, can significantly enhance performance. For example, cells based on 3-Zn:PC₇₁BM achieved a PCE of 6.18% [108]. Similarly, an active layer composed of Zn-PDPP:PC₇₁BM delivered an efficiency exceeding 9% [109]. A higher PCE exceeding 17.7% was achieved using a DAPor-DPP/por-BR: 6TIC (A-D-A) active layer, which was attributed to enhanced exciton generation and dissociation, as well as reduced charge recombination [110]. In D-A-D structures, an enhanced push–pull effect was observed, resulting from broad light absorption in the red region, the formation of a charge transfer band, and increased hole mobility. A ternary blend comprising VC7, PC₇₁BM, and IT-4F, in which the bis-porphyrin compound containing VC7 served as the donor and exhibited a PCE of 15.08%. This improvement was ascribed to increases in open circuit voltage, short circuit current density, and fill factor [111]. The observed performance enhancements were attributed to faster exciton generation and charge extraction, facilitated charge transport, and suppressed recombination. Additionally, an efficiency approaching 9% was obtained for an OSC based on BD-tPor, BODIPY, and DPP, which was linked to the favorable alignment of the BD-tPor LUMO energy level [112].

Organic solar cells, which reached efficiencies of approximately 10% during the first decade of research starting in 2006, achieved almost twice as high a PCE of 19.92% in 2025 [113]. These advancements were accompanied by improvements in mechanical robustness and device stability, largely attributed to the incorporation of the dynamic H-bonding ethyl ester chains into small molecule acceptors (SMAs). The synthesized BTA-E3 acceptor, when blended with the PM6 donor, enhanced charge carrier generation, reduced charge recombination, and facilitated faster charge transport. Other investigations highlighted the advantages of asymmetric BTP-BO-TBO SMAs, which promote efficient charge transfer while maintaining effective exciton dissociation, resulting in a PCE of 19.76% [114].

4.3. Inverted Architecture

One promising approach to enhancing the performance of OSC is the use of inverted architectures, depicted in different variants in Figure 6. In such devices, the illuminated electrode serves as the cathode, consisting of a glass substrate with ITO coating, and a ZnO electron transport layer, followed by the photoactive blend, a hole transport layer, and a metal anode (e.g., Ag or Au) formed via thermal evaporation. The performance of inverted OSC historically lagged behind that of conventional architectures, with reported power conversion efficiencies of 2.04% [115] or 7.43% [116] for cells incorporating fullerene acceptors, and 15.7% for non-fullerene acceptors [117]. However, recent advances in both efficiency and stability highlight the potential of inverted OSC. In a novel approach, the commonly used ZnO electron transport layer was passivated with SiO_xN_y grown by solution deposition in ambient atmosphere, reducing surface defects and enabling a PCE of 18.49% for the cells based on a PM6:L8-BO non-fullerene active layer [118]. Table 3 summarizes the characteristic parameters of organic solar cells with different compositions.

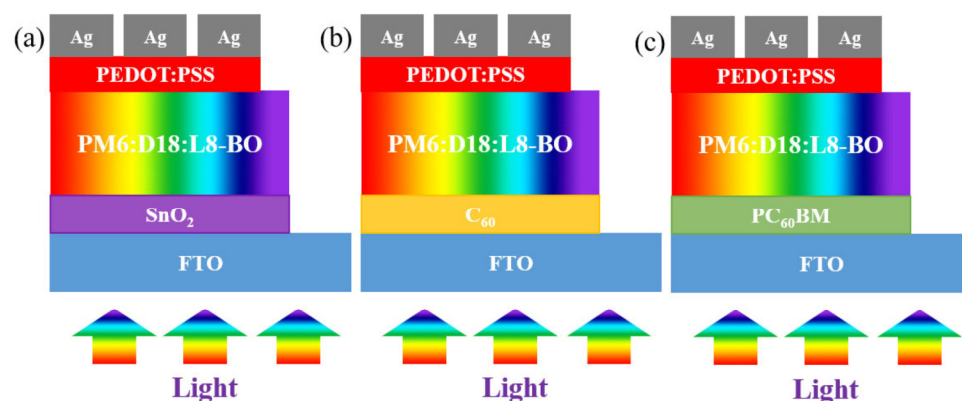


Figure 6. Structure of an inverted OSC with three different ETLs: (a) SnO_2 , (b) C_{60} , and (c) PC_{60}BM . Copied with no changes under Creative Commons Attribution 4.0 International License from: [119].

Table 3. Photovoltaic parameters of organic solar cells determined under STCs.

Year	Donor–Acceptor Blend	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)	Ref.
2019	DPP-2TTP:DR3TBDTTF:PC ₇₁ BM	17.78	0.82	0.77	11.01	[120]
2020	PBDB-TF:BTP-eC9	26.2	0.841	0.811	17.3 (certified value)	[100]
2020	D18:Y6	27.7	0.859	0.76	18.22	[99]
2020	ZnP-TBO: 6TIC: 4TIC	24.58	0.8	0.74	14.73	[104]
2021	VC7:PC ₇₁ BM:IT-4F	23.74	0.87	0.73	15.08	[111]
2022	C19-PdP:PC ₇₁ BM	12.82	0.94	0.67	8.07	[106]
2023	PBDB-T:VC11:Y6	23.47	0.89	0.73	15.25	[121]
2023	Zn-PDPC ₇₁ BM	17.28	0.81	0.65	9.1	[109]
2023	PBDB-T:VC11:Y6	23.47	0.89	0.73	15.25	[121]

2024	PM6:Y6	25.9	0.80	0.72	15.57	[122]
2024	PM6:Y6	26.5	0.844	0.71	16.1	[123]
2024	PM6:ITIC	16.1	0.974	0.67	10.7	[123]
2024	PM6:BTP-eC9	27.64	0.85	0.78	18.42	[124]
2024	PM6:BTP-eC9	26.57	0.845	0.79	17.9	[125]
2024	RC19:TOCR1	21.36	0.91	0.71	13.72	[107]
2024	RC20:TOCR1	10.02	0.98	0.53	5.2	[107]
2025	RC18:DICTF:Y6	24.22	0.93	0.71	16.06	[126]
2025	PM6:BTP-eC9:BTP-4CI	27.63	0.846	0.79	18.62	[127]
2025	D18 (PY-IT diluted)/L8-BO:C5-16	27.7	0.914	0.82	20.25 (certified value)	[102]
2025	PM6:DIBP3F-Se:BTP-J17	26.7	0.941	0.78	19.6	[128]

4.4. Summary

The introduction of non-fullerene acceptors has led to significant improvements in light absorption, device stability, and the reduction in recombination losses. Binary and ternary blends consisting of non-fullerene acceptors combined with efficient donor materials have proven to be a successful strategy, resulting in power conversion efficiencies exceeding 18%. The implementation of inverted device architectures has contributed to enhanced performance parameters by reducing interfacial defects. Particular attention should also be paid to the facile deposition methods of the active materials. The use of the conductive polymer blend PEDOT:PSS represents a low-cost solution that can be readily deposited onto flexible substrates. Despite these advantages, major challenges remain, including interfacial defects and difficulties associated with efficient charge separation.

5. Quantum Dot Solar Cells

The development of quantum dot solar cells (QDSCs) followed advances in the synthesis and understanding of semiconductor quantum dots. Early research focused on the unique size-dependent optical and electronic properties of quantum dots, such as tunable band gaps and enhanced absorption. Based on the concept of using quantum dots for photovoltaics, in experimental quantum dot-sensitized solar cells, quantum dots were attached to wide-band-gap semiconductors like TiO₂. Since then, research has expanded toward improved power conversion efficiencies and enhanced stability.

5.1. QDSSC Operation Principle

Quantum dot solar cells (QDSSCs) are a promising photovoltaic technology, structurally similar to DSSCs, in which quantum dots are used to absorb incident light instead of sensitizing dyes. A typical QDSSC consists of a glass substrate coated with a conductive layer, an electron transport material, a quantum dot layer, an electrolyte, and a counter electrode [129]. In a quantum dot-sensitized solar cell, the quantum dots of PbS, CdS, or CdSe [130] are attached to a mesoporous wide bandgap ETL (e.g., TiO₂) semiconductor. The dots can be deposited by chemical bath deposition, atomic layer deposition, or successive ionic layer adsorption and reaction. Upon illumination, quantum dots absorb photons, which excite electrons, and as a result, electron-hole pairs are created. The excited electron is injected from the quantum dot into the conduction band of the semiconductor due to its lower energy level, then moves through the TiO₂ porous network and reaches the transparent conductive oxide layer connected to the external electric circuit. The redox electrolyte donates electrons to QD, which is, in consequence, regenerated, while the oxidized electrolyte is reduced at the counter electrode [131,132]. Polysulfide electrolytes are commonly used, as they efficiently facilitate charge separation and stabilize quantum dots [133]. Figure 7 depicts the typical structure of a QDSSC, and the electron transfer process (v.i.).

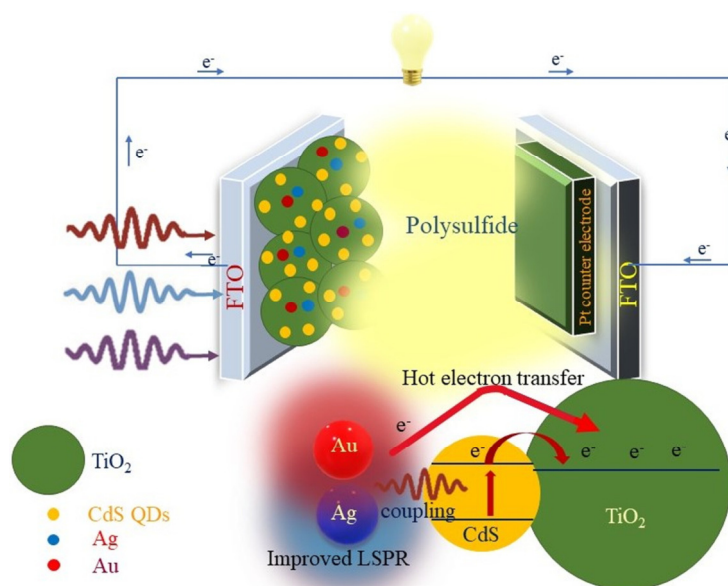


Figure 7. Scheme of the QDSSC structure and mechanism of electron transfer in surface plasmonic resonance (v.i.). Copied with no changes under Creative Commons Attribution 4.0 International License from: [134].

5.2. Improvements of Quantum Dot Properties

Quantum dots, a characteristic component of QDSSCs, are semiconductor nanoparticles that form quasi-zero-dimensional structures of diameters below 10 nm [135]. Their exceptional properties include a tunable band gap, a high molar extinction coefficient, and the ability to generate multiple excitons from the absorption of a single photon [136]. Band gap tuning can be achieved as a result of the quantum size effect, through variations in quantum dot size that modify the energy bands [137]. Due to the decrease in the quantum size, the band gap increases, leading to absorption of shorter wavelength light. II-VI semiconductors, chalcogenides, such as PbS, CdS, CdTe, CdSe, are particularly effective in solar cell applications, due to their highly tunable band gaps, ranging from approximately 0.2 eV to 4 eV. This allows for broadening of the absorption spectrum and high absorption coefficients on the order of 10^6 cm^{-1} [138,139]. Additionally, doping quantum dots can further modify the band gap and influence their electronic structure, energy levels, charge transport, and optical absorption. An example is the addition of transition metal ions such as Mn^{2+} or Co^{2+} , which can reduce the band gap and extend light absorption to longer wavelengths, thereby enhancing solar energy harvesting [140].

The synergistic effect of Mn doping and the introduction of graphene oxide (GO), nitrogen, and co-sensitized porphyrin compound on the performance of QDSSCs based on a $\text{TiO}_2/\text{CdS}/\text{ZnS}$ photoanode was also studied, showing improvements in device performance [141]. However, investigations also indicate that the doping has to be carefully controlled, as it can introduce defect states that act as recombination centers, and achieving uniform doping remains a challenge, which affects reproducibility.

An effective strategy for enhancing QDSSC performance is also the co-sensitization of quantum dots with nanocarbon materials [142,143]. Successful results were provided in an investigation on $\text{TiO}_2/\text{N-GQD}/\text{CdSe}$ QDs covered photoanode, in which nitrogen-doped graphene quantum dots (N-GQD) play the role of sensitizer and provide additional nucleation sites for the growth of CdSe quantum dots. The incorporation of quantum dots also facilitates the electron transport in the TiO_2 layer and suppresses charge recombination at the $\text{TiO}_2/\text{electrolyte}$ interface through surface passivation. In this system, CdSe

quantum dots absorb photons, and the resulting excited electrons are subsequently transferred to N-GQD and then into the TiO₂ conduction band. This approach yielded a PCE of 4.88% [144].

Another approach for effectively modifying quantum dots is the fabrication of alloyed quantum dots composed of three or more elements within a single crystal lattice (e.g., Zn–Cu–In–S, Pb_xCd_{1-x}S) [145,146]. By tuning the composition and relative proportions of the elements, the bandgap width, optical absorption, and charge carrier transport can be optimized, leading to power conversion efficiencies of up to 8.47% [147]. Alloying enables broader light absorption and stronger photocurrent generation compared to pure CdS or PbS sensitizer. The changes in bandgap value and the corresponding alignment of energy levels for PbCdS are depicted in Figure 8. Moreover, electron injection from the quantum dot to TiO₂ is accelerated, and charge recombination is suppressed due to the reduced defect density in the alloyed material [148].

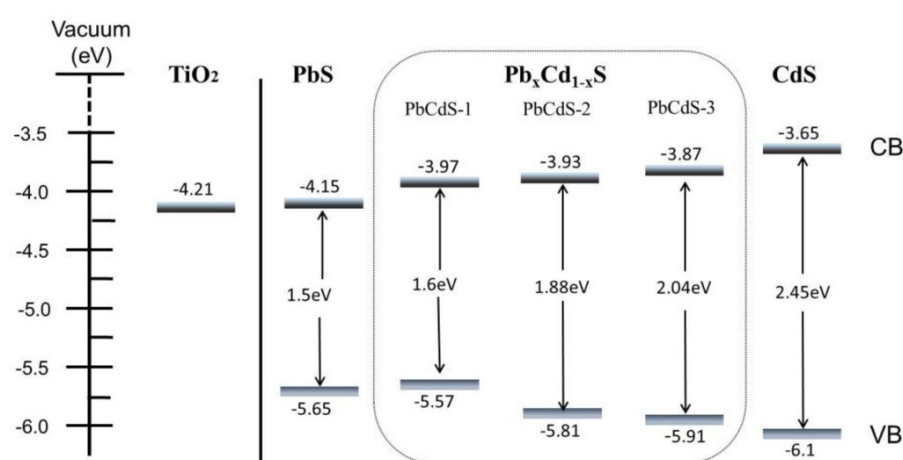


Figure 8. Diagram of energy levels alignment for Pb_xCd_{1-x}S quantum dots and TiO₂. Copied with no changes under Creative Commons Attribution 4.0 International License from: [149].

An alternative to multi-component quantum dots is the use of core–shell nanocrystal semiconductor structures, in which a core material (e.g., CdSe, AgInS₂) is surrounded by a shell composed of a different semiconductor with a distinct bandgap (e.g., CdS, ZnS, CdSe). This architecture forms a heterojunction that enables the tuning of electronic and optical properties through band alignment and interface effects [150,151]. Additionally, the core serves to passivate dangling bonds, suppress trap states, and enhance carrier lifetimes [152]. A representative example is Mg/CdS core–shell quantum dots, additionally passivated with ZnS, which increased the efficiency from 2.87% to 7.47% [153]. Table 4 presents the photovoltaic parameters obtained by QDSSCs based on different types of quantum dots.

Table 4. Photovoltaic parameters of quantum dot-sensitized solar cells determined under STCs.

Year	Structure of the QDSSC	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)	Ref.
2016	TiO ₂ /Mn: CdSe _{0.65} Te _{0.35} QDs/Mn: ZnS/SiO ₂	20.87	0.688	0.655	9.4	[154]
2018	TiO ₂ /alloyed Zn–Cu–In–S QDs/polysulfide electrolyte/Cu ₂ S counter electrode	22.62	0.613	0.61	8.47	[147]
2019	FTO/TiO ₂ /ZCISe/ZCIS QDSCs/	25.93	0.762	0.657	12.98% (certified value)	[155]
2020	GO/N-doped TiO ₂ /CdS/10MnZnS/Zn-porphyrine-electrolyte/CuS counterelectrode	11.47	0.72	0.6	4.62	[141]
2020	FTO/TiO ₂ /CdSeTe/polysulfide electrolyte/Au	4.362	0.602	0.53	1.419	[145]

2020	ITO/ZnO/Au/PbS/Ag	26.05	0.53	0.62	8.64	[156]
2024	TiO ₂ /core-shell AgInS ₂ /CdSe QDs/polysulfide electrolyte/CuS counter electrode	23.85	0.65	55.2	8.57	[152]
2024	FTO@TiO ₂ @CdS:Cu@CdSe:Cu(0.3)@ZnS	27.35	0.5	0.35	4.68	[157]
2024	TiO ₂ /Ag–CdS QDs/Polysulfide/C	3.32	0.84	0.60	1.72	[158]
2025	FTO/1% hexagonal boron nitride doped TiO ₂ /CdS/Cu ₂ S	0.56	0.78	0.62	1.08	[159]
2025	FTO/TiO ₂ /CuS/Mn/Co/Na ₂ S/Graphene/FTO	6.73	0.37	0.67	1.675	[160]
2025	FTO/TiO ₂ /CdS/CdSe:Cu ²⁺ /ZnS/electrolyte/PbS@rGO@CNT	0.112	0.54	0.488	6.139	[161]
2025	FTO/TiO ₂ /Mn/co-doped CdS/I ₃ /I ⁻ /graphene/FTO	6.74	0.37	0.67	1.67	[160]
2025	FTO/TiO ₂ /ZnCuLaSe/polysulfide electrolyte/counter electrode	6.11	0.62	0.61	2.32	[148]
2025	FTO/TiO ₂ /CuLaSe/polysulfide electrolyte/counter electrode	5.56	0.62	0.56	1.94	[148]

5.3. Multiple Exciton Generation

An exceptionally unique phenomenon observed in quantum dot-sensitized solar cells is multiple exciton generation (MEG), in which a single high-energy photon produces more than one electron–hole pair (exciton). When the photon energy significantly exceeds the bandgap, the excess photon energy over the bandgap, which is usually lost as phonons, generates additional excitons in the quantum dots before the energy loss. MEG has the potential to enhance photocurrent and efficiency due to the generation of multiple charge carriers by the conversion of high-energy photons to excitons. In practice, however, the MEG phenomenon is limited by carrier transport losses and long-term stability issues. The additional involvement of plasmonic effects can contribute to the solution of these problems. Such an approach requires the introduction of plasmonic nanoparticles (e.g., Au and Ag), which can facilitate electron transfer and promote charge pair generation in the MEG process [134,162]. In addition, plasmonic nanoparticles enhance light absorption and interfacial charge transfer in QDSSCs. Devices incorporating Au and Ag nanoparticles to exploit dual plasmonic effect provided a PCE of 8.64% [156]. The mechanism of electron transfer in surface plasmonic resonance is shown in Figure 7.

5.4. Summary

Quantum dots constitute a unique class of materials used in solar cells due to the possibility of tuning their absorption range through size variation, as well as their involvement in the multiple exciton generation phenomenon. Modifications of the composition and structure of quantum dots provide broad opportunities for improving the properties of quantum dots.

The tunability of the quantum dot band gap, together with the use of TiO₂ as the electron transport layer (ETL), represents a significant advantage of QDSSCs. However, the presence of toxic elements such as Pb and Cd in the composition of the quantum dots, as well as the relatively low efficiencies compared with other photovoltaic technologies, still remains a major drawback.

6. Perovskite Solar Cells

The development of perovskite solar cells began when the use of organic–inorganic lead halide perovskites as light absorbers in dye-sensitized solar cell architectures was reported. These early devices demonstrated very low power conversion efficiencies and suffered from poor stability due to liquid electrolytes. A major breakthrough occurred in 2012, when solid-state hole transport materials replaced liquid electrolytes, leading to

rapid efficiency improvements. Since then, perovskite solar cells have evolved quickly, and their efficiencies have increased to levels comparable to established photovoltaic technologies, making them one of the most rapidly advancing areas in photovoltaic research.

6.1. Perovskite Cell Operation and Materials

The operating mechanism of a perovskite solar cell can be divided into several photophysical and electrochemical stages. The work cycle starts with absorption of a photon by photoactive perovskite material, the general formula of which is ABX_3 (Figure 9), where A is a monovalent cation (e.g., $CH_3NH_3^+$, FA^+ , Cs^+), B is a divalent metal cation (commonly Pb^{2+} or Sn^{2+}), and X is a halide anion (Cl^- , Br^- , or I^-). Photon absorption results in the promotion of electrons from the valence band to the conduction band, leaving behind holes. Charge separation is then facilitated by alignment of energy levels of the adjacent electron transport layer (ETL) deposited by spin coating or chemical bath deposition and hole transport layer (HTL) formed by spin coating or the doctor blade method [163]. Perovskite materials are characterized by numerous advantageous properties, such as high absorption coefficient exceeding $1.5 \cdot 10^4 \text{ cm}^{-1}$, long carrier lifetimes, large diffusion lengths surpassing $1 \mu\text{m}$, and high mobility of electrons ($7.5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and holes ($12.5\text{--}66 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$), which support efficient charge transport to the electrodes [164]. The outstanding characteristics of perovskites motivated extensive research, which resulted in rapid improvements of power conversion efficiency: 22.6% in 2018, 23.32% in 2019, 25.2% in 2021 [165], 26.1% [166], and 26.72% [167].

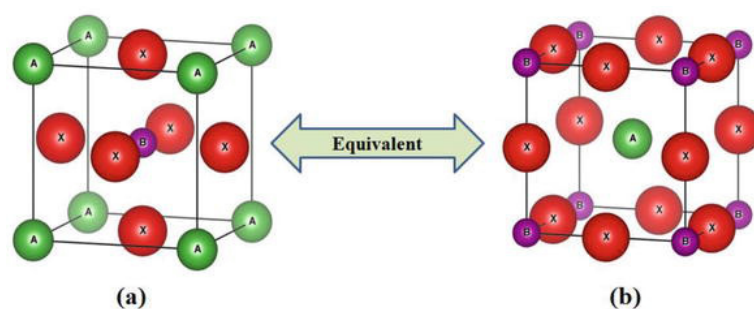


Figure 9. (a) Structure of perovskite and (b) the equivalent structure of perovskite. Copied with no changes under Creative Commons Attribution 3.0 International License from: [168].

In a solar cell, perovskite material is sandwiched between ETL, which can be mesoporous or flat, and HTLs connected to electrodes. The traditional structure of the perovskite cell can also be inverted. The inverted structure of PSC and the corresponding J-V characteristic are depicted in Figure 10.

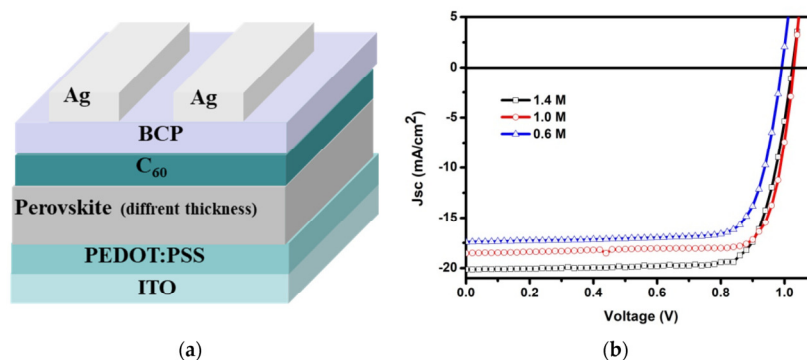


Figure 10. Schematic of the inverted structure PSC (a), J-V characteristic of PSCs for different concentrations of perovskite precursor material (b). Copied with no changes under Creative Commons Attribution 4.0 International License from: [169].

Two main groups of perovskite materials can be distinguished: organic–inorganic hybrid materials, such as methylammonium lead iodide $\text{CH}_3\text{NH}_3\text{PbI}_3$ (MAPbI₃) and formamidinium lead iodide $\text{CH}_3\text{NH}_3\text{PbBr}_3$ (MAPbBr₃), and all-inorganic perovskite materials, e.g., CsPbI₃. Both types of materials are deposited mainly by solution processing methods or thermal evaporation. A crucial feature of the perovskites is the ability to tailor their band gap to optimally match the solar spectrum. A common strategy for band gap tuning is structural modification through the introduction of different ions. For example, varying the halide composition in $\text{MAPb}(\text{Br}_x\text{I}_{1-x})_{3-y}\text{Cl}_y$, ($0 \leq x \leq 1$) leads to a linear change in the band gap value [170].

All-inorganic perovskites provide an alternative to hybrid materials, offering improved thermal stability and enhanced resistance to moisture [171,172]. The investigations focused on the representative of all-inorganic perovskites, cesium lead halide perovskite, proved that a high and stable efficiency of up to 18.4% can be achieved [173]. Moreover, treating highly crystalline CsPbI₃ films with choline iodide enhances charge carrier lifetimes and ensures proper alignment of energy levels, further improving device performance.

One of the factors influencing the performance of PSCs is the metal contacts, whose morphology and electrical properties depend on both the choice of material used and the deposition method. Among various deposition techniques, such as thermal evaporation, electron beam evaporation, or screen printing, magnetron sputtering is commonly employed because it produces contact layers with good adhesion and uniform morphology. However, precise control of the sputtering process is required to prevent damage to the hole transport layer (HTL) during deposition. A systematic study optimizing magnetron power, chamber pressure, and sputtering duration demonstrated that the PCSs with Ag contacts fabricated under optimized conditions achieved a PCE of 18.35% [174]. Table 5 presents photovoltaic parameters of perovskite cells with different structures and materials.

Table 5. Photovoltaic parameters of solar cells determined under STCs.

Year	Perovskite Solar Cell	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)	Ref.
2017	ITO/PEDOT:PSS/CH ₃ NH ₃ PbI ₃ /RGO-PCBM/PFN/Ag	22.92	0.85	0.65	14.5	[175]
2017	ITO/SWCNT-TiO ₂ /Perovskite/Spiro-OMeTAD/Au	21.62	1.04	0.70	15.58	[176]
2018	FTO/C60/CH ₃ NH ₃ PbI ₃ /carbon	23.08	1.07	0.61	15.38	[177]
2018	FTO/TiO ₂ /CsPbIBr/PTAA	12.3	1.28	0.65	10.3	[171]
2019	ITO/TiO ₂ /CsPbI ₃ -CHI/spiro-OMeTAD	19.41	1.09	0.716	15.2	[173]
2021	FTO/SnO ₂ /MAPbI ₃ /Spiro-OMETAD/Ag MAPbI ₃	22.56	1.1	0.73	18.35	[174]
2022	Inverted ITO/PE-DOT:PSS/MAPbI ₃ (Cl)/C ₆₀ /(BCP)/Ag	20.14	1.025	0.79	16.31	[169]
2024	(FTO)/cp-TiO ₂ /mp-TiO ₂ /3D FAPbI ₃ /DMPESE/spiro-OMeTAD/Au	25.37–25.79	1.094–1.139	0.753–0.792	21.37–23.22	[178]
2025	glass/fluorine-doped tin oxide (FTO)/blocking-layer-SnO _x (bl-SnO _x)/SnO ₂ /α-FAPbI ₃ /hole transport material (HTM)/Au	26.40	1.15	0.83	23.51 (certified value)	[179]
2025	ITO/2D3DOcMA:FAPbI ₃ -MAPbBr ₃ /spiro-MeOTAD	25.76	1.184	0.83	25.32	[180]

2025	Inverted ITO/NiO _x /Me-4PACz/perovskite (phFACl, APCL, or TFACl modulation)/C ₆₀ /BCP/Cu	26.36	1.194	0.85	26.32 (certified value)	[181]
2025	Inverted ITO/4PADCB/Al ₂ O ₃ /FA _{0.95} CS _{0.05} PbI ₃ /PI/PCBM/BCP/Ag	26.558	1.192	0.84	26.88 (certified value)	[182]
2025	Inverted ITO/NiO _x /Me-4PACz/Cs _{0.05} MA _{0.05} FA _{0.9} PbI ₃ /C ₆₀ /BCP/Ag	26.34	1.206	0.85	26.79 (certified value)	[183]
2026	FTO/NiO _x /PSK(E-PSK)/Spiro-OMeTAD/MoO ₃ /Ag	23.1	1.06	0.78	19.33	[184]
2026	ITO/SnO ₂ /CDs interface/FAPbI ₃ /Spiro-OMeTAD/Ag	23.48	1.14	0.80	21.5	[185]
2026	Inverted ITO/MeO-2PACz/Perovskite/PipDI/PCBM/BCP/Ag	25.00	1.19	0.78	23.26	[186]
2026	Inverted ITO/NiO _x /Me-4PACz/Perovskite/(DTBP)/C ₆₀ /BCP/Cu	25.89	1.16	0.84	25.3	[187]
2026	FTO/SnO ₂ /CsPbI _{2.85} Br _{0.15} /Spiro-OMeTAD/BCP/Ag	20.26	1.252	0.79	20.3	[188]
2026	ITO/PEDOT:PSS/PTAA/MAPbI ₃ perovskite/PCBM/Ag	23.82	1.158	0.82	22.81	[189]
2026	Lead free glass/ITO/EMIC-PEDOT: PSS/Sn-perovskite/ICBA/C ₆₀ /BCP/Cu	23.89	0.85	0.78	16.00	[190]

6.2. Inverted Structure of Perovskite Cells

Inverted perovskite solar cells attracted significant attention due to their numerous important advantages. Inverted perovskite cells can be fabricated at a lower temperature, which facilitates integration with flexible substrates and tandem structures. The inverted structure also typically exhibits a reduced hysteresis effect and a more efficient charge extraction, resulting from favorable energy level alignment at the interfaces as well as a reduction in ion accumulation at the electrodes. Moreover, lower defect densities at the interface between perovskite and charge transport layers suppress interfacial recombination, enhancing overall operational stability [191,192]. The key differences between traditional and inverted PSCs are summarized in Table 6.

The great potential of inverted PSCs is highlighted by devices providing recent record efficiencies for perovskite technology. For example, the incorporation of PHNS + BNAC bimolecular additives in perovskite FA_{0.95}CS_{0.05}PbI₃ films employed in inverted PSC resulted in an efficiency of 27.02%, accompanied by 98.2% maintained efficiency after 2000 h of continuous illumination [182]. Another inverted PSC device, modified with C8A, achieved a champion efficiency of 27.18% while retaining 95% of the initial efficiency after 1015 h [183], attributed to defect passivation and suppression of ion migration.

Table 6. The key differences between traditional and inverted PSCs.

Aspect	Traditional PSCs of n-i-p Structure	Inverted PSCs of p-i-n Structure
Device architecture	TCO/ETL/Perovskite/HTL/metal	TCO/HTL/Perovskite/ETL/Metal
Charge extraction	Electrons extracted first	Holes extracted first
Typical ETLs	TiO ₂ (compact/mesoporous), SnO ₂	PCBM, C ₆₀ , ZnO, SnO ₂
Typical HTLs	Spiro-OMeTAD, PTAA, P3HT	PEDOT:PSS, NiO _x , SAMs
Interfacial recombination	Higher at the ETL/perovskite interface	Lower due to the beneficial layout of energy levels

Instability reasons	Dopant migration, UV-induced ETL degradation	HTL chemical instability and limited hole transport
Stability of performance	Moderate	Very good
Compatibility with flexible substrates	Limited	Very good
Tandem integration	Complex	More facilitated
Large-area scalability	Challenging	More favorable

Recently, a novel approach involving the introduction of hole-selective self-assembled monolayers (SAMs) between the perovskite and a metal oxide-coated substrate significantly boosted the performance of both conventional and inverted PSCs, achieving a PCE exceeding 26% [193–195]. A SAM typically consists of an anchoring group and a terminal group connected by a molecular linker, and it influences charge transport, surface work function, and the hydrophilicity of the underlying layer. Although SAM layers offer numerous advantages, they can also become disordered or degrade.

6.3. Lead-Free Perovskite Cells

It is worth emphasizing that the best performance of both traditional and inverted structures of PSCs is achieved by the cells based on perovskite materials containing lead. However, the investigations aiming for environmental sustainability tend to substitute lead with more friendly elements, e.g., tin, which have a similar electronic structure and ionic radius to lead. Moreover, the band gap of the tin-based perovskites has a suitable value of 1.3–1.4 eV. Despite these advantages, the introduction of Sn to the perovskite structure results in several issues that have to be solved on the way to the commercialization of the photocells. One of them is oxidation of Sn-based perovskite, which affects the crystal structure, leads to phase transition, and broadening of the bandgap [196]. The increase in bulk defects and surface trap states induces charge recombination. The changes in energy levels alignment also have to be addressed by proper modifications of composition [197,198]. Nowadays, tin-based PSCs still face challenges, and their photovoltaic performance as well as stability is not sufficient. Recently reported efficiency of 16% was achieved by the addition of CF₃BTd into FASnI₃ absorber, the role of which is to limit the oxidation of Sn and passivate the bulk defects [190]. Novel study of lead-free copper halides was performed, in the context of nonlinear up-conversion luminescence properties, due to the lack of such research, which hinders the wider applications of these materials. The CsCu₂I₃ and Cs₃Cu₂I₅ thin films exhibited a unique two-photon absorption mechanism, and high absorption coefficients of 2.63×10^7 and 1.76×10^7 cm/MW, respectively, were determined, showing potential in advanced applications [199]. Another all-inorganic lead-free perovskite, CsSn_{0.5}Ge_{0.5}I₃, passivated by the native oxide layer, delivered an efficiency of up to 7.11% (Figure 11). The oxide layer fully covered and encapsulated the perovskite, which led to very high stability [200].

6.4. Summary

A crucial feature of perovskites is their ability to absorb light over a very broad spectral range. Another important advantage is that they can be deposited using simple solution-processing methods. Moreover, all-inorganic perovskites contribute to improved device stability under external environmental conditions.

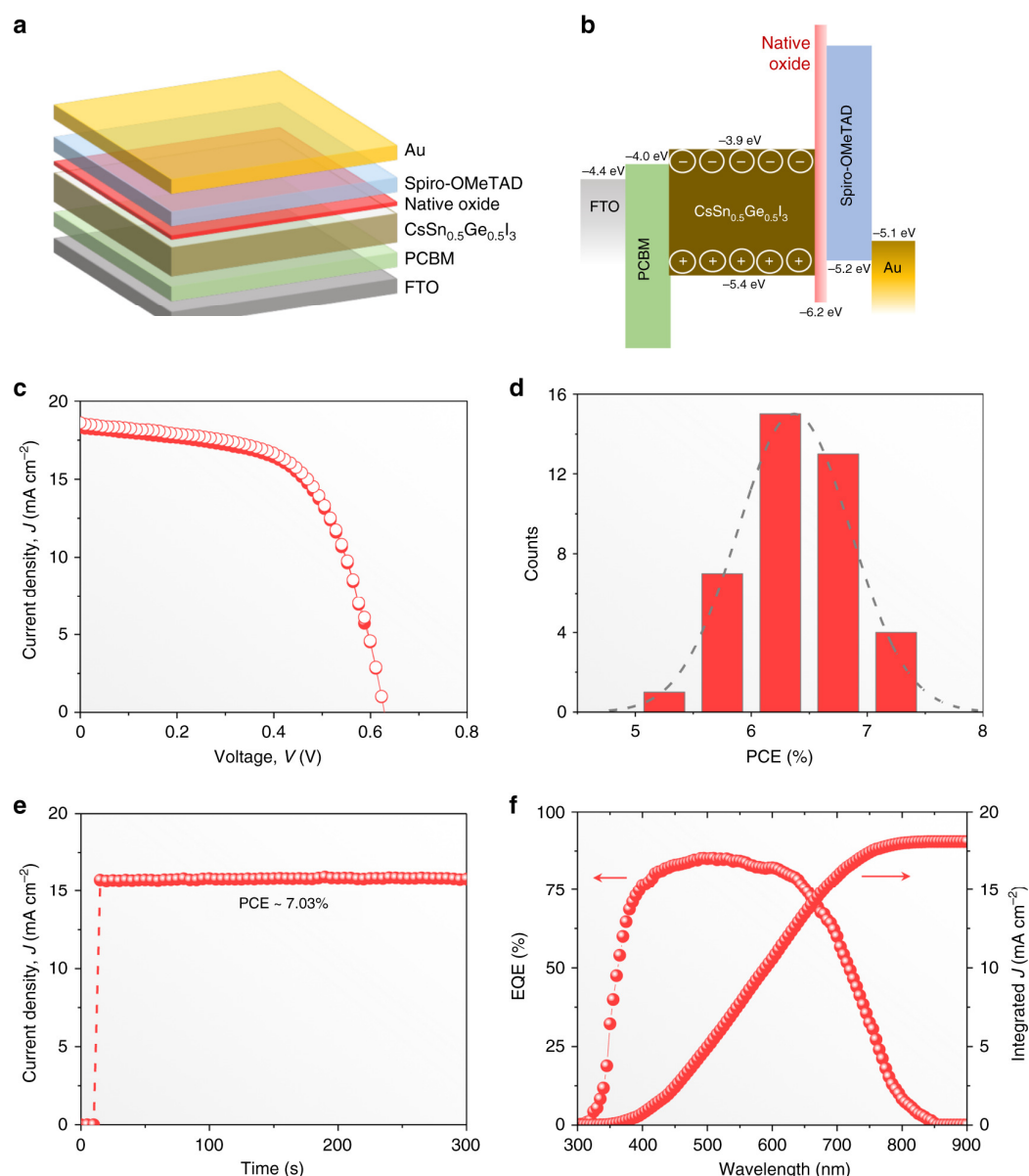


Figure 11. Structure of perovskite solar cell (a), scheme of energy levels (b), I-V characteristic (c), efficiency statistic (d), stability of current (e), external quantum efficiency of the champion photocell (f). Copied with no changes under Creative Commons Attribution 4.0 International License from: [200].

A strategy based on the inverted cell architecture offers several advantages, including reduced charge carrier recombination, enhanced stability, and compatibility with flexible substrates. Charge transport is also facilitated due to the favorable alignment of energy levels, resulting in the highest achieved power conversion efficiencies. However, the perovskite materials that provide the highest efficiencies still contain lead, which should be eliminated for environmental and health-related reasons.

7. Hybrid Cells Involving Emerging Technologies

In addition to the research focused on innovations in specific third-generation photovoltaic technologies, attention is also directed toward hybrid solar cells, which integrate different types of photovoltaic materials. Among these hybrid devices, the most efficient currently are perovskite-based tandem cells, especially perovskite/silicon and perovskite/organic tandems, achieving a PCE of approximately 35% and 26%, respectively [201]. Hybrid tandem or multi-junction cells offer the potential to surpass the Shockley–Quisser

limit defined for single junction cells, which originate from different loss mechanisms including absorption limited to photons the energy of which matches the semiconductor bandgap, thermalization losses, and the finite lifetime and mobility of charge carriers. The realistic theoretical model of perovskite/Si cells indicates a high efficiency of 43.2% that can be achieved by the tandem when the optimal top perovskite cell bandgap is equal to 1.71 eV and the thickness of the silicon bottom cell is 300 μm [202].

7.1. Perovskite/Si Tandem Cell

Perovskite/silicon hybrid tandem solar cells can play a significant role in next-generation photovoltaics because they combine the mature reliability of crystalline silicon with the excellent light absorption and tunable bandgap of perovskite materials. In a typical tandem of this type, a wide-bandgap perovskite solar cell is deposited on top of a crystalline silicon bottom cell. The perovskite absorber absorbs high-energy photons from the visible region of the spectrum. Photons with lower energy, which are not absorbed by the perovskite layer, are transmitted to the silicon sub-cell, where they can be absorbed.

In the perovskite top cell, photon absorption results in the generation of free charge carriers with relatively low exciton binding energy. Electrons are transported through the electron transport layer (ETL), while holes migrate through the hole transport layer (HTL). Similarly, in the silicon bottom cell, absorbed photons generate charge carriers that are separated by the internal electric field of the p–n junction. If two sub-cells are electrically connected in series, they share two external electrodes (two-terminal cell). If perovskite and silicon sub-cells operate independently, there are two pairs of electrodes (four-terminal cell).

An efficient approach is also an inverted structure of such a hybrid cell, in which the perovskite sub-cell has an inverted charge transport architecture. Inverted structure provides advantages similar to inverted PSCs, such as smooth interfaces and limited recombination. Moreover, charge transport layers in such a structure can be fabricated at a low temperature, which is important as the bottom silicon cell is sensitive to heat.

An example configuration of such a hybrid structure is FTO/ NiO_x /perovskite/PCBM/Rh101/Ag/ MoO_3 stacked in tandem with Ag/PEDOT:PSS/n-Si/In:Ga, as shown in Figure 12. The top cell is a solution-processed inverted structure perovskite cell. The bottom cell contains a Si layer with a textured surface coated with PEDOT:PSS, which acts as an anti-reflection layer and provides a high-quality junction with Si. This type of hybrid cell achieved a PCE of 15.41%. Although the efficiency is lower than that of state-of-the-art tandem devices, its main advantage lies in the low-cost solution processing technique and the use of a thin PEDOT:PSS film, which exhibits high conductivity and transparency [203].

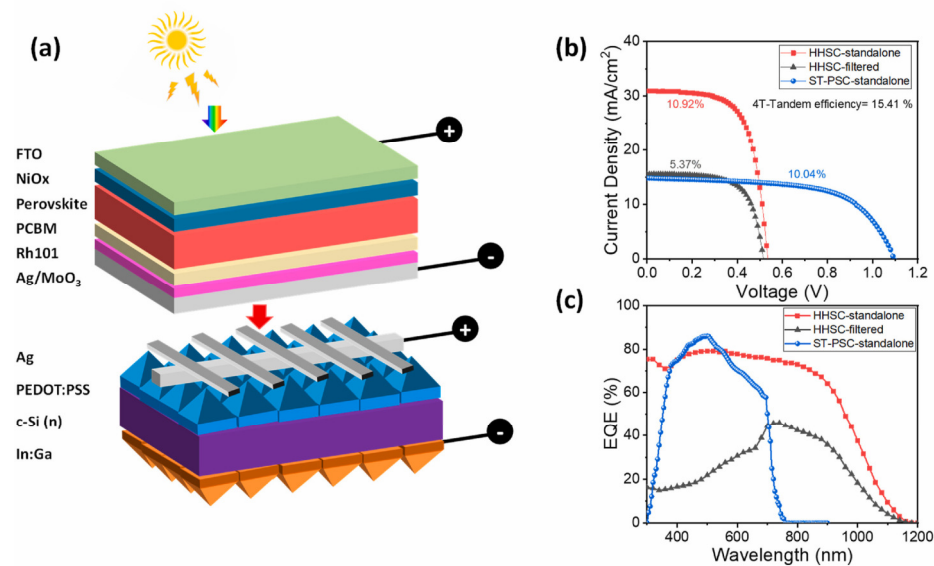


Figure 12. Structure of perovskite cell and Si cell (a), current–voltage characteristic of a hybrid heterojunction solar cell (HHSC) and perovskite cell (ST-PSC) (b), and external quantum efficiency (c). Copied with no changes under Creative Commons Attribution 4.0 International License from: [203].

The long-term stability and durability of hybrid perovskite/Si solar cells depend on the perovskite materials, which are responsible for most of the challenges related to the reliability of the performance. Phase segregation, which occurs in perovskite material, leads to (1) an increased number of defect states, band disorder, and results in a decrease in V_{oc} and overall efficiency, (2) an increased light scattering, (3) limited charge transport at grain boundaries, and (4) interfacial degradation [204]. The ways of preventing phase segregation include interface engineering. Addition of inorganic cations enhances stability and the introduction of anions, e.g., Cl^- , decreases lattice strain, reduces defect formation and contributes to optimizing the matching energy levels. Perovskite phase stability in hybrid cells can also be enhanced as a consequence of the introduction of ITO or aluminum-doped zinc oxide (AZO) to reflect infrared radiation and prevent the heating of the top cell.

It is worth emphasizing that the already highly efficient tandem perovskite/Si cells can further improve the operation by harvesting additional back-side illumination offered by bifacial architecture. Bottom silicon sub-cell, which absorbs light transmitted through the perovskite top layer (low energy photons), can additionally utilize reflected and diffused light in a bifacial cell. The investigations showed that reflective coating of different albedos present on the ground below modules modifies the spectrum of incident light and changes the operating point of the solar cell. The energy yield gains can vary from +6% for sandstone to +20% for grass compared to a zero albedo surface [205].

To compare perovskite/Si tandem cells with other hybrid structures, as well as with single cells or submodules of specific technology, their photovoltaic parameters were summarized in Table 7. Table 7 presents the highest confirmed performance parameters of third-generation photovoltaic devices measured under STCs in certified laboratories, e.g., NREL or Newport [166]. For comparison, it also includes data for a conventional crystalline Si cell with a relatively large illumination area of 158.66 cm². Both perovskite cells and submodules exhibit the highest efficiency among the representatives of third-generation PV. Table 7 shows that perovskite and Si-based technologies separately are the most successful. Among hybrid structures, the highest efficiency value of 35% was recorded for a 1 cm² perovskite/Si tandem cell, as confirmed by the European Solar Test Installation (ESTI).

For each investigated technology, an increase in the illuminated area is generally accompanied by a decrease in efficiency and other photovoltaic parameters. The observed tendency hinders further commercialization, which requires the application of large-area devices. It is also important to emphasize that the reported efficiencies for perovskite/Si tandem structures correspond to initial performance values. Therefore, in the context of adaptation and spreading the new technology on the market, stability remains a critical issue that has to be addressed.

Table 7. Certified photovoltaic parameters of the best cells, submodules, and minimodules of different technologies measured under STCs. Data selected from ref. [166] under permission granted by John Wiley & Sons.

Technology	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	Record PCE (%)	Illuminated Area (cm ²)
Si crystalline cell	43.01	0.7447	87.1	27.9	158.66 cm ²
Dye-sensitized cell	22.47	0.744	71.2	11.9	1.005
Dye-sensitized submodule	18.42	0.697	68.7	8.8	398.8
Perovskite cell	26.67	1.203	83.7	26.9	1.017
Perovskite submodule	24.31	1.180	79.9	22.9	756.0
Organic cell	26.31	0.9341	79.1	19.4	1.003
Organic submodule	23.32	0.8315	74.6	14.5	204.11
Perovskite/Si cell multijunction	20.76	2.007	84.3	35.0	1.0028
Perovskite/Si submodule multijunction	18.94	1.903	79.3	28.6	330.56 (total area)
Perovskite/perovskite cell	16.59	2.159	78.9	28.2	1.038
Perovskite/perovskite minimodule	15.60	2.182	77.4	26.2	64.84

7.2. Summary

An important advantage of hybrid solar devices is their improved utilization of the solar energy spectrum. High-energy photons are absorbed by the perovskite layer in the top sub-cell with reduced thermalization losses, while lower-energy photons are efficiently converted by the silicon bottom sub-cell. In inverted tandem architectures, the arrangement of the charge transport layers facilitates efficient charge extraction and suppresses interfacial recombination. Nevertheless, several challenges associated with perovskite solar cells remain and influence the performance of hybrid cells, e.g., interfacial defect formation, ion migration within the perovskite materials, and the presence of toxic lead in high-efficiency perovskite compositions.

8. Future Directions

8.1. Indoor Photovoltaics

Third-generation solar cells provide the potential for the development of flexible and lightweight photovoltaic modules, which can be implemented not only in rooftop or large-scale installations but also in a wide range of emerging applications, including wearable electronics (solar fabrics), portable power systems, and integration into vehicles or buildings as solar windows. Recent investigations on the performance of novel photovoltaic devices under ambient indoor light have also demonstrated a huge potential. The main future application field is the Internet of Things (IoT), which requires an uninterrupted power supply for the connected devices. The domains of IoT include smart infrastructure (air quality sensors, lighting control), home and individual needs (temperature sensors, door/windows sensors, smart blinds), security systems (building monitoring, occupancy sensors), healthcare (medical patches, diagnostic wearable devices), transportation (smart railway systems, emergency electronics), retail (product movement sensors, smart refrigerating), and industry (automation, predictive maintenance sensors).

Artificial light sources (e.g., LEDs, halogen or fluorescent lamps, and incandescent bulbs) exhibit specific irradiance spectra, different from the solar light spectrum. The irradiance intensity increases gradually, starting from around 450 nm for an incandescent bulb and 500 nm for a halogen bulb, towards longer wavelengths. LED light shows the highest intensity in the range of 425–475 nm and from around 500–550 nm to 700 nm, depending on the color temperature. The fluorescent lamp exhibits numerous narrow intensity bands in the visible light range, with the most intense one around 600 nm. This provides the opportunity to match the type of light source to the spectral response of the photoactive material in a solar cell [206]. Due to increasing interest in indoor applications of photovoltaics, as standard illumination for indoor conditions, the light of 1000 lux coming from fluorescent or light-emitting diodes was adapted.

Among photoactive materials used in third-generation solar cell dyes, such as N719, N3, D205, and polymers, e.g., PCDTBT:PC₇₁BM, exhibit a good spectral match to the LED bulb intensity distribution. Absorption of perovskite materials is usually high in the entire visible light range, which indicates that each type of artificial light can be proper; however, in laboratory tests, fluorescent lamps are usually used. The results of the research in this area are surprisingly successful, showing a power conversion efficiency of 36.2%, obtained under illumination of a fluorescent lamp, for a perovskite cell consisting of glass with ITO, NiOx, MAPbI_{2-x}BrCl_x perovskite with a tailored bandgap, PC₆₁BM, BCP, and Ag [207]. The very high PCE of 34% was also obtained for DSSCs co-sensitized with XY1 and L1 dyes [208], and 31.8% was also obtained for DSSCs co-sensitized with XY1b and Y123 dyes under fluorescent light [209]. The structure of these cells was typical, based on TiO₂ as ETL, and a PEDOT-coated counter electrode.

The development of indoor photovoltaics can benefit directly from the key advantage of third-generation solar cells, which is the tunability of their absorption properties. This can be achieved through the selection of appropriate sensitizing dyes in DSSCs, optimization of absorber composition, or control of the size of quantum dots. It is also worth emphasizing that the theoretical limit for indoor photovoltaics is significantly higher (55%) than for AMG1.5 light (33%) due to better utilization of the narrow emission spectrum of artificial light.

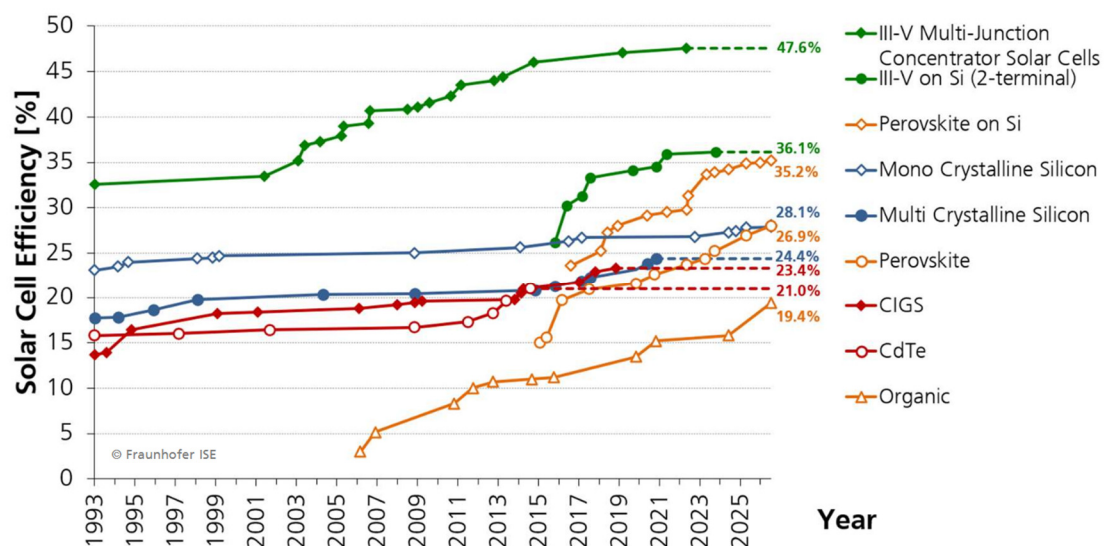
8.2. Commercialization

The review of recent achievements in the field of third-generation solar cells indicates the prospects as well as challenges towards commercialization. In this context, a major goal defined for each type of photovoltaic technology is increasing the power conversion efficiency. The main obstacles are low charge carrier mobility, insufficient charge collection, and charge transport resistance. Additionally, non-radiative recombination and trap formation remain one of the major loss pathways that limit open circuit voltage and overall power conversion.

At present, the most efficient devices are based on perovskite and perovskite/Si tandem architectures, which surpass the efficiency of single-junction cells [210–212]. Certified efficiencies have exceeded 34% for perovskite/silicon tandem devices, significantly outperforming single junction PSCs (~27%) (Figure 13). This improvement is attributed to advanced bandgap engineering, which enables optimal matching of the perovskite absorber to the narrow bandgap silicon, thereby enhancing solar spectrum utilization. The properties of the photoactive perovskite layer in solar cells can be enhanced through material engineering, including the development of perovskite quantum dots with tunable bandgap and the introduction of passivation layers, which facilitate charge transport. OSCs also present high efficiency, which can be linked to the potential of commercialization. Other technologies, such as DSSCs and QDSSCs, exhibit lower efficiencies.

On the way to commercialization, the scalability issue is also an important aspect, as it involves losses in efficiency at the module level and large-scale manufacturing. Comparison of the efficiency of submodules of particular technologies indicates perovskite and perovskite/Si as the most efficient. However, the cells based on perovskite also face key challenges due to non-uniform fabrication conditions, leading to variations in film quality, resulting in the formation of degradation pathways. Furthermore, uneven thermal and mechanical stress may induce cracks and delamination, thereby facilitating the ingress of moisture and oxygen, accelerating device degradation [213].

Significant challenges on the way towards commercialization also include the operation lifetime and durability of the cells under real external conditions. The stability of photovoltaic devices under external operation conditions is strongly influenced by morphological changes in the photoactive material over time, which can reduce charge separation efficiency. Enhancing the stability and lifetime of the next-generation photovoltaic devices requires a complex approach, including defect passivation, the development of stable buffer layers, advanced interface engineering, increased material crystallinity, and improved device architecture and structural design.



Data: Solar Cell Efficiency Tables (Versions 1 to 68), Progress in Photovoltaics: Research and Applications, 1993-2026. Graph: Fraunhofer ISE 2026. Date of data: 06/2026

Figure 13. Efficiency of solar cells [214].

Recently reported studies indicate significant improvements in the stability of representative perovskite technology. Rapid progress in efficiency accompanied by long-term stability was also demonstrated for inverted perovskite cells. The example is a device incorporating a TMSBr buffer layer, which exhibited operational stability for 2000 h while maintaining 82.8% of the initial efficiency under continuous operation [215]. For example, a perovskite mini-module with an effective area of 10.86 cm² retained over 97.2% of the initial certified power conversion efficiency of 23.37% after 2500 h of continuous operation of [167]. Organic solar cells, which are also promising candidates for commercialization, achieved a lifetime of up to 24,700 h at 80% of the initial certified efficiency value of 18.49% for devices with active areas of 5.77 mm² [118]. In these successful cells, an inorganic Si-O_xN_y interlayer effectively passivates surface defects in the ZnO electron transport layer. A large-area organic photovoltaic device (100.17 mm²) exhibits a slightly lower PCE of 18.06%, which further confirms the scalability challenge demonstrated by all photovoltaic technologies (Table 8).

Furthermore, insufficient encapsulation affecting the stability and operation lifetime remains a significant barrier on the way to commercialization [216]. Oxygen and moisture

ingress lead to chemical degradation of the active layer and electrodes, and photodegradation contributes to performance loss. Proper encapsulation is required in the case of each third-generation cell due to their sensitivity to UV, humidity, and oxygen, as well as to avoid electrolyte leakage or evaporation in DSSCs.

In the context of commercialization, a crucial future direction for third-generation photovoltaics is also the reduction of manufacturing costs. In this regard, the goal is the development of cells produced by using simple solution processing, printing techniques, and roll-to-roll manufacturing, which enable low-cost, large-scale production. Significant efforts are also directed toward the reduction of material consumption and costs.

Transparent conductive glass, commonly used in most third-generation cells, accounts for around 30% of the total cost (price of 8–12 USD/m²). For example, in DSSCs, FTO is the most expensive part, which accounts for 30–45% of the total cost [3]. However, the TiO₂, used as ETL in most cells, is extremely cheap. The cost of the counter electrode (Au, Ag, Cu), the price of which is in the range of 5–30 USD/m², is a 10–30% share of the total cost. The highest cost of the cells is ascribed to encapsulation, its share amounting to 20–40%, and the price is in the range of 10–30 USD/m². The sealing used in DSSCs accounts for 15–25% of the total cost.

Photoactive layers, which are very thin in the studied cells, do not raise the cost significantly. The maximum price of a perovskite absorber is 2 USD/m², and the average is up to 0.5 USD [217]. Sensitizers in DSSCs are applied in very small amounts with a typical dye loading of 10–20 mg/m². However, the important aspect is the trade-off between ruthenium dyes, which are expensive due to the scarcity of ruthenium but provide higher efficiencies, and cheap natural dyes, which provide low efficiencies. In general, the substitution of ruthenium dyes and platinum coating in the counter electrode would lower the cost of DSSCs. In OSCs, the conductive polymer photoactive layer is cheap, and its thickness is in the range of 100–300 nm, and the ITO price is the largest share of the cost.

In a hybrid perovskite/Si cell, a share of 35–50% is ascribed to the Si cell and 25% to encapsulation; however, the cost distribution depends on the detailed structure of the cell [218]. The largest cost contribution comes from the ITO glass, which is priced at around 30 USD/m²; lamination with a price of 1.535 USD/m²; and the cost of the Si cell, which is around 50–100 USD/m². Similar to other described emerging technologies, the commercialization of hybrid perovskite/Si solar cells depends mainly on efficiency and costs. Although commercialization examples were demonstrated in pilot prototype installations by several manufacturers, long-term stability and large-scale manufacturing are the primary challenges before widespread deployment of the perovskite/Si technology.

Ways to reduce the final cost of emerging PV technologies include replacing ITO with FTO due to indium deficiency or introducing graphene; substituting gold and platinum with biocarbon, graphite, or PEDOT; and developing a new, cheaper sealing material.

Despite numerous obstacles on the way to the widespread commercialization of third-generation solar cells, various outdoor and indoor pilot demonstration installations were mounted. Table 8 summarizes the diversity of potential application fields, advantages, and challenges.

Table 8. Comparison of application aspects of various types of third-generation solar cells.

Technology	Application	Advantages on the Way to Commercialization	Challenges	Example Company
DSSC	Portable electronics (wireless headphones, helmets, sensors)	Excellent indoor performance, flexibility, and customized color	Low outdoor efficiency and sealing failure	Exeger Powerfoyle (Stockholm, Sweden)

	Indoor IoT (indoor sensors, smart building, warehouse devices)	Excellent low-light indoor performance under fluorescent or LED lightning		Ricoh (Tokyo, Japan)
	Building integrates photovoltaics (semi-transparent window, colored glass facades)	Tunable transparency, customized color, and good performance under diffuse light		Solaronix (Aubonne, Switzerland), semi-commercial, pilot installations
	Agrovoltaics (on-field installations, greenhouses)	Tunable absorption, transparent to light useful in photosynthesis, crops, and power generation in the same area)		Pilot installations, prototypes
OSC	Building integrated photovoltaics (solar foils on facades, roofs, windows)	Lightweight, adhesive back, and flexible	Short operational lifetime, too low efficiency, and thermal instability	Heliatek (Dresden-Pieschen, Germany)
	Indoor and wearable electronics	Lightweight, adhesive back, and flexible		Dracula Technologies (Valence, France)
	Agrivoltaics	Semitransparent, reduces overheating, crops, and power generation in the same area		Pilot installations, prototypes
	Vehicle-integrated PV (car roofs, cabin sensors)	Flexibility, light weight		Prototype installations
QDSSC	Building integrated photovoltaics (smart windows, facades, decorative glass)	High theoretical specific power (W/kg)	Poor stability and toxicity concern	ML System (Rzeszów, Poland), Pilot installations
	Wearable photovoltaics	Flexible films, portable charging, and lightweight		Pilot, experimental examples
Perovskite	BIPV (smart blinds, facades, semi-transparent windows)	Printable manufacturing, flexible, and decorative parts	Degradation, lead toxicity concerns, and scale-up difficulties	Saule Technologies (Warsaw, Poland)
	Solar plants	Under testing		Pilot plants in China
	Indoor applications (building sensors, retail electronics, wireless devices)	Extremely good performance under low-light conditions, diffuse light, and low-cost printing		Demonstration devices
Hybrid perovskite/Si	Outdoor large-scale installations	High efficiency and high power production	Stability issue, complex manufacturing process, expensive encapsulation, and lead toxicity concerns	Oxford PV (Oxon, UK) demonstration installations

8.3. Sustainability

According to life cycle assessment (LCA) studies, DSSCs generally exhibit lower energy payback time (EPBT) and reduced carbon emissions compared with traditional crystalline silicon solar cells due to lower manufacturing energy requirements. DSSCs are considered a promising alternative to conventional silicon photovoltaics because they can be manufactured using low-temperature processes and relatively inexpensive materials. However, the environmental performance strongly depends on the choice of dye, solvent, electrolyte composition, and counter-electrode materials. The use of rare metals (e.g., ruthenium) or toxic organic solvents can increase ecological impacts. Recycling strategies and replacement of hazardous substances are therefore important for improving DSSC

sustainability. Overall, LCA demonstrates that DSSCs have significant potential as an environmentally favorable photovoltaic technology, particularly for low-cost and indoor energy harvesting applications.

Organic solar cells are considered attractive for sustainable energy production because they can be manufactured using lightweight, flexible materials and low-temperature solution-processing techniques. Compared with conventional silicon photovoltaics, OSCs generally require lower manufacturing energy due to simplified processing and reduced material consumption. However, environmental impacts may arise from the use of organic solvents, synthetic polymers, fullerene derivatives, and rare electrode materials such as indium.

Studies indicate that OSCs can achieve short energy payback times and low carbon footprints, especially in applications involving flexible or large-area modules. Nevertheless, the relatively limited operational lifetime and stability of organic materials remain major challenges affecting long-term environmental performance. Improvements in material durability, solvent recovery, recyclable substrates, and the development of non-toxic active materials are essential for enhancing sustainability.

In the case of QDSSCs, a significant environmental impact is associated with the synthesis of semiconductor quantum dots, which may contain heavy metals such as cadmium, lead, or selenium, as well as the use of organic solvents and energy-intensive purification processes. Additional impacts arise from conductive substrates, electrolytes, and counter-electrode materials used in device assembly. A sustainable approach to material selection of QDSSCs emphasizes the use of eco-friendly, lead-free, and cadmium-free sensitizers, such as InP-ZnS quantum dots or copper-based chalcogenides [219,220]. Despite such concerns, QDSSCs can exhibit relatively low energy payback times because of thin-film architectures and low-temperature manufacturing methods. Environmental performance can be improved through the development of non-toxic quantum dots, solvent recycling, and efficient recovery of critical materials at the end of the device's lifetime.

The LCA studies of perovskite solar cells indicate that major contributors to the environmental burden include the synthesis of perovskite precursor materials, solvent use, transparent conductive substrates, and metal electrodes. Particular attention is given to the presence of lead compounds in many perovskite formulations, as lead leakage during manufacturing or disposal may pose environmental and health risks. However, PSCs can achieve low energy payback times and relatively small carbon footprints because of their thin active layers and scalable fabrication methods. The EPBT of perovskite technology differs among the literature reports. Low values of the EPBT equal to 0.35 years are ascribed to perovskite/perovskite tandem and 1.46 years to perovskite/Si tandem [221]. The results of an LCA analysis are always influenced by assumptions regarding the cell structure, the materials used, as well as its efficiency and operational lifetime. Environmental performance can be improved through lead recycling, development of lead-free perovskites, solvent recovery systems, and enhanced device stability to extend operational lifetime. LCA results suggest that perovskite solar cells have strong potential as a sustainable photovoltaic technology if the issues related to toxicity, durability, and recycling are effectively addressed.

The life cycle assessment studies of high-performance perovskite/Si solar cells indicate the need for further improvements in minimizing the environmental impact of this technology. In particular, the development of more stable perovskites is necessary to extend the lifetime of the cells, while the use of hazardous materials, e.g., toxic solvents, should be eliminated. Table 9 compares the main sustainability characteristics of the third-generation photovoltaic technologies.

Another aspect, which is important in the context of transition toward sustainable solutions, concerns the recycling of photovoltaic modules. In general, the end-of-life treatment of third-generation cells is rarely described as these technologies are not widely spread in applications, and there are no reliable data on dismantled installations. Third-generation technologies are still emerging, so industrial recycling infrastructure is limited. However, approximate analysis indicates that conductive glass, which is one of the most expensive materials, can be reused after removing photoactive layers (e.g., TiO₂ with adsorbed dye), but the limitation, e.g., the dimensions of glass, can only be reused in the same type of cells [222]. On the other hand, conductive polymers are so cheap that their recycling is not profitable. The retrieval of platinum or other metals from the counter electrode is possible, but it depends on the amount, which limits economic profitability. Other parts of the cells are often multicomponent, occur in tiny quantities, and their recovery is complicated [223].

Table 9. Comparison of different types of third-generation solar cells. Data selected from: [3,133,224–230].

Characteristic Property	DSSC	OSC	QDSSC	PSC	Hybrid Perovskite/Si
Efficiency	low	high	lowest	high	highest
Cost (USD) per 1 m ²	30–50	20–40	30–60	25–50	100–200
Operation time (years)	10–15	5–10 years	Under 5 years	5–20 years	10–20
Achieved stability	700–1000 h	1058 h	1320 h	1015–2000 h	1000 h
Toxicity	low	low	high	high	moderate
Scalability	low	good	low	good	good
EPBT (years)	1–2	1–3	1–3	1–2	1.5
Global warming potential (gCO ₂ eq/kWh)	30–60	20–60	30–70	10–50	20–40
Application	roof-top, indoor, BIPV, wearable	indoor	niche applications	indoor, BIPV	roof-to, BIPV, portable devices
Commercial readiness	moderate	moderate	low	moderate	high

9. Conclusions

The solar cells belonging to the class of third generation differ significantly from silicon cells and offer numerous advantages that open the way to specific applications in the future. However, despite significant improvements in efficiency in recent years, third-generation photovoltaic technologies are still at the stage of transitioning from laboratory research to large-scale commercialization. Their market entry is hindered by essential trade-offs between efficiency, stability, toxicity, scalability, fabrication cost, and manufacturability.

The most successful representative of this class of solar cells is the perovskite solar cell, which demonstrated remarkable progress in power conversion efficiency. Perovskite-based photovoltaics constitute the newest emerging technology, with their first efficiency report appearing approximately a decade ago. Since then, their efficiency increased from initial values of ~15% to current levels ~27%, which is comparable to the record efficiencies achieved by a single junction Si cell.

However, it is worth emphasizing that, despite extensive research effort, perovskites are prone to degradation under external conditions, and instability is still a major barrier to widespread commercialization. Nevertheless, recent laboratory studies showed promising progress, indicating that perovskite solar cells can maintain performance over extended operational periods under laboratory conditions. Another obstacle is the presence

of lead in efficient perovskites, which raises concerns about toxicity and end-of-life disposal. Perovskite solar cells currently demonstrate the highest power conversion efficiencies among emerging photovoltaic technologies and can be fabricated using relatively low-cost solution-processing methods. However, the issues with their insufficient long-term operational stability and the presence of toxic lead compounds should be overcome.

Nevertheless, significant expectations for future photovoltaic development are associated with perovskite materials and hybrid structures combining perovskite and silicon. The recent PCE records demonstrated by this type of hybrid cells, which combine the most mature, well-known silicon technology with the most successful third-generation perovskite technology, established a benchmark for high-efficiency emerging photovoltaics. Such tandem structures achieved PCE values of up to 35%, mainly due to enhanced absorption of solar light enabled by the two complementary photoactive materials. The excellent laboratory efficiency of a perovskite/Si cell surpassed the practical limits of conventional silicon photovoltaics; additionally, it is worth emphasizing that the theoretical efficiency limit for this technology is 43.2%.

The principal barrier to the further development and commercialization of perovskite/silicon tandem solar cells remains in perovskite. The drawbacks of this technology primarily arise from stability issues with the perovskite layer, since silicon itself is a highly mature, stable, and well-optimized technology. However, it is worth emphasizing that the cost of 1 m² of perovskite/Si tandem is a few times higher than other technologies because of fabrication complexity.

OSCs rank second in terms of achieved efficiency. In the field of organic photovoltaics, there is a growing interest in replacing fullerene-based acceptors with non-fullerene acceptors due to their broader light absorption, lower energy losses, tunable energy levels, and facile synthesis. Additionally, inverted organic solar cell architectures attracted attention due to their enhanced stability and easier manufacturing. In an inverted structure, stable metals such as Ag or Au are employed as bottom electrodes instead of, e.g., Ca or Al, which oxidize in air and contribute to device degradation. Moreover, ZnO used as a top electrode exhibits stability under ambient conditions, can be easily processed, and enables roll-to-roll printing. Organic solar cells are attractive because they can be manufactured using solution processing, which facilitates roll-to-roll fabrication. Organic solar cells and dye-sensitized solar cells offer advantages such as mechanical flexibility, lightweight structure, semitransparency, and low-temperature fabrication, but they generally exhibit lower efficiencies and shorter lifetimes.

The technology of dye-sensitized solar cells, which seemed very promising, has been under intensive development since the 90s; however, since that time, the efficiency has changed from 11 to 15% and lagged behind others. DSSCs have not yet entered the market due to stability issues, which are mainly attributed to the liquid electrolyte. Evaporation and leakage of the electrolyte are the main problems mentioned in the context of stability and implementation of DSSCs in applications. Gel and solid electrolytes were investigated as alternatives, although their operational performance remains limited. At present, the highest efficiencies are still achieved by DSSCs employing liquid electrolytes, despite their poor thermal stability. Efforts to improve DSSC performance focused on several strategies, including the introduction of buffer layers, the replacement of nanoparticles with alternative nanostructured architectures, and the substitution of the traditional iodide electrolyte with a cobalt-based redox shuttle. The latter approach, particularly accompanied by the co-sensitization of TiO₂, proved great potential, leading to efficiencies that constitute an important benchmark. Furthermore, the development of DSSCs increasingly emphasizes environmentally friendly solutions, such as the elimination of ruthenium from molecules of sensitizing dyes, the use of metal-free dyes or natural pigments, as well

as the substitution of platinum counter electrodes with carbon nanoallotropes or biocarbon materials. Dye-sensitized solar cells use relatively simple deposition methods and can perform well under indoor light, but electrolyte leakage and evaporation, as well as long-term durability, remain environmental and technical concerns. Their future will depend on the trade-off between efficiency and cost, which may be minimized through the use of natural dyes or other inexpensive sensitizers, as well as by replacing platinum with carbon-based materials.

Quantum dot-sensitized solar cells, which are conceptually similar to DSSCs, offer tunable light absorption through variation in the quantum dot size, resulting in improved matching to the solar spectrum and making them promising candidates for multi-junction structures. Despite significant progress, their power conversion efficiencies remain well below leading photovoltaic technologies, mainly due to losses associated with charge recombination and imperfections, which make it difficult to control interfaces between quantum dots and electrodes or electrolytes. Quantum dot systems have the lowest efficiency compared to other third-generation devices and may use hazardous materials such as cadmium or lead. Quantum-dot-sensitized solar cells provide tunable optical properties and strong light absorption; nevertheless, their commercialization is limited by charge recombination losses, stability issues, and the toxicity of Pb and Cd metal-based quantum dots.

A comparison of third-generation solar cells indicates that a common feature of most of them is the widespread use of titanium dioxide as the electron transport layer (ETL), which is advantageous due to its low cost and environmental friendliness. Moreover, carbon-based materials or inexpensive conductive polymers can be employed as substitutes for conventional metallic electrodes. Furthermore, the use of very small amounts of both photoactive and electrode materials represents a significant advantage shared by all third-generation solar cell technologies. In terms of the deposition of active layers, simple and cost-effective solution-processing techniques, such as spin coating or chemical bath deposition, can be applied in each type of cell, which enables roll-to-roll manufacturing.

Remaining challenges on the way to commercialization include an increase in efficiency, which is limited by charge recombination losses, interface defects, and energy alignment issues. Moreover, the durability of the cells under deleterious real environmental conditions should be improved. Difficulties in large-scale fabrication and reproducibility of devices also still remain an important issue in the context of commercialization. Environmental and safety concerns, e.g., toxicity of lead in perovskites, should also be addressed.

The review of third-generation photovoltaics also indicates conclusions regarding the emergence of new trends in research. One of them is the investigation of solar cell performance under ambient indoor light. In recent years, laboratory studies on measurements of photovoltaic performance under artificial light have begun to appear more and more often as a standard supplement to the typical set of parameters collected under STCs. This new trend led to the introduction of standard indoor illumination that should be used to enable comparison of performance metrics. Indoor photovoltaics opens a high-potential future direction for third-generation solar devices, as they can achieve efficiency exceeding 30% in indoor conditions where traditional Si cells perform poorly. A key factor is the spectral matching between the artificial light source and the spectral response of a given emerging PV technology. Future outlook includes the widespread adoption of indoor third-generation photovoltaics in smart home devices, integration into smart buildings, and devices powered continuously by ambient light without charging.

Another new or more pronounced trend is the assessment of novel solar cells in the context of sustainability. In general, photovoltaic devices of the third generation are known for advantages such as minimal materials usage and simple solution processing

techniques. However, toxicity concerns associated with the use of Pb and Cd raise environmental concerns and regulatory challenges in a prospective large-scale production process. Therefore, current research is focused on the development of environmentally friendly materials, potentially recyclable components, such as carbon-based electrode materials, natural pigments, absorbers free from toxic metals, and the use of green solvents. The crucial goal of achieving greater efficiencies and longer lifetimes is also associated with a reduction in resource consumption, decreased waste generation, and can lead to shorter energy pay-back-time, which is also in line with sustainable development. The investigations should include cost reduction by substitution of expensive materials (e.g., platinum, gold, ruthenium, indium tin oxide) with cheaper and more environmentally friendly counterparts (e.g., carbon, natural dyes, fluorine tin oxide), as well as the implementation of recycling procedures when it is economically viable. Thus, beyond achieving record efficiencies, ensuring environmental friendliness has become an additional essential criterion that has to be met on the way to the commercialization of emerging photovoltaic technologies.

A broad range of research, numerous recent advancements, and a huge potential of third-generation solar cells indicate their important place in prospective sustainable energy systems. Commercialization perspectives depend on the possible trade-off between efficiency, cost, and sustainability. Key research priorities for the next 3–5 years include improving stability and lifetime, low-cost manufacturing of scale-up modules, increasing efficiency through tandem architectures, reducing environmental impacts, accelerating commercialization through fabrication and the widespread of applications.

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