



Recent advances in dye-sensitized solar cells: Materials, mechanisms, and performance enhancement strategies

Boya duyarlı güneş hücrelerinde güncel gelişmeler: Malzemeler, mekanizmalar ve performans artırma stratejileri

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Abstract

Dye-sensitized solar cells (DSSCs) have emerged as an alternative photovoltaic technology to conventional systems due to their low cost, flexibility, semi-transparency, and adaptability to various application domains. In recent years, advancements in materials engineering, device architecture, and performance optimization have made DSSCs a prominent topic of research, particularly in indoor, wearable, and building-integrated energy systems. This review systematically addresses recent developments in DSSC technology, focusing on fundamental components such as n-type and p-type cell architectures, photoanodes, dyes, electrolytes, and counter electrodes. While the effects of material selection and nanostructure engineering on photovoltaic performance are detailed, major technical and economic barriers to commercialization such as the thermal instability and leakage risk of liquid electrolytes, the limited lifetime of organic dyes, efficiency ceilings, and the high cost of platinum-based counter electrodes are also highlighted. Opportunities and future research directions are discussed in the context of solid-state electrolytes and their potential in next-generation applications such as flexible devices, textile integration, and low-light indoor environments. In conclusion, DSSCs represent a versatile and innovative photovoltaic platform with significant future application potential, offering a promising balance of cost, stability, and performance.

Keywords: Dye-sensitized solar cells (DSSC), n-type DSSC, p-type DSSC, Photoanode, Sensitizer (dye), Electrolyte.

Öz

Boya duyarlı güneş hücreleri (DSSC'ler), uygun maliyetleri, esnek ve yarı saydam yapıları, farklı uygulama alanlarına uyarlabilirlikleri sayesinde geleneksel fotovoltaik teknolojilere alternatif teknoloji olarak öne çıkmaktadır. Son yıllarda malzeme mühendisliği, cihaz mimarisi ve performans optimizasyonunda kaydedilen ilerlemeler, DSSC'leri özellikle iç mekân, giyilebilir ve bina entegreli enerji sistemlerinde önemli bir araştırma konusu haline getirmiştir. Bu derleme, DSSC teknolojisindeki güncel gelişmeleri sistematik olarak ele alarak, n-tipi ve p-tipi hücre yapıları ile fotoanotlar, boyar maddeler, elektrolitler ve karşı elektrotlar gibi temel bileşenlere odaklanmaktadır. Malzeme seçimi ve nano yapı mühendisliğinin fotovoltaik performans üzerindeki etkileri detaylandırılırken; sıvı elektrolitlerin termal kararsızlığı ve sızma riski, organik boyaların uzun ömür sorunları, verimlilik limitleri ve platin karşı elektrotların yüksek maliyeti gibi, ticarileşmenin önündeki başlıca teknik ve ekonomik engeller de vurgulanmaktadır. Katı hal elektrolitler esnek cihazlar, tekstil entegrasyonu ve düşük ışıktaki iç mekân uygulamaları gibi yeni nesil kullanım alanları ile birlikte, gelecekte DSSC'lerin karşılaşılabileceği fırsatlar ve araştırma yönelimleri de tartışılmaktadır. Sonuç olarak, DSSC'ler; maliyet, stabilite ve performans dengesini sağlayan çok yönlü ve yenilikçi bir fotovoltaik platform olarak gelecekte geniş kullanım kapasitesi bulunan bir teknolojidir.

Anahtar kelimeler: Boya duyarlı güneş hücreleri (DSSC), n-tipi DSSC, p-tipi DSSC, Fotoanot, Duyarlılaştırıcı (boyar madde), Elektrolit.

1 Introduction

The rapid growth of the global population, accelerated industrialization, and urbanization have led to a sharp increase in energy demand worldwide. This rapid increase has placed unprecedented pressure on existing energy infrastructures and long-term resource planning strategies [1]-[3]. However, factors such as the limited reserves of fossil fuels, environmental pollution, and climate change pose significant threats to the sustainability of current energy production and consumption models [4]. Therefore, the transition to clean, renewable, and sustainable energy sources has become not merely a choice but an inevitable necessity [5]. In this transformation process, solar energy plays a pivotal role due to its high potential, environmental friendliness, and widespread availability. The modular nature of solar technologies further enables their integration into both centralized and decentralized energy systems [6]. The growing global energy

demand and the increasing need for sustainable resources have driven a shift towards innovative and cost-effective solutions in solar energy technologies [7]. Dye-sensitized solar cells (DSSCs) stand out among solar energy technologies due to their cost-effectiveness and semi-transparent structure [8]. Organic dye-sensitized solar cells, inspired by the process of photosynthesis, were first developed by Michael Grätzel and Brian O'Regan with an initial efficiency of 7%, and they represent a class of solar cells that continue to evolve to this day [9]. Unlike conventional silicon-based photovoltaic devices, DSSCs can maintain relatively high performance under low-light and diffuse illumination conditions [10]. In this context, DSSCs have attracted significant attention due to their low-cost materials, facile fabrication processes, and flexible design possibilities [11],[12]. DSSCs possess significant potential to provide economical and lightweight energy solutions, particularly for indoor applications and portable electronics [13].

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These characteristics make DSSCs especially suitable for next-generation Internet-of-Things (IoT) devices and self-powered sensors [14]. They can be uniquely manufactured for niche applications, particularly in indoor environments, building-integrated photovoltaic (BIPV) systems, and wearable electronics. Such application diversity highlights the adaptability of DSSC architectures to emerging and customized energy-harvesting demands [15]. Despite all its advantages, there are still fundamental challenges that hinder the widespread commercialization of DSSC technology. Chief among these are the thermal instability and leakage risk of liquid electrolytes, long-term stability issues of organic dyes, efficiency limitations, and the high cost of platinum counter electrodes. These technical and economic barriers necessitate the optimization of the balance between performance, durability, and cost in DSSC systems [16]-[20]. In light of all these advantages and challenges, DSSCs continue to stand out as an active area of research and development in the field of sustainable energy, both scientifically and industrially. This review aims to systematically examine the recent scientific and technological advances in the field of DSSCs. It focuses on the n-type and p-type configurations, the properties of the constituent materials (semiconductors, dyes, electrolytes, and counter electrodes), and their effects on device performance. The fundamental operating principles and structural components are summarized, and comparisons among material variants are made in terms of efficiency, stability, and ease of fabrication. Furthermore, recent developments in p-type DSSCs and performance enhancement strategies are elaborated in the context of next-generation applications such as low-light indoor environments, building-integrated photovoltaic systems, and flexible electronics.

2 Fundamental structure and operating mechanism of DSSCs

Research has demonstrated that titanium dioxide (TiO_2), which is abundant and inexpensive, provides optimal operating conditions when employed as the electron transport material in DSSCs [21]-[23].

Figure 1 schematic overview of a typical dye-sensitized solar cell (DSSC), illustrating the layered device architecture together with its main advantages, limitations, and representative efficiency ranges reported in the literature.

Figure 2 illustrates the basic structure and electron flow of a typical n-type DSSC. Typically, a TiO_2 layer deposited on a transparent conductive oxide (TCO) substrate interacts with incident light, initiating the charge transfer process. The electrolyte maintains the continuity of the charge transport cycle, while electrons returning from the external circuit via the counter electrode are transferred back to the electrolyte, thus completing a closed photovoltaic cycle [10],[17],[24].

The band gap alignment between the dye and the semiconductor titanium dioxide is of critical importance [25]. If the band gap of the dye is not properly aligned with that of titanium dioxide, the photoexcited electrons cannot be efficiently transferred from the dye to the semiconductor. Titanium dioxide exists in three different crystalline phases: anatase, rutile, and brookite [26]. Among these crystalline phases, the anatase structure is the most commonly used in research studies [27]. Recent studies have shown that surface modification of TiO_2 nanoparticles through doping or the addition of passivation layers can significantly improve electron injection efficiency and reduce charge recombination losses. Furthermore, optimizing the morphology of the TiO_2 layer, such as by creating mesoporous or nanorod structures, enhances light harvesting and electron transport pathways within the cell [28]. Since platinum is a precious metal, alternative electrode materials with high electrical conductivity, such as graphene, have been investigated for use in DSSCs. Studies have demonstrated that graphene-based electrodes can yield successful results, offering a promising substitute for platinum [29]. As a carbon-based material, graphene holds significant potential for large-scale production and is expected to be increasingly utilized in dye-sensitized solar cells (DSSCs) in the future. Moreover, graphene electrodes offer key advantages for the commercialization of DSSC technology by enabling flexible, transparent, and cost-effective fabrication processes [30],[31].

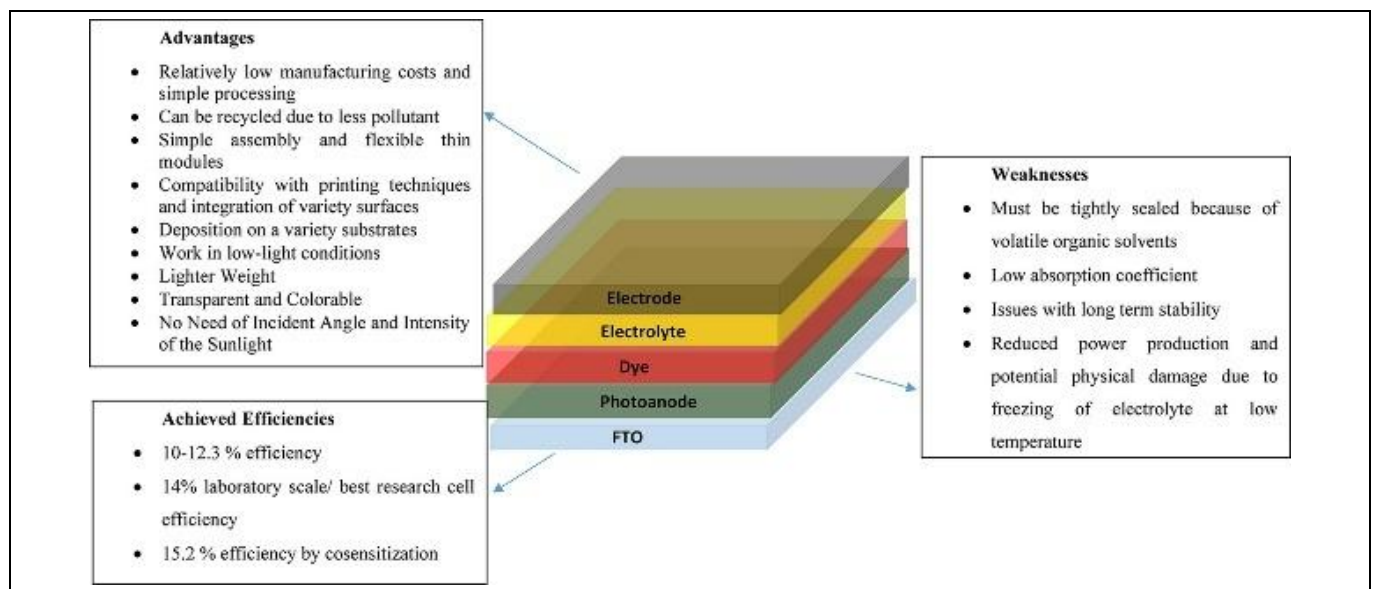


Figure 1. Illustrates the basic structure and electron flow of a typical n-type DSSC [10].

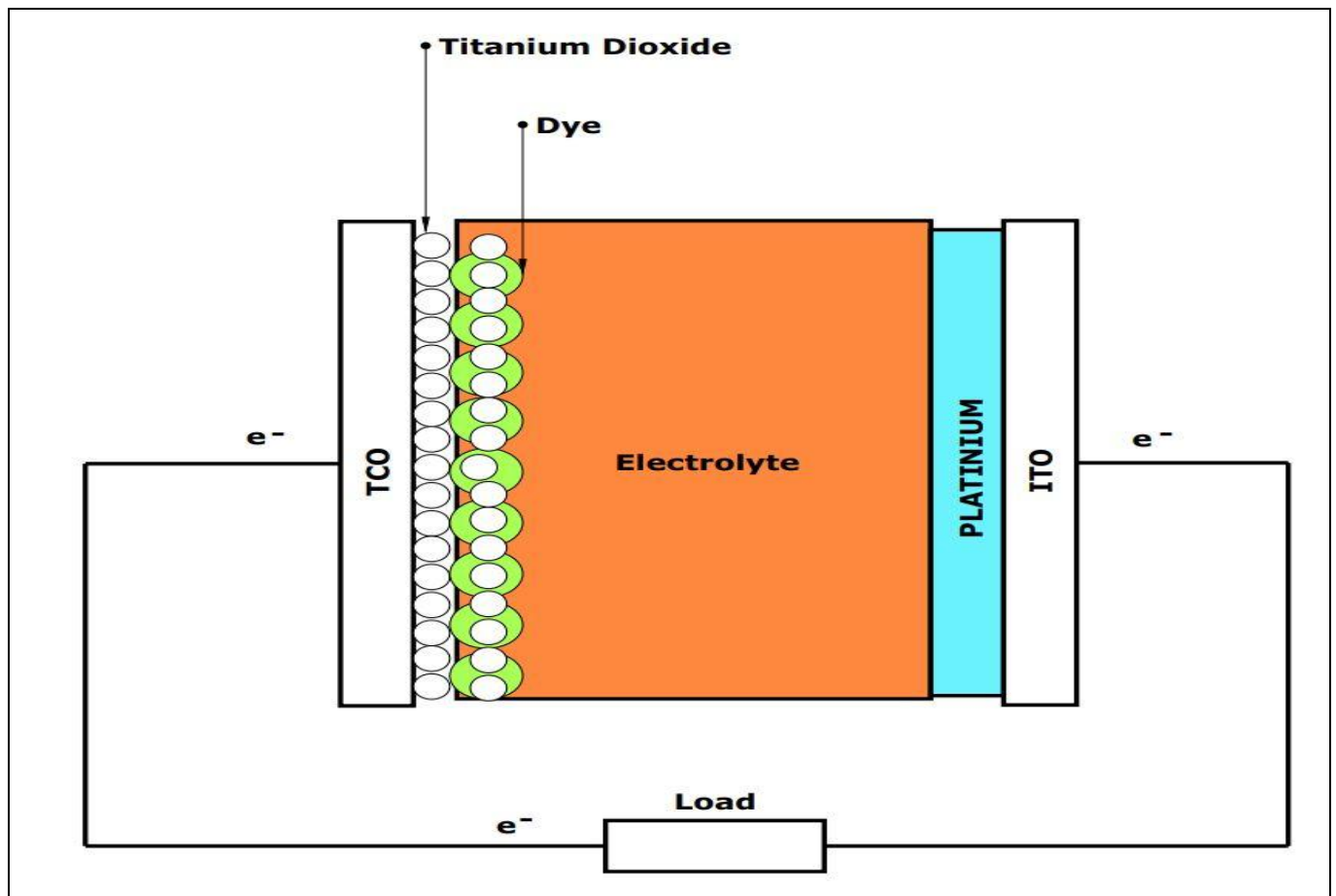


Figure 2. Schematic structure and operating principle of a typical n-type dye-sensitized solar cell.

2.1 N-type DSSCs: structure and working mechanism

In dye selection, the design of donor, π -bridge, and acceptor groups in organic dyes is critically important for enhancing both efficiency and long-term stability [32]. In organic dye design, the spatial separation and energetic alignment of donor, π -bridge, and acceptor units play a decisive role in directing photoinduced charge transfer and suppressing charge recombination. In particular, a well-engineered D- π -A architecture enables efficient electron delocalization toward the acceptor moiety and facilitates subsequent electron injection into the TiO_2 conduction band. As illustrated in Figure 3, the donor- π -bridge-acceptor (D- π -A) architecture promotes photoinduced electron transfer from the donor unit toward the acceptor group and facilitates subsequent electron injection into the conduction band of TiO_2 [33].

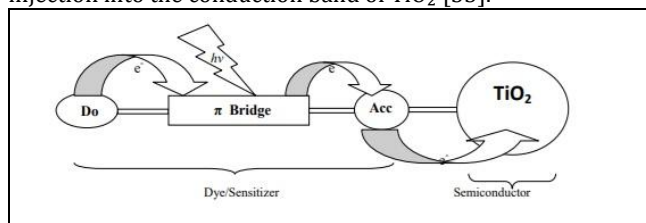


Figure 3. Design principle of photosensitizer dye.

A dye-sensitized solar cell (DSSC) fundamentally consists of four key components: the photoanode, the dye, the electrolyte, and the counter electrode. The photoanode typically utilizes

semiconductor materials with a high surface area, such as nanocrystalline TiO_2 . When selecting a dye for the titanium dioxide semiconductor layer, particular attention is paid to its absorption coefficient, electron transport rate, and stability. The dye layer is uniformly adsorbed onto the nanocrystalline titanium dioxide structure to ensure effective light harvesting and charge transfer. In n-type DSSCs, photovoltaic operation relies on a dye-sensitized electron injection mechanism, where photoexcited dye molecules inject electrons into the conduction band of a nanostructured semiconductor, typically TiO_2 . The injected electrons are transported through the photoanode and external circuit, while the oxidized dye is regenerated by a redox electrolyte, completing a cyclic charge-transfer process. The triiodide ions are reduced to iodide ions by the incoming electrons. Simultaneously, the oxidized dye molecules retrieve their missing electrons from the iodide ions in the electrolyte, thus returning to their ground (reduced) state. Throughout this cycle, the electrolyte facilitates continuous charge transfer without undergoing any permanent chemical change. This mechanism enables DSSCs to achieve relatively high photovoltaic efficiencies despite their simple structure [13],[17],[34],[35].

The overall efficiency of DSSCs depends on several key components: the type of dye used, the photoanode material, the electrolyte phase, and the counter electrode material. For optimal performance, the dye must be uniformly adsorbed onto the semiconductor surface, which necessitates careful control of particle size and surface area.

The electrolyte, in either liquid or solid phase, facilitates the redox cycle by enabling the regeneration of dye molecules that have lost electrons during photoexcitation. The counter electrode, typically made from platinum or carbon-based materials, completes the electrical circuit of the cell. Unlike conventional p-n junction-based solar cells, DSSCs operate through a photochemical cycle, offering various advantages such as low material cost, flexible and semi-transparent form factors, and high specific efficiency under low-light conditions. Additionally, the modularity of DSSC components allows for device customization according to application-specific power requirements, such as in building-integrated photovoltaics or indoor IoT devices. This flexibility in structural and material design provides a unique platform for integrating DSSCs into next-generation energy-harvesting systems [36].

In dye-sensitized solar cells, transparent conductive oxide (TCO) glass substrates are commonly employed as carrier layers. Materials such as fluorine-doped tin oxide (FTO) and indium tin oxide (ITO) not only function as electron collectors but also provide 80–90% transmittance in the visible spectrum, ensuring efficient light delivery to the photoanode [37],[38]. In the photoanode component, the most widely used nanocrystalline semiconductor is titanium dioxide (TiO_2) [39]. However, alternative materials such as zinc oxide (ZnO) [40], and tin oxide (SnO_2) [41] are also being investigated due to their faster electron transport properties, distinct band gaps, and broader spectral absorption potentials. Surface engineering of these semiconductors is critically important. In particular, the use of one-dimensional (1D) nanowires or three-dimensional (3D) hierarchical porous structures enhances the surface area, thereby optimizing dye adsorption. As a result, the short-circuit current density (J_{sc}) of the cells can be increased by up to 30% [42]. The dyes used in DSSCs play a critical role in light absorption, electron injection, and overall energy conversion efficiency of the cell. Ruthenium polypyridyl complexes, owing to their high quantum yield, broad absorption spectrum, and excellent photochemical stability, have demonstrated power conversion efficiencies (PCE) of up to approximately 14%, representing some of the highest-performing DSSCs reported in the literature [17],[43]. Nevertheless, natural pigments particularly plant-derived compounds such as bixin, anthocyanins, and betalains are considered attractive for their low cost and biocompatibility, making them appealing from a sustainability standpoint. However, due to their limited thermal and photochemical stability, these dyes often exhibit efficiency degradation in long-term cell applications [44]-[49].

2.2 Photoanode materials

For DSSCs, the chemical structure, morphology, and surface area of the photoanode are key factors that directly influence cell efficiency. Titanium dioxide (TiO_2) is the most commonly used material in this context. TiO_2 offers several advantages, including high dye-loading capacity, effective light scattering, and efficient photoelectron injection, making it highly suitable for dye-sensitized solar cell applications [50]-[52].

To date, the highest power conversion efficiencies (~6–12%) have predominantly been achieved using TiO_2 -based DSSCs [53],[54]. The band gap refers to the energy difference between the conduction band and the valence band of a semiconductor. In its anatase phase, TiO_2 typically exhibits a band gap of approximately 3.2 eV. However, this value can vary depending on factors such as nanocrystal size, doping, surface states, or

structural distortions [55]-[56]. However, TiO_2 also presents certain limitations, such as low electron mobility and charge recombination at the surface. The passivation of TiO_2 photoanodes with TiCl_4 has been widely reported in the literature to reduce recombination losses and enhance charge collection efficiency [57]. Therefore, extensive research is being conducted on various nanostructures and composites based on metal oxides that offer suitable band gaps and high electron mobility, such as wurtzite-structured ZnO, aluminum-doped ZnO (AZO), and perovskite-type oxides like BaSnO_3 and SrTiO_3 [58]. Advanced materials such as metal-organic frameworks (MOFs), graphene oxide (GO), reduced graphene oxide/bismuth oxide (rGO/ Bi_2O_3) composites, and conductive polymers also show significant potential to enhance dye loading capacity and efficiency due to their large surface areas and rapid electron transport properties [52],[59]. Photoanodes engineered through nanostructuring to possess porous and high-surface-area architectures enable more effective adsorption of dye molecules and facilitate efficient charge transport processes [39],[51]. In particular, hierarchical TiO_2 structures such as nanowires and hydrangea-shaped aggregates as well as the application of scattering layers, can enhance light harvesting and electron transport, thereby improving overall cell efficiency [60]. In conclusion, the selection and design of the photoanode material play a crucial role in enhancing the efficiency of DSSC systems [61].

2.2.1 Interface engineering in DSSCs

Interfacial engineering has emerged as a key strategy for improving charge transfer efficiency and suppressing recombination losses in dye-sensitized solar cells. Surface passivation layers, energy-level alignment modifiers, and interfacial dipole engineering at the dye/semiconductor and semiconductor/electrolyte interfaces play a crucial role in enhancing both open-circuit voltage and long-term stability. Techniques such as TiCl_4 treatment, ultrathin oxide coatings, and molecular interface modifiers reduce surface trap states and optimize interfacial energetics, resulting in improved photovoltaic performance.

2.2.2 Quantitative comparison of photoanode and dye materials in DSSCs

A quantitative comparison of photoanode and dye materials is essential for understanding the performance limits and design trade-offs of dye-sensitized solar cells. Table 1 summarizes the key electronic and photovoltaic parameters of commonly used n-type photoanode materials, highlighting the dominance of TiO_2 due to its balanced bandgap, favorable interfacial energetics, and superior chemical stability, despite its lower intrinsic electron mobility compared to ZnO and SnO_2 . In contrast, ZnO and SnO_2 exhibit significantly higher electron mobilities; however, increased charge recombination and interfacial instability often limit their achievable power conversion efficiencies. Table 2 presents a comparative overview of representative dye families. Ru(II)-based complexes remain benchmark sensitizers, offering broad spectral absorption, high short-circuit current densities, and excellent long-term stability. Metal-free organic dyes, typically based on donor- π -acceptor architectures, provide competitive open-circuit voltages and reduced material costs, albeit with moderately lower efficiencies and stability. Natural dyes exhibit limited absorption ranges and poor durability, resulting in substantially reduced device performance.

Table 1. Quantitative comparison of common n-type photoanode materials used in DSSCs.

Photoanode	Bandgap (eV)	Electron mobility (cm ² /V.s)	Jsc (mA/cm ²)	Voc (V)	PCE (%)	Stability
TiO ₂ (anatase)	~3.2	~0.1-1	15-22	0.7-0.9	6-12	Excellent
ZnO	~3.3	~200	12-20	0.6-0.8	4-9	Moderate
SnO ₂	~3.6	~250	10-18	0.5-0.7	3-7	Good

Table 2. Quantitative comparison of representative dye families used in DSSCs.

Dye type	Absorption range	Voc (V)	Jsc (mA/cm ²)	PCE (%)	Cost	Stability
Ru(II) complexes	Broad (400-750 nm)	0.75-0.9	18-22	11-14	High	Excellent
Metal-free organic (D-π-A)	Tunable	0.8-1.0	14-20	9-12	Low	Moderate
Natural dyes	Narrow	0.4-0.6	5-10	1-4	Very low	Poor

2.3 Electrolyte

One of the most critical components determining the long-term stability and operational durability of photovoltaic systems is the electrolyte. This is because the electrolyte must maintain its chemical stability during electron transfer processes and effectively facilitate charge transport throughout the system [16],[62]. Therefore, electrolyte design in DSSCs plays a critical role not only in energy conversion efficiency but also in structural reliability. In liquid electrolyte-based solar cells, the limited operational lifetime is primarily due to the thermal instability of the electrolyte and the risk of leakage [63].

To overcome these issues, solid-state DSSCs have been developed, in which liquid electrolytes are replaced by solid-phase hole-transporting layers such as organic or inorganic hole-transport materials (HTMs) [64],[65]. Solid-state DSSCs eliminate problems such as leakage and evaporation, thereby providing advantages in terms of long-term stability and simplified device encapsulation [63],[66]. In solid-state DSSCs utilizing hole transport materials (HTMs), the power conversion efficiency is generally lower. The primary reasons for this are the limited infiltration of solid-state conductors into the porous TiO₂ structure and their lower ionic conductivity compared to liquid electrolytes.

These limitations lead to reductions in short-circuit current density (Jsc), open-circuit voltage (Voc), and fill factor (FF) [64],[67]-[69]. One of the most critical parameters determining the performance and long-term stability of DSSCs is the selection of the electrolyte phase. In conventional DSSCs, electron transfer and the redox cycle are typically facilitated by liquid electrolytes, most commonly an I⁻/I₃⁻ solution. In recent years, substantial progress has been made toward optimizing the trade-off between efficiency and lifetime in solid-state DSSCs through the development of next-generation HTMs and hybrid electrolyte systems. Consequently, while liquid-electrolyte DSSCs stand out with their high efficiencies, solid-state DSSCs offer advantages in terms of safety, stability, and module fabrication; in the future, application-specific hybrid designs may have the potential to combine the benefits of both approaches [70]-[73]. Specifically, polymer-based and lamellar nanostructured solid-state electrolytes enhance both efficiency and thermal stability by improving ionic conductivity and interfacial contact. Quasi-solid (gel) and hybrid electrolytes offer efficiencies comparable to those of liquid electrolytes

while significantly mitigating issues such as leakage and evaporation [74]-[76]. This hybrid approach holds the potential to simultaneously address all the major challenges.

2.3.1 Liquid electrolytes

Liquid electrolytes are the most widely used electrolyte systems in dye-sensitized solar cells due to their high ionic conductivity and efficient charge transport characteristics. Conventional DSSCs typically employ iodide/triiodide (I⁻/I₃⁻) redox couples dissolved in organic solvents, which enable rapid dye regeneration and low internal resistance, resulting in high short-circuit current densities and power conversion efficiencies. Owing to their excellent pore infiltration capability within mesoporous TiO₂ photoanodes, liquid electrolytes provide intimate interfacial contact, which is essential for efficient charge transfer. However, their practical deployment is limited by inherent drawbacks, including solvent volatility, thermal instability, and electrolyte leakage, which negatively affect long-term device stability and encapsulation reliability [77]-[78].

2.3.2 Solid-state electrolytes

Solid-state electrolytes replace liquid redox mediators with solid hole-transporting materials (HTMs), such as organic small molecules, conductive polymers, or inorganic semiconductors. This architecture effectively eliminates leakage and evaporation issues, significantly enhancing mechanical robustness, thermal stability, and device lifetime. Solid-state DSSCs also facilitate simplified encapsulation and improved compatibility with flexible and miniaturized device platforms. Nevertheless, the infiltration of solid HTMs into the nanoporous TiO₂ network remains a major challenge, often leading to incomplete pore filling and reduced interfacial contact. As a result, solid-state DSSCs typically exhibit lower ionic conductivity and reduced charge transport efficiency, which manifest as decreased short-circuit current density, open-circuit voltage, and overall power conversion efficiency compared to their liquid-electrolyte counterparts [72],[79].

2.3.3 Quasi-solid (gel) electrolytes

Quasi-solid or gel electrolytes represent an intermediate approach that combines the high ionic conductivity of liquid electrolytes with the improved stability of solid-state systems.

These electrolytes are generally formed by immobilizing liquid redox couples within polymer matrices, ionic gels, or lamellar nanostructures, thereby suppressing leakage and solvent evaporation. Quasi-solid DSSCs exhibit enhanced thermal and mechanical stability while maintaining efficient dye regeneration and charge transport. Owing to their balanced performance characteristics, gel electrolytes have demonstrated power conversion efficiencies comparable to liquid systems, along with significantly improved operational durability. Consequently, quasi-solid electrolytes are considered a promising solution for application-specific DSSCs, particularly in flexible, wearable, and indoor energy-harvesting devices [80],[81].

2.4 Nanostructure and surface area

In DSSCs, the surface area plays a directly determining role in dye molecule adsorption and, consequently, in light-harvesting capacity. TiO_2 nanoparticles with high surface area enable increased dye loading, thereby enhancing the short-circuit current density (J_{sc}) and overall efficiency; for instance, TiO_2 nanoparticles with a surface area ranging from 120 to 168 m^2/g have been shown to improve cell efficiency by optimizing both electron transport and light absorption [82],[83]. Increasing the surface area not only enhances dye loading but also improves light scattering and electron transport pathways, thereby contributing to higher overall efficiency [84]-[86]. Moreover, as the active surface area increases, both the generated current and voltage tend to rise; however, at excessively large surface areas, efficiency losses may occur due to trap states, making the selection of an optimal surface area critically important [87]. In recent years, approaches such as hybrid and multilayer architectures, as well as plasmonic nanoparticle decoration, have significantly enhanced DSSC performance by increasing both surface area and light-harvesting capacity [88]. The nanostructured morphological properties of the photoanode material play a crucial role in determining the performance of DSSCs [89]. Although conventional 0D nanoparticles offer a high surface area, the random diffusion of electrons within this structure increases the risk of recombination and consequently limits the overall efficiency [90]. In contrast, 1D structures such as nanorods, nanowires, or nanotubes enable linear and rapid electron transport, thereby reducing recombination losses and increasing the short-circuit current density (J_{sc}). In particular, TiO_2 nanotube matrices and ZnO nanorod-based core-shell architectures can offer up to a 30% increase in J_{sc} and achieve power conversion efficiencies approaching 8%, owing to their combination of high surface area and efficient electron transport, outperforming conventional nanoparticle-based structures [91],[92]. Three-dimensional (3D) hierarchical structures, formed by the integration of multiple nanostructures, maximize both dye-loading capacity and light scattering. These architectures facilitate light entry from various angles and enhance dye adsorption. For example, 3D structures such as ZnO nanoflowers or TiO_2 hollow spheres significantly improve efficiency due to their high surface area and low charge transfer resistance [41],[93].

In conclusion, 1D and 3D nanostructured morphologies have significant potential to enhance the efficiency of DSSCs by simultaneously accelerating electron transport and improving light harvesting and dye-loading capacity.

3 P-type dye-sensitized solar cells

P-type dye-sensitized solar cells (p-DSSCs) are an alternative DSSC technology developed as a complement to the conventional n-type DSSC architecture and are particularly investigated for use in tandem solar cell configurations. The first p-type DSSC was successfully demonstrated in 1999 by He, Lindström, Hagfeldt, and Lindquist, using a nanostructured NiO photocathode sensitized with a porphyrin dye and a liquid electrolyte [94]. P-DSSCs represent a third-generation solar cell technology that aims to generate electricity from light energy by employing dye-sensitized photocathodes [95]. P-DSSCs have the potential to increase the overall open-circuit voltage (V_{oc}) by enabling spectral complementarity through tandem configurations with n-type DSSCs. NiO-based p-DSSCs offer high chemical and thermal stability while providing advantages in terms of cost and ease of fabrication. Moreover, due to the favorable energy level alignment of NiO, charge transport efficiency and electrocatalytic performance can be improved when the redox couples are optimally matched [96]. However, the primary barrier to the widespread application of p-DSSCs is their low photovoltaic performance. This performance limitation is mainly attributed to the restricted open-circuit voltage (V_{oc}). The fundamental cause of the low V_{oc} is the narrow energy difference between the valence band maximum of NiO and the redox potential of the I^-/I_3^- redox couple used. This limited energy gap results in a low photovoltage generated from photon absorption and facilitates rapid back-transfer of charge carriers to the redox couple, thereby increasing recombination rates. Additionally, surface trap states frequently observed on NiO further restrict the mobility and lifetime of hole carriers, further reducing the overall device efficiency [97]-[100].

Figure 4 illustrates the mechanism, revealing three primary recombination pathways in dye-sensitized solar cells. Pathway (a) involves the direct recombination of the photoexcited electron in the dye's lowest unoccupied molecular orbital (LUMO) with the hole in the valence band (VB) of the NiO layer.

Pathway (b) describes the interaction of the reduced form of the electrolyte with the hole on the NiO surface coated onto fluorine-doped tin oxide (FTO), resulting in electron loss.

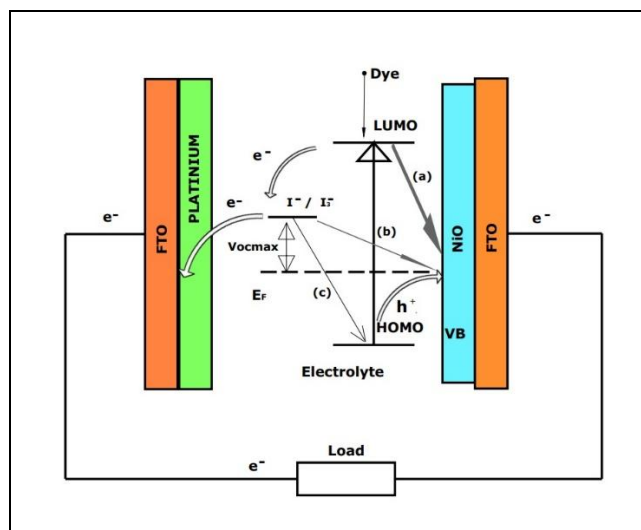


Figure 4. Schematic diagram of the operation of the NiO-based p-DSC. EF and VB indicate the Fermi level and the valence band edge of the NiO electrode.

These three recombination channels are regarded as the fundamental processes that directly limit the photovoltaic efficiency of the cell, and identifying the dominant pathway is critical for both material selection and device-architecture optimization. P-DSSCs exhibit a light-to-current conversion efficiency of approximately 2.5 % [101]. P-type dye-sensitized solar cells (p-DSSCs) are multilayer electrochemical systems that convert light energy into electrical energy. A typical p-DSSC architecture consists of a conductive FTO glass substrate, a nanostructured p-type semiconductor layer, a light-absorbing dye, a redox electrolyte, and a platinum counter electrode. This layered configuration enables the sequential processes of photon absorption, charge separation, and charge transport. The performance of p-DSSCs is governed by the generated photocurrent, the achievable output voltage, and the fill factor, which represents internal losses within the cell. In particular, the open-circuit voltage is limited by the energy difference between the quasi-Fermi level of the semiconductor and the redox potential of the electrolyte. The operating mechanism begins with photon absorption by the dye molecules. Upon excitation, the dye injects holes into the valence band of the p-type semiconductor, while the reduced dye is regenerated to its ground state via the electrolyte. Simultaneously, charge transport through the semiconductor and electrolyte generates a continuous photocurrent in the external circuit. Performance enhancement in p-DSSCs can be achieved by suppressing recombination losses, optimizing energy level alignment, and employing electrolytes with fast redox kinetics. These strategies improve the suitability of p-DSSCs for tandem configurations and advanced photovoltaic architectures [23],[102]-[104].

3.1 P-type DSSCs: developments and challenges

P-type DSSCs are based on the concept of dye-sensitized photocathodes. In n-type DSSCs, the photoexcited dye molecule injects an electron into the conduction band of the n-type semiconductor, whereas in p-type DSSCs, this process operates in the opposite direction. Dye-sensitized photocathodes function in this reverse mode: upon photoexcitation, the excited dye rapidly transfers an electron into the valence band of the p-type semiconductor. As a result, a photogenerated hole is transported through the valence band of the p-type semiconductor, while the reduced dye molecule is subsequently regenerated to its ground state by the redox electrolyte. Schematically, while p-type DSSCs operate based on the dye-sensitized hole injection mechanism, n-type DSSCs utilize dye-sensitized electron injection [97],[105].

NiO is distinguished by its wide bandgap (approximately 3.6 eV), good optical transparency, chemical stability, and favorable energy level alignment. Moreover, hole transport can be enhanced through surface modifications and nanostructural engineering. However, NiO suffers from short hole diffusion lengths, low mobility, and high recombination rates [106]-[108].

4 Key differences between p-type and n-type DSSCs

P-type DSSCs operate by adsorbing dye molecules onto a p-type semiconductor most commonly nickel oxide (NiO). When sunlight excites the dye, it loses an electron, resulting in the formation of a hole that is injected into the p-type semiconductor (e.g., NiO). This hole then migrates through the valence band of the semiconductor to the external circuit,

generating a photocathodic current. In contrast, in n-type DSSCs, the photoexcited electron is injected into the conduction band of an n-type semiconductor (such as TiO₂), producing a photoanodic current. Thus, the fundamental difference between the two cell types is that p-type DSSCs utilize holes as charge carriers, whereas n-type DSSCs utilize electrons [98],[109]. Alternatively, copper oxides (CuO, Cu₂O) have been investigated. Cu₂O, with its direct bandgap (~2.0 eV) and high absorption coefficient, has the potential to harvest a broader portion of the solar spectrum. Conversely, CuO is advantageous due to its low cost and ease of synthesis [110]. However, neither copper oxide has yet achieved the required long-term stability or optimal energy-level alignment (i.e., interface compatibility with the dye) [111].

4.1 Hole transport mechanisms and recombination processes

To enhance the efficiency of p-DSSCs, the energy levels of the dye and the p-type semiconductor must first be well aligned. This alignment particularly between the dye's HOMO-LUMO levels and the semiconductor's valence band facilitates efficient hole injection. Additionally, applying polymeric, metal-oxide, or organic functional-group coatings to the semiconductor surface can improve hole-transport pathways, while nano-morphology control increases the active surface area to further optimize transport efficiency. Finally, the catalytic activity and conductivity of the counter electrode play a decisive role in overall cell performance. The key parameters governing p-DSSC efficiency are the transport velocity and diffusion length of holes within the semiconductor. Upon photoexcitation, the dye injects a hole into the valence band of the p-type semiconductor (typically NiO), while the reduced dye molecule is subsequently regenerated by the redox electrolyte. These holes must then migrate rapidly and with minimal loss to the back-contact electrode (typically conductive glass). However, in p-type semiconductors, hole mobility and diffusion length are often limited, leading to rapid recombination and a corresponding drop in photocurrent. Interfacial defects can further accelerate recombination rates. Consequently, the most critical factor limiting p-DSSC performance is the inherently low mobility and short diffusion length of holes in the p-type semiconductor (commonly NiO), which leads to rapid recombination, reduced photovoltage, and overall photocurrent losses [107],[108],[112],[113].

In order to improve hole transport, surface modifications of p-type semiconductors have, in recent years, delivered significant performance enhancements in p-DSSCs. Specifically, surface treatments with polymers, metal oxides, and organic functional groups reduce surface trap states, thereby enabling more efficient hole transport [114]-[116].

Moreover, when the HOMO level is positioned close to the valence band, hole transfer from the photoexcited dye to the semiconductor occurs more rapidly and efficiently, thereby enhancing the overall device efficiency [96],[115],[116].

5 Transition to tandem DSSCs (n+p hybrid cells)

Tandem dye-sensitized solar cells (n+p hybrid DSSCs) have the potential to exceed the efficiency limits of single-junction cells by harvesting a broader range of the solar spectrum. Recent studies have demonstrated that tandem DSSC architectures, combining optimized n-type and p-type subcells, enable more efficient utilization of the solar spectrum and significantly

higher open-circuit voltages compared to single-junction DSSCs. By integrating complementary absorption ranges and reducing interfacial recombination losses, tandem DSSCs have achieved reported efficiencies exceeding 12%, highlighting their increasing relevance in next-generation photovoltaic research. The key advantage of p-type DSSCs lies in their integration with conventional n-type DSSCs in tandem configurations, enabling more effective utilization of full-spectrum sunlight for electricity generation. In such a device architecture, the n-type DSSC (typically TiO_2 -based) is positioned on top, while the p-type DSSC (e.g., NiO - or Cu_2O -based) is placed at the bottom.

Within this tandem setup, the electron flow from the n-DSSC and the hole flow from the p-DSSC are connected in series, thereby increasing the overall open-circuit voltage (V_{oc}) and enhancing the theoretical power conversion efficiency. However, in practice, the relatively low efficiency of p-type DSSCs remains a bottleneck, limiting the performance of the tandem cell. As a result, optimizing p-type DSSCs has emerged as one of the most crucial research priorities for tandem DSSC development. Recent progress such as the development of novel organic dyes, supramolecular dye assemblies, advanced interface engineering, and hybrid nanostructures has led to photon-to-electron conversion efficiencies of up to 96% and device efficiencies exceeding 2.5% in p-type photocathodes [105],[117],[118].

Moreover, parallel or series tandem configurations are employed to optimize light harvesting at different wavelengths, thereby enhancing overall efficiency. For instance, tandem DSSC efficiencies as high as 12.8% have been reported using novel organic dyes [119]. Nevertheless, fundamental issues such as the low current density and rapid recombination in p-type cells hinder the full realization of the potential of tandem solar cells [117],[118],[120],[121]. However, these values still lag significantly behind those of n-DSSCs, and bridging this performance gap requires precise interface control, fine-tuning of energy levels, and the development of next-generation hole-transport materials.

5.1 Optical matching, current balancing, and device engineering challenges in tandem DSSCs

Tandem dye-sensitized solar cells (n+p DSSCs) offer an effective strategy to surpass the efficiency limits of single-junction devices by exploiting complementary spectral absorption. However, their practical implementation is constrained by several critical engineering challenges. One of the primary issues is optical matching between the n-type and p-type subcells.

Since the top n-DSSC partially filters the incident light, the spectral response of the bottom p-DSSC must be carefully engineered to ensure efficient utilization of the transmitted photon flux. Mismatched absorption profiles lead to parasitic optical losses and reduced photocurrent generation. Another fundamental limitation is current balancing between the two subcells. In series-connected tandem architectures, the overall photocurrent is limited by the weaker subcell, which is typically the p-type DSSC due to its intrinsically lower short-circuit current density. This current mismatch significantly restricts the achievable power conversion efficiency, even when high open-circuit voltages are obtained. Strategies such as dye co-sensitization, thickness optimization of the photoelectrodes, and band-level tuning have been proposed to mitigate this issue. Interfacial recombination at the junction between the n-

type and p-type cells represents an additional loss mechanism. The recombination layer must provide efficient charge recombination while remaining optically transparent and electrically conductive. Inadequate recombination layers introduce resistive losses and exacerbate charge accumulation, leading to voltage losses and long-term stability concerns. Finally, tandem DSSCs pose substantial device engineering challenges, including mechanical alignment, electrolyte compatibility, sealing reliability, and scalable fabrication. The increased architectural complexity compared to single-junction DSSCs necessitates precise control over interfaces and materials to ensure reproducible and durable device performance. Addressing these challenges is essential for translating tandem DSSC concepts from laboratory-scale demonstrations to practical photovoltaic applications.

6 Quantum dots and perovskite hybrids in DSSCs

Quantum dot sensitization offers a significantly broader and tunable spectral absorption range compared to conventional dye molecules. Semiconductor quantum dots such as CdSe , CdS , and PbS , when anchored onto the photoanode surface, lead to substantial improvements in light harvesting. However, their commercial application remains limited due to concerns related to stability and toxicity. In recent years, record efficiencies have been achieved in hybrid DSSCs by replacing conventional dyes with perovskite materials such as MAPbI_3 . These perovskite hybrids retain the architectural flexibility and ease of fabrication inherent to DSSCs, while providing much higher light absorption and superior charge carrier mobility. As a result, power conversion efficiencies (PCE) exceeding 15% have been reported in DSSC-perovskite hybrid systems. Nevertheless, challenges related to long-term stability, material toxicity, and device longevity still need to be addressed [122]-[125].

7 Performance enhancement strategies

To achieve commercial success, DSSC technology requires significant improvements in efficiency, stability, and long-term durability. In recent years, various performance-enhancing technologies have been developed in both materials engineering and device design. Functionalization of the photoanode surface enables stronger and more uniform attachment of dye molecules, while silane-based surface modifications, in particular, have been shown to accelerate electron transfer [126].

D- π -A type supramolecular dyes provide broad spectral absorption and optimize electron transfer, while anchoring groups such as carboxyl or phosphonate enable strong attachment to the surface and enhanced stability [127]. To provide a clearer historical perspective on the evolution of DSSC performance, Table 3 summarizes the key efficiency milestones achieved between 1991 and 2025. The timeline highlights how advances in dye molecular engineering, electrolyte chemistry, and counter electrode materials have collectively driven the progressive increase in power conversion efficiency. This visualization emphasizes the stepwise nature of DSSC development and illustrates the close interplay between material innovation and device performance. Table 3 highlights the stepwise efficiency improvements in DSSCs driven by advances in dye chemistry, electrolyte systems, and electrode materials over the past three decades.

Table 3. Milestones in the development of dye-sensitized solar cells (DSSCs): key material innovations and their impact on device efficiency [17].

Year(s)	Key advancement	Main materials / concepts	Reported efficiency impact
1991	First DSSC demonstration	Ru-based dyes, I^-/I_3^- electrolyte	~7%
2004–2006	Nanocrystalline photoanode optimization	Mesoporous TiO_2	Improved charge collection
2011–2014	Molecular engineering of sensitizers	Porphyrin dyes	~12–13%
2015–2018	Advanced redox couples and HTMs	Co-based electrolytes, Cu-based HTMs	Higher Voc, stability
2020–2023	Indoor-optimized DSSCs and carbon electrodes	MXenes, carbon-based electrodes	Enhanced low-light efficiency
2024–2025	Tandem and hybrid DSSC architectures	n+p tandem, solid-state systems	>12% (tandem devices)

Molecular co-sensitization is an effective strategy for broadening the absorption spectrum and enhancing light-harvesting efficiency in DSSCs. By employing multiple dyes with complementary absorption profiles, co-sensitized systems improve short-circuit current density without adversely affecting charge injection dynamics. Recent studies have shown that rational co-sensitization design, particularly when combined with optimized interfacial engineering, can lead to significant improvements in overall power conversion efficiency. The co-sensitization approach, which involves the simultaneous use of dyes operating at different spectral regions, can offer significant advantages in energy conversion efficiency.

The short-circuit current density (J_{sc}) can be enhanced by increasing the surface area and improving charge transport pathways, while the open-circuit voltage (V_{oc}) can be improved through energy level alignment and reduction of surface trap states. Additionally, minimizing internal resistances and improving contact quality are key factors influencing the fill factor (FF) [128],[129]. An ideal energy alignment in DSSCs is achieved when the LUMO level of the dye molecules lies above the conduction band of the semiconductor, and the HOMO level is below the redox potential of the electrolyte. This alignment can be optimized through molecular engineering, dopant incorporation, and surface modifications, thereby enhancing both photochemical stability and overall device efficiency. Proper energy level matching enhances electron transfer efficiency, suppresses recombination, and improves device stability, enabling DSSCs to achieve high performance for both indoor and outdoor applications [130]-[132].

8 Discussion

Among photovoltaic technologies, dye-sensitized solar cells (DSSCs) hold significant potential for sustainable energy generation due to their unique material architectures and low-

cost fabrication processes. This review provides a broad perspective on recent developments in the field, ranging from the fundamental building blocks of DSSCs to advanced material combinations, performance optimization strategies, and innovative application areas. The discussion topics are elaborated below. The most critical factor determining DSSC performance is the chemical composition and morphology of its key components: the photoanode, dye, electrolyte, and counter electrode. Titanium dioxide (TiO_2) remains the most widely used photoanode material, offering the highest efficiencies to date. Alternative semiconductors such as ZnO and SnO_2 are also under investigation. However, ZnO has exhibited chemical instability and interfacial compatibility issues with dyes, which continue to pose challenges for large-scale applications. Balancing stability and efficiency across different electrolyte types liquid, gel, and solid-state remains a key debate in both energy storage and DSSC-based devices. The balanced optimization of all these parameters will be key to positioning DSSC technology as a strategic component in next-generation photovoltaic systems. Table 4 summarizes the comparative characteristics of major photovoltaic technologies [133]-[139].

Liquid electrolytes offer high ionic conductivity and efficiency, but they suffer from leakage and flammability, raising safety concerns. Solid-state electrolytes, on the other hand, are generally safer and more durable, yet often face efficiency losses and poor interfacial contact with the electrodes [140],[141]. DSSC technology offers flexible, semi-transparent, and colored fabrication capabilities that go beyond the traditional “rigid panel” format. This versatility enables its use in building-integrated photovoltaics (BIPV), indoor low-light applications, and wearable or textile-integrated energy solutions. Notably, the high specific efficiency achieved under indoor lighting conditions such as LEDs and fluorescent lamps makes DSSCs suitable as battery-independent power sources for IoT devices and low-power sensors. Flexible DSSCs can be integrated into textile surfaces, providing energy autonomy for wearable electronics and biomedical sensors.

However, at the module level, long-term durability and mechanical robustness remain critical challenges that require further improvement [142]-[144]. Moreover, environmental and lifecycle assessments have highlighted the importance of adopting recyclable, low-toxicity materials in future DSSC production to ensure true sustainability across manufacturing, usage, and disposal stages. Such an approach aligns DSSC research with circular economy principles and global carbon-neutral energy goals [145]. In recent years, commercially available “indoor DSSC” solutions have emerged, significantly reducing battery requirements in office sensors, smart home devices, and portable electronics. These cells are spectrally optimized to maximize the energy harvesting potential of existing indoor lighting conditions [146]-[148].

8.1 Future Trends and Outlook in DSSC Technology

From a forward-looking perspective, the evolution of dye-sensitized solar cell (DSSC) technology is expected to be shaped by advances in materials engineering, device architecture, and sustainable manufacturing approaches. In this context, one of the most prominent research trends involves replacing precious and scarce counter-electrode materials such as platinum with more abundant, low-cost, and environmentally sustainable alternatives, including carbon-based materials, conductive polymers, and transition metal compounds.

Table 4. Comparison of key characteristics of major photovoltaic technologies, including crystalline silicon, thin-film, perovskite, and dye-sensitized solar cells (n-type and p-type).

Feature/Parameter	Crystalline Silicon PV	Thin Film (CdTe, CIGS)	Perovskite PV	DSSC (n-type)	DSSC (p-type)
Operating Principle	p-n junction [133]	p-n junction [134]	p-n junction [135]	Dye-sensitized electron injection (n-type) [136]	Dye-sensitized hole injection (p-type) [137]
Main Materials	Si	CdTe, CIGS, a-Si [138]	MAPbI ₃ , FAPbI ₃ [139]	TiO ₂ /ZnO + Dye + Electrolyte + Counter Electrode	NiO/CuO + Dye + Electrolyte + Counter Electrode
Manufacturing Method	High temp., wafer-based	Vacuum/sol-gel, low T	Spin coating, inkjet	Sol-gel, printing, low temperature	Sol-gel, printing, low temperature
Transparency/Flexibility	Low, rigid	Moderate	High	Very high	Very high
Main Advantages	Mature tech, efficiency, stability	Low cost, lightweight, large area	High efficiency potential, printable	Low cost, transparency, color, indoor use, flexible	Transparency, flexible, tandem potential
Main Disadvantages	High energy input, brittle, rigid	Toxic materials (Cd), lower stability	Stability issues, toxicity	Electrolyte leakage, dye instability, lower efficiency	Very low efficiency, fast recombination
Typical Applications	PV panels, solar farms	BIPV, mobile, integrated	BIPV, indoor, niche	BIPV, indoor, sensors, textiles	Tandem DSSC, niche, laboratory

Such strategies not only enhance the economic feasibility of DSSCs but also offer significant potential for reducing their environmental footprint. Another major direction is the transition from conventional liquid electrolyte systems to solid-state, quasi-solid, and self-healing electrolyte architectures. These next-generation electrolytes aim to combine high ionic conductivity with enhanced safety, long-term chemical and thermal stability, and simplified encapsulation requirements, thereby improving module-level durability. In parallel, the development of organic-inorganic hybrid structures and biomimetic dye systems has emerged as a key research focus, providing promising pathways for broadening light-harvesting capability, suppressing recombination losses, and enabling the use of environmentally benign cell components.

Flexible and textile-integrated DSSCs are expected to play an increasingly critical role in future energy-harvesting scenarios. The use of polymer substrates such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN), together with conductive fibers and threads, enables the fabrication of lightweight, bendable, and wearable photovoltaic modules.

These systems are particularly well suited for indoor and low-light environments, where DSSCs exhibit high specific efficiency under LED and fluorescent illumination. In this regard, DSSCs are attracting considerable attention as battery-free and sustainable power sources for Internet of Things (IoT) sensors, wireless data transmission systems, and wearable biomedical devices [149]. At the industrial scale, low-temperature printing techniques and roll-to-roll manufacturing processes are expected to enable the cost-effective and scalable production of large-area DSSC modules. When considered alongside life-cycle-oriented material selection, recycling strategies, and the use of low-toxicity components, these approaches align DSSC technology with circular economy principles and global carbon-neutral energy targets. Although fundamental challenges related to long-term stability, efficiency scalability, and module durability persist, a holistic integration of nanostructure engineering, molecular-level energy band alignment, and sustainable material innovations positions DSSCs as a versatile and forward-looking photovoltaic platform. To successfully translate laboratory-scale advances into real-world applications, sustained interdisciplinary collaboration among materials science, chemistry, and device

engineering disciplines remains essential. Overall, while the progress achieved in DSSC technology is promising, key challenges related to material stability, module-scale scalability, and environmental and economic sustainability remain unresolved. The integration of organic-inorganic hybrid systems, biocompatible and natural pigments, and self-healing electrolyte architectures represents a critical roadmap for future developments. Achieving a balance between efficiency, cost, and long-term durability will be decisive for the large-scale industrial commercialization of DSSC technology. As a result, flexible DSSCs employing transparent polymer substrates such as PET and PEN offer significant advantages in terms of lightweight design and mechanical adaptability, while textile-integrated DSSCs enable direct energy harvesting from garments, bags, and functional fabrics. The integration of conductive threads with nanoscale photoanode coatings allows the development of foldable and dynamic cell architectures that can be fabricated using low-temperature manufacturing processes. Owing to their high efficiency under indoor and low-light conditions, DSSCs emerge as a particularly suitable technology for powering Internet of Things (IoT) devices, wireless sensor networks, and low-power electronic systems. Furthermore, the use of biocompatible dyes and environmentally friendly materials opens up new opportunities for sensitive applications such as medical devices and on-skin integrated sensors [149]-[151].

9 Conclusions

Dye-sensitized solar cells (DSSCs) have emerged as a significant research topic in the field of photovoltaic technologies due to their unique features such as flexible design capabilities, low production costs, and semi-transparency. Recent advances in nanostructure engineering, as well as the design of dye molecules and electrode materials, have led to continuous improvements in the power conversion efficiency of DSSCs.

Today, laboratory-scale efficiencies approaching 14%, high performance under low-light conditions, and versatile application potential reflect the remarkable progress in the development of this technology. One of the main barriers to commercialization is the limited stability of dyes and the inability to produce high-performance dyes at industrial scale due to their high cost. From an industrial perspective, DSSCs are expected to experience rapid growth in At the industrial scale,

the adoption of low-temperature printing techniques and roll-to-roll manufacturing processes may enable the cost-effective production of large-area DSSC modules, particularly for niche markets such as building-integrated photovoltaics (BIPV), indoor sensors, and flexible and wearable devices. The development of scalable manufacturing techniques and the standardization of long-term module-level durability testing are critical for accelerating commercialization and enabling DSSCs to compete with silicon-based solar cells. In light of these considerations, DSSCs are expected to make a notable impact in both academic and industrial domains in the coming years as a versatile and innovative photovoltaic platform offering an optimal balance between performance, cost, and stability.

10 Author contribution statements

In the scope of this study, Olcay Kaan Çakır primarily contributed to the conception and development of the research idea, performed an extensive literature review, structured the methodology, and prepared the initial draft of the manuscript. Olcay Kaan Çakır was also responsible for integrating the collected knowledge into a coherent framework, refining the arguments, and ensuring the overall organization of the paper as a review article. Şule Erten Ela provided continuous supervision throughout the preparation of the manuscript, critically evaluated the structure and scientific content, and guided the refinement of the arguments. In addition, Şule Erten Ela supported the revision of the manuscript by giving constructive feedback, ensuring that the final version of the article achieved both scientific clarity and academic rigor.

11 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared". "There is no conflict of interest with any person / institution in the article prepared".

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