Dye-sensitized solar cells (DSSCs): Sensitizers engineering design, photophysical principles, and strategies for improvement of energy conversion efficiency – A review

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This review examines the fundamental principles guiding the photovoltaic solar energy conversion and the current state of research on dye-sensitized solar cells (DSSCs) as a promising third-generation technology for environmentally sustainable energy applications. Particular attention is given to the dye sensitizer as the key component of DSSCs, governing the spectral response, the efficiency of electron injection into nanostructured TiO_2 as semiconductor, and the long-term stability of the device. The review summarizes the characteristics of the three major classes of sensitizers: ruthenium complexes, metal-free organic donor–π–acceptor (D–π–A) dyes based on triphenylamine, and the natural pigments, including anthocyanins, betalains, chlorophylls, and carotenoids. The optical absorption properties, HOMO/LUMO energy levels, photostability, and adsorption behavior on TiO_2 surfaces are comparatively analyzed. Ruthenium complexes remain the benchmark sensitizers, achieving power conversion efficiencies (PCEs) of approximately 10–14%, whereas organic triphenylamine (TPA)-based dyes exhibit comparable performance while offering greater structural tunability and lowering of potential toxicity. In contrast, natural dyes still suffer from relatively low efficiencies due to their narrow absorption spectra and limited photochemical stability. Recent strategies for improving DSSC performance are also discussed, including co-sensitization, cobalt- and copper-based redox mediators, TiO_2 nanostructuring, D–A–π–A molecular architectures, and the integration of metal–organic frameworks (MOFs). Finally, the major barriers to DSSC commercialization are highlighted, together with promising application areas such as indoor photovoltaics, the Internet of Things (IoT), building-integrated photovoltaics (BIPV), agrivoltaics, and the development of environmentally benign photovoltaic systems.

Keywords: dye sensitized solar cells; ruthenium dyes; organic D-π-A dyes; triphenylamine; natural dyes.

Бояғышпен сенсибилизацияланған күн элементтері (БСКЭ): сенсибилизаторларды инженерлік жобалау, фотофизикалық принциптер және энергияны түрлендіру тиімділігін арттыру стратегиялары — шолу

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Бұл шолуда күн энергиясын фотоэлектрлік түрлендірудің негізгі принциптері және экологиялық тұрақты энергетикалық қосымшаларға арналған перспективалы үшінші буын технологиясы ретінде бояғышпен сенсибилизацияланған күн элементтері (БСКЭ) саласындағы зерттеулердің қазіргі жайы қарастырылады. БСКЭ негізгі құрамдас бөлігі болып табылатын және спектрлік сипаттамаларын, наноқұрылымды TiO_2 жартылай өткізгішіне электрондардың инжекциялану тиімділігін, сондай-ақ құрылғының ұзақ мерзімді тұрақтылығын анықтайтын бояғыш-сенсибилизаторға ерекше назар аударылады. Шолуда сенсибилизаторлардың үш негізгі класының сипаттамалары жинақталған: рутений кешендері, трифениламин негізіндегі металсыз органикалық донор–π–акцепторлық (D–π–A) бояғыштар және антоциандар, беталаиндер, хлорофиллдер мен каротиноидтарды қамтитын табиғи пигменттер. Олардың оптикалық жұтылу қасиеттері, HOMO/LUMO энергетикалық деңгейлері, фототұрақтылығы және TiO_2 бетімен адсорбциялану ерекшеліктері салыстырмалы түрде талданады. Рутений кешендері қуатты түрлендіру тиімділігі (PCE) шамамен 10–14% болатын эталондық сенсибилизаторлар болып қала береді. Ал трифениламин (TPA) негізіндегі органикалық бояғыштар құрылымдық түрлендіру мүмкіндіктерінің кеңдігімен және ықтимал уыттылық деңгейінің төмендігімен ерекшелене отырып, салыстырмалы тиімділік көрсетеді. Керісінше, табиғи бояғыштар жұтылу спектрінің тар болуына және фотохимиялық тұрақтылығының шектеулілігіне байланысты әлі де салыстырмалы түрде төмен тиімділік көрсетеді. Сондай-ақ БСКЭ жұмыс сипаттамаларын жақсартуға бағытталған заманауи стратегиялар қарастырылады. Олардың қатарына ко-сенсибилизация, кобальт және мыс негізіндегі тотығу-тотықсыздану медиаторларын қолдану, TiO_2 наноқұрылымын оңтайландыру, D–A–π–A молекулалық архитектураларын жобалау және металл-органикалық қаңқалық құрылымдарды (MOFs) интеграциялау жатады. Қорытынды бөлімде БСКЭ технологиясын коммерцияландырудағы негізгі кедергілер және оны қолданудың перспективалы бағыттары, соның ішінде үй-жайларға арналған фотоэлектрлік жүйелер, заттар интернеті (IoT), ғимараттарға интеграцияланған фотоэлектрлік жүйелер (BIPV), агровольтаика және экологиялық қауіпсіз фотоэлектрлік жүйелерді әзірлеу мәселелері айқындалады.

Түйін сөздер: бояғышпен сенсибилизацияланған күн элементтері; рутений бояғыштары; D–π–A типті органикалық бояғыштар; трифениламин; табиғи бояғыштар.

Сенсибилизированные красителем солнечные элементы (СКСЭ): инженерное проектирование сенсибилизаторов, фотофизические принципы и стратегии повышения эффективности преобразования энергии — обзор

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В данном обзоре рассматриваются фундаментальные принципы фотоэлектрического преобразования солнечной энергии и современное состояние исследований сенсибилизированных красителем солнечных элементов (СКСЭ) как перспективной технологии третьего поколения для экологически устойчивого применения в энергетике. Особое внимание уделяется красителю-сенсибилизатору как ключевому компоненту СКСЭ, определяющему спектральные характеристики, эффективность инжекции электронов в наноструктурированный полупроводник TiO_2, а также долговременную стабильность устройства. В обзоре обобщены характеристики трех основных классов сенсибилизаторов: комплексов рутения, безметалльных органических красителей донорно–π–акцепторного (D–π–A) типа на основе трифениламина и природных пигментов, включая антоцианы, беталаины, хлорофиллы и каротиноиды. Проведен сравнительный анализ их оптических характеристик поглощения, энергетических уровней HOMO/LUMO, фотостабильности и особенностей адсорбции на поверхности TiO_2. Комплексы рутения по-прежнему остаются эталонными сенсибилизаторами, обеспечивающими эффективность преобразования энергии (PCE) на уровне приблизительно 10–14%. В то же время органические красители на основе трифениламина (TPA) демонстрируют сопоставимые характеристики, предоставляя более широкие возможности структурной модификации и снижая потенциальную токсичность. Напротив, природные красители характеризуются относительно низкой эффективностью, обусловленной узким спектром поглощения и ограниченной фотохимической стабильностью. Также обсуждаются современные стратегии повышения эффективности СКСЭ, включая ко-сенсибилизацию, применение окислительно-восстановительных медиаторов на основе кобальта и меди, наноструктурирование TiO_2, разработку молекулярных архитектур типа D–A–π–A и интеграцию металл-органических каркасных структур (MOFs). В заключение рассматриваются основные препятствия на пути коммерциализации СКСЭ, а также перспективные области их применения, такие как комнатные фотоэлектрические системы, Интернет вещей (IoT), фотоэлектрические системы, интегрированные в здания (BIPV), агровольтаика и разработка экологически безопасных фотоэлектрических систем.

Ключевые слова: сенсибилизированные красителем солнечные элементы; рутениевые красители; органические красители D–π–A-типа; трифениламин; природные красители.

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(2026) Chem Bull Kaz Nat Univ 4:N-NN

CHEMICAL BULLETIN
of Kazakh National University
http://bulletin.chemistry.kz/

IRSTI 31.21.00 https://doi.org/10.15328/cb2026_152

Review

Dye-sensitized solar cells (DSSCs): Sensitizers engineering design, photophysical principles, and strategies for improvement of energy conversion efficiency – A review

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1. Introduction

With the rapid development of human civilization, the issue of energy supply has become one of the major global challenges. Continuous growth in population, migration, industrialization, and technological advancement has led to a steady increase in global energy demand, placing increasing pressure on energy resources worldwide [1]. Fossil fuels remain the dominant sources of energy, accounting for a substantial share of global energy consumption. However, the continued reliance on conventional energy sources is associated with the depletion of natural reserves and has accelerated the transition toward low-carbon energy systems [2].

Among renewable energy sources, solar energy is of particular importance, as solar radiation represents an almost inexhaustible and globally available resource [3]. The development of photovoltaic technologies is focused on improving the efficiency of converting solar energy into electricity, reducing the associated cost of electricity generation, and expanding the range of their applications–from large-scale power plants to autonomous and decentralized energy systems [4, 5].

Against this background, considerable efforts have been directed toward dye-sensitized solar cells (DSSCs), a class that has now been associated to the next-generation photovoltaic devices. DSSCs are attractive due to their relatively low production cost, simple fabrication process, and extensive opportunities for the molecular design of functional components. The key component of these devices is the sensitizing dye, which determines the light absorption range, the efficiency of electron injection into the semiconductor, and the long-term operational stability of the DSSC [6].

In recent years, organic and metal-free dyes for DSSCs, particularly those based on donor–π–acceptor (D–π–A) architectures, have attracted increasing interest because they combine the flexibility of molecular design with the potential to reduce both toxicity and cost when compared to the conventional metal-complex sensitizers. Tailoring the donor and acceptor units, the nature of the π-conjugated bridge, and the anchoring groups enables precise control over the photovoltaic performance of DSSCs. Nevertheless, several challenges remain unresolved, which include: improvement in photostability of the sensitizing dyes, broadening of the absorption spectra towards longer wavelengths in particularly, to the near-infrared region, and lastly, achievement of more efficient electron injection into the conduction band of the semiconductor [7–10].

Therefore, in the analysis of modern photovoltaic technologies, laying particular emphasis on photosensitizing dye materials for DSSCs, it is highly relevant for advancing fundamental understanding of photo- and electrochemical energy conversion processes and the development of next-generation photovoltaic devices.

The present review is primarily based on publications from 2021 to 2025, while studies published between 2012 and 2020 were also included to provide broader coverage of the development of DSSCs.

Received 23 Jul 2026; Received in revised form 01 Oct 2026; Accepted 06 Oct 2026; Available online 12 Nov 2026.

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2. Main Part

2.1 Photovoltaic conversion of solar energy

The photovoltaic conversion of solar energy is based on the ability of semiconductor materials to convert a portion of the energy of incident radiation into electrical energy through the generation and separation of charge carriers. Upon absorption of a photon with sufficient energy, an electron in the semiconductor is excited to a higher energy state, resulting in the formation of a free electron and a positively charged "hole." Under the influence of an internal electric field, these charge carriers are separated and transported toward opposite electrodes, leading to the generation of an electric current [11].

A key element of this structure is the p-n junction – a region within a semiconductor where an electric field is generated that promotes the separation of the electron-hole pair formed under light irradiation and prevents their rapid recombination. In early-generation devices, this electric field is formed due to the difference between the p- and n-type regions of the same semiconductor (homojunction). At the interface between these regions, an electric field is established that can drive photoexcited electrons and holes in opposite directions. As a result, a potential difference (photovoltage) develops across the contacts of the solar cell. Thus, when an external electrical circuit is connected, electrons begin to flow through it, generating an electric current that determines the efficiency of converting solar energy into electrical energy [12].

It should be noted that a p-n junction can form not only within a single semiconductor but also at the interface between two different semiconductor materials (heterojunction). At the contact between two different semiconductors, charge carriers diffuse until their Fermi levels become aligned, resulting in the formation of a space-charge region and an internal electric field. In semiconductor devices of later generations, charge separation can occur at the interface between an n-type semiconductor, such as TiO_2, ZnO, or SnO_2, and a p-type semiconductor, such as NiO or Cu_2O. A key factor determining the efficiency of a heterojunction is the alignment of the energy structures of the materials. The positions of the conduction- and valence-band edges of the semiconductors should provide sufficient thermodynamic driving force for the injection and transport of charge carriers while minimizing potential barriers and suppressing back-recombination processes [13,14].

The efficiency of photovoltaic energy conversion depends on several factors, including the ability of the material to absorb solar radiation, the capacity to generate free electrons and holes, the rate of charge separation and transport, as well as the energy losses caused by charge recombination and electrical resistance within the device. To achieve broader coverage of the solar spectrum and improve photovoltaic performance, materials with enhanced electronic and optical properties, as well as multilayer and bifacial solar cell architectures, are being actively developed. In addition, considerable research efforts are focused on alternative photovoltaic technologies, including dye-sensitized, organic, and perovskite solar cells. Although these devices operate on the same fundamental principles of photovoltaic energy conversion, the functions of light harvesting and charge transport are distributed among different components. This separation provides greater flexibility in molecular and device design, thereby enabling further improvements in the performance and efficiency of solar cells [15, 16].

2.2 Structure and operating principle of DSSC

DSSCs are thin-film photovoltaic devices in which the functions of light harvesting and charge transport are carried out by different components of the system as mentioned earlier. A typical DSSC consists of a working (photoanode) electrode comprising a conductive substrate coated with a nanostructured semiconductor oxide layer (most commonly TiO_2), on whose surface a sensitizing dye is adsorbed, together with an electrolyte containing a redox couple and a counter electrode with a catalytic surface [17].

The photoanode consists of a transparent conductive substrate, most commonly FTO- or ITO-coated glass, sequentially covered with a compact layer of titanium dioxide (TiO_2), which serves as a barrier layer, and a mesoporous layer with a high specific surface area. The mesoporous surface enables the adsorption of a large number of dye molecules and, consequently, increases the amount of absorbed light and the number of photogenerated electrons. The interconnected network of TiO_2 nanoparticles facilitates the transport of injected electrons to the conductive substrate. A sensitizer dye is adsorbed onto the surface of mesoporous TiO_2, where it absorbs solar radiation and initiates the electron injection process. The photoanode should exhibit high electrical conductivity, excellent chemical and photochemical stability, and a conduction band edge notably positioned sufficiently below the lowest unoccupied molecular orbital (LUMO) of the dye to facilitate efficient electron injection. In addition, the ability of the photoanode structure to effectively absorb and scatter incident light plays a crucial role. These properties increase the probability of dye excitation and charge generation, thereby contributing to improved photovoltaic performance of the solar cell [18, 19].

The dye in a DSSC is responsible for harvesting solar radiation and transferring the excited electrons to the TiO_2 semiconductor. An ideal sensitizer should exhibit strong light absorption, particularly in the visible and near-infrared regions of the solar spectrum, together with a high molar extinction coefficient. In addition, its photoluminescent properties are important for investigating the photophysical processes occurring within the device. The energy levels of the dye must be properly aligned with those of the other cell components. Specifically, the LUMO should be positioned above the conduction band edge of TiO_2 to enable efficient injection of photoexcited electrons into the semiconductor. At the same time, the highest occupied molecular orbital (HOMO) should lie below the redox potential of the electrolyte to facilitate rapid regeneration of the oxidized dye after electron transfer. Long-term stability of DSSCs also requires strong adsorption of dye molecules onto the TiO_2 surface and suppression of molecular

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aggregation, as dye aggregation significantly reduces charge-transfer efficiency. For this reason, co-adsorbents such as CDCA (please insert the full meaning of CDCA here) are frequently employed to inhibit aggregation, while robust attachment of the dye to the semiconductor surface is achieved through various anchoring groups, including carboxylic, phosphonic, alkoxysilyl, and related functional groups [6, 17, 19, 20].

The space between the electrodes is filled with an electrolyte, which typically contains the I^-/I_3^- redox couple, although alternative electrolyte systems have also been developed (Figure 1). The primary function of the electrolyte is to transport charge and regenerate the oxidized dye after electron injection into TiO_2. Therefore, the electrolyte should be capable of rapidly and efficiently reducing the oxidized sensitizer while exhibiting high ionic conductivity and excellent ion mobility. Furthermore, it should possess high chemical, thermal, and electrochemical stability and should not cause corrosion of the other cell components. Ideally, the electrolyte should exhibit minimal light absorption so that it does not compete with the dye for incident photons, thereby maximizing photocurrent generation and overall photovoltaic efficiency [6, 17, 19, 20].

The counter electrode completes the electrical circuit and catalyzes the regeneration of the oxidized form of the redox couple. It is typically composed of a transparent, highly conductive substrate coated with a catalytic layer, such as platinum, carbon-based materials, or conductive polymers. An effective counter electrode should exhibit high electrocatalytic activity, excellent electrical conductivity, good chemical stability in the electrolyte, and low fabrication cost [6, 17, 19, 20].

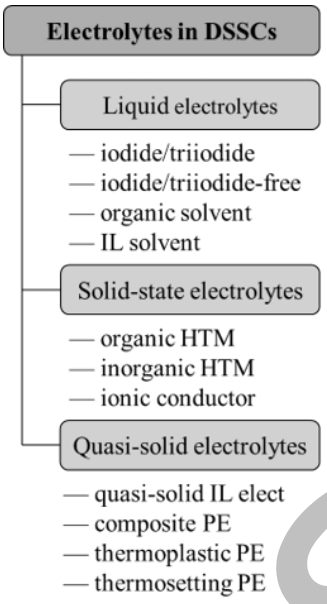
The operation of a DSSC is based on a sequence of elementary photoelectrochemical processes (Figure 2). Upon illumination, the dye molecule is excited to a higher energy state, as described by Equation 1. Subsequently, the excited electron is injected into the conduction band of TiO_2 (Equation 2). The injected electron is then transported through the TiO_2 layer to the transparent photoanode and flows through the external circuit to the counter electrode, generating an electric current. After electron injection, the dye is left in its oxidized state but is rapidly regenerated by the electrolyte containing the redox couple, as shown in Equation 3. The oxidized electrolyte is, in turn, regenerated at the surface of the counter electrode, where the redox mediator accepts electrons returning from the external circuit (Equation 4). In this manner, the charge-transfer cycle is completed, enabling continuous photovoltaic energy conversion [17, 21, 22].

$$Dye + photon \rightarrow Dye^* \quad (1)$$

$$Dye^* \rightarrow Dye^+ + e^- (injected) \quad (2)$$

$$Dye^+ + 3/2I^- \rightarrow Dye\ (adsorbed) + 1/2I_3^- \quad (3)$$

$$I_3^- + 2e^- (Cathode) \rightarrow 3I^- (Cathode) \quad (4)$$



Note: IL – Ionic Liquid; PE – Polymer Electrolyte; HTM – Hole Transport Material.

Figure 1 – Classification of the electrolytes used in dye-sensitized solar cells

The performance of DSSCs depends on several key parameters. A crucial role is played by the ability of the sensitizer to absorb light over a broad spectral range and by the alignment of its HOMO and LUMO energy levels with the conduction band edge of TiO_2 and the redox potential of the electrolyte. In addition, the rates of electron injection and transport, charge recombination, and the physicochemical properties of the electrolyte significantly influence device performance. The morphology and porosity of the TiO_2 photoanode, as well as the electrocatalytic activity and stability of the counter electrode, are also critical factors that determine the overall efficiency of photovoltaic energy conversion [23].

2.3 Key Photovoltaic Parameters of DSSCs

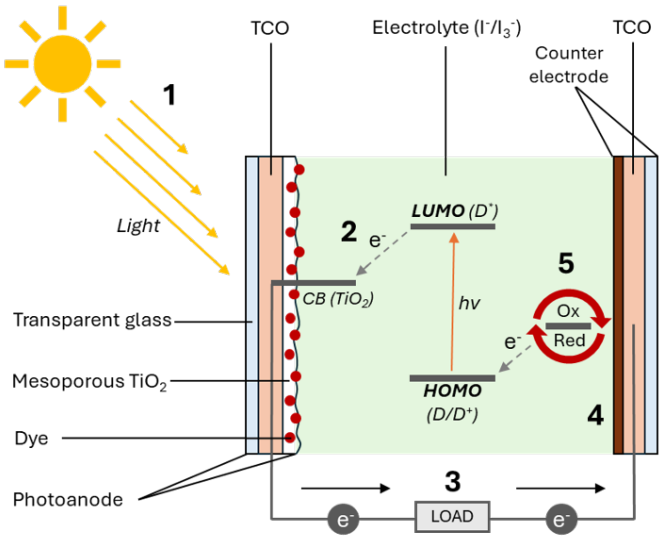
The performance of DSSCs is commonly evaluated in terms of the power conversion efficiency (PCE), which represents the overall efficiency of converting incident solar energy into electrical energy. The PCE can be calculated using Equation 5,

$$PCE = \frac{J_{sc}V_{oc}FF}{P_{in}} \times 100\% \quad (5)$$

where J_{sc} – is the short-circuit current density, V_{oc} – is the open-circuit voltage, FF – is the fill factor, P_{in} – is the incident light power density.

Equation 6 describes the calculation of the short-circuit current density (J_{sc}), which is determined by the spectral light-

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Note: CB = conduction band, D = ground state of dye sensitizer molecule, D* = excited state of dye sensitizer molecule, D^+ = oxidized dye, I^- = iodide ion and I_3^- = triiodide ion.

Figure 2 – Operating Principle of DSSCs 1) Light absorption by the sensitizer. 2) Electron injection into the TiO_2 conduction band. 3) Electron transport through the external circuit. 4) Regeneration of the redox couple at the counter electrode. 5) Dye regeneration by the redox couple

harvesting capability of the dye and the interfacial processes occurring within the DSSC.

$$J_{sc} = LHE(\lambda) \times \phi_{inject} \times \eta_{coll} \times d\lambda \quad (6)$$

where LHE(λ) is the fraction of absorbed light, Ψ_{inject} is the injection efficiency, and η_{coll} is the electron collection efficiency.

In the simplest approximation, the dye's contribution to V_{oc} can be related to the position of its LUMO relative to the conduction band, as shown in equation 7,

$$V_{oc} = E_{LUMO} - E_{CB} \quad (7)$$

where E_{LUMO} is the LUMO energy of the sensitizer, E_{CB} is the conduction band energy of TiO_2, equal to −4.0 eV.

Using equation 8, LHE can be calculated,

$$LHE = 1 - 10^{-f} \quad (8)$$

where f is the oscillatory strength of the dye.

2.4 Dyes for DSSC

2.4.1 Ruthenium complexes

Ruthenium polypyridyl complexes have long been the most extensively studied and highly efficient sensitizers for conventional TiO_2-based DSSCs under laboratory conditions. The dyes shown in Figure 3, N3 (cis-bis(isothiocyanato)bis(2,2′-bipyridyl-4,4′-dicarboxylato)ruthenium(II)) and N719 (cis-diisothio- cyanato-bis(2,2′-bipyridyl-4,4′-dicarboxylato) ruthenium(II) bis(tetrabutylammonium)), are characterized by a broad absorption spectrum in the 350–800 nm range. The highest photon-to-current conversion efficiency is observed in the 400–700 nm range, whereas Black Dye (tris(tetrabutylammonium) tris(isothiocyanato) (2,2′:6′,2″-terpyridyl-4,4′,4″-tricarboxylato)- ruthenium (II)) provides absorption with a photoresponse extending into the near-infrared region up to 920 nm. These complexes achieved solar energy conversion efficiencies of 10–11% and became benchmark systems due to their favorable combination of spectral characteristics and stability. According to recent comparative studies, the overall efficiency range of ruthenium-based sensitizers in modern DSSCs has been extended to 10–14% [18, 24–27].

Later-generation dyes of the H112/HRS-1 series (with effective light absorption in the 400–800 nm range) and C106/MC112 (featuring a metal-to-ligand charge-transfer band in the 524–546 nm region), containing extended π-conjugated systems, exhibit more intense light absorption and also demonstrate conversion efficiencies of approximately 10–11%. Despite their excellent photovoltaic performance, ruthenium complexes suffer from several inherent limitations, including the high cost of ruthenium, the complexity of multistep synthetic procedures, and relatively limited absorption in the near-infrared region. Consequently, recent research has increasingly focused on the development of more cost-effective and technologically accessible sensitizers. For example, Ref. [28] reported a series of mixed-ligand ruthenium complexes based on $RuCl_2(PPh_3)_3$ and readily available nitrogen-containing ligands, exhibiting absorption maxima in the 504–571 nm range. The most promising complex exhibited a DSSC power conversion efficiency of approximately 9%, approaching the performance

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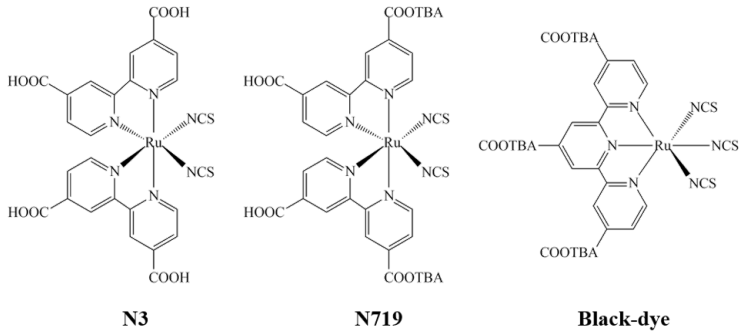


Figure 3 – Chemical structures of Ru complexes [30, 31]

of the classical ruthenium sensitizers described above while being synthesized through a simpler and more economical route. In parallel, increasing attention has been devoted to sensitizers based on more abundant and less expensive transition metals, including iron, zinc, and nickel.

However, the performance of these alternative metal-based sensitizers remains inferior to that of benchmark ruthenium complexes. For most iron-based sensitizers, the power conversion efficiency of DSSCs typically does not exceed 2%. Nevertheless, appropriate molecular and structural modifications can significantly improve their photovoltaic performance, with efficiencies reaching approximately 6%. Further enhancements have also been achieved by combining iron complexes with other metal centers to optimize their photophysical and electrochemical properties [29].

Although ruthenium-based sensitizers continue to represent the state-of-the-art in terms of photovoltaic efficiency, increasing research attention is being directed toward organic and natural dyes because of their lower toxicity, reduced cost, and simpler synthetic routes. These advantages make them promising candidates for the development of sustainable and economically viable next-generation DSSCs.

2.4.2 Organic D-π-A sensitizers

Unlike metal-complex sensitizers, organic sensitizers are generally designed according to a modular architecture consisting of an electron donor, a π-conjugated bridge, and an electron acceptor/anchoring group, forming the characteristic D–π–A structure. This molecular design enables precise tuning of the absorption spectrum, energy levels, and the efficiency of electronic coupling between the dye and the semiconductor surface (Figure 4). The most widely investigated systems are

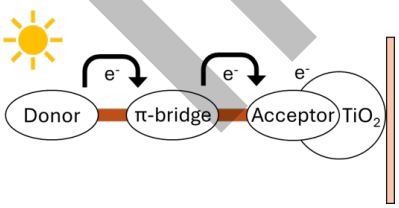


Figure 4 – Schematic of the D–p–A structure of an organic dye

metal-free D–π–A sensitizers incorporating donor moieties such as triphenylamine, perylene, and related electron-rich aromatic units. A distinct class of organic sensitizers is represented by porphyrin-based dyes, in which the porphyrin macrocycle serves as the primary light-harvesting chromophore [32, 33, 34].

The donor unit primarily determines the position of the HOMO energy level and influences the rate of dye regeneration by the electrolyte. The π-conjugated bridge governs the extent of electronic conjugation within the molecule, thereby affecting both the light absorption spectrum and intramolecular charge transfer. The acceptor–anchoring group is responsible for binding the dye to the TiO_2 surface and facilitating electron injection into the semiconductor conduction band. Common donor moieties include triphenylamine (TPA), perylene, carbazole, and related electron-rich aromatic systems. Thiophene-, phenylene-, and vinylene-based units are widely employed as π-conjugated bridges, whereas formic acid, cyanoacrylic acid, cyanoacetic acid, and structurally related functional groups are commonly used as acceptor–anchoring units [32].

Among these donor groups, triphenylamine (TPA) has become one of the most widely used building blocks in metal-free DSSC sensitizers because of its excellent electron-donating ability, high hole-transport capability, and the ease with which its molecular structure can be tuned through the introduction of various substituents. TPA-based sensitizers typically exhibit power conversion efficiencies (PCEs) of approximately 5–8% under standard DSSC operating conditions [35].

The widespread interest in the TPA moiety is attributed to its strong electron-donating ability, excellent thermal stability, and outstanding electrochemical stability, as well as its unique three-dimensional molecular geometry. The non-planar structure of TPA reduces the tendency of dye molecules to aggregate on the TiO_2 surface. Its characteristic propeller-like architecture also suppresses charge recombination by decreasing the probability of back-electron transfer from the TiO_2 conduction band to the electrolyte at the TiO_2/dye/electrolyte interface. Furthermore, the TPA unit can be readily combined with a wide variety of π-conjugated bridges and

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acceptor–anchoring groups, making it an exceptionally versatile platform for the molecular design of new sensitizers [36–41].

As discussed previously, conventional metal-free TPA-based sensitizers typically adopt a D–π–A architecture, in which the electron-donating TPA unit is connected through a π-conjugated bridge to an electron-accepting moiety bearing an anchoring group for attachment to the semiconductor surface. These dyes are characterized by two main absorption bands: a localized band associated with electronic transitions in the short-wavelength region (300–430 nm) and an intense intramolecular charge-transfer band in the visible range (400–600 nm). In such molecular systems, the highest occupied molecular orbital (HOMO) is generally localized on the donor unit and partially delocalized over the π-conjugated bridge, whereas the lowest unoccupied molecular orbital (LUMO) is predominantly localized on the acceptor and anchoring moieties. This spatial separation promotes directional intramolecular charge transfer following photoexcitation. Consequently, the efficient operation of TPA-based sensitizers requires appropriate alignment of their energy levels with both the conduction band edge of TiO_2 and the redox potential of the electrolyte. Such energy-level matching enables efficient electron injection into the semiconductor as well as rapid regeneration of the oxidized dye [36–41].

Another major advantage of TPA-based sensitizers is the possibility of finely tuning their properties through molecular engineering. For example, modifying the electron-donating strength of the TPA unit, altering the length and structure of the π-conjugated bridge, or varying the nature of the acceptor–anchoring group allows precise control over the absorption spectrum, energy-level alignment, and the efficiency of intramolecular charge transfer. In general, extending the π-conjugated framework results in a red shift of the absorption bands and enhances charge-transport properties. However, excessive enlargement of the conjugated system may increase the tendency of the dye molecules to aggregate on the TiO_2 surface, which can adversely affect photovoltaic performance. Representative molecular structures of metal-free TPA-based sensitizers incorporating various auxiliary donor units, acceptor groups, and π-conjugated bridges are presented in Figure 5 [36–41].

TPA-based dyes should not be regarded as merely one of many classes of organic sensitizers but rather as one of the most important directions in the development of metal-free sensitizers for DSSCs. Their combination of strong electron-donating capability, structural versatility, and extensive opportunities for molecular engineering makes them an outstanding platform for the design of next-generation high-performance sensitizers. Consequently, TPA-based D–π–A systems continue to attract considerable research interest and remain among the most promising candidates for achieving highly efficient, stable, and cost-effective dye-sensitized solar cells.

2.4.3 Natural dyes

Natural dyes are considered a promising environmentally friendly alternative to synthetic sensitizers for dye-sensitized solar cells. Their main advantages include the abundant availability of raw materials, straightforward extraction from plant sources, non-toxicity, low cost, and, importantly, biodegradability. The most extensively studied natural sensitizers include anthocyanins, betalains, chlorophylls, and carotenoids. These pigments contain functional groups such as carboxyl (-COOH) and hydroxyl (-OH) moieties, which are capable of chemically binding to the semiconductor surface while simultaneously absorbing solar radiation, thereby enabling electron injection into the semiconductor [30, 42].

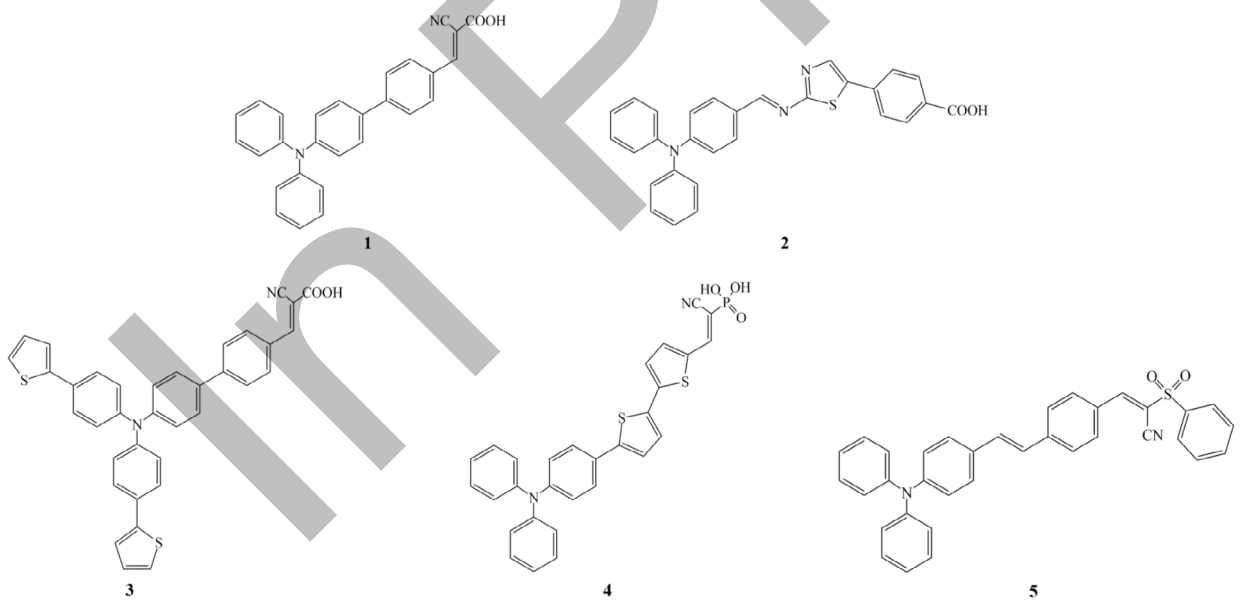


Figure 5 – Chemical structures of metal-free TPA dyes (1-5)

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Despite these advantages, the photovoltaic performance of DSSCs based on natural dyes remains relatively low. The PCE is typically limited to only a few tenths of a percent, even after optimization of dye extraction and purification procedures. Consequently, natural pigments still perform significantly below both ruthenium-based sensitizers and modern metal-free synthetic dyes. The primary limitations arise from their relatively narrow absorption spectra, insufficient photochemical stability, and less efficient charge-transfer processes. Anthocyanin dyes predominantly absorb light in the 500–600 nm range, with an additional absorption band in the UV region of 300–400 nm. Betalain dyes are characterized by an absorption band in the 450–600 nm range. Chlorophyll dyes (chlorophylls a and b) exhibit a two-band absorption spectrum in the blue (400–480 nm) and red (620–700 nm) regions, with negligible light absorption in the green region (500–600 nm). Carotenoid dyes exhibit absorption only in the short-wavelength region (400–550 nm) [30]. Nevertheless, owing to their environmental sustainability, low cost, and renewable origin, natural dyes continue to represent an important area of research in the development of DSSCs [43, 44]. The principal classes of natural dyes employed as sensitizers in DSSCs are summarized in Table 1.

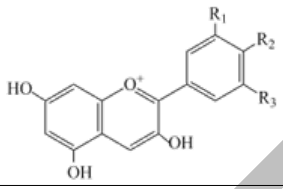
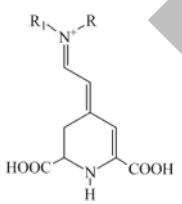
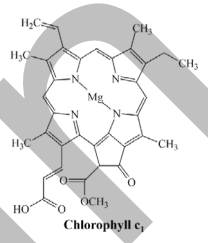
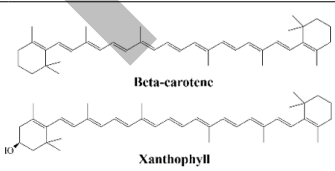
2.5 Photophysical and structural properties of dyes

Regardless of the chemical nature of the sensitizer-whether metal-complex, organic, or natural–its performance in a DSSC is governed by a combination of optical, electronic, and interfacial properties. In particular, the absorption characteristics, the alignment of the HOMO/LUMO energy levels relative to the conduction band edge of TiO_2, the photochemical stability of the dye, and its adsorption behavior on the semiconductor surface collectively determine the efficiency of light harvesting, electron injection, and the subsequent regeneration of the oxidized sensitizer [17, 47, 48].

2.5.1 Spectral properties

The spectral properties of sensitizers play a decisive role in determining the performance of DSSCs, as they define the portion of the solar spectrum that can be utilized for photocurrent generation. To achieve high PCEs, a sensitizer should exhibit strong absorption throughout the visible region and, in particular, extend into the near-infrared region, where a substantial fraction of the solar energy is concentrated. Another key parameter is the molar extinction coefficient, which quantifies the light-absorbing capability of a molecule and thus serves as a measure of its light-harvesting ability. Particularly high molar extinction coefficients are characteristic of metal-free organic sensitizers [40, 47, 49].

Table 1 – Major classes of natural dyes used as sensitizers in dsscs and their characteristics [30, 42, 43, 45, 46].

Class of compounds	Structural formula	Key structural features	Typical natural sources
Anthocyanins		Polyphenolic structure based on the flavylium cation; contains carboxyl (-COOH) and hydroxyl (-OH) functional groups; water-soluble; exhibits broad light absorption due to HOMO–LUMO electronic transitions.	Red cabbage (*Brassica oleracea*), plum (*Prunus domestica*), onion peel (*Allium cepa* L.), hibiscus (*Hibiscus rosa-sinensis*), and others.
Betalains		Nitrogen-containing heterocyclic compounds; hydroxyl (-OH) anchoring groups; water-soluble; exhibit efficient electronic coupling with the TiO_2 surface.	Beetroot (*Beta vulgaris*), parsnip (*Pastinaca sativa*), and others.
Chlorophylls		Magnesium-containing tetrapyrrolic macrocycle; relatively weak adsorption onto the semiconductor surface; the absorption spectrum is strongly dependent on the solvent.	Spinach (*Spinacia oleracea* L.), indigo (*Indigofera tinctoria*), *Calotropis procera*, and others.
Carotenoids		Extended conjugated polyene system; relatively inefficient electron injection; lipid-soluble (fat-soluble).	Jackfruit (*Artocarpus heterophyllus*), tomato (*Lycopersicon esculentum*), turmeric (*Curcuma longa*), and others.

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For TPA-based and related organic sensitizers, the molecular architecture of the π-conjugated system and the nature of the donor and acceptor moieties are of critical importance. Extending or modifying the π-conjugated bridge, as well as introducing additional electron-donating or electron-withdrawing units, generally leads to an increase in the molar extinction coefficient and, consequently, to improved photovoltaic performance of DSSCs. Modern TPA-based dyes typically exhibit broad absorption throughout the visible spectral region together with high LHEs [37, 40, 50].

For natural sensitizers, the spectral properties are primarily governed by the chemical nature of the pigment itself. Anthocyanins, betalains, chlorophylls, and carotenoids constitute the principal classes of natural pigments and exhibit pronounced absorption in the visible region, enabling them to function as light-harvesting materials. However, compared with synthetic sensitizers, natural pigments generally possess lower molar extinction coefficients. As a result, their ability to harvest solar energy is more limited, leading to lower photovoltaic efficiencies in DSSCs employing natural dyes [30, 43, 51].

2.5.2 HOMO/LUMO energy level alignment and density function theory of sensitizers

The alignment of the frontier molecular orbitals of the sensitizer with respect to the energy levels of TiO_2 and the redox potential of the electrolyte is a key factor governing the feasibility and efficiency of electron injection as well as the regeneration of the oxidized sensitizer. As discussed previously, efficient operation of a DSSC requires that the LUMO energy level of the photoexcited dye be positioned above the conduction band edge of TiO_2, thereby providing a sufficient driving force for energetically favorable electron injection into the semiconductor. At the same time, the HOMO energy level should lie below the redox potential of the electrolyte to enable efficient regeneration of the oxidized dye and sustain the continuous charge-transfer cycle. This favorable energy-level alignment accounts for the high electron injection efficiency and the effective regeneration of Ru(III) to Ru(II) in ruthenium-based sensitizers, allowing these dyes to achieve stable PCEs of up to 11% [17, 24].

Density functional theory (DFT) and time-dependent density functional theory (TD-DFT) studies have shown that, in metal-free D–π–A sensitizers, the HOMO is predominantly localized on the electron-donating TPA moiety and partially delocalized over the π-conjugated bridge, whereas the LUMO is mainly localized on the electron-accepting anchoring group. This spatial distribution of electron density promotes directional intramolecular charge transfer (ICT) from the donor to the acceptor upon photoexcitation, thereby creating favorable conditions for subsequent electron injection into the TiO_2 conduction band, following a mechanism analogous to that observed in ruthenium-based sensitizers. Compared with ruthenium complexes, however, organic sensitizers offer substantially greater flexibility in tuning their electronic properties. In particular, modification of the donor unit, the π-conjugated bridge, and the acceptor–anchoring group enables precise adjustment of the HOMO and LUMO energy levels, as well as the energy gap (HOMO–LUMO gap), which corresponds to the minimum energy required for electronic excitation. In ruthenium-based sensitizers, the electronic properties are determined primarily by the nature of the metal center, whereas in organic D–π–A systems the individual structural components can be modified largely independently, providing significantly greater opportunities for molecular engineering [32, 40, 52, 53].

For natural sensitizers, the energy-level alignment is governed by the molecular structure of the natural chromophore and by the functional groups responsible for binding to the semiconductor surface. In contrast to synthetic metal-complex and organic dyes, the possibilities for systematically tuning the electronic structure of natural pigments are considerably more limited. Although the excited-state energy levels of many natural dyes are sufficiently high to enable electron injection into the TiO_2 conduction band, regeneration of the oxidized dye is generally less efficient, resulting in reduced overall photovoltaic performance [42, 43, 47].

2.5.3 Photostability of the dye

Long-term operation of a DSSC requires high photochemical and electrochemical stability under conditions of prolonged exposure to solar radiation, elevated temperatures, and contact with electrolyte components. Degradation of the dye under the influence of these factors leads to a decrease in the number of active molecules on the TiO_2 surface, changes in spectral characteristics, and a gradual deterioration of photoelectric parameters (J_{sc}, V_{oc}, FF). In terms of photochemical stability, ruthenium dyes remain among the most reliable sensitizers, whereas many organic dyes–and especially natural dyes–are more susceptible to degradation processes. Natural dyes degrade under the influence of physical and chemical mechanisms: UV radiation, thermal decomposition, and photooxidative processes in the presence of water and oxygen [43, 53–55].

2.5.4 Adsorption on TiO_2

The adsorption of the dye on the TiO_2 surface plays an important role in the operation of a DSSC, as it determines the light-collecting area of the photoanode and the nature of the interphase electron interaction. The rate of electron injection into the semiconductor and the probability of their subsequent recombination depends on the quality and characteristics of the dye's immobilization. Typically, adsorption occurs via anchor groups–such as carboxyl, phosphonate, cyanoacrylate, and other moieties capable of forming bonds with the hydroxylated surface of TiO_2 [45]. For example, in the case of ruthenium sensitizers, which were mentioned earlier in this review, immobilization on the TiO_2 surface occurs primarily through the carboxylate groups of polypyridyl ligands. These bonds are highly stable and ensure effective electronic coupling between the dye and the semiconductor. For this reason, ruthenium complexes provide rapid electron injection and relatively low recombination losses, which contributes to their benchmark status in DSSCs [44].

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For organic sensitizers, which include TPA dyes with a D-π-A system, the nature of adsorption is primarily determined by the structure of the acceptor-anchor fragment. The binding mode can be monodentate, bidentate, or chelate. Each mode affects the stability of the binding and the efficiency of charge transfer in different ways. Changing the nature and number of anchoring groups allows one to control the orientation of the molecule on the surface, the coverage density of the photoanode, and the degree of dye aggregation. Optimal conditions for forming the layer on the surface contribute to an increase in dye loading, improved electron injection, and a reduction in recombination losses [56, 57].

For natural sensitizers, adsorption also occurs via hydroxyl, carbonyl, and carboxyl groups. However, compared to ruthenium complexes and organic sensitizers, the interfacial layer formed by them is often characterized by lower stability and less favorable conditions for charge transport, which leads to a decrease in PCE [30, 43].

2.6 Approaches to improving DSSC efficiency

To overcome PCE limitations, the current strategy for DSSC development focuses on the coordinated optimization of the spectral response, charge transfer kinetics, and stability of all key components–the sensitizer, electrolyte, and photoanode. The most promising strategies for improving DSSC efficiency to be considered include dye co-sensitization, replacing the iodide pair with cobalt/copper redox systems in combination with functional additives, as well as nanostructuring and engineering the TiO_2 interface at the nano- and micro-scales.

2.6.1 Co-sensitization and spectral optimization

One of the main limitations on DSSC efficiency is the incomplete absorption of the solar spectrum by a single sensitizer, which hinders an increase in J_{sc}. To address this issue, co-sensitization is widely used, based on the use of two or more dyes with complementary absorption spectra and matched energy levels. This approach allows for broadening the range of absorbed solar radiation, increasing light harvesting efficiency, and reducing losses due to charge recombination [58, 59].

It is known that for natural dyes, the combination of different pigments–such as anthocyanins with chlorophylls or betalains–leads to more complete coverage of the visible spectral region. In a number of studies, mixed systems demonstrated a significant increase in efficiency compared to their individual components. For example, the use of a mixture of chlorophyll and anthocyanins isolated from plant sources resulted in a more than twofold increase in PCE due to a broadened absorption spectrum and more efficient charge transfer [60].

Co-sensitization is also widely used for synthetic organic dyes. Using a combination of different dyes, such as ADEKA-1 and LEG4, which have different spectral properties, allows for a more panchromatic response–that is, more complete coverage of the solar radiation spectrum–optimizes energy matching with the semiconductor, and reduces recombination losses. A classic example is the co-sensitization of porphyrin or D-π-A sensitizers with an organic carboxylic dye in combination with cobalt electrolytes, which enables PCE values exceeding 14% under standard solar illumination conditions [23, 61].

Co-sensitization for Cu electrolytes warrants separate consideration. The combination of organic D-π-A sensitizers with copper redox systems ensures high efficiency under both sunlight and weak artificial lighting. The improvement in performance in this case is due to the high molar extinction of the dyes, optimal adsorption of molecules on the TiO_2 surface, and a reduction in the recombination rate [23]. Thus, co-sensitization can be considered one of the most effective approaches to increasing the efficiency of DSSCs, as it allows for simultaneously broadening the absorption spectral range, optimizing charge transfer, and improving operational stability.

2.6.2 Modification of electrolytes

The transition from the traditional I/I_3 redox pair to alternative systems based on metal complexes is one of the most effective ways to increase PCE. Despite their widespread use, iodide electrolytes have certain drawbacks, including corrosive activity toward metal contacts, light absorption in the blue region of the spectrum, and a relatively low redox potential that limits Voc. The most widely used are cobalt redox systems based on the $[Co(bpy)_3]^{2+/3+}$ and $[Co(phen)_3]^{2+/3+}$ complexes. A key advantage of these systems is the ability to finely tune the redox potential depending on the sensitizer used, which allows Voc to be increased to >0.9 V. The combination of cobalt electrolytes with highly efficient dyes has made it possible to achieve record PCE values exceeding 14%. However, the bulky ligands of cobalt complexes can slow down the diffusion of charge carriers and contribute to the intensification of recombination processes [23, 59].

Copper-containing redox systems, particularly complexes of the $[Cu(tmby)_2]^{2+/+}$ type, are attracting significant attention. Compared to their cobalt counterparts, copper-based complexes are more readily available, less toxic, and enable even higher Voc values, reaching 1.3 V and above. Such electrolytes are particularly promising for devices operating under low-light and artificial lighting conditions. Under these conditions, their efficiency can reach 32–34% PCE. In addition, copper-based systems can continue to function in solid-state mode after the solvent has evaporated, forming so-called “zombie cells” [23, 59].

Various functional additives have a significant effect on the performance of the electrolyte. One promising additive is 4-tert-butylpyridine (TBP), which adsorbs onto the TiO_2 surface, suppresses interphase recombination, and helps increase Voc. Another effective additive is lithium salts. Li^+ ions alter the energy state of the TiO_2 surface and can help increase the photocurrent density by improving electron injection, although this is sometimes accompanied by a slight decrease in Voc. The combined use of redox systems and functional additives makes it possible to significantly improve the efficiency and stability of DSSCs [43, 47, 61].

2.6.3 Nanostructured anodes

The development of DSSC photoanodes is aimed at improving electron transport efficiency and achieving more

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complete light absorption. Traditional TiO_2 nanoparticles have a larger surface area but contain numerous intergranular boundaries, which can act as recombination centers and slow down charge transport [47]. One way to address this problem is to use one-dimensional (1D) nanostructures, such as nanowires, nanorods, and nanotubes. Thanks to a more direct path for electron transport, such structures reduce the likelihood of electrons being captured by traps and help increase the diffusion length of charge carriers. This leads to more efficient electron collection and a reduction in recombination losses [47, 62].

Another promising area of research involves hierarchical three-dimensional (3D) structures that combine elements of different dimensions. Such architectures make it possible to simultaneously maintain a large surface area for dye adsorption and enhance light scattering within the photoanode. In particular, “inverted opal”-type structures can increase the optical path length of photons and enhance radiation absorption in the red and near-infrared regions of the spectrum [63, 64]. The modification of photoanodes with two-dimensional (2D) materials, particularly graphene and graphene oxide, is also of significant interest. The introduction of such components improves the system’s electronic conductivity by creating additional charge transport pathways between TiO_2 particles. Furthermore, graphene-based materials can enhance light absorption and reduce recombination losses. The use of such nanocomposites allows for the creation of thinner and more efficient photoanodes, which is particularly important when working with electrolytes based on cobalt and copper complexes [23, 48, 60, 62, 63].

2.7 Advanced architectures and modern design strategies

Current strategies for DSSC development aim to overcome the theoretical efficiency limit of single-junction solar cells–known as the Shockley–Kwaisers limit (approximately 33%)–through the use of multilayer structures and new principles of molecular design. Among the most promising approaches are the creation of tandem systems, the development of dyes with a D-A-π-A architecture, and the integration of metal-organic frameworks (MOFs) into the photoanode structure [47, 59].

One of the most promising development strategies for DSSCs is the creation of n-p-type tandem photovoltaic systems based on the sequential use of several light-absorbing layers. This approach allows for more efficient utilization of various regions of the solar spectrum and is considered one of the ways to overcome the efficiency limitations of single-junction devices [59, 62]. In n-p-type tandem configurations, the upper n-cell based on TiO_2 primarily absorbs short-wavelength radiation, whereas the lower p-cell, containing a NiO-based photocathode, utilizes photons in the red and near-infrared regions of the spectrum. This separation of spectral functions makes it possible to reduce energy losses and increase the overall photoelectric conversion efficiency. For a number of tandem DSSCs with organic alkylated (e.g., SGT-137) and porphyrin (SGT-021) sensitizers in combination with cobalt electrolytes, PCE values of up to 14.64% were achieved [59, 61]. In addition to the configurations mentioned above, hybrid DSSC/Si systems are being actively researched. The use of a silicon solar cell as the bottom subcell allows for the efficient utilization of the long-wavelength portion of the spectrum and achieves an efficiency of about 18% [59].

Modern molecular design of metal-free dyes focuses on introducing an auxiliary acceptor between the donor moiety and the π-conjugated bridge. The use of fragments such as benzothiadiazole or pyridothiadiazole helps reduce the energy gap between the HOMO and LUMO and also broadens the absorption region into the long-wavelength part of the spectrum [22, 65]. Dyes of this type are characterized by high extinction coefficients, which allow for efficient light absorption even when using relatively thin TiO_2 layers. Reducing the thickness of the photoanode helps lower charge transfer resistance and reduce recombination losses, which positively impacts the efficiency of DSSCs [65].

The incorporation of MOF-801-type materials into the mesoporous TiO_2 layer increases the amount of adsorbed dye and creates additional channels for electron transport, which raises the PCE to 55% compared to an unmodified photoanode. This is due to the fact that MOFs have high porosity and a larger specific surface area. In quasi-solid-state DSSCs, the use of TiO_2 and Ni-MOF-based composites has increased efficiency by 30%, meaning that PCE rose from 6.8% to approximately 8.9% [18, 62]. In addition, surface-oriented MOF films (SURMOF) have attracted significant interest, as they can enhance the photocurrent through triplet-triplet annihilation upconversion and other energy conversion mechanisms [58]. Current research on DSSCs is increasingly focused not only on optimizing individual components but also on creating multifunctional architectures that enable more efficient utilization of the solar spectrum and improved charge transport processes.

2.8 Stability challenges and barriers to commercialization

The transition of DSSCs from laboratory prototypes to industrial production is complicated by the need to strike a balance between high efficiency and durability under real-world conditions. While silicon panels dominate the market thanks to a service life of over 20 years and a PCE of about 25%, DSSCs still face fundamental limitations inherent in their constituent components [18, 47, 60, 66]. Table 2 provides an overview of the barriers to commercialization and possible solutions.

2.9 Future perspectives and research directions

The future prospects for DSSCs lie not only in competing with traditional silicon solar cells but also in leveraging their unique optical properties in specialized applications. One of the most successful areas is indoor photovoltaics and the Internet of Things (IoT), since under low-light indoor conditions, DSSCs demonstrate high efficiency, reaching a PCE of 32–34%, which significantly outperforms silicon systems under similar conditions. This makes DSSCs promising autonomous power sources for wireless sensors, wearable electronics, medical devices, and other low-power devices, enabling a significant increase in their battery life. The commercial potential of this

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Table 2 – Key barriers to the commercialization of DSSCS and strategies for overcoming them

Barrier category	Problem	Impact on commercialization	Possible solutions	References
Durability	Leakage and evaporation of liquid electrolyte	A sharp reduction in service life, as well as the risk of environmental pollution	Transition to solid-state or gel electrolytes (e.g., single-salt polyvinyl alcohol)	[61, 66, 67]
Chemical stability	Corrosion of the counter electrode by the I/I_3 pair, temperature sensitivity	The need to use precious metals (Pt, Au)	Replacement with non-corrosive copper or cobalt redox systems; use of carbon materials in the counter electrode	[23, 59, 60, 64]
Photostability	Photodegradation of organic and natural dyes under UV exposure	Decrease in PCE over time, fading	Use of UV filters, co-sensitization, D-A-π-A molecular design	[42, 43, 60]
Economy	The high cost of ruthenium and platinum	High cost per watt of energy compared to silicon-based systems	The use of metal-free organic or natural dyes and carbon counter-electrodes	[60, 62–64]
Scalability	Insufficient compatibility of materials with industrial application methods	The challenge of producing mass-produced panels that meet PCE laboratory specifications	The use of inkjet and screen printing methods for applying layers	[23, 59, 66]
Working temperatures	The narrow working temperature range of electrolytes	Restrictions on use in extreme weather conditions	Development of electrolytes based on eutectic mixtures and high-temperature polymer matrices	[48, 60, 62, 66, 68]

niche area has already been confirmed by companies such as Ricoh and Exeger, with the introduction of ready-to-use products in the market, which include ultra-thin, flexible photovoltaic material Powerfoyle.

Another promising area is the integration of DSSCs into BIPV (building-integrated photovoltaics) structures and agrivoltaic systems. Thanks to their high transparency and wide color palette. These cells blend seamlessly into windows and building facades, serving both decorative and energy-generating functions. In agriculture, the use of translucent panels in greenhouses allows for the generation of electricity while transmitting the spectrum of light necessary for plant photosynthesis. In addition, DSSCs are capable of partially absorbing ultraviolet radiation, reducing its negative impact on plants while continuing to efficiently convert solar energy into electricity. The use of such photovoltaic systems helps increase the energy independence of rural areas and reduce consumption of non-renewable energy sources.

In the development of environmentally friendly "green", DSSCs remains an important and promising area of research. Current research is focused on replacing expensive and toxic ruthenium sensitizers with more affordable, eco-friendly organic and natural dyes, as well as in the creation of safe water-based electrolytes and other environmentally friendly components. Although the efficiency of such devices remains low at present, further improvements in materials and cell architecture could make them a promising foundation for the development of inexpensive, safe, and environmentally sustainable photovoltaic systems.

A transition from organic dyes to semiconductor nanocrystals – quantum dots – is also being actively developed for use in quantum-dot-sensitized solar cells (QDSSCs). Due to the quantum confinement effect, quantum dots can precisely tune their bandgap and exhibit high optical absorption coefficients. An additional advantage is the multiple exciton generation (MEG) effect, in which a high-energy photon can be utilized to generate additional electron–hole pairs. As a result, a theoretical power conversion efficiency (PCE) of 44% has been calculated for QDSSCs, substantially exceeding the Shockley-Queisser limit. At the same time, the practical performance of QDSSCs has also increased significantly, from initial values of approximately 0.12% to 18.1%.

Acknowledgments

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26100661).

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A. Abdullanova: Conceptualization, Visualization, Writing – Review & Editing. A.O. Adeloye: Conceptualization, Project Administration, Writing – Original Draft, Writing – Review & Editing. D. Abduakhytova: Conceptualization, Visualization, Writing – Original Draft, Writing – Review & Editing; R. Tokpayev: Resources, Writing – Review & Editing; A. Atchabarova: Writing – Review & Editing; M. Lepikhin: Supervision, Funding Acquisition, Writing – Review & Editing.

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