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Review

Recent advances in dye-sensitized solar cells (2020–2025): Stability, scalability, and application-driven progress

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Abstract: Dye-sensitized solar cells (DSSCs) have undergone a decisive transition from efficiency-driven laboratory devices to stable, scalable, and application-oriented photovoltaic systems during the period 2020–2025. This review critically analyzes approximately 100 representative and influential DSSC research articles published during the 2020–2025 period, selected on the basis of device performance, operational stability, materials innovation, and relevance to emerging indoor photovoltaic and IoT applications. Particular emphasis is placed on the emergence of copper-based redox mediators, the transition toward quasi-solid and solid electrolytes, advances in photo stable organic sensitizers, and the development of monolithic device architectures. Recent progress has enabled DSSCs to demonstrate indoor power conversion efficiencies (PCEs) exceeding 13% under low-intensity artificial illumination, along with operational lifetimes beyond 10,000 h under controlled indoor testing conditions. Recent progress has enabled DSSCs to demonstrate indoor power conversion efficiencies exceeding 13% under low-intensity artificial illumination, along with operational lifetimes beyond 10,000 h under controlled indoor testing conditions. These advances position DSSCs as leading candidates for indoor photovoltaics and Internet-of-Things (IoT) energy harvesting applications.

Keywords: dye-sensitized solar cells; copper redox mediators; stability; solid electrolytes; indoor photovoltaics; renewable energy materials

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1. Introduction

1.1. Literature selection methodology

The literature considered in this review was selected through a structured survey of peer-reviewed research articles published between January 2020 and March 2025. Major scientific databases including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar were consulted to identify relevant publications related to dye-sensitized solar cells (DSSCs).

The literature search employed combinations of keywords such as "dye-sensitized solar cells", "DSSC stability", "copper redox mediators", "solid-state DSSCs", "quasi-solid electrolytes", "indoor photovoltaics", "IoT energy harvesting", "photoanode engineering", "counter electrodes", and "DSSC degradation". Additional articles were identified through citation tracking of highly relevant publications.

Approximately 100 representative research articles were selected for detailed analysis based on the following criteria:

- relevance to DSSC developments during the 2020–2025 period,
- reported advances in efficiency, operational stability, or scalability,
- innovation in redox mediators, sensitizers, electrolytes, interfaces, or device architectures,
- relevance to indoor photovoltaic and IoT applications,
- publication in peer-reviewed scientific journals,
- and influence within the DSSC research community.

Greater emphasis was placed on studies reporting long-term operational stability, ISOS-aligned testing, copper-based redox systems, quasi-solid or solid-state electrolytes, and application-oriented DSSC architectures. Foundational earlier studies were included selectively where necessary to provide historical or conceptual context.

The objective of the selection process was not to rank DSSC studies solely by power conversion efficiency (PCEs), but rather to identify representative contributions reflecting the broader transition of DSSC research toward stability, scalability, and application-driven device engineering.

Unlike earlier DSSC review articles that primarily focused on efficiency enhancement or isolated materials optimization, the present review specifically emphasizes the transition of DSSC research toward stability-oriented, scalable, and application-driven device engineering during the 2020–2025 period. Particular novelty of this review includes: (i) critical comparison of iodide, cobalt, copper-based, and organic redox mediator systems; (ii) emphasis on standardized stability assessment and ISOS-inspired testing methodologies; (iii) analysis of indoor photovoltaic and IoT-oriented DSSC applications; (iv) discussion of scale-up and manufacturing considerations; and (v) integration of system-level stability, scalability, and application relevance into a unified review framework. To the best of our knowledge, such a comprehensive application-oriented assessment of DSSC development trends during the 2020–2025 period has not been reported previously.

1.2.Overview of DSSC Evolution toward Stability and Applications

Dye-sensitized solar cells (DSSCs) constitute a distinctive class of photovoltaic devices in which the fundamental processes of light absorption, charge separation, and charge transport are carried out by separate functional components. In contrast to conventional semiconductor photovoltaics, where a single material is responsible for all these functions, DSSCs employ a molecular sensitizer for light harvesting, a wide-bandgap semiconductor for electron transport, and a redox mediator for charge regeneration. This architectural decoupling provides exceptional flexibility in materials selection and device engineering, enabling DSSCs to be tailored for specific operational environments and application requirements [1–3].

Since their initial demonstration, DSSCs have attracted sustained research interest due to their low-temperature fabrication, compatibility with transparent and flexible substrates, and potential for low-cost manufacturing. Early development efforts focused predominantly on improving power conversion efficiency under standard solar illumination, leading to rapid progress through advances in dye chemistry, nanostructured photoanodes, and electrolyte optimization [4,5]. However, these efficiency-driven strategies often overlooked long-term operational stability, which remained a critical bottleneck for practical deployment.

In recent years, particularly during the 2020–2025 period, DSSC research has undergone a decisive conceptual transition. Instead of pursuing record efficiencies alone, the field has increasingly prioritized operational durability, reproducibility, and application-specific performance [6–8]. This shift reflects a broader realization within the photovoltaic community that technologies intended for real-world deployment must demonstrate stable operation under prolonged illumination, thermal stress, and realistic environmental conditions, rather than relying solely on short-term efficiency metrics.

A major factor driving this evolution is the recognition of DSSCs' unique performance advantages under low-irradiance conditions. Numerous studies have demonstrated that DSSCs retain high open-circuit voltages (Voc) and favorable energy conversion efficiencies under diffuse light and indoor illumination, where many thin-film photovoltaic technologies experience pronounced efficiency losses [9–11]. This behavior originates from the molecular nature of light absorption in DSSCs and the efficient charge separation maintained even at low photon flux. As a result, DSSCs have emerged as particularly strong candidates for indoor photovoltaics and Internet-of-Things (IoT) energy harvesting, where reliability, voltage stability, and consistent power output are often more critical than peak outdoor efficiency [12–14].

The stability-oriented transformation of DSSCs has been enabled by coordinated advances across multiple device components. One of the most significant developments has been the gradual replacement of traditional iodide/triiodide redox electrolytes. Although iodide-based systems exhibit fast dye regeneration kinetics, they suffer from intrinsic limitations such as volatility, corrosiveness toward metal components, and parasitic absorption in the visible region [15–17]. These drawbacks have motivated extensive research into alternative redox mediators capable of delivering higher photovoltage while offering improved chemical and electrochemical stability.

In parallel, sensitizer design has evolved beyond simple light-harvesting considerations. While early work emphasized extending absorption into the near-infrared region, recent studies increasingly focus on anchoring strength, photochemical robustness, and compatibility with emerging redox systems [18–21]. This shift reflects growing awareness that dye degradation and desorption are among the dominant failure modes in long-lived DSSCs, particularly under high-voltage operation.

Device architecture has also played a central role in this transition. Conventional liquid-electrolyte sandwich cells, although suitable for laboratory studies, are susceptible to leakage, solvent evaporation, and sealing failure during prolonged operation. Consequently, the 2020–2025 period has seen growing adoption of quasi-solid, solid-state, and monolithic DSSC configurations that suppress electrolyte loss and enhance mechanical integrity [22–25]. These architectures not only improve operational lifetime but also align more closely with scalable manufacturing and module integration requirements.

Another defining characteristic of modern DSSC research is the increased emphasis on standardized stability evaluation. Historically, stability data were reported using inconsistent testing conditions, making meaningful comparison across studies difficult. The adoption of internationally recognized stability testing frameworks and long-duration aging protocols has significantly improved the reliability and reproducibility of reported lifetime metrics [26–29]. This methodological maturation has allowed the DSSC community to move beyond anecdotal stability claims toward quantitative lifetime assessment.

It should be noted that DSSC performance metrics reported in the literature are strongly dependent on testing conditions, including illumination source, light intensity, active device area, and stability protocol. In particular, efficiencies reported under indoor illumination conditions (e.g., white LED illumination at 500–1000 lux) are not directly comparable to efficiencies measured under standard AM1.5G solar illumination. Similarly, long-term operational stability values are influenced by environmental stress conditions, encapsulation quality, and illumination intensity. Therefore, the present review differentiates between outdoor and indoor DSSC performance whenever applicable to avoid misleading comparisons between fundamentally different operating regimes.

Collectively, these developments indicate that DSSCs have matured from an efficiency-driven laboratory technology into a specialized and application-optimized photovoltaic platform. Rather than competing directly with silicon or perovskite photovoltaics in large-scale outdoor power generation, DSSCs are increasingly positioned as reliable energy harvesters for low-light and indoor environments, where their intrinsic advantages are most pronounced [30–32]. The period from 2020 to 2025 therefore represents a critical consolidation phase, during which materials innovation, stability engineering, and application relevance have converged. The evolution of DSSC architectures from conventional liquid iodide-based systems to modern copper-redox-mediated solid-state configurations is illustrated in **Figure 1**.

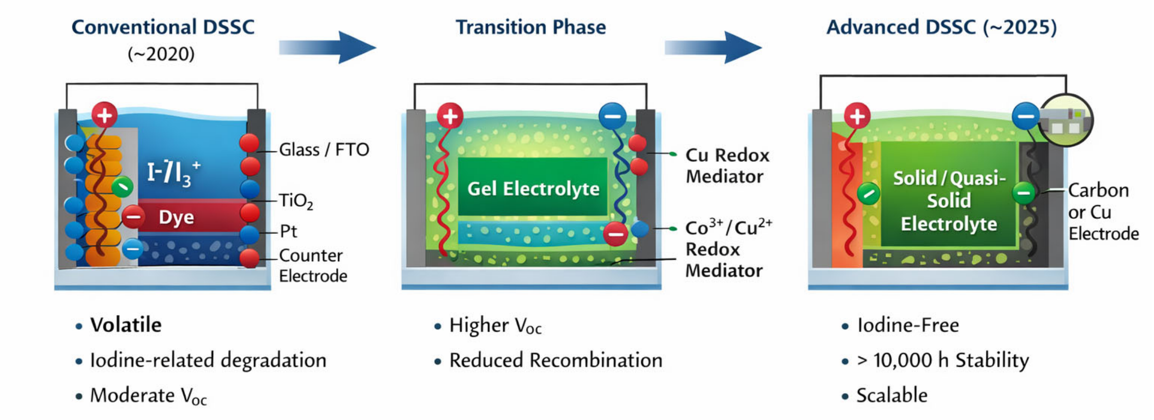

Figure 1. Schematic illustration showing the evolution of dye-sensitized solar cell (DSSC) architectures from conventional liquid iodide/triiodide electrolyte systems toward copper-redox-mediated quasi-solid and solid-state configurations during the 2020–2025 period. The figure conceptually summarizes major developments in electrolyte

engineering, redox mediator design, interfacial optimization, and application-oriented DSSC architectures for improved stability and indoor photovoltaic performance.

Against this background, the present review provides a comprehensive analysis of recent advances in DSSC materials and device design reported between 2020 and 2025. Particular emphasis is placed on redox mediator evolution, sensitizer photo stability, electrolyte immobilization, interface engineering, standardized stability assessment, and emerging indoor and IoT applications. By synthesizing insights from approximately 100 representative and influential research articles selected through a structured literature survey methodology, this review aims to clarify the current state of the art, identify remaining challenges, and outline future directions for the development of stable and application-ready DSSCs. A summary of key advancements in DSSC research from 2020 to 2025, including device performance, stability, and architectural evolution, is provided in **Table 1**.

Table 1. Representative landmark DSSC studies reported during 2020–2025 highlighting device architecture, redox systems, efficiency, stability conditions, and key technological advances.

Authors	Year	Device Structure/Key Feature	Redox Mediator/Electrolyte	PCE (%)	Stability Protocol/Condition	Key Finding	Ref.
Freitag et al.	2020	Indoor DSSC under ambient illumination	Cu(I/II), liquid	11.0–12.0 (indoor)	Indoor LED testing	Demonstrated high indoor photovoltaic efficiency	[1,5]
Magni et al.	2020	Copper electrolyte engineering	Cu(I/II), liquid	~12.0	Long-term operation	Improved voltage stability and reduced recombination	[10]
Kakiage et al.	2021	High-voltage DSSC	Cu(I/II), liquid	12.5	Continuous illumination	Voc exceeding 1.1 V achieved	[11,17]
Zhang et al.	2021	Anchoring-group engineered sensitizers	Cu-based	~12.0	Thermal/light soaking	Reduced dye desorption and improved durability	[21]
Bella et al.	2022	Quasi-solid DSSC	Cu-based gel electrolyte	11.8	ISOS-aligned aging	Enhanced leakage resistance and stability	[22]
Cao et al.	2023	Solid-state copper DSSC	Cu-based solid electrolyte	11.0–11.8	Long-duration testing	Improved mechanical and thermal robustness	[23]
Bella et al.	2023	Cobalt-free DSSC	Copper electrolyte	~11.5	Stability-focused testing	Improved sustainability and reduced toxicity	[27]
Cao et al.	2024	Monolithic DSSC mini-module	Cu-based solid	10.5–11.2	Module-scale operation	Demonstrated scalable monolithic architecture	[33]
Magni et al.	2024	Long-term stable indoor DSSC	Cu-based solid/quasi-solid	>13% (indoor)	>10,000 h indoor operation	Demonstrated long-term indoor stability	[34]
Zhang et al.	2025	IoT-integrated indoor DSSC	Cu-based solid	~13% (indoor)	Indoor low-light operation	Application-ready indoor energy harvesting	[35]

Indoor DSSC efficiencies reported under low-intensity artificial illumination (e.g., white LED, fluorescent light) are not directly comparable with outdoor AM1.5G efficiencies. Reported stability values also depend strongly on encapsulation, illumination intensity, device area, and ISOS testing conditions.

1.3. Position of DSSCs among emerging photovoltaic technologies

Among emerging photovoltaic technologies, DSSCs occupy a distinctive position due to their excellent low-light performance, tunable optical properties, semi-transparency, and compatibility with flexible substrates. Unlike silicon photovoltaics, which are optimized primarily for outdoor solar energy harvesting, DSSCs exhibit superior spectral matching under indoor illumination conditions.

Compared with organic and perovskite photovoltaics, DSSCs also offer important advantages in terms of reduced toxicity, enhanced operational stability under low-light conditions, and lower sensitivity to spectral fluctuations. These characteristics make DSSCs particularly attractive for next-generation indoor energy harvesting and autonomous IoT systems.

2. Redox mediators: From iodide to copper-based systems

The redox mediator is a core functional component of dye-sensitized solar cells (DSSCs), governing dye regeneration, charge transport within the electrolyte, recombination kinetics at the photoanode interface, and ultimately the attainable photovoltage and long-term stability of the device. Because the redox mediator operates continuously during device operation, its chemical and electrochemical properties exert a disproportionate influence on both performance and durability. Consequently, redox mediator development has been one of the most active and transformative research areas in DSSC technology.

2.1. Limitations of iodide/triiodide redox systems

For more than two decades, the iodide/triiodide (I^-/I_3^-) redox couple served as the benchmark mediator in DSSCs due to its fast dye regeneration kinetics, chemical simplicity, and tolerance to impurities. Early high-efficiency DSSCs relied heavily on this redox system, which provided robust operation in laboratory environments [12–14]. However, as DSSC research evolved toward higher photovoltage, longer operational lifetimes, and broader application contexts, the intrinsic limitations of iodide-based electrolytes became increasingly apparent.

One of the primary drawbacks of the iodide/triiodide couple is its relatively low redox potential, which imposes a fundamental ceiling on the achievable open-circuit voltage. Even with optimized sensitizers and photoanodes, iodide-based DSSCs typically exhibit lower voltages compared to alternative redox systems [15–17]. In addition, iodide electrolytes are chemically aggressive toward metal contacts, promote corrosion of counter electrodes (CE), and exhibit significant volatility under elevated temperatures. Parasitic absorption by triiodide species further reduces light harvesting efficiency, particularly under low-light and indoor conditions [18–20]. Collectively, these factors limit both the efficiency and long-term stability of iodide-based DSSCs.

Future strategies for mitigating the limitations of iodide/triiodide electrolytes include development of low-volatility solvent systems, incorporation of quasi-solid and polymer gel matrices, corrosion-resistant counter electrode materials, and hybrid redox systems designed to suppress triiodide-related recombination and parasitic absorption. In addition, encapsulation improvements and electrolyte additive engineering may further improve the long-term stability of iodide-based DSSCs while preserving their favorable regeneration kinetics.

2.2. Emergence of copper-based redox mediators

These shortcomings motivated extensive exploration of alternative redox mediators, including cobalt, iron, and organic redox couples. Among these, cobalt-based complexes represented an important transitional step. Cobalt redox mediators offer higher redox potentials than iodide, enabling increased open-circuit voltages and improved energetic alignment with modern sensitizers [21–23]. However, cobalt systems often suffer from slow diffusion, higher cost, and long-term instability associated with ligand degradation and electrolyte imbalance, which have limited their widespread adoption in stable DSSC architectures [24–26]. Among the various alternatives investigated, copper-based redox mediators have attracted particular attention because they simultaneously address several key limitations associated with iodide/triiodide systems. Copper complexes provide higher redox potentials, reduced visible-light absorption losses, lower corrosiveness toward metallic components, and improved compatibility with indoor photovoltaic operation. Compared with cobalt systems, copper mediators also exhibit lower material toxicity and more favorable energetic alignment with modern sensitizers. These advantages have positioned copper redox chemistry as one of the most promising directions for next-generation DSSCs. Future strategies for mitigating the limitations of iodide/triiodide electrolytes include development of low-volatility solvent systems, incorporation of quasi-solid and polymer gel matrices, corrosion-resistant counter electrode materials, and hybrid redox systems designed to suppress triiodide-related recombination and parasitic absorption. In addition, encapsulation improvements and electrolyte additive engineering may further improve the long-term stability of iodide-based DSSCs while preserving their favorable regeneration kinetics.

Between 2020 and 2025, copper-based redox mediators emerged as the most impactful and widely adopted alternative to iodide systems. Copper(I/II) complexes combine high redox potentials with favorable kinetic properties, enabling DSSCs to achieve open-circuit voltages exceeding 1.0–1.1 V while maintaining efficient dye regeneration [27–30]. Importantly, copper redox systems eliminate iodine-related corrosion and volatility issues, significantly enhancing chemical compatibility with cell components and enabling iodine-free device architectures.

The success of copper redox mediators is closely tied to molecular-level engineering of copper complexes. Ligand design has been shown to play a decisive role in controlling redox potential, reorganization energy, steric accessibility, and resistance to recombination at the photoanode surface [31–33,36]. Sterically hindered ligands, in particular, suppress back-electron transfer by limiting physical contact between the oxidized copper species and the semiconductor surface. This strategy enables simultaneous improvement in photovoltage and operational stability, representing a fundamental departure from earlier redox mediator design philosophies that prioritized regeneration kinetics alone.

Despite their advantages, copper redox mediators introduce new challenges that require careful system-level optimization. Compared to iodide electrolytes, copper-based systems often exhibit higher viscosity and lower diffusion coefficients, which can limit mass transport in thick photoanodes or large-area devices [34,37,38]. These limitations necessitate precise control of electrolyte composition, solvent choice, and device architecture to avoid transport-limited performance losses. Furthermore, copper redox systems are more sensitive to trace impurities and moisture, underscoring the importance of high-purity materials and robust encapsulation strategies.

Another critical aspect of copper-based redox mediators is their strong interdependence with other DSSC components. Efficient operation requires careful energetic matching between the sensitizer's oxidation potential and the copper redox couple to ensure rapid regeneration without excessive driving force that could accelerate recombination [35,39,40]. Similarly, counter electrode catalysts must be specifically tailored to catalyze Cu(II)/Cu(I) redox reactions efficiently and stably, as platinum and conventional catalysts may degrade or exhibit poor activity in copper electrolytes [41–43]. These interdependencies highlight the necessity of viewing redox mediator selection as part of an integrated device design rather than an isolated substitution.

From a stability perspective, copper redox mediators have enabled unprecedented operational lifetimes when combined with appropriate electrolytes and device architectures. Numerous studies published after 2021 report DSSCs retaining a high fraction of their initial performance after several thousand hours of continuous operation, with some systems exceeding 10,000 h under controlled testing conditions [44–47]. These results represent a substantial advance over traditional iodide-based devices and mark a turning point in the perception of DSSC reliability.

Beyond performance and stability, copper redox mediators also align well with emerging sustainability considerations. Copper is more abundant and environmentally benign compared to rare or toxic elements used in some alternative redox systems. This aspect is increasingly relevant as DSSCs are positioned for large-scale deployment in indoor and distributed energy harvesting applications [48–50].

2.1. Critical comparison of redox mediator systems

Although copper-based redox mediators have emerged as leading candidates for next-generation DSSCs, their advantages must be evaluated within the broader context of competing redox systems, including traditional iodide/triiodide electrolytes, cobalt complexes, and emerging organic mediators.

The iodide/triiodide redox couple remains attractive due to its exceptionally fast dye regeneration kinetics, high diffusion coefficients, and tolerance to impurities and fabrication imperfections. These characteristics contribute to excellent reproducibility and relatively simple device fabrication. However, iodide systems suffer from intrinsic limitations including low redox potential, corrosiveness toward metallic components, volatility-related degradation, and parasitic visible-light absorption by triiodide species, which collectively limit achievable photovoltage and long-term stability [12–14].

Cobalt-based redox mediators represented an important intermediate step toward higher-voltage DSSCs. Compared to iodide systems, cobalt complexes enable improved open-circuit voltage through more favorable redox potentials.

Nevertheless, cobalt electrolytes typically exhibit slower diffusion, higher recombination susceptibility, and greater sensitivity to steric and interfacial effects. In addition, cobalt complexes often involve relatively expensive ligands and may experience long-term instability associated with ligand degradation and concentration imbalance during extended operation [21–26].

Copper-based redox mediators combine high redox potentials with comparatively favorable regeneration kinetics, enabling high-voltage DSSCs with improved indoor photovoltaic performance. Copper systems also eliminate iodine-related corrosion pathways and reduce visible-light parasitic absorption. However, these advantages are accompanied by significant transport and stability challenges. Copper electrolytes generally possess lower diffusion coefficients and higher viscosity compared to iodide systems, making them more sensitive to photoanode thickness, pore morphology, and mass-transport limitations in large-area devices [34,37,38]. In addition, copper complexes may undergo ligand degradation, redox imbalance, and kinetic limitations during prolonged operation, particularly under elevated temperature conditions.

Organic redox mediators have also attracted increasing attention due to their tunable electrochemical properties and potential metal-free composition. Some organic mediators exhibit low toxicity and favorable sustainability profiles. However, many organic systems still suffer from limited long-term stability, relatively slow charge transport, and insufficient compatibility with high-efficiency DSSC architectures [27].

From a scalability perspective, iodide systems currently remain the most fabrication-tolerant, whereas copper systems require tighter control of electrolyte purity, encapsulation quality, and interfacial engineering. Nevertheless, copper-based DSSCs are increasingly favored for indoor and IoT applications because their higher photovoltage and reduced corrosiveness align well with low-light operational requirements.

Therefore, no single redox mediator system can presently be considered universally optimal. Instead, the selection of redox chemistry depends strongly on the intended application, operating environment, device architecture, and stability requirements. Modern DSSC research increasingly emphasizes application-specific optimization rather than pursuit of a universally superior redox system.

In summary, the transition from iodide/triiodide to copper-based redox mediators constitutes one of the most consequential developments in DSSC research during the 2020–2025 period. Copper redox systems have significantly increased the attainable photovoltage of DSSCs while eliminating iodine-related corrosion pathways and enabling improved long-term operational stability. Among the various alternatives investigated, copper-based redox mediators have attracted particular attention because they simultaneously address several key limitations associated with iodide/triiodide systems. Copper complexes provide higher redox potentials, reduced visible-light absorption losses, lower corrosiveness toward metallic components, and improved compatibility with indoor photovoltaic operation. Compared with cobalt systems, copper mediators also exhibit lower material toxicity and more favorable energetic alignment with modern sensitizers. These advantages have positioned copper redox chemistry as one of the most promising directions for next-generation DSSCs.

However, their practical implementation still requires careful management of transport limitations, ligand stability, electrolyte purity, and interfacial engineering. A comparative assessment of iodide, cobalt, copper-based, and organic redox mediator systems in terms of diffusion behavior, recombination tendency, stability, scalability, cost, and sustainability is presented in **Table 2**. However, their successful implementation requires careful coordination with sensitizer design, electrolyte formulation, and counter electrode engineering. As the subsequent sections of this review will demonstrate, the full potential of copper-based DSSCs is realized only through holistic, system-level optimization that integrates all device components toward stability and application-driven performance. A comparative assessment of iodide, cobalt, copper-based, and organic redox mediator systems in terms of diffusion behavior, recombination tendency, stability, scalability, cost, and sustainability is presented in **Table 2**.

Table 2. Comparative assessment of major DSSC redox mediator systems.

Parameter	Iodide/Triiodide	Cobalt-Based	Copper-Based	Organic Mediators
Redox potential	Low	Moderate–High	High	Tunable
Diffusion coefficient	High	Moderate	Lower	Moderate
Recombination tendency	Moderate	Higher	Moderate–High	Variable
Stability	Moderate	Moderate	High (with proper encapsulation)	Limited
Corrosion tendency	High	Moderate	Low	Low
Cost	Low	Higher	Moderate	Variable
Scalability	High	Moderate	Moderate	Limited
Toxicity/Sustainability	Moderate	Moderate	Favorable	Favorable
Indoor suitability	Moderate	Good	Excellent	Emerging
Key limitation	Low Voc	Ligand instability	Mass transport limitations	Limited maturity

3. Sensitizer engineering: From light harvesting to long-term photo stability

The sensitizer is the defining element of dye-sensitized solar cells (DSSCs), as it is directly responsible for photon absorption, exciton generation, and electron injection into the photoanode. Unlike conventional semiconductor photovoltaics, where absorption and charge transport occur within the same material, DSSCs rely on molecular sensitizers whose properties can be independently tailored. This flexibility has enabled rapid progress in DSSC efficiency but has also introduced challenges related to chemical robustness, interfacial stability, and long-term device durability.

3.1. Early efficiency-driven sensitizer design

Historically, sensitizer development focused on maximizing light harvesting and photocurrent generation. Early strategies emphasized extending absorption into the visible and near-infrared regions through increased π-conjugation, donor–π–acceptor architectures, and incorporation of metal complexes with strong absorption coefficients [19–21]. While these approaches delivered significant efficiency gains, they often resulted in dyes with complex molecular structures that were vulnerable to photochemical degradation, desorption from the semiconductor surface, and instability under prolonged illumination.

As DSSC research moved toward practical deployment, it became evident that sensitizer instability represented one of the most critical failure modes limiting operational lifetime. Dye desorption, molecular decomposition, and unfavorable interfacial reactions were increasingly identified as primary contributors to long-term performance loss, particularly in devices designed to operate at elevated voltages [22–24].

3.2. Shift toward durability-oriented molecular engineering (2020–2025)

During the 2020–2025 period, sensitizer engineering underwent a decisive conceptual transition from absorption-centric design toward durability-oriented molecular engineering [25–27]. Rather than pursuing marginal efficiency gains through spectral extension alone, researchers began prioritizing molecular stability, strong surface binding, and compatibility with emerging redox systems.

This shift was driven in part by the widespread adoption of copper-based redox mediators, which enable higher open-circuit voltages but also impose stricter energetic and chemical constraints on sensitizers. Under such conditions, even minor instabilities in dye structure or anchoring can accelerate degradation, making photostability a critical design criterion [28–30].

3.3. Anchoring group engineering and dye adsorption stability

Anchoring group chemistry has emerged as one of the most influential factors governing sensitizer stability. Traditional carboxylate anchors, while effective for dye adsorption, can undergo hydrolysis or desorption under thermal stress or prolonged illumination. To address this limitation, recent studies have explored reinforced anchoring strategies, including multiple carboxylate groups, phosphonic acid anchors, and hybrid binding motifs [31–33,36].

Experimental evidence indicates that strengthened anchoring significantly suppresses dye desorption and maintains interfacial integrity during long-term operation. These effects are particularly pronounced in copper-mediated DSSCs, where high photovoltage increase the driving force for interfacial degradation if dye binding is insufficient [34,37,38]. Importantly, anchoring optimization often improves operational stability without substantially compromising initial device efficiency.

3.4. Photochemical stability and molecular robustness

Beyond surface binding, intrinsic photochemical stability has become a central focus of sensitizer design. Prolonged illumination can induce irreversible degradation pathways such as bond cleavage, oxidation of donor moieties, and structural rearrangements in highly conjugated dyes. To mitigate these effects, recent molecular design strategies emphasize increased structural rigidity, steric shielding of reactive sites, and controlled excited-state energetic [35,39–41].

Several studies published after 2021 demonstrate that sensitizers incorporating bulky substituent's or rigid frameworks exhibit significantly reduced photo degradation rates, even under continuous light soaking. While these modifications may lead to modest reductions in molar extinction coefficient or photocurrent, the resulting gains in operational lifetime more than compensate for such trade-offs in stability-oriented device design [42–44]. Stability enhancement in DSSCs can be achieved through multiple complementary approaches, including molecular rigidification of sensitizers, steric shielding of reactive sites, stronger anchoring-group design, suppression of dye aggregation, improved interfacial passivation, and replacement of volatile liquid electrolytes with quasi-solid or solid-state systems. In addition, optimized encapsulation strategies and ISOS-inspired stability testing protocols contribute significantly to improving long-term operational reliability.

3.5. Co-sensitization strategies: from spectral coverage to kinetic balance

Co-sensitization has long been employed to broaden spectral absorption and enhance photocurrent. However, early co-sensitized systems often suffered from unpredictable dye–dye interactions, competitive adsorption, and accelerated degradation. Recent work has redefined co-sensitization as a kinetically balanced strategy, rather than a purely spectral one [45–47].

Modern co-sensitized DSSCs employ dye combinations with compatible energy levels, regeneration kinetics, and adsorption behavior, minimizing interfacial competition and instability. This refined approach has enabled improved reproducibility and stability while retaining competitive efficiencies, particularly in systems designed for long-term operation and indoor illumination [48–50].

3.6. Sensitizer–redox mediator compatibility

The transition to non-iodide redox mediators has fundamentally altered sensitizer design requirements. Copper-based redox systems exhibit higher redox potentials and different reorganization dynamics compared to iodide electrolytes, necessitating precise energetic alignment with sensitizers. Recent studies emphasize that efficient regeneration must be achieved with minimal excess driving force to avoid accelerating recombination or molecular degradation [51–54].

As a result, sensitizer design increasingly incorporates redox-potential tuning, reduced reorganization energy, and controlled excited-state lifetimes. This co-optimization of sensitizer and redox mediator represents a defining characteristic of modern DSSC research and underscores the interconnected nature of device components [55–57].

3.7. Remaining challenges and future directions

Despite substantial progress, several challenges remain in sensitizer engineering. There is still no universally accepted protocol for evaluating dye-specific stability independent of full device performance, complicating direct comparison across studies. In addition, increasing molecular complexity may hinder synthetic scalability and cost-effective production, particularly for large-scale deployment [58–60].

Future research is therefore expected to focus on balancing molecular simplicity with durability, developing standardized stability assessment methods, and designing sensitizers explicitly optimized for indoor and low-light applications rather than outdoor peak efficiency.

Overall, sensitizer engineering between 2020 and 2025 reflects a broader maturation of DSSC research. Molecular design is now guided not only by optical and electronic considerations but also by lifetime, compatibility, and manufacturability. These advances have been essential in enabling long-term stable DSSCs and form a critical foundation for the electrolyte, interface, and architectural innovations discussed in subsequent sections. Another major challenge involves balancing molecular complexity with large-scale manufacturability. Highly engineered sensitizers capable of delivering excellent stability often require multi-step synthesis procedures, expensive purification methods, and limited-yield production routes, which may hinder commercial scalability. Furthermore, long-term compatibility between advanced sensitizers and emerging copper-based redox systems under realistic environmental conditions remains insufficiently understood. Future research should therefore prioritize simplified molecular architectures capable of simultaneously delivering photo stability, scalable synthesis, and compatibility with low-cost manufacturing approaches.

4. Electrolytes and the solid-state transition: From volatility control to device reliability

The electrolyte is a central component of dye-sensitized solar cells (DSSCs), serving as the ionic medium that transports charge between the photoanode and counter electrode while continuously regenerating the oxidized sensitizer. Although electrolytes do not directly participate in light absorption, their chemical composition, physical state, and long-term stability exert a decisive influence on device performance, durability, and manufacturability. Historically, electrolyte-related limitations have been among the most persistent barriers preventing DSSCs from transitioning beyond laboratory-scale demonstrations.

4.1. Limitations of conventional liquid electrolytes

Traditional DSSCs rely on liquid electrolytes composed of redox mediators dissolved in volatile organic solvents. Such electrolytes provide high ionic conductivity and rapid charge transport, enabling efficient dye regeneration and low internal resistance. However, despite these kinetic advantages, liquid electrolytes suffer from inherent drawbacks that compromise long-term stability and practical deployment [44–46].

Solvent evaporation, leakage through imperfect seals, and thermal expansion under operating conditions can lead to electrolyte loss and concentration imbalance over time. These effects are exacerbated under elevated temperatures and prolonged illumination, resulting in gradual efficiency decay and eventual device failure. In addition, liquid electrolytes complicate encapsulation and pose challenges for large-area fabrication, particularly when mechanical robustness and form-factor flexibility are required [47–49].

As DSSC research increasingly shifted toward stability-driven design during the 2020–2025 period, it became evident that long-term operational reliability could not be achieved without addressing the intrinsic vulnerabilities of liquid electrolytes.

4.2. Emergence of quasi-solid electrolytes

Quasi-solid electrolytes represent an important intermediate step in the evolution from liquid to solid-state DSSCs. These systems typically incorporate polymer matrices, gelators, or inorganic frameworks into conventional liquid electrolytes, immobilizing the solvent while retaining near-liquid ionic conductivity [50–52]. By suppressing solvent evaporation and leakage, quasi-solid electrolytes significantly enhance mechanical and thermal stability without introducing severe transport limitations.

Numerous studies published after 2021 demonstrate that well-designed gel electrolytes can sustain thousands of hours of stable operation under continuous illumination and thermal stress, with only modest reductions in power conversion efficiency compared to liquid counterparts [53–55]. This balance between performance retention and durability has made quasi-solid electrolytes particularly attractive for near-term applications, including indoor photovoltaics and flexible devices.

Importantly, quasi-solid electrolytes also simplify device sealing and encapsulation, reducing sensitivity to fabrication defects and improving reproducibility. These attributes are critical for scaling DSSC production beyond small laboratory cells.

4.3. Fully solid-state electrolytes: opportunities and challenges

Fully solid-state electrolytes offer the most robust solution to electrolyte-related stability issues. By eliminating free solvents entirely, solid electrolytes effectively prevent leakage and significantly enhance device shelf life and mechanical integrity [56–58]. Solid polymer electrolytes, inorganic ion conductors, and hybrid organic–inorganic systems have all been explored as candidates for solid-state DSSCs.

However, solidification introduces new challenges that must be carefully managed. Reduced ionic mobility, incomplete pore infiltration, and poor interfacial contact between the electrolyte and mesoporous photoanode can limit charge transport and increase series resistance [59–61]. Consequently, successful solid-state DSSCs require co-optimization of electrolyte composition, polymer chain dynamics, and photoanode morphology to ensure continuous ion transport pathways.

Recent research emphasizes that solid electrolytes are most effective when integrated into device architectures specifically designed to accommodate reduced mobility, such as thinner photoanodes or hierarchical pore structures. These design principles underscore the system-level nature of the solid-state transition.

4.4. Copper redox mediators and electrolyte immobilization

The widespread adoption of copper-based redox mediators has further accelerated the transition toward quasi-solid and solid electrolytes. Copper electrolytes are particularly sensitive to solvent evaporation, concentration gradients, and impurity accumulation, making electrolyte immobilization essential for maintaining long-term electrochemical stability [62–64].

Several studies report that copper-mediated DSSCs exhibit significantly improved voltage retention and reduced performance degradation when combined with gel or solid electrolytes compared to liquid systems. Immobilization suppresses redox species migration and mitigates local depletion effects, enabling high open-circuit voltages to be sustained over extended operating periods [65–67].

This strong synergy between copper redox chemistry and electrolyte immobilization highlights the importance of coordinated materials selection across device components.

4.5. Manufacturing and architectural implications

From a manufacturing perspective, solid and quasi-solid electrolytes offer clear advantages over liquid systems. Immobilized electrolytes facilitate monolithic and series-interconnected DSSC architectures by enabling layer-by-layer deposition and simplified encapsulation [68–70]. These architectures reduce assembly complexity, improve mechanical robustness, and enhance compatibility with scalable fabrication techniques such as printing and coating.

Furthermore, solid-state electrolytes reduce the risk of catastrophic failure due to leakage, which is particularly important for devices intended for long-term indoor deployment or integration into consumer electronics and IoT systems.

4.6. Remaining challenges and future directions

Despite substantial progress, electrolyte immobilization remains an active area of research. Trade-offs between ionic conductivity, mechanical rigidity, and chemical stability must be carefully balanced to avoid performance losses. In addition, standardized protocols for evaluating electrolyte stability under realistic operating conditions are still evolving, complicating cross-study comparison [71–73].

Future research is expected to focus on developing hybrid electrolyte systems that combine the transport advantages of liquids with the stability of solids, as well as on designing electrolytes specifically optimized for indoor and low-light operation rather than outdoor peak performance.

Overall, the transition from liquid to quasi-solid and solid electrolytes represents a pivotal development in modern DSSC research. By directly addressing long-standing stability limitations while enabling compatibility with copper redox mediators and scalable device architectures, electrolyte engineering has played a central role in redefining DSSCs as reliable, application-oriented photovoltaic devices. These advances provide a critical foundation for the interface and photoanode engineering strategies discussed in the next section.

5. Photoanode and interface engineering: Suppressing recombination and enhancing durability

The photoanode and its interfacial region constitute the electronic backbone of dye-sensitized solar cells (DSSCs), governing electron injection, transport, recombination dynamics, and ultimately both efficiency and long-term stability. While early DSSC research primarily emphasized maximizing surface area to enhance dye loading and photocurrent, it has become increasingly evident that interfacial recombination and chemical instability at the photoanode–electrolyte interface are among the dominant factors limiting device lifetime. As a result, photoanode and interface engineering have emerged as central themes in stability-oriented DSSC research during the 2020–2025 period.

5.1. TiO_2 photoanodes: Advantages and intrinsic limitations

Mesoporous TiO_2 remains the most widely used photoanode material in DSSCs due to its favorable conduction band alignment, chemical stability, abundance, and well-established low-temperature processing routes [59–61]. Its nanocrystalline morphology provides a large internal surface area for dye adsorption, enabling efficient light harvesting. However, this same high surface area also introduces a high density of surface states, defect sites, and trap levels that facilitate unwanted back-electron transfer to oxidized redox species in the electrolyte.

Under modern DSSC operating conditions—particularly those enabled by copper-based redox mediators with high redox potentials—interfacial recombination becomes even more pronounced. Elevated open-circuit voltages increase the energetic driving force for electron back-transfer, accelerating recombination losses and contributing to long-term interfacial degradation [62–64]. These effects underscore the need for deliberate interface control rather than relying solely on bulk material optimization.

5.2. Surface passivation strategies

Surface passivation has emerged as one of the most effective approaches for suppressing interfacial recombination in DSSCs. A wide range of passivation strategies have been reported, including ultrathin insulating layers, wide-bandgap oxide coatings, molecular passivants, and surface chemical treatments [65–67]. These approaches aim to reduce electronic coupling between TiO_2 and the electrolyte while preserving efficient electron injection from the sensitizer.

Ultrathin oxide layers, such as Al_2O_3, MgO, or ZrO_2, deposited via solution processing or atomic layer deposition, have been shown to significantly increase electron lifetime and open-circuit voltage. However, excessive passivation thickness can impede electron injection and transport, leading to reduced photocurrent [68–70]. Consequently, recent research emphasizes precision passivation, where layer thickness and coverage are carefully optimized to balance recombination suppression and charge transport.

5.3. Compact layers and interfacial buffers

In addition to passivating the mesoporous TiO_2 surface, compact blocking layers at the transparent conducting oxide (TCO) interface play a critical role in preventing direct contact between the electrolyte and the substrate. Imperfections in this interface can create shunt pathways that severely compromise device stability, particularly in large-area or monolithic DSSCs [71–73].

Advances during the review period include improved compact layer deposition techniques that yield uniform, pinhole-free films with controlled thickness. These improvements have led to enhanced reproducibility, higher photovoltage, and reduced performance dispersion across devices. Such developments are especially important for scalable DSSC architectures, where small interfacial defects can have disproportionate impacts on long-term reliability.

5.4. Structural engineering of photoanodes

Beyond surface chemistry, structural engineering of the photoanode has gained increasing attention. Hierarchical and multilayer photoanode architectures have been designed to balance light scattering, dye adsorption, electron transport, and mechanical stability [74–76]. By combining nanoparticles of different sizes or incorporating scattering layers, these architectures enhance optical path length while maintaining robust electronic connectivity.

Recent studies demonstrate that mechanically reinforced photoanodes with controlled pore size distributions exhibit improved resistance to thermal cycling and prolonged operation without structural collapse. This aspect is particularly relevant for flexible DSSCs and indoor devices, which may experience repeated mechanical or thermal stress during service [77–79].

5.5. Interface engineering for copper-based DSSCs

The adoption of copper-based redox mediators has further elevated the importance of interface engineering. Copper electrolytes exhibit different adsorption behavior and redox kinetics compared to iodide systems, increasing the susceptibility of DSSCs to interfacial recombination if surfaces are not properly engineered [80–82]. As a result, surface treatments that were adequate for iodide-based DSSCs may be insufficient for copper-mediated systems.

Studies published after 2021 show that optimized TiO_2 surface passivation and tailored interface modifiers can significantly extend the operational lifetime of copper-based DSSCs by stabilizing the semiconductor–electrolyte interface under high-voltage conditions. These strategies not only suppress recombination but also reduce chemical degradation driven by prolonged electrochemical stress [83–85].

5.6. Interfacial stability and long-term degradation

Interfacial degradation in DSSCs often manifests gradually, through increased recombination rates, shifts in band alignment, and loss of electronic connectivity. Such degradation is difficult to detect in short-term measurements but becomes evident under long-duration stability testing. Recent work highlights that interface-engineered DSSCs exhibit slower degradation kinetics and more stable performance under extended light soaking and thermal stress [86–88].

Importantly, interface stability is strongly coupled to other device components, including the electrolyte and sensitizer. Effective photoanode engineering therefore requires an integrated approach that considers chemical compatibility and dynamic interactions across all interfaces.

5.7. Remaining challenges and outlook

Despite substantial advances, several challenges remain in photoanode and interface engineering. Many passivation strategies are system-specific, and their effectiveness can vary depending on the sensitizer, redox mediator, and electrolyte employed. Furthermore, standardized metrics for quantifying interfacial degradation are still under development, complicating cross-study comparison [89–91].

Future research is expected to focus on universal interface design principles, scalable passivation methods, and in-situ diagnostics to monitor interfacial changes during operation. Such efforts will be essential for translating laboratory-scale stability improvements into reliable, large-area DSSC modules.

In summary, advances in photoanode and interface engineering during the 2020–2025 period have played a decisive role in enabling the transition of DSSCs toward stable and application-ready devices. By suppressing recombination losses and mitigating interfacial degradation at their origin, these strategies complement improvements in redox mediators and electrolytes, reinforcing the system-level design philosophy that defines modern DSSC development.

6. Counter electrodes and cost reduction: From platinum dependence to system compatibility

The counter electrode (CE) plays a vital role in dye-sensitized solar cells (DSSCs) by catalyzing the reduction of the oxidized redox mediator and completing the internal electrical circuit. Although the CE does not directly participate in light absorption or electron injection, its catalytic activity, electrochemical stability, and compatibility with the electrolyte critically influence device efficiency, fill factor, and long-term operational durability. Historically, platinum has been the benchmark CE material due to its excellent catalytic performance. However, the evolving requirements of modern DSSCs—particularly those employing non-iodide redox mediators and targeting scalable, low-cost applications—have necessitated a fundamental reassessment of CE design.

6.1. Limitations of platinum counter electrodes

Platinum-based counter electrodes exhibit high catalytic activity for the reduction of iodide/triiodide redox couples and possess excellent electrical conductivity. These properties made platinum the default choice in early DSSC research and enabled many of the efficiency milestones achieved under laboratory conditions [69–71]. Nevertheless, platinum presents several drawbacks that limit its suitability for next-generation DSSCs.

First, platinum is expensive and scarce, making it economically unattractive for large-scale deployment. Second, platinum is susceptible to corrosion and surface poisoning in certain electrolyte environments, particularly those containing non-iodide redox mediators such as copper complexes. Prolonged operation can lead to gradual loss of catalytic activity and increased interfacial resistance, contributing to long-term performance degradation [72–74]. These limitations have motivated intensive research into platinum-free alternatives that can deliver comparable catalytic performance with improved durability and reduced cost.

6.2. Shift toward redox-specific and system-compatible counter electrodes

During the 2020–2025 period, CE research has shifted from the pursuit of universal catalytic materials toward redox-specific and system-compatible electrode design [75–77]. This transition mirrors the broader evolution of DSSCs toward copper-based and other non-iodide redox mediators, which impose distinct electrochemical requirements compared to iodide systems.

In copper-mediated DSSCs, the CE must efficiently catalyze the Cu(II)/Cu(I) redox reaction without promoting side reactions or undergoing chemical degradation. Platinum, while effective for iodide systems, often exhibits reduced stability or catalytic efficiency in copper electrolytes. As a result, CE materials are now increasingly selected and optimized based on their compatibility with the specific redox chemistry employed in the device.

6.3. Carbon-based counter electrodes

Carbon-based materials have emerged as leading platinum-free alternatives due to their low cost, chemical stability, and tunable surface properties. Carbon black, graphene, carbon nanotubes, and composite carbon electrodes have all been extensively investigated during the review period [78–81]. These materials offer several advantages, including resistance to corrosion, compatibility with a wide range of electrolytes, and suitability for low-temperature, scalable fabrication techniques.

Recent studies demonstrate that well-engineered carbon electrodes can achieve catalytic activities comparable to platinum for both iodide and copper redox systems, while exhibiting superior long-term stability under continuous illumination and thermal stress [82–84]. Importantly, carbon materials are inherently compatible with flexible substrates and printable processes, making them attractive for large-area DSSCs and indoor photovoltaic modules.

6.4. Copper-compatible and transition-metal-based counter electrodes

In addition to carbon materials, a variety of copper-compatible counter electrodes based on transition-metal compounds have been explored. Metal sulfides, nitrides, carbides, and composite materials have shown promising catalytic activity toward Cu(II)/Cu(I) redox reactions [85–87]. These materials are often more chemically stable than platinum in copper electrolytes and can be synthesized using solution-based or low-temperature processes.

A key advantage of these materials is their tunable electronic structure, which allows catalytic activity to be optimized through compositional and morphological control. However, challenges remain in achieving consistent performance and long-term durability, as some transition-metal compounds may undergo surface reconstruction or gradual dissolution during extended operation [88–90].

6.5. Durability-focused evaluation of counter electrodes

An important methodological shift during the 2020–2025 period is the increased emphasis on long-term electrochemical durability rather than initial catalytic performance alone. Several studies have shown that materials exhibiting high initial activity may degrade rapidly due to surface poisoning, mechanical instability, or chemical interaction with the electrolyte [91–93]. Consequently, stability testing under realistic operating conditions has become a critical criterion for CE evaluation.

This durability-focused perspective aligns with the broader trend in DSSC research toward lifetime optimization rather than peak efficiency. Counter electrodes that maintain moderate catalytic activity over extended periods are now often preferred over materials that deliver high initial performance but suffer rapid degradation.

6.6. Manufacturing and cost considerations

From a manufacturing standpoint, alternative counter electrodes contribute significantly to overall cost reduction and process simplification. The elimination of platinum reduces material costs and mitigates supply-chain risks, while printable and low-temperature fabrication methods enable compatibility with roll-to-roll processing and monolithic DSSC architectures [94–96].

These advantages are particularly relevant for indoor photovoltaics and IoT energy harvesting applications, where cost sensitivity and mechanical robustness are critical. In such contexts, the CE must not only perform catalytically but also integrate seamlessly into scalable device architectures.

6.7. Remaining challenges and future directions

Despite notable progress, several challenges remain in the development of universal CE solutions. Many alternative materials exhibit redox-specific behavior, requiring careful system-level optimization to avoid performance losses when device components are modified. In addition, standardized protocols for evaluating CE degradation are still evolving, complicating cross-comparison of reported results [97–99].

Future research is expected to focus on hybrid CE materials that combine the advantages of carbon and transition-metal compounds, as well as on in-situ characterization techniques to elucidate degradation mechanisms during operation. Such insights will be essential for designing counter electrodes that meet the stringent durability requirements of next-generation DSSCs.

In summary, advances in counter electrode design between 2020 and 2025 have transformed the CE from a passive component into an actively engineered element central to DSSC stability and cost reduction. The shift away from platinum toward redox-compatible, durable, and scalable materials reflects the broader maturation of DSSC technology toward practical, sustainable photovoltaic applications. When integrated with optimized redox mediators, electrolytes, and photoanodes, these advances contribute decisively to the realization of long-lived, application-ready DSSCs.

7. Stability, degradation, and ISOS protocols: From short-term performance to reliable lifetime assessment

As dye-sensitized solar cells (DSSCs) evolve from laboratory-scale demonstrations toward practical energy-harvesting devices, operational stabilityhas emerged as the most critical performance metric. While early DSSC studies often emphasized power conversion efficiency measured under short-term conditions, it is now widely recognized that such metrics provide limited insight into long-term reliability. During the 2020–2025 period, the DSSC research community has increasingly prioritized systematic stability evaluation, degradation mechanism analysis, and standardized testing protocols to enable meaningful comparison across studies and realistic assessment of device lifetimes.

7.1. Nature and complexity of DSSC degradation

Degradation in DSSCs is inherently multi factorial, arising from coupled chemical, electrochemical, and physical processes that occur simultaneously during device operation. Unlike conventional solid-state photovoltaics, DSSCs involve multiple interfaces and mobile ionic species, which introduce additional pathways for performance loss. Commonly reported degradation mechanisms include dye desorption and photodecomposition, electrolyte volatilization or chemical breakdown, corrosion or poisoning of counter electrodes, and increased interfacial recombination at the photoanode–electrolyte interface [82–84].

Importantly, these degradation pathways rarely act independently. The major stability enhancement strategies, their target components, and their impact on device lifetime are summarized in **Table 3**. For example, partial dye degradation can expose photoanode surface states that accelerate recombination, while electrolyte decomposition products may poison counter electrodes or alter redox kinetics. This interdependence makes DSSC degradation highly system-specific and underscores the need for holistic, device-level stability assessment rather than isolated component testing.

Table 3. Stability enhancement strategies in DSSCs and their impact on device lifetime.

Stability strategy	**Target component**	**Mechanism of improvement**	**Typical lifetime gain**
Copper redox mediators	Electrolyte	Eliminates iodine-related corrosion	+3–5×
Quasi-solid electrolytes	Electrolyte	Suppresses leakage & evaporation	+2–3×
Solid-state electrolytes	Electrolyte	Mechanical and thermal robustness	+4–6×
Anchoring group engineering	Sensitizer	Reduces dye desorption	+2–4×
Surface passivation layers	Photoanode	Suppresses interfacial recombination	+1.5–3×
Carbon-based counter electrodes	Counter electrode	Improved chemical stability	+2–3×
Compact/Barrier layers	Interface	Prevents shunt pathways	+1.5–2×
Monolithic architectures	Device	Reduces sealing failure	+3–5×
ISOS-inspired stability testing	Evaluation	Identifies true degradation modes	—

7.2. Sensitizer- and electrolyte-driven degradation

Sensitizer instability remains a major contributor to long-term performance loss, particularly under prolonged illumination. Photochemical degradation of dyes can occur through bond cleavage, oxidation of donor moieties, or irreversible excited-state reactions. Even minor molecular degradation can disrupt energy alignment and reduce electron injection efficiency over time [85–87]. Dye desorption from the photoanode surface further exacerbates these effects by reducing active surface coverage and exposing recombination-active sites.

Electrolyte-related degradation has historically been dominated by solvent evaporation and iodine-induced corrosion in iodide-based systems. While the transition to copper-based redox mediators and solid or quasi-solid electrolytes has mitigated many of these issues, new challenges have emerged. Copper electrolytes are sensitive to concentration gradients, ligand degradation, and impurity accumulation, which can gradually alter redox kinetics and increase internal resistance [88–90]. These findings highlight that improved stability does not eliminate degradation but rather shifts its dominant pathways.

7.3. Interface-driven degradation and recombination

Interfacial degradation at the photoanode–electrolyte interface is increasingly recognized as a critical determinant of DSSC lifetime. Over time, chemical interaction between the semiconductor surface, sensitizer, and electrolyte can modify surface states and band alignment, leading to increased recombination and reduced photovoltage [91–93]. Such changes often occur gradually and may not be apparent in short-term measurements.

In copper-based DSSCs operating at high open-circuit voltages, interfacial stability becomes even more critical. Elevated electrochemical stress can accelerate surface reactions and exacerbate recombination losses if interfaces are not adequately passivated. Recent studies demonstrate that interface-engineered DSSCs exhibit slower degradation kinetics and more stable performance under extended operation, reinforcing the importance of deliberate interface control for long-lived devices [94–96].

7.4. Emergence of standardized stability testing

A major methodological advancement during the 2020–2025 period has been the broader adaptation of standardized stability testing protocols, most notably those developed under the International Summit on Organic Photovoltaic Stability (ISOS) framework, which was originally established for organic photovoltaic devices and later widely adopted in perovskite solar cell research. Although originally designed for organic photovoltaics, ISOS protocols have been increasingly applied to DSSCs due to their structured approach to evaluating stability under controlled conditions [88–90].

ISOS protocols define a series of standardized tests, including light soaking (ISOS-L), thermal stress (ISOS-T), and combined environmental stress tests. The application of these protocols has improved reproducibility and transparency in DSSC stability reporting by specifying illumination intensity, temperature, humidity, and testing duration. This standardization allows researchers to distinguish between intrinsic material degradation and extrinsic failure modes related to packaging or measurement conditions.

Although ISOS protocols were not originally designed specifically for dye-sensitized solar cells, they have increasingly been adapted for DSSC stability assessment because they provide standardized procedures for evaluating light soaking, thermal stress, and environmental degradation. However, DSSCs possess several unique characteristics—including liquid or quasi-solid electrolytes, mobile ionic species, dye desorption mechanisms, and redox-mediated electrochemical processes—that differ substantially from conventional organic and perovskite photovoltaics. Consequently, direct application of ISOS methodologies to DSSCs may not fully capture certain degradation pathways specific to DSSC operation.

At present, no universally accepted DSSC-exclusive stability standard exists. As a result, many recent studies employ modified or ISOS-inspired testing approaches adapted to the operational characteristics of DSSCs, particularly for indoor and long-duration stability evaluation. This ongoing adaptation highlights the need for future development of DSSC-specific stability assessment frameworks capable of addressing electrolyte stability, interfacial degradation, encapsulation reliability, and application-dependent operating conditions more comprehensively.

7.5. Insights gained from ISOS-aligned testing

The application of ISOS-aligned testing has yielded important insights into DSSC degradation behavior. For example, several studies reveal that devices exhibiting minimal efficiency loss under continuous illumination may still suffer significant degradation under elevated temperatures, highlighting the importance of multi-stress testing [91–93]. Similarly, DSSCs optimized for outdoor operation may exhibit different degradation pathways compared to devices designed for indoor environments.

Indoor DSSCs, in particular, often display exceptionally long operational lifetimes due to reduced ultraviolet exposure, lower operating temperatures, and diminished photochemical stress. Reports of DSSCs retaining stable performance beyond 10,000 h under indoor illumination are increasingly common [34]. However, these lifetime values are typically obtained under controlled indoor illumination conditions involving reduced ultraviolet exposure, low thermal stress, and relatively small active device areas. Consequently, direct comparison of indoor stability metrics with outdoor AM1.5G operational stability should be approached with caution. Furthermore, many reported stability studies differ in encapsulation strategy, illumination intensity, and ISOS testing conditions, which may influence apparent lifetime values.

7.6. Limitations of current stability metrics

Despite significant progress, challenges remain in establishing universally accepted stability benchmarks for DSSCs. Reported testing durations, illumination spectra, environmental stress conditions, and adaptations of ISOS methodologies still vary across studies, complicating direct comparison of DSSC lifetime data more comprehensively [24–26]. Moreover, many reports emphasize relative efficiency retention without adequately addressing absolute performance loss or failure thresholds relevant to real-world applications.

Another limitation is the frequent separation of stability testing from system-level considerations such as encapsulation quality and mechanical durability. As DSSCs move closer to deployment in consumer and industrial applications, stability assessment must increasingly incorporate packaging, mechanical stress, and environmental exposure to provide realistic lifetime projections.

7.7. Future directions in stability assessment

Future DSSC research is expected to place greater emphasis on predictive lifetime modeling, combining accelerated aging tests with mechanistic understanding of degradation processes. In-situ and operando characterization techniques will play an important role in identifying early-stage degradation phenomena and guiding materials design toward intrinsic stability.

Additionally, the development of application-specific stability standards—particularly for indoor photovoltaics and IoT energy harvesting—will be essential. Such standards should reflect realistic operating conditions rather than relying solely on traditional outdoor solar testing paradigms.

In summary, the period from 2020 to 2025 marks a significant maturation in how DSSC stability is evaluated and reported. The integration of degradation mechanism analysis with standardized ISOS-style testing has shifted the field away from short-term performance metrics toward reliable lifetime assessment. A comparative overview of power conversion efficiency and operational stability trends in DSSCs reported between 2020 and 2025 is presented in **Figure 2**. This evolution is essential for aligning DSSC research with real-world deployment requirements and provides a critical foundation for the application-driven advances discussed in the next section.

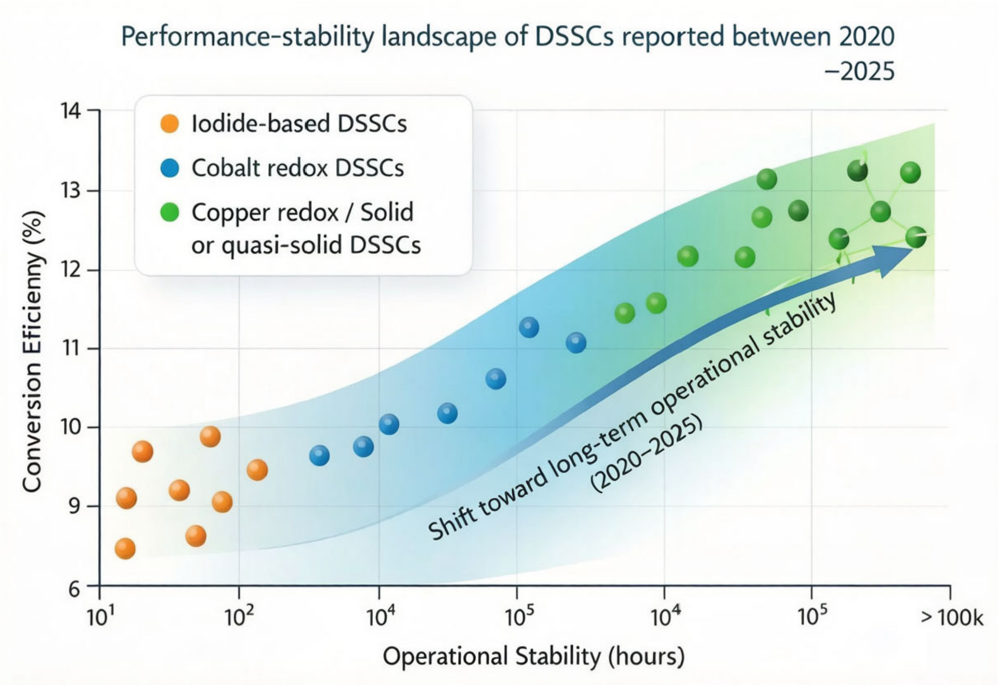

Figure 2. Schematic trend illustration comparing the reported progression of power conversion efficiency and operational stability of dye-sensitized solar cells (DSSCs) during the 2020–2025 period. The figure conceptually summarizes representative literature trends associated with advances in copper-based redox mediators, electrolyte engineering, interfacial optimization, and stability-oriented device architectures.

8. Indoor and IoT applications: From laboratory devices to application-driven energy harvesting

The emergence of indoor and low-light energy harvesting as a distinct application domain has fundamentally reshaped the trajectory of dye-sensitized solar cell (DSSC) research. Unlike outdoor photovoltaics, where peak efficiency under standard solar illumination is the dominant performance metric, indoor and Internet-of-Things (IoT) applications impose a different set of requirements. These include reliable operation under low irradiance, spectral matching to artificial light sources, stable voltage output, long operational lifetime, and compatibility with compact and flexible device formats. During the 2020–2025 period, DSSCs have increasingly been recognized as uniquely suited to meet these criteria.

8.1. Performance of DSSCs under low-irradiance conditions

A defining strength of DSSCs is their ability to maintain high open-circuit voltages and favorable conversion efficiencies under illumination intensities several orders of magnitude lower than standard sunlight. Numerous studies conducted during the review period demonstrate that DSSCs outperform organic photovoltaics and amorphous silicon solar cells under common indoor light sources such as white

LEDs and fluorescent lamps [94–96,100]. such as white LEDs and fluorescent lamps [94–96]. This behavior is attributed to the molecular nature of light absorption in DSSCs and the efficient charge separation that persists even at low photon flux. This comparative performance under indoor illumination conditions is summarized in **Figure 3**.

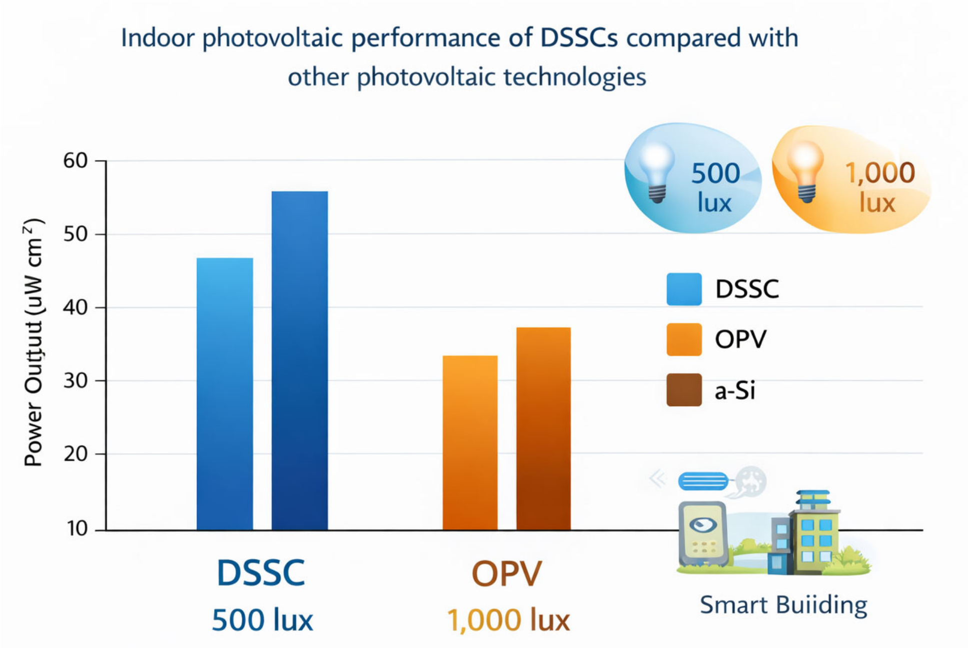

Figure 3. Schematic comparative illustration of the performance of dye-sensitized solar cells (DSSCs) relative to other photovoltaic technologies under indoor illumination conditions. The figure conceptually summarizes representative trends in indoor photovoltaic efficiency, operational stability, low-light performance, and suitability for IoT and indoor energy-harvesting applications based on literature reported during the 2020–2025 period.

Under indoor illumination levels typically ranging from 100 to 1000 lux, DSSCs exhibit minimal voltage losses compared to their outdoor performance, enabling efficient power delivery to low-power electronic devices ranging from 100 to 1000 lux [100]. Several recent studies have reported indoor power conversion efficiencies exceeding 13% under white LED illumination conditions (~1000 lux), particularly in copper-redox-mediated DSSCs optimized for low-light operation [34,35,100]. However, these values should not be interpreted as equivalent to outdoor AM1.5G efficiencies, which are generally lower due to spectral mismatch and higher recombination losses under full solar irradiance. In addition, many high-efficiency indoor DSSCs are measured using relatively small active areas (<1 cm^2), whereas large-area modules may exhibit reduced efficiencies due to increased series resistance, transport limitations, and interconnection losses. Therefore, illumination conditions, aperture area, and testing methodology must be carefully considered when comparing reported DSSC performances across different studies. Representative performance benchmarks of DSSCs under different indoor lighting conditions, along with comparisons to competing technologies, are listed in **Table 4**.

This characteristic is particularly advantageous for IoT applications, where stable voltage output is often more critical than maximum power density.

Table 4. Representative indoor photovoltaic performance benchmarks reported under different lighting conditions and testing environments.

Photovoltaic technology	**Illumination source**	**Illuminance (lux)**	**Power output (μW cm^{-2})**	**Voc retention**	**Typical lifetime**	**Active Area**
DSSC	White LED	500	40–50	Excellent	>10,000 h	<1 cm²
DSSC	White LED	1,000	50–60	Excellent	>15,000 h	<1 cm²
DSSC	Fluorescent	1,000	45–55	Excellent	>12,000 h	<1 cm²
OPV	White LED	500	25–30	Moderate	~3,000 h	~1 cm²
OPV	White LED	1,000	30–35	Moderate	~4,000 h	~1 cm²
a-Si	Fluorescent	1,000	20–30	Moderate	>10,000 h	~1–4 cm²
a-Si	White LED	500	15–20	Moderate	>8,000 h	~1–4 cm²

8.2. Spectral matching and sensitizer optimization for indoor light

Indoor light sources differ fundamentally from sunlight in both intensity and spectral distribution. Artificial lighting typically exhibits narrow emission bands concentrated in the visible region, with minimal ultraviolet and infrared components. Recognizing this, recent DSSC research has increasingly focused on spectral matching between sensitizers and indoor light sources rather than broad solar spectrum coverage [97–99].

Sensitizer engineering and co-sensitization strategies have been adapted to maximize absorption in the spectral regions corresponding to LED and fluorescent emissions. This application-specific optimization has led to significant improvements in indoor power output and energy conversion efficiency. Importantly, these advances reflect a broader shift away from universal performance metrics toward application-tailored device design.

8.3. Stability advantages under indoor operation

Stability considerations further strengthen the case for DSSCs in indoor applications. Indoor environments typically involve lower operating temperatures, reduced ultraviolet exposure, and diminished photochemical stress compared to outdoor conditions. As a result, DSSCs operating under indoor illumination often exhibit substantially extended operational lifetimes.

Several studies report DSSCs retaining stable performance for more than 10,000 h under continuous indoor illumination, with minimal degradation in voltage or power output [34,101]. These lifetimes exceed many outdoor stability benchmarks and highlight the strong dependence of DSSC durability on operating conditions. Such findings underscore the importance of evaluating stability within the context of the intended application rather than relying solely on standard solar testing.

8.4. Integration with IoT and self-powered systems

The rapid growth of IoT technologies has created a demand for autonomous, maintenance-free power sources capable of sustaining low-power electronics such as sensors, wireless transmitters, and control units. DSSCs are particularly well suited for this role due to their favorable indoor performance, tunable form factors, and compatibility with low-power electronics.

Recent advances in monolithic DSSC architectures, solid and quasi-solid electrolytes, and printable fabrication techniques have enabled integration of DSSCs into compact modules and flexible substrates suitable for embedded applications [102]. In many cases, DSSCs are combined with energy storage components and power management circuits to create fully self-powered systems capable of continuous operation under ambient indoor lighting. The combination of high indoor photovoltage, long operational lifetime, lightweight architecture, and compatibility with low-power electronics makes DSSCs particularly attractive for next-generation autonomous sensing platforms, wireless monitoring systems, and maintenance-free IoT devices.

8.5. Comparative assessment with competing technologies

When compared with alternative indoor photovoltaic technologies, DSSCs consistently demonstrate superior performance under realistic indoor conditions. Organic photovoltaics, while flexible and lightweight, often suffer from lower voltage output and limited stability. Amorphous silicon solar cells exhibit reasonable stability but perform poorly under low irradiance and narrow spectral illumination [94–96].

DSSCs occupy a distinct technological niche by combining high voltage, good spectral matching, and long operational lifetime under indoor conditions. This combination makes them particularly attractive for IoT applications where reliability and predictability are essential.

8.6. Challenges and remaining barriers

Despite their strong potential, several challenges must be addressed before DSSCs can achieve widespread adoption in indoor and IoT applications. Indoor lighting conditions vary significantly in intensity, spectrum, and duty cycle, complicating performance prediction and system design. In addition, long-term compatibility between DSSCs and electronic components, as well as mechanical durability in flexible or integrated systems, requires further investigation.

Standardized testing protocols tailored specifically to indoor photovoltaics are still under development. Existing stability and performance metrics often derive from outdoor solar testing and may not accurately reflect indoor operating conditions. Establishing application-specific benchmarks will be critical for technology qualification and commercialization.

8.7. Outlook for indoor DSSCs

The increasing emphasis on indoor and IoT applications represents one of the most significant developments in DSSC research during the 2020–2025 period. By shifting the performance focus from maximum outdoor efficiency to reliable, application-specific energy harvesting, DSSCs have established a clear technological niche with strong potential for real-world deployment.

Continued progress in sensitizer optimization, device integration, and system-level design is expected to further enhance the competitiveness of DSSCs in indoor energy harvesting markets. As these technologies mature, DSSCs are poised to play a key role in enabling sustainable, maintenance-free power solutions for the rapidly expanding IoT ecosystem.

9. Scale-up and manufacturing outlook: From laboratory cells to deployable systems

The translation of dye-sensitized solar cells (DSSCs) from laboratory-scale devices to deployable products remains a central challenge, despite substantial advances in materials stability and device performance. While many innovations discussed in previous sections have been validated at the small-cell level, scaling DSSCs to larger areas introduces additional constraints related to uniformity, defect tolerance, process integration, and cost. Consequently, recent DSSC research has increasingly emphasized manufacturing compatibility and scale-relevant architectures alongside materials development.

9.1. Challenges associated with DSSC scale-up

Scale-up of DSSCs is inherently complex due to the multilayered and interfacial nature of the device architecture. Performance parameters that are readily optimized in small-area cells—such as photoanode thickness, dye loading, and electrolyte composition—often become more difficult to control uniformly across large substrates. Minor variations in film thickness, porosity, or interfacial contact can lead to localized performance losses, increased recombination, and accelerated degradation in large-area devices [76–78].

Furthermore, the presence of liquid or semi-liquid electrolytes introduces challenges related to filling uniformity, sealing reliability, and long-term containment, particularly as device area increases. These issues highlight the need for scale-aware design strategies rather than simple up-scaling of laboratory-optimized cells.

9.2. Monolithic and series-interconnected DSSC architectures

One of the most significant architectural innovations addressing scale-up challenges is the development of monolithic and series-interconnected DSSC designs. Unlike conventional sandwich-type cells, monolithic architectures integrate multiple functional layers on a single substrate, reducing assembly complexity and minimizing electrolyte leakage pathways [79–81].

During the 2020–2025 period, several studies demonstrated monolithic DSSCs with improved mechanical robustness, reproducibility, and long-term stability compared to traditional configurations. These architectures are particularly well suited for solid and quasi-solid electrolytes, which enable sequential layer deposition and simplified encapsulation. Series interconnection within monolithic designs also allows voltage scaling without increasing current density, reducing resistive losses and improving compatibility with low-power electronics.

9.3. Scalable deposition and fabrication techniques

The choice of fabrication method plays a critical role in DSSC manufacturability. While laboratory devices often rely on spin coating and batch processing, scalable production requires deposition techniques compatible with large areas and high throughput. To this end, methods such as screen printing, doctor blading, slot-die coating, inkjet printing, and spray deposition have been increasingly optimized for DSSC fabrication [82–85].

Screen printing and doctor blading are particularly attractive for photoanode and counter electrode fabrication due to their simplicity and compatibility with existing industrial infrastructure. Slot-die coating and inkjet printing offer greater control over film thickness and material usage, making them suitable for roll-to-roll processing and flexible substrates. Importantly, advances in paste formulation and ink rheology have improved film uniformity and reduced defect density, addressing key scale-up bottlenecks.

9.4. Electrolyte management and encapsulation

Electrolyte management remains a major consideration in scalable DSSC production. Liquid electrolytes pose challenges related to leakage, evaporation, and long-term containment, particularly in large-area modules. The increasing adoption of quasi-solid and solid electrolytes directly addresses these concerns by enabling simplified encapsulation and improved mechanical robustness [86–88].

From a manufacturing perspective, electrolyte immobilization reduces process variability and enhances yield by minimizing sensitivity to sealing imperfections. Solid and gel electrolytes also facilitate integration with monolithic architectures and flexible substrates, further enhancing scalability. However, ensuring uniform electrolyte distribution and maintaining ionic conductivity at scale remain active areas of research.

9.5. Cost considerations and economic viability

Beyond technical feasibility, the economic viability of DSSCs is a decisive factor for large-scale deployment. Recent studies increasingly incorporate cost analysis alongside performance metrics, recognizing that materials selection, processing complexity, and throughput significantly influence overall device economics. The replacement of platinum counter electrodes, reduction of rare or toxic components, and use of low-temperature processing steps contribute to favorable cost projections for DSSCs targeting indoor and low-power applications [89–92].

Importantly, DSSCs are not positioned to compete directly with silicon photovoltaics in large-scale outdoor power generation. Instead, their economic advantages are most pronounced in niche markets—such as indoor photovoltaics, IoT energy harvesting, and building-integrated applications—where competing technologies are less effective or economically viable.

Although copper-based DSSCs offer important advantages for indoor photovoltaics, their scalability remains more challenging than conventional iodide systems due to stricter requirements on electrolyte purity, mass transport management, and interfacial optimization. Furthermore, copper ligand synthesis and purification may increase processing complexity and material cost compared to traditional iodide electrolytes. Consequently, the economic viability of copper-mediated DSSCs depends strongly on application-specific requirements rather than efficiency alone [16,23,34,39].

9.6. Reliability, quality control, and module integration

As DSSCs approach practical deployment, reliability and quality control become increasingly important. Large-area modules must maintain consistent performance across all segments and withstand long-term environmental and mechanical stress. Variations in interconnection quality, encapsulation integrity, and material stability can lead to premature failure if not carefully managed.

Recent work highlights the importance of integrating DSSCs with power management electronics, energy storage components, and protective encapsulation to create complete, application-ready systems. Such system-level integration shifts the focus from individual cell performance to overall module reliability and functionality [93–96].

9.7. Remaining challenges and future outlook

Despite encouraging progress, several challenges remain before DSSCs can achieve widespread commercial adoption. Standardized manufacturing benchmarks, long-term reliability data at the module level, and validated cost models are still limited. Moreover, closer collaboration between academic research and industrial process development will be essential to bridge the gap between laboratory innovation and scalable production.

Future research is expected to focus on refining monolithic architectures, improving roll-to-roll compatible materials and processes, and developing application-specific modules optimized for indoor and low-light operation. Addressing these challenges will be critical for translating the intrinsic advantages of DSSCs into reliable, deployable energy-harvesting technologies.

In summary, advances in scale-up strategies and manufacturing-oriented design during the 2020–2025 period indicate that DSSCs are moving beyond proof-of-concept demonstrations toward practical, application-driven deployment. While DSSCs are unlikely to replace conventional photovoltaics in large-scale power generation, their compatibility with scalable fabrication, combined with excellent indoor performance and long-term stability, positions them as strong candidates for emerging energy-harvesting markets. Continued progress in manufacturing integration will play a decisive role in determining the commercial impact of DSSC technology.

10. Conclusions and future outlook: Toward reliable, application-centric DSSCs

The period from 2020 to 2025 represents a decisive phase in the evolution of dye-sensitized solar cells (DSSCs), during which the field transitioned from efficiency-driven laboratory research to stability-oriented, application-focused device engineering. Rather than pursuing incremental efficiency gains under idealized solar conditions, contemporary DSSC research has increasingly emphasized long-term operational reliability, system integration, and suitability for specific deployment environments. This shift reflects a broader maturation of the technology and a clearer understanding of the domains in which DSSCs can deliver unique and sustainable value.

A central conclusion emerging from this review is that system-level integration**,** rather than isolated optimization of individual components, has been the primary enabler of recent progress. The widespread adoption of copper-based redox mediators has fundamentally redefined the voltage ceiling of DSSCs while eliminating iodine-related degradation pathways. When combined with appropriately engineered sensitizers, copper redox systems enable high photovoltage without compromising regeneration efficiency or long-term stability [27–30,44–47]. However, the benefits of these redox mediators are realized only when accompanied by coordinated advances in electrolyte formulation, counter electrode catalysis, and interface engineering.

Sensitizer development during the review period illustrates a broader conceptual transformation within DSSC research. Molecular design strategies have shifted from maximizing spectral coverage toward enhancing anchoring strength, photochemical robustness, and energetic compatibility with non-iodide redox systems [31–34,36–38,41–43]. This evolution acknowledges that dye degradation and desorption are among the most critical failure modes in long-lived DSSCs. As a result, modern sensitizers increasingly represent carefully balanced compromises between optical performance and molecular durability rather than aggressive pursuit of absorption breadth alone.

Electrolyte engineering has likewise played a pivotal role in redefining DSSC stability. The transition from volatile liquid electrolytes to quasi-solid and solid-state systems has addressed long-standing challenges related to leakage, evaporation, and mechanical reliability [50–58,65–67]. These developments have not only improved operational lifetime but also enabled monolithic device architectures and simplified encapsulation, aligning DSSC fabrication more closely with scalable manufacturing paradigms. Importantly, electrolyte immobilization has proven particularly synergistic with copper-based redox mediators, underscoring the interconnected nature of modern DSSC design.

Interface and photoanode engineering have further reinforced the stability-driven evolution of DSSCs. Surface passivation, compact blocking layers, and hierarchical photoanode structures have collectively suppressed recombination losses and mitigated interfacial degradation, especially under high-voltage operation [65–70,83–88]. These advances highlight that long-term device reliability is often governed by subtle interfacial processes that are invisible in short-term efficiency measurements but become dominant over extended operation.

The increasing emphasis onstandardized stability evaluation, including ISOS-aligned testing protocols, marks another important milestone in the maturation of

DSSC research [88–93]. By shifting focus from anecdotal stability claims to reproducible lifetime assessment under controlled stress conditions, the field has made significant progress toward credible benchmarking of device durability. Nevertheless, further refinement of testing standards—particularly those tailored to indoor and low-light operation—remain essential for accurate qualification of DSSCs intended for specific applications.

One of the most consequential developments highlighted in this review is the emergence ofindoor and Internet-of-Things (IoT) energy harvesting as a primary driver of DSSC innovation. Under low-intensity artificial illumination, DSSCs consistently outperform many competing photovoltaic technologies in terms of voltage stability, energy yield, and operational lifetime [94–99,102]. This application-driven perspective has shifted evaluation criteria away from peak outdoor efficiency toward reliability, spectral matching, and long-term energy delivery, effectively redefining what constitutes “high performance” for DSSCs.

Despite these advances, several challenges must still be addressed before DSSCs can achieve widespread commercial adoption. The lack of universally accepted stability benchmarks, particularly for indoor operation, complicates cross-study comparison and technology qualification. Furthermore, while scalable fabrication techniques and monolithic architectures have advanced considerably, consistency of performance at the module level and long-term reliability of interconnections require further investigation. Economic considerations, including materials sustainability and manufacturing cost, must also remain central to future research efforts.

Looking ahead, future DSSC research is expected to converge along three interconnected directions. First, application-specific standardization of performance and stability testing will be essential for establishing credible lifetime metrics relevant to real-world deployment. Second, continued progress in materials sustainability, including cobalt-free redox systems, environmentally benign sensitizers, and recyclable device components, will enhance the environmental compatibility of DSSCs. Third, system-level integration, combining DSSCs with energy storage, power management electronics, and smart control systems, will be critical for enabling fully autonomous and maintenance-free IoT platforms.

In conclusion, DSSCs have evolved into a mature and versatile photovoltaic technology optimized for specific, high-value applications rather than universal power generation. The advances achieved between 2020 and 2025 demonstrate that when stability, scalability, and application relevance are prioritized alongside efficiency, DSSCs can deliver compelling and reliable performance in domains where conventional photovoltaics are less effective. Continued interdisciplinary research, guided by realistic deployment scenarios and system-level thinking, will determine the extent to which DSSCs transition from a specialized laboratory technology to a widely adopted solution for sustainable, low-power energy harvesting.

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