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Recent Advances in Counter Electrodes for Dye-Sensitized Solar Cells (DSSCs): A Comprehensive Review

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Abstract: Dye-sensitized solar cells (DSSCs) is one of the a promising class of third-generation photovoltaic devices, because of its low production costs, easy methods of fabrication, and transparency. Among the critical components of DSSCs, the counter electrode (CE) plays a cruicial role in facilitating the reduction of the redox electrolyte and completing the electrical circuit. Traditionally, platinum (Pt) has been the material of choice for CEs due to its superior electrocatalytic activity and conductivity. However, its high cost, scarcity, and poor long-term stability in corrosive electrolytes have driven the search for alternative materials. This review presents a comprehensive overview of recent advances in counter electrode materials for DSSCs, focusing on Pt-free alternatives such as carbon-based materials, conducting polymers, transition metal compounds, 2D materials (e.g., MXenes), and metal-organic framework (MOF)-derived structures. Emphasis is placed on their electrochemical performance, structural morphology, fabrication techniques, and compatibility with various electrolytes. Comparative performance analysis is provided to highlight the efficiency and stability trade-offs among different CE materials. Despite substantial progress, challenges such as scalability, long-term operational stability, and integration into flexible/wearable systems remain. Future research is likely to benefit from sustainable synthesis strategies, nano structuring techniques, and artificial intelligence-guided material discovery. This review aims to serve as a roadmap for researchers seeking cost-effective and high-performance CE materials for next-generation DSSCs.

Keywords: *Dye-Sensitized Solar Cells (DSSCs), Counter Electrode, Electrocatalyst, Pt-Free Materials, Conductivity, Charge Transfer, Nanomaterials.*

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I. INTRODUCTION

➢ *Fundamentals of DSSCs: Working Principles and Components*

Dye-sensitized solar cells (DSSCs) are a class of photoelectrochemical systems that convert sunlight into electricity using a photosensitizing dye adsorbed onto a semiconductor, typically titanium dioxide (TiO_2). The basic structure of a DSSC comprises a transparent conducting oxide (TCO) glass substrate coated with a nanocrystalline TiO_2 film, a dye sensitizer, an electrolyte containing a redox couple (commonly I^-/I_3^-), and a counter electrode[1,2]. When sunlight strikes the dye, electrons are excited and injected into the conduction band of TiO_2, traveling through the external circuit and returning to the cell via the counter electrode, where they reduce triiodide to iodide.[2]

➢ *Role and Significance of the Counter Electrode (CE)*

The counter electrode (CE) plays a critical role in the regeneration of the redox mediator and the completion of the circuit. It must exhibit high electrical conductivity, low charge-transfer resistance, excellent catalytic activity for the redox reaction, and good chemical stability in the electrolyte environment[3] [4]. Its performance significantly affects the fill factor (FF) and overall power conversion efficiency (PCE) of the DSSC.

➢ *Historical Background and Traditional Use of Pt in CEs*

Platinum (Pt) has traditionally been used as the CE material due to its outstanding electrocatalytic properties and low overpotential for the I_3^- reduction reaction[5]. The deposition of Pt on fluorine-doped tin oxide (FTO) glass provides a highly effective interface for redox catalysis,

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making it a benchmark for evaluating alternative CE materials.

➢ *Limitations of Conventional Pt-Based Counter Electrodes*

Despite its superior performance, Pt-based counter electrodes suffer from several drawbacks: high cost due to the rarity of Pt, poor electrochemical stability in iodine-based electrolytes, and incompatibility with certain alternative redox couples such as cobalt or sulfide/polysulfide systems [6,7]. Moreover, Pt's catalytic activity can deteriorate over time, affecting the long-term efficiency and stability of DSSCs[8].

➢ *Objective and Scope of the Review*

This review aims to provide a comprehensive analysis of recent advances in counter electrode materials for DSSCs, focusing on Pt-free alternatives that are cost-effective, stable, and efficient. We categorize emerging CE materials into several classes—carbon-based materials, conducting polymers, transition metal compounds, 2D materials, and metal-organic frameworks—highlighting their synthesis methods, electrochemical characteristics, and practical performance. The review also discusses current challenges, fabrication methods, comparative studies, and future prospects to guide material selection and design for next-generation DSSCs. [9]

II. WORKING MECHANISM AND REQUIREMENTS OF COUNTER ELECTRODES

➢ *Electron Transfer Mechanism in DSSCs*

In dye-sensitized solar cells (DSSCs), the counter electrode (CE) plays a vital role in maintaining the continuity of electron flow by catalyzing the reduction of the oxidized redox mediator, typically triiodide (I_3^-), back to iodide (I^-) in the electrolyte[1] . After photoexcitation of the dye and injection of electrons into the conduction band of TiO_2, the electrons pass through the external circuit and reach the CE, where they reduce I_3^- ions. This regeneration process is crucial for sustaining the redox cycle and overall device performance. The electrochemical reaction occurring at the CE surface is:

$$I_3^- + 2e^- \rightleftharpoons 3I^-$$

A rapid and efficient electron transfer at this interface minimizes energy losses and enhances the fill factor (FF) and power conversion efficiency (PCE) of the device[10].

➢ *Key Functions of CEs: Electrocatalysis, Conductivity, and Stability*

An ideal counter electrode must simultaneously fulfill several functional requirements. First, it should possess excellent electrocatalytic activity to accelerate the reduction of I_3^- and maintain a low overpotential [11]. Second, it must ensure high electrical conductivity to facilitate the rapid movement of electrons from the external circuit to the electrolyte. Materials with poor conductivity can bottleneck the current flow, leading to decreased efficiency. Lastly, the CE must exhibit chemical and electrochemical stability in the corrosive iodide/triiodide environment to ensure long-term operation of the DSSC[12] These functional requirements directly influence the selection and engineering of CE materials in modern DSSC research.

➢ *Performance Parameters:*

(Electrocatalytic Activity, Charge Transfer Resistance, Overpotential, Cost) The evaluation of a CE's performance is typically based on several electrochemical and practical parameters. Electrocatalytic activity is often assessed via cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS), with lower charge transfer resistance (Rct) indicating better catalytic behavior[13].A CE with low Rct can facilitate faster redox reactions, reducing the overall series resistance of the cell. Another key parameter is overpotential, the extra voltage required to drive the redox reaction at a practical rate. Low overpotential values are desirable as they reduce energy losses and improve voltage output [14,15].Additionally, the cost and abundance of the CE material are important for the scalability of DSSCs. While platinum remains the benchmark in terms of electrochemical performance, its high price and scarcity limit its large-scale use. Therefore, recent efforts have focused on developing Pt-free alternatives that can offer comparable performance at lower cost [16].

In summary, the counter electrode in DSSCs is not merely a passive component but a central player in determining the device's electrochemical behavior. Innovations in CE materials are guided by the need to optimize these parameters while ensuring durability and economic viability

A. Materials for Counter Electrodes: Recent Innovations

➢ *Platinum and Its Alternatives*

Platinum (Pt) has long been considered the benchmark material for counter electrodes (CEs) in dye-sensitized solar cells (DSSCs) due to its high electrical conductivity and exceptional electrocatalytic activity for the reduction of triiodide (I_3^-) (Papageorgiou et al., 1996). Pt-based electrodes consistently deliver high power conversion efficiencies and low charge-transfer resistance. However, the major demerits of Pt include its high cost, limited earth abundance, and poor chemical durability in iodide/triiodide electrolytes, especially under prolonged illumination[17] [18].

To overcome these limitations, researchers have investigated alloying Pt with cheaper transition metals such as Ni, Co, and Cu to enhance catalytic activity and reduce cost[12]. In addition, surface engineering approaches, including nanoparticle deposition, roughening, and porous film formation, have been explored to increase the electroactive surface area and reduce material usage while maintaining performance[19]

➢ *Carbon-Based Materials*

Carbon-based materials have emerged as promising Pt-free alternatives due to their excellent conductivity, chemical stability, and low cost. Graphene, carbon nanotubes (CNTs),

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carbon black, and activated carbon have been extensively studied for CE applications.[20]. These materials exhibit a high surface area and good catalytic activity towards the I_3^-/I^- redox couple.

The advantages of carbon materials include abundance, thermal and electrochemical stability, and ease of processing[21] However, their catalytic activity is generally lower than that of Pt, which has motivated research into surface modifications and composite fabrication. For example, hybrid CEs combining graphene with metal sulfides or conducting polymers have shown improved performance due to synergistic effects [22] . Similarly, acid treatment and nitrogen doping of CNTs can enhance their electrocatalytic performance. [23]

- *Conducting Polymers*

Conducting polymers, such as poly(3,4-ethylenedioxythiophene) (PEDOT:PSS), polyaniline (PANI), and polypyrrole (PPy), have been studied as cost-effective alternatives due to their facile synthesis and good redox activity [24]. PEDOT, in particular, demonstrates low charge-transfer resistance and compatibility with flexible substrates, making it ideal for wearable DSSCs[25].

To improve mechanical integrity and catalytic efficiency, composite materials combining conducting polymers with carbon nanostructures or metal oxides have been developed. For example, PANI–graphene and PPy–TiO_2 composites exhibit enhanced conductivity and surface area, promoting better redox kinetics[26].

- *Transition Metal Compounds*

A wide variety of transition metal compounds have been explored, including metal sulfides (e.g., MoS_2, CoS_2), selenides, oxides (e.g., NiO, Co_3O_4), carbides, and nitrides, owing to their tunable electronic properties and low cost[27]. These materials often provide excellent electrocatalytic activity through fast charge transport and multiple oxidation states.

Bimetallic or hybrid CEs, such as Co–Ni sulfides and Fe–Mo carbides, have shown superior performance due to synergistic effects that improve electron mobility and catalytic efficiency[25]. Additionally, nanostructuring techniques such as hydrothermal synthesis and electrodeposition have enabled the development of porous, high-surface-area morphologies, further enhancing redox activity [26].

- *2D Materials and MXenes*

Two-dimensional (2D) materials, particularly MXenes (e.g., Ti_3C_2Tx), have recently gained attention as counter electrode candidates due to their metallic conductivity, tunable surface chemistry, and layered structure[27]. These materials offer a large number of exposed active sites and excellent electron transfer characteristics.

However, challenges such as oxidation susceptibility, scalability, and electrolyte compatibility remain significant barriers to widespread implementation[28]. Efforts to overcome these issues include hybridization with graphene or metal compounds and surface functionalization to improve stability and performance in iodide-based and cobalt-based electrolytes [29].

- *Perovskite-Based and MOF-Derived Materials*

Though typically known for their light-harvesting properties, perovskite-based materials have been explored for counter electrodes due to their electrical conductivity and catalytic activity. For example, Sr-doped $LaMnO_3$ has been reported to show reasonable performance in DSSCs [30,31]

Another exciting development is the use of metal-organic frameworks (MOFs) and their carbonized derivatives. MOFs offer a high degree of porosity and tunable chemistry, making them attractive as templates for porous carbon and metal oxide CEs. Upon pyrolysis, MOFs can yield carbon–metal nanocomposites with excellent catalytic behavior[32]. These materials combine high surface area with conductivity and can be engineered for compatibility with multiple redox couples.

III. COMPARATIVE PERFORMANCE ANALYSIS

- *Efficiency Comparison of Different CE Materials in DSSCs*

The efficiency of dye-sensitized solar cells (DSSCs) is closely linked to the properties of the counter electrode (CE). Platinum-based CEs continue to deliver the highest power conversion efficiencies (PCEs), often exceeding 9–11% under standard illumination with iodide/triiodide electrolytes (Papageorgiou et al., 1996). However, significant progress has been made with Pt-free materials. For instance, graphene-based composites have achieved PCEs of around 8.5%, while transition metal sulfides like CoS and MoS_2 have shown comparable results up to 8.8% under optimized conditions[15,33].

Conducting polymer-based electrodes such as PEDOT:PSS have also delivered promising efficiencies of 7–9%, especially when hybridized with carbon materials to enhance conductivity and catalytic sites [34] [35]. Recently, MXene and MOF-derived CEs have reached efficiencies above 9% with improved electrolyte compatibility and structural stability[36,36,37].

- *Electrochemical Parameters: Rct, Voc, FF*

The charge transfer resistance (Rct) at the CE/electrolyte interface is a critical metric for assessing catalytic performance. Platinum typically exhibits Rct values below 5 $\Omega \cdot cm^2$, which enables fast reduction of I_3^- [15,38]. Carbon materials generally show higher Rct (10–30 $\Omega \cdot cm^2$), though surface doping and nanostructuring can reduce this significantly[39]. PEDOT:PSS-based electrodes typically have moderate Rct values (~8–15 $\Omega \cdot cm^2$), whereas optimized metal sulfides can reach as low as 6 $\Omega \cdot cm^2$ [40].

In terms of open-circuit voltage (VOC) and fill factor (FF), most alternative materials perform comparably with Pt, often achieving VOC between 0.70–0.78 V and FF between

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60–75%, depending on the redox couple and dye used [45][12,41,42]

➢ *Stability and Degradation Under Operation*

Operational stability is another decisive factor in the selection of CE materials. While Pt demonstrates good initial stability, it tends to degrade in iodide electrolytes over extended exposure to light and heat, forming PtI_4 and other corrosive by-products[6]. In contrast, carbon materials and conducting polymers show higher chemical inertness and long-term operational stability, although some suffer from structural degradation in humid environments[18].Metal sulfides and MOF-derived electrodes exhibit variable stability depending on composition and morphology. Recent studies show that MXene-based Ces maintain over 90% of their efficiency after 1000 hours of light soaking[43], marking a significant step toward commercialization.

➢ *Tabulated Summary of Recent Studies*

Table 1 Tabulated Summary of Recent Studies

Material Type	CE Material	Electrolyte Type	PCE (%)	Rct (Ω·cm²)	Voc (V)	FF (%)	Reference
Noble Metal	Pt	I^-/I_3^-	11.2	~2	0.78	74	[44]
Carbon-Based	N-doped Graphene	I^-/I_3^-	8.5	12	0.75	71	[20,45]
Conducting Polymer	PEDOT:PSS	I^-/I_3^-	8.1	10	0.76	70	[12,46]
Metal Sulfide	MoS_2	I^-/I_3^-	8.8	6	0.77	73	[24,24]
Bimetallic Sulfide	CoNiS	I^-/I_3^-	9.0	5.5	0.76	72	[47]
2D Material	Ti_3C_2 Mxene	$Co(bpy)_3^{3+/2+}$	9.2	4.8	0.78	75	[57][48,49]
MOF-Derived	ZIF-67-derived Co@C	I^-/I_3^-	9.1	5.2	0.77	74	[50] [51,52]

A. Fabrication Techniques

➢ *Doctor Blade, Screen Printing, Electrodeposition, Hydrothermal Synthesis, Spray Pyrolysis*

Various fabrication techniques have been developed to deposit counter electrode (CE) materials onto substrates in dye-sensitized solar cells (DSSCs), each offering distinct advantages in terms of cost, uniformity, scalability, and material compatibility. The doctor blade method is one of the most straightforward and low-cost techniques, often used for carbon-based materials and conducting polymers. It involves spreading a slurry of active material over a substrate using a flat blade, followed by drying and sintering [12] [53]. This method enables uniform film thickness and is suitable for large-scale applications.

Screen printing is widely used in industrial settings for fabricating platinum and composite electrodes. It offers precise control over layer thickness and geometry and is compatible with roll-to-roll processing[54] However, it typically requires high-temperature sintering, which limits the choice of substrates to rigid materials like FTO glass.

Electrodeposition offers a controllable and efficient means of depositing metallic and polymeric CEs. It allows for conformal coatings and fine-tuning of material morphology by adjusting parameters like voltage, current density, and electrolyte composition[12] This technique is particularly useful for preparing nanostructured metal sulfides and alloys.

Hydrothermal synthesis is often employed to fabricate crystalline nanomaterials like MoS_2 and CoS_2 directly onto conductive substrates. The advantage lies in its ability to form well-defined morphologies (e.g., nanosheets, nanorods) with enhanced surface area and catalytic activity[12].

Spray pyrolysis, another scalable method, involves spraying a precursor solution onto a heated substrate to form thin films through thermal decomposition. It is especially suited for large-area applications and can be used to deposit metal oxides, selenides, or carbon composites with fine control over stoichiometry. [55]

➢ *Influence of Morphology and Structure on Performance*

The morphology and nanostructure of CE materials significantly influence their electrocatalytic performance. Porous or nanostructured electrodes offer larger surface areas, providing more active sites for redox reactions and promoting faster charge transfer kinetics[56]. For example, vertically aligned MoS_2 nanosheets fabricated via hydrothermal methods have shown better performance than their bulk counterparts due to improved electrolyte diffusion and electron transport [24].

Similarly, graphene films with wrinkled or mesoporous textures prepared through chemical reduction or spray techniques show enhanced redox activity and lower charge-transfer resistance compared to flat films [57]. In the case of conducting polymers, nanofiber or nanotube morphologies offer improved charge mobility and interfacial contact with the electrolyte . Thus, the choice of synthesis technique is tightly linked to achieving an optimized microstructure.[58]

➢ *Scalable and Cost-Effective Methods for Commercialization*

For commercial-scale production of DSSCs, the scalability and cost-effectiveness of CE fabrication methods are critical. Techniques such as screen printing and spray pyrolysis are already being integrated into large-area module manufacturing due to their compatibility with roll-to-roll and continuous processing [59,60]

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Moreover, low-temperature deposition methods such as electrodeposition and solution casting are attracting interest for flexible and wearable DSSC applications, where polymer or plastic substrates are used. These methods reduce energy consumption during processing and are often compatible with eco-friendly, Pt-free materials like carbon and polymers.[61–63]

The integration of automated printing technologies and scalable hydrothermal reactors is also being explored for producing structured CE films on a commercial scale. A key future challenge lies in optimizing material formulations and deposition conditions for high-throughput, uniform, and defect-free electrode fabrication without compromising efficiency.[64,65]

IV. CHALLENGES AND LIMITATIONS

➢ *Material Scalability and Cost*

One of the primary challenges in developing counter electrodes (CEs) for dye-sensitized solar cells (DSSCs) is achieving material scalability without compromising performance. While platinum remains the gold standard due to its low charge-transfer resistance and high catalytic activity, its prohibitive cost and scarcity restrict its practical use in large-scale or commercial applications [66]. Alternative materials such as graphene, carbon black, and transition metal compounds have demonstrated promising catalytic properties, but the scaling of synthesis processes like chemical vapor deposition (for graphene) or hydrothermal synthesis (for metal sulfides) poses technical and economic constraints. [64,67,68]Additionally, maintaining uniform morphology and performance at scale remains a significant hurdle for many lab-scale materials.

➢ *Compatibility with Iodine-Free or Solid-State Electrolytes*

While iodide/triiodide redox couples are widely used in DSSCs, they present issues like volatility, leakage, and corrosion, prompting a shift toward iodine-free or solid-state electrolytes. However, many CE materials—especially carbon-based or polymer-based ones—are optimized for the I^-/I_3^- system and show reduced catalytic activity when paired with alternative redox couples such as $Co(bpy)_3^{3+/2+}$ or ferrocene[6]. The interfacial charge-transfer kinetics and energy alignment vary significantly with different electrolytes, leading to mismatches in redox potential and lower power conversion efficiencies[62]. Designing CE materials with broad-spectrum catalytic capability that perform efficiently across a range of electrolytes remains an unsolved challenge in the field.

➢ *Long-Term Stability in Outdoor Conditions*

Long-term environmental and photochemical stability is essential for the commercial viability of DSSCs, especially for outdoor and flexible photovoltaic applications. Platinum electrodes, though highly efficient, suffer from gradual degradation in iodide-containing electrolytes, forming unstable PtI_4 complexes that reduce efficiency over time[44].Similarly, conducting polymers like polyaniline and PEDOT:PSS may undergo structural degradation upon prolonged exposure to UV light, oxygen, and humidity [12,22]. Transition metal compounds, while more stable in many cases, may still experience oxidation, dissolution, or aggregation, particularly under fluctuating temperature and moisture conditions[5,60]. Strategies such as encapsulation, surface passivation, and robust composite formulations are actively being researched to mitigate these stability issues.

➢ *Toxicity and Environmental Concerns*

Another important consideration is the environmental impact and toxicity of materials used in CEs. Although many Pt-free materials are promoted as eco-friendly, some transition metal compounds (e.g., CoS_2, NiS) and synthesis methods involve hazardous precursors, solvents, or byproducts. Improper disposal of such materials could raise environmental and health concerns. Additionally, the energy consumption and emissions associated with high-temperature or vacuum-based fabrication methods challenge the goal of sustainable solar technology[57]. Therefore, future research must prioritize green chemistry approaches, low-energy synthesis routes, and life-cycle assessments of CE materials to ensure environmental compliance alongside performance.

V. FUTURE PERSPECTIVES AND EMERGING DIRECTIONS

➢ *Integration with Flexible and Wearable DSSCs*

With the growing demand for portable and wearable energy-harvesting devices, the integration of counter electrodes (CEs) into flexible DSSCs represents a significant advancement in the field. Traditional CEs, especially those fabricated on rigid substrates like fluorine-doped tin oxide (FTO) glass, are incompatible with flexible electronics. Recent research focuses on developing CE materials that retain high electrocatalytic activity while being mechanically bendable and lightweight. Materials such as PEDOT:PSS, carbon nanotubes (CNTs), and graphene films have shown promise due to their inherent flexibility and conductivity[12,22] .Moreover, low-temperature fabrication methods like screen printing and electrodeposition on plastic substrates are being optimized to support wearable DSSC modules without compromising performance[24].

➢ *Sustainable and Green Synthesis of CEs*

Environmental concerns and energy-intensive fabrication techniques have sparked interest in the green synthesis of CE materials. Conventional synthesis often involves toxic solvents, high energy consumption, and non-biodegradable reagents. In contrast, green methods such as biotemplating, sol–gel processing, plant extract-mediated reduction, and microwave-assisted synthesis offer eco-friendly routes to produce nanostructured electrocatalysts[65]. These approaches aim to minimize environmental footprints while maintaining the structural and electrochemical quality of CE materials. For instance, carbonaceous materials derived from biomass or agricultural waste have been successfully used as sustainable alternatives to commercial carbon black in DSSCs[28,47]. The push for non-toxic, recyclable, and low-energy CE fabrication aligns with broader global goals for clean energy technologies.

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➢ *AI/ML-Assisted Material Screening*

Artificial Intelligence (AI) and Machine Learning (ML) are emerging as powerful tools for accelerating material discovery and optimization in DSSC research. By analyzing large datasets of experimental results and material properties, ML algorithms can predict the performance of new CE candidates, optimize synthesis conditions, and design materials with targeted characteristics[69]. Recent models have been trained to forecast electrocatalytic efficiency, charge transfer resistance, and long-term stability of CE composites using structural and compositional data[70]. This data-driven approach significantly reduces experimental trial-and-error and offers a systematic strategy for high-throughput material screening, potentially leading to breakthroughs in CE design.

➢ *Role in Tandem Solar Systems and Hybrid Devices*

Another promising direction is the integration of DSSCs into tandem or hybrid solar systems, where CEs must be tailored to support varying redox mediators and interface with other photovoltaic technologies such as perovskite or organic solar cells. In tandem configurations, DSSCs can be stacked to enhance light absorption and overall efficiency, with CEs engineered to handle multiple redox couples or transparent electrodes[33] .Hybrid devices combining DSSCs with energy storage units—such as supercapacitors or lithium-ion batteries—also demand multifunctional CEs that serve dual roles as electrocatalysts and charge collectors[57] .The development of such multifunctional, adaptive counter electrodes will be critical for the evolution of smart solar technologies.

VI. CONCLUSION

This review highlights the critical role of counter electrodes (CEs) in dye-sensitized solar cells (DSSCs) and summarizes the advancements made in recent years to replace conventional platinum with cost-effective, efficient, and scalable alternatives. While Pt-based CEs continue to serve as the performance benchmark due to their outstanding electrocatalytic activity and low charge transfer resistance, their high cost, limited abundance, and instability in iodide-based electrolytes limit their commercial viability.

Among Pt-free alternatives, carbon-based materials (e.g., graphene, CNTs) offer excellent stability and conductivity, making them attractive for both rigid and flexible DSSC platforms. Conducting polymers like PEDOT:PSS and polyaniline provide lightweight, low-cost solutions with good catalytic activity, especially when used in composites. Transition metal compounds such as sulfides and oxides have shown remarkable electrocatalytic performance, rivaling or even exceeding that of Pt in some cases. 2D materials like MXenes and MOF-derived composites represent the frontier of CE development, combining high surface area, tunability, and compatibility with next-generation redox couples.

Looking ahead, the most promising materials for future applications are those that balance high efficiency, chemical stability, low cost, and ease of large-scale fabrication. Hybrid materials, green synthesis routes, and flexible substrates are expected to dominate future research. Additionally, integrating AI/ML-based material discovery, improving compatibility with solid-state or cobalt-based electrolytes, and exploring multifunctional CEs for tandem or hybrid energy devices will be vital for the evolution of DSSCs from laboratory concepts to commercial reality.

In conclusion, while significant progress has been made, continued interdisciplinary research is essential to develop scalable, eco-friendly, and high-performance counter electrodes that can accelerate the transition of DSSC technology toward real-world applications.

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