



OPEN Highly transparent dye-sensitized solar cells with UV-absorbing fluorene dyes and tetramethylthiourea electrolytes

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This study demonstrates the development of highly transparent dye-sensitized solar cells (DSSCs) through the strategic combination of UV-absorbing, metal-free dyes and a novel non-iodine-based electrolyte system. We systematically investigated four UV-absorbing dyes – FCA, FQA, FPCN, and FFCN – with the FPCN emerging as the optimal candidate, demonstrating superior visible light transmittance while maintaining effective power conversion efficiency (PCE). When coupled with a tetramethylthiourea/tetramethyl formamidine disulfide (TMTU/TMFDS²⁺) electrolyte system, the FPCN-sensitized solar cells achieved remarkable visible light transmittance (VLT) exceeding 68% alongside a PCE of 1.58%, surpassing the performance metrics of conventional I^-/I_3^- systems. The implementation of the non-iodine electrolyte significantly enhanced the optical properties, as quantified by improved chromaticity coordinates and color rendering index (CRI) values, establishing these cells as viable candidates for transparent solar panel applications. Our findings demonstrate that the synergistic combination of UV-absorbing dyes and non-iodine electrolytes enables the development of highly transparent, aesthetically appealing DSSCs.

Keywords Dye-sensitized solar cells, UV, Visible light transparency, Chromaticity, Color rendering

In photovoltaic (PV) research, the predominant goal is to approach the Shockley-Queisser (S-Q) limit, typically via opaque technologies. In contrast, visibly transparent solar cells offer a revolutionary alternative by integrating PV elements into architectural designs without sacrificing aesthetics^{1–5}. Although transparent PV technologies (TPVs) have inherently lower performance than conventional opaque counterparts, they enable discrete integration into glass windows and curtain walls, simultaneously providing visual transparency and energy harvesting capabilities. A primary challenge in developing PV windows lies in optimizing balance between visible light transmittance (VLT) and power conversion efficiency (PCE).

To achieve optimal VLT and PCE balance, it is crucial to selectively harvest the invisible parts of the solar spectrum, specifically ultraviolet (UV) and near-infrared (NIR) regions that lie outside human visual response. This approach has led to the development of wavelength-selective TPVs with theoretical PCE potential of 20.6%, while maintaining 100% average visible transmittance (AVT)⁶. Conventional inorganic semiconductors present challenges in achieving high transparency due to their inherent absorption of all photons exceeding their bandgap energy, resulting in non-selective photon absorption. In contrast, organic molecules offer distinct advantages through their discrete orbital energy levels, enabling precise absorption characteristic tuning. Molecular design modifications, such as extending conjugation lengths or introducing specific functional groups, enable precise tuning of absorption properties, facilitating efficient and transparent TPVs.

Dye-sensitized solar cells (DSSCs) particularly benefit from this molecular flexibility, as their photosensitizers can be finely engineered for wavelength-selective absorption^{7–10}. The use of metal-free organic dyes is especially advantageous due to their high molar extinction coefficients, ease of molecular customization, cost-effective synthesis, and scalability^{11–13}. Notable progress includes the development of UV- or NIR-selective dyes that

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effectively eliminate noticeable coloration to human eyes. For example, Han *et al.* introduced the squaraine dye HSQ5, achieving a 2.30% PCE and 67% transmittance at 540 nm, whereas Y1/HSQ5 co-sensitized cells demonstrated a 3.66% PCE with a VLT of 60.3%¹⁴. Similarly, Sauvage *et al.* achieved a PCE of 2.5% and an AVT of 70% using the heptamethine cyanine dye VG20-16 paired with the I^-/I_3^- redox couples⁷. While NIR-selective dyes such as squaraines, and cyanines have seen significant advancement^{15–19}, the exploration of UV-absorbing dyes has been comparatively limited. Nevertheless, theoretical calculations suggest achievable efficiencies up to 7% in the UV region, despite lower solar photon flux²⁰. Our recent studies have explored the potential of UV-absorbing dyes, expanding DSSC capabilities to achieve PCEs ranging from 0.65 to 2.70% with corresponding VLTs from 63.6 to 58.2%^{21,22}.

The electrolyte is another critical component affecting DSSC transparency. Traditionally, the I^-/I_3^- redox couple has been used extensively due to its slow recombination rates but results in a yellowish coloration that could detract from aesthetic qualities^{23,24}. Emerging organic sulfur-based electrolytes, such as sulfurothioate-based formulations, have shown promise in replacing iodine-based systems, providing enhanced transparency and non-corrosive properties²⁵. The exploration extends to other sulfur-based electrolytes like sulfide/polysulfide (S^{2-}/S_x^{2-}), tetramethyl formaminium disulfide/tetramethyl thiourea (TMFDS²⁺/TMTU), and 5-mercato-1-methyltetrazole and its disulfide dimer (T^-/T_2), which enhance transparency and mitigate corrosive effects^{26–30}. In our ongoing research, we aim to enhance the visible light transmission and color rendering properties of through non-iodine redox couples, specifically TMFDS²⁺/TMTU, paired with our UV-harvesting dyes (FPCN, FFCN, FCA, and FQA). These UV-selective and visibly transparent DSSCs have achieved VLT exceeding 70%, marking significant progress toward practical building-integrated photovoltaics (BIPV) applications. We also continue to investigate the color perception and rendering properties of transmitted light through these DSSCs, demonstrating their potential for widespread adoption.

Experimental Materials

Tetramethylthiourea (TMTU, 98%) was procured from TCI. Nitrosonium tetrafluoroborate (NOBF₄, 98%) and nitrosonium hexafluorophosphate (NOPF₆, 98%) were purchased from Thermo Fisher Scientific Korea Ltd. High-purity solvents such as acetonitrile (MeCN, 99.999% trace metal basis), diethyl ether (Et₂O, 99%), and dimethylformamide (DMF, 99.8%, anhydrous) were obtained from Daehan. UV-absorbing dyes were synthesized following procedures outlined in previous literature^{21,22}. Fluorine-doped tin oxide (FTO) glass substrates (TEC 8, sheet resistance = 10 Ω/sq) were sourced from Pilkington. Nanocrystalline TiO₂ paste (Ti-Nanoxide T/SP, Solaronix) and the iodide/triiodide electrolyte (Iodolyte AN-50) were provided by Solaronix (Switzerland).

Preparation of electrolytes

Tetramethyl formaminidinium disulfide tetrafluoroborate (TMFDS(BF₄)₂) and tetramethyl formaminidinium disulfide hexafluorophosphate (TMFDS(PF₆)₂) were synthesized through chemical oxidation reaction. Initially, 1.65 g TMTU was dissolved in 50 mL of MeCN. A 1.1 molar equivalents of NOBF₄ or NOPF₆ were added dropwise under an N₂ atmosphere. The mixture was stirred for 4 h, after which the solvent was evaporated to obtain a solid product. This solid was redissolved in MeCN, stirred for 10 min before precipitation was induced using Et₂O to remove any unreacted TMTU. The precipitates were filtered and dried at 40 °C under vacuum overnight. The molecular structures and synthesis scheme are shown in **Figure S1**. Different TMTU/TMFDS²⁺ electrolytes were prepared by dissolving TMTU and its oxidized derivatives (TMFDS(BF₄)₂ or TMFDS(PF₆)₂) in MeCN under constant stirring. A commercial iodine-based electrolyte (Iodolyte AN-50, Solaronix) was used as a reference for comparison.

DSSC fabrication

DSSCs were fabricated using TiO₂ photoanodes sensitized with UV-absorbing dyes (FPCN, FFCN, FCA, or FQA), a platinum counter electrode, and the TMTU/TMFDS²⁺ electrolyte. The FTO glass substrates were sequentially cleaned via ultrasonic bathing in acetone, isopropanol, and deionized water (15 min each), baked at 120 °C for 10 min, and treated with O₂ plasma (100 W) for 10 min. The substrates were further immersed into an aqueous TiCl₄ solution (40 mM) at 75 °C for 30 min, rinsed thoroughly with deionized water, and dried under a stream of N₂ gas. A nanocrystalline TiO₂ paste was screen-printed onto the substrates and calcinated at 300 °C for 30 min, followed by at 575 °C for 1 h in a muffle furnace. The resultant transparent TiO₂ film was an active area of 0.25 cm² and a thickness of 5 μm. The same TiCl₄ treatment was applied to the calcined film, followed by additional heating at 500 °C for 30 min. After exposure to O₂ plasma (100 W) for 10 min, the photoanode was sensitized by immersion in a 0.7 mM dye solution (FPCN, FFCN, FCA or FQA) for 2 h^{21,22}. The Pt counter electrode was prepared by spin-coating a 10 mM chloroplatinic acid/ethylene glycol solution onto FTO glass and sintering it at 190 °C for 10 h in a muffle furnace. The dye-sensitized photoanode and Pt counter electrode were assembled using a 25 μm-thick thermoplastic film (SurlynTM, Solaronix) and sealed at 125 °C. The electrolyte was introduced through pre-drilled holes on the counter electrode side, and these holes were sealed with a 60 μm-thick thermoplastic film and a cover glass.

Characterization and photovoltaic performance

UV-Vis absorbance and transmittance spectra were recorded using a UV-2600 spectrophotometer (Shimadzu, Japan). Cyclic voltammetry (CV) measurements were conducted at a scan rate of 100 mV/s using a CompactStat.e potentiostat/galvanostat (Ivium Tech., Netherlands) with a three-electrode cell (Pt disc working electrode, Pt wire counter electrode, and Ag/Ag⁺ reference electrode). Ferrocene/ferrocenium (Fc/Fc⁺) was used as an external reference. Before measurements, solutions were purged with nitrogen for 15 min. Ionic conductivity of the electrolytes was measured using AC complex impedance in an FTO/electrolyte/FTO sandwich configuration.

Measurements involved a sinusoidal potential perturbation with a 10-mV amplitude, frequency sweeping from 1 MHz to 0.1 Hz at zero bias potential, and data were analyzed using a ZView[®] software (Scribner Associates Inc.). Photovoltaic performance was evaluated under AM 1.5G one-sun illumination (100 mW/cm²) using a solar cell I-V measurement system (K3000 LAB, McScience). Incident photon-to-current conversion efficiency (IPCE) was assessed using a K3100 system (McScience). At least five DSSC devices were fabricated and evaluated for each dye under optimized conditions.

Color analysis

The color properties of light transmitted through the DSSCs were calculated based on the transmitted light spectrum, $S(\lambda) = T(\lambda) \cdot I(\lambda)$ using the AM 1.5G light source spectrum, $I(\lambda)$, and the transmittance spectrum, $T(\lambda)$. Chromaticity was analyzed using the CIE 1931 (x, y) coordinates³¹. For better clarity of color, we calculated correlated color temperature (CCT) and Duv, widely recognized for describing the color appearance of light sources³². Positive Duv indicates a greenish shift, while negative Duv indicates a purplish shift. Additionally, we calculated the Color Rendering Index (CRI), which includes both general CRI (R_a) and special CRI (R_9 – R_{15}) to evaluate the accuracy color reproduction, particularly in more saturated hues^{33,34}.

Results and discussion

Figure 1a illustrates the molecular structures of the UV-absorbing dyes employed in this study (FCA, FQA, FPCN, and FFCN). FCA and FQA are fluorene-based dyes that differ in their anchoring groups: a cyano acetic acid for FCA and 2-methyl-quinoline-6-carboxylic acid for FQA²². On the other hand, FPCN and FFCN are donor- π -bridge-acceptor (D- π -A) dyes featuring planar fluorene as the electron donor, π -conjugated bridges (benzene and furan, respectively), and cyanoacrylic acid as the electron acceptor²¹. The inclusion of a planar fluorene moiety enhances light harvesting abilities in the short wavelength region, various anchoring groups facilitate efficient adsorption onto the TiO₂ surface, promoting electron injection.

Figure 1b shows the experimental UV-Vis absorbance spectra of the dyes dissolved in DMF solution. Each dye exhibits distinct absorption bands within the UVA (315–400 nm) and violet light (380–435 nm) ranges. This absorption pattern is characteristic of intramolecular charge transfer (ICT) transitions, which are modulated by the donor-acceptor strengths and the extent of electronic coupling between their orbitals. The molar extinction coefficients for FCA, FQA, FPCN, and FFCN were measured as 31,510, 34,820, 36,200, and 35,400 M^{−1} cm^{−1}, respectively, with corresponding optical bandgaps of 3.29, 2.97, 3.14, and 2.79 eV. Table S1 summarizes

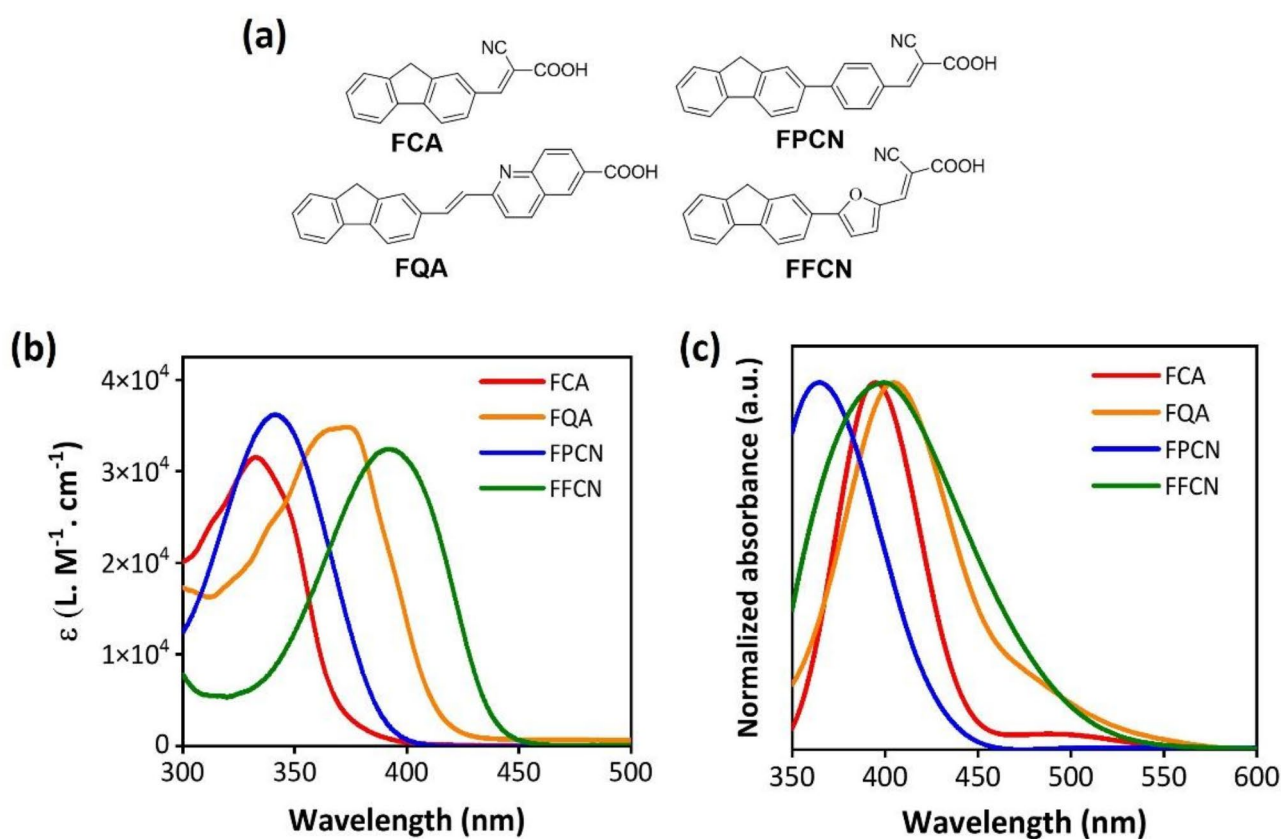


Fig. 1. (a) Molecular structures of UV-absorbing dyes used in this study: FCA, FQA, FPCN, and FFCN, (b) UV-Vis absorbance spectra of the dyes in DMF solution and (c) normalized UV-Vis absorbance spectra of dyes adsorbed onto TiO₂ films.

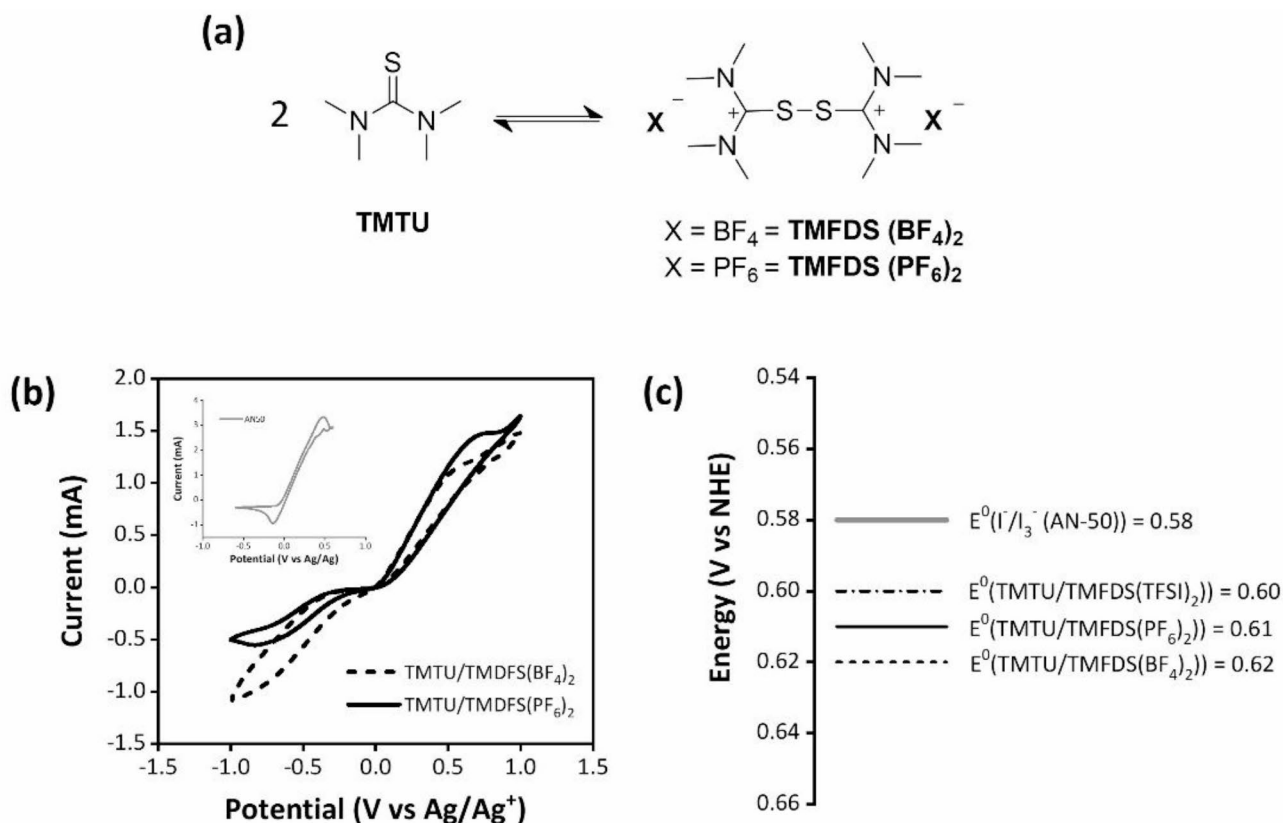


Fig. 2. (a) Schematic of the chemical structure of TMTU and TMFDS(X)₂, where X is either BF_4^- or PF_6^- , (b) CV profiles TMTU/TMFDS(BF₄)₂ and TMTU/TMFDS(PF₆)₂ electrolytes, and (c) redox potentials of TMTU/TMFDS²⁺ compared to the I^-/I_3^- redox couple.

X (anion)	TMTU Concentration (M)	Ratio (TMTU: TMFDS(X) ₂)			
		1:1	2:1	3:1	5:1
BF_4^-	0.05	4.91×10^{-6}	6.64×10^{-6}	5.90×10^{-6}	4.70×10^{-6}
	0.1	5.50×10^{-6}	7.23×10^{-6}	6.19×10^{-6}	6.11×10^{-6}
	0.3	7.81×10^{-6}	8.05×10^{-6}	9.48×10^{-6}	9.11×10^{-6}
	0.5	1.21×10^{-5}	1.26×10^{-5}	1.21×10^{-5}	1.02×10^{-5}
PF_6^-	0.3	-	-	5.21×10^{-6}	4.83×10^{-6}

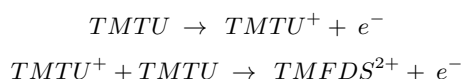
Table 1. Comparative ionic conductivity (S/cm) of various TMTU/TMFDS²⁺ electrolytes. Null data: low solubility.

photophysical and electrochemical properties of the UV-absorbing dyes. Figure 1c presents the normalized UV-Vis absorbance spectra of the dyes adsorbed on nanocrystalline TiO₂ films. The spectra reveal a red shift relative to those in solution, which likely arises from the altered microenvironment of the dye molecules when adsorbed on TiO₂. This shift may result from intermolecular interactions between neighboring dye molecules or dye-TiO₂ surface interaction. Notably, FPCN-grafted TiO₂ films show the least absorption in the visible light range, suggesting that FPCN-sensitized solar cells would exhibit superior transparency compared to the others.

Figure 2a illustrates the molecular structures of TMTU and TMFDS(X)₂, where X represents either BF_4^- or PF_6^- . The TMFDS²⁺ molecule is composed of two TMTU⁺ units connected via an S-S bond. Ionic conductivity (σ), a crucial factor for determining the photovoltaic efficiency of DSSCs, depends on both ion concentration and mobility. This property was assessed using AC impedance spectroscopy. Table 1 presents the ionic conductivities of various electrolytes as a function of TMTU concentration, stoichiometric ratio of TMTU to TMFDS²⁺, and anion type. As seen in the table, ionic conductivity increases with increasing TMTU concentration. However, PF_6^- exhibited lower solubility when combined with TMFDS²⁺, likely due to its larger ionic radius (0.254 nm) compared to BF_4^- (0.229 nm). For DSSC performance optimization, an electrolyte composition of 0.3 M TMTU with a 3:1 ratio of TMTU:TMFDS²⁺ in MeCN was selected. This choice balanced ion transport efficiency

with electrolyte stability, mitigating potential issues related to solubility and viscosity that can arise at higher concentrations.

Figure 2b shows cyclic voltammetry (CV) curves for an electrolyte containing 0.3 M TMTU and 0.1 M TMFDS(BF₄)₂ or 0.1 M TMFDS(PF₆)₂ in MeCN. The CV traces, recorded at a scan rate of 100 mV/s, feature distinct oxidation and reduction peaks. The oxidation peak corresponds to the conversion of TMTU to TMTU⁺, leading to TMFDS²⁺ formation, while the reduction peak reflects the reverse reaction. The redox processes involved can be described by the following reactions²⁶:



The redox potentials of the TMTU/TMFDS(BF₄)₂ and TMTU/TMFDS(PF₆)₂ were measured as −0.01 V and −0.02 V, versus ferrocene/ferrocenium (Fc/Fc⁺) reference, corresponding to 0.62 V and 0.61 V) versus NHE, assuming Fc/Fc⁺ is 0.63 V versus NHE³⁵. Figure 2c demonstrates that the redox potential of the TMTU/TMFDS²⁺ couple is more positive than that of the conventional I[−]/I₃[−] system (AN-50). The increased redox potential is anticipated to enhance the open-circuit photovoltage of DSSCs employing the TMTU/TMFDS²⁺ redox couple compared to those utilizing the I[−]/I₃[−] system.

Figure 3a shows the UV-Vis absorbance spectra of 0.01 mM TMTU, TMFDS(BF₄)₂, and TMFDS(PF₆)₂ in MeCN. As expected, TMTU exhibits no absorbance in the visible region, while TMFDS²⁺ displays slight

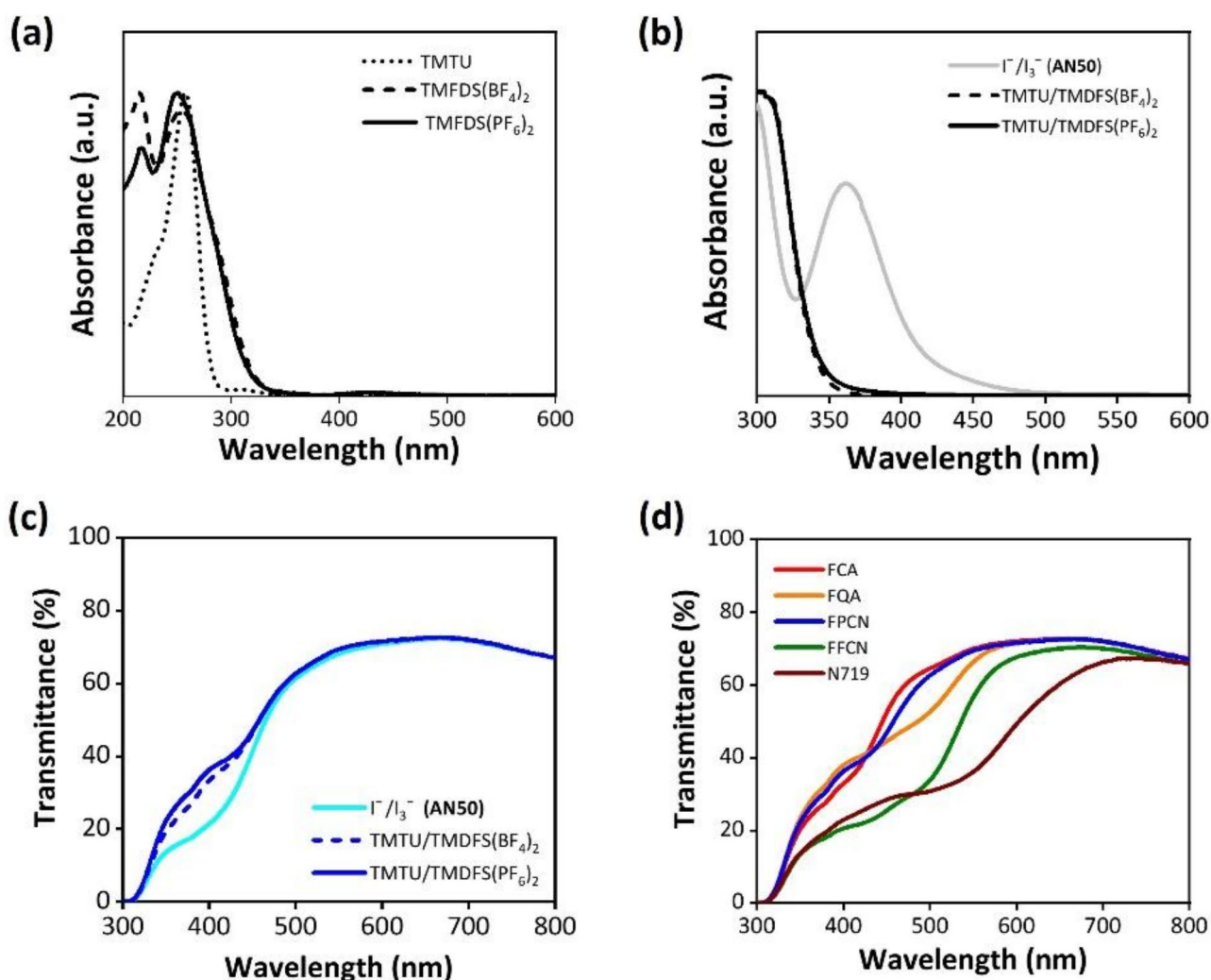


Fig. 3. (a) UV-Vis absorbance spectra of 0.01 mM TMTU, TMFDS(BF₄)₂, and TMFDS(PF₆)₂ in MeCN solution, (b) UV-Vis absorbance spectra of FTO glass/electrolyte/FTO glass configurations using I₃[−]/I[−] (AN-50) and TMTU/TMFDS²⁺ electrolytes, (c) Transmission spectra of FPCN-sensitized solar cells using different electrolytes, and (d) Transmission spectra of DSSCs with various UV-absorbing dyes and TMTU/TMFDS(PF₆)₂.

absorption extending into the UVA region. This minimal absorbance by the TMTU/TMFDS²⁺ redox couple makes it an ideal choice for applications requiring high transparency in the visible range. Figure 3b compares the UV-Vis absorbance spectra of FTO glass/electrolyte/FTO glass configurations for the conventional I^-/I_3^- electrolyte and the TMTU/TMFDS²⁺ system. The I^-/I_3^- electrolyte shows distinct absorption peaks at 208 nm and 246 nm (I^-) and additional peaks at 291 and 361 nm (I_3^-), with a long absorption tail into the visible blue region (~500 nm), which is particularly undesirable for transparent photovoltaic (TPV) applications³⁶. In contrast, the TMTU/TMFDS²⁺ electrolyte exhibits minimal absorption in the visible region, providing a significant advantage for maximizing light utilization, particularly when used with UV-harvesting dyes, as it minimizes spectral overlap in the UV region.

When assessing the aesthetics and visible light transparency of solar cells, two crucial metrics to consider are the average optical transmittance (T_{avg}) and the visible light transmittance (τ_{vis}). T_{avg} is defined as the average transmittance of light through the solar cell across a specified wavelength range. It provides a comprehensive understanding of the overall light transmittance properties of the device, expressed as follows:

$$T_{avg} = \frac{1}{\lambda_{max} - \lambda_{min}} \int_{\lambda_{min}}^{\lambda_{max}} T(\lambda) d\lambda$$

where $T(\lambda)$ is the spectral transmittance at wavelength λ , and λ_{max} and λ_{min} are the maximum and minimum wavelengths of the specified range, respectively. In contrast, τ_{vis} quantifies the percentage of natural light that can pass through the solar cell, specifically weighted according to the sensitivity of the human eye. It can be calculated based on the ISO standard method (ISO 9050:2003) as follows³⁷:

$$\tau_{vis} = \frac{\sum_{380\text{ nm}}^{780\text{ nm}} T(\lambda) D65(\lambda) V(\lambda) d\lambda}{\sum_{380\text{ nm}}^{780\text{ nm}} D65(\lambda) V(\lambda) d\lambda}$$

where $T(\lambda)$ represents the spectral transmittance of the device, $D65(\lambda)$ is the relative spectral distribution of illuminant D65, $V(\lambda)$ is the CIE spectral luminosity function for photopic vision, and $d\lambda$ is the wavelength interval. Figure 3c and d display the transmittance spectra for DSSCs using TMTU/TMFDS²⁺ and I^-/I_3^- electrolytes and various UV-absorbing dyes. Notably, FPCN-sensitized solar cells show low transmittance below 450 nm, but a substantial increase in the visible range, achieving ~65% transmittance at wavelengths beyond 550 nm. This indicates strong UV light harvesting while maintaining excellent visible light transmission. The TMTU/TMFDS²⁺ electrolyte, by contrast, exhibits almost no absorption beyond 350 nm, unlike the I^-/I_3^- electrolyte, which absorbs up to 500 nm. This low absorption contributes positively to overall light transmission and enhances the photocurrent generation in DSSCs. Table 2 summarizes T_{avg} and τ_{vis} for DSSCs sensitized with different dyes. The TMTU/TMFDS²⁺ electrolytes show superior transmittance values compared to the conventional I^-/I_3^- electrolyte. Moreover, τ_{vis} values for UV-harvesting DSSCs are generally higher than their corresponding T_{avg} values, owing to the absorbance characteristics of the UV dyes, which are mostly outside the human eye's sensitivity range. This contributes to enhanced aesthetics and functionality by ensuring maximum visible light transmission while effectively utilizing UV light for energy conversion.

The photovoltaic performance of DSSCs was evaluated under standard one-sun illumination (AM 1.5G, 100 mW/cm²), as shown in Fig. 4a and d. The photovoltaic parameters for all devices are summarized in Table 3. FPCN-sensitized solar cells utilizing TMTU/TMFDS(BF₄)₂ and TMTU/TMFDS(PF₆)₂ electrolytes demonstrated maximum power conversion efficiencies (PCEs) of 1.58% and 1.55%, respectively, as shown in Fig. 4a. This represents a notable enhancement in the J_{sc} when transitioning from traditional I^-/I_3^- electrolytes to the TMTU/TMFDS²⁺ system. However, DSSCs employing the TMTU/TMFDS²⁺ redox couple with the standard ruthenium-based dye N719 exhibited worse photovoltaic performance than those with fluorene-based dyes. Moreover, the distinct absorption spectra of these UV-harvesting dyes contribute to varying DSSC performance levels.

Figures 4b and e show the incident photon conversion efficiency (IPCE) spectra for FPCN-sensitized solar cells employing different electrolytes and DSSCs incorporating various UV-absorbing dyes with 66. The integrated IPCE over the spectral range reveals the efficiency of light utilization in each dye-electrolyte combination. Cells employing the TMTU/TMFDS²⁺ redox couple showed a notable improvement in IPCE compared to those using the I^-/I_3^- electrolyte, particularly in the UVA region. Among the configurations, the FPCN dye achieved the highest J_{sc} due to its superior light-harvesting capabilities in both UVA and visible light regions. Meanwhile, the FPCN and FCA cells demonstrated selective absorption in the UVA and violet light regions, enhancing their potential for visible transparency.

Nyquist plots from EIS are displayed in Fig. 4c and f, which were used to analyze internal resistances. The absence of Warburg-like features indicates efficient electron transport within the TiO₂. EIS parameters extracted from Nyquist plots using an equivalent circuit model are summarized in Table S2. The intersection with Z' axis represents the series resistance (R_s), while the high- and mid-frequency semicircles correspond to charge transfer processes at the counter electrode/electrolyte and photoanode/electrolyte interfaces, respectively. Notably, the TMTU/TMFDS²⁺ redox couple displayed a higher charge transfer resistance (R_{CE}) at the Pt counter electrode than the I^-/I_3^- system, contributing to lower fill factors, as shown in the inset of Fig. 4c. Furthermore, the charge transfer resistance (R_{TiO_2}) at the N719-TiO₂ electrode was the highest, reflecting inefficient dye regeneration by the TMTU/TMFDS²⁺ electrolyte. The suboptimal performance of N719-TMTU devices can likely be attributed to inefficient dye regeneration due to an insufficient driving force for the regeneration process. For Ru-based

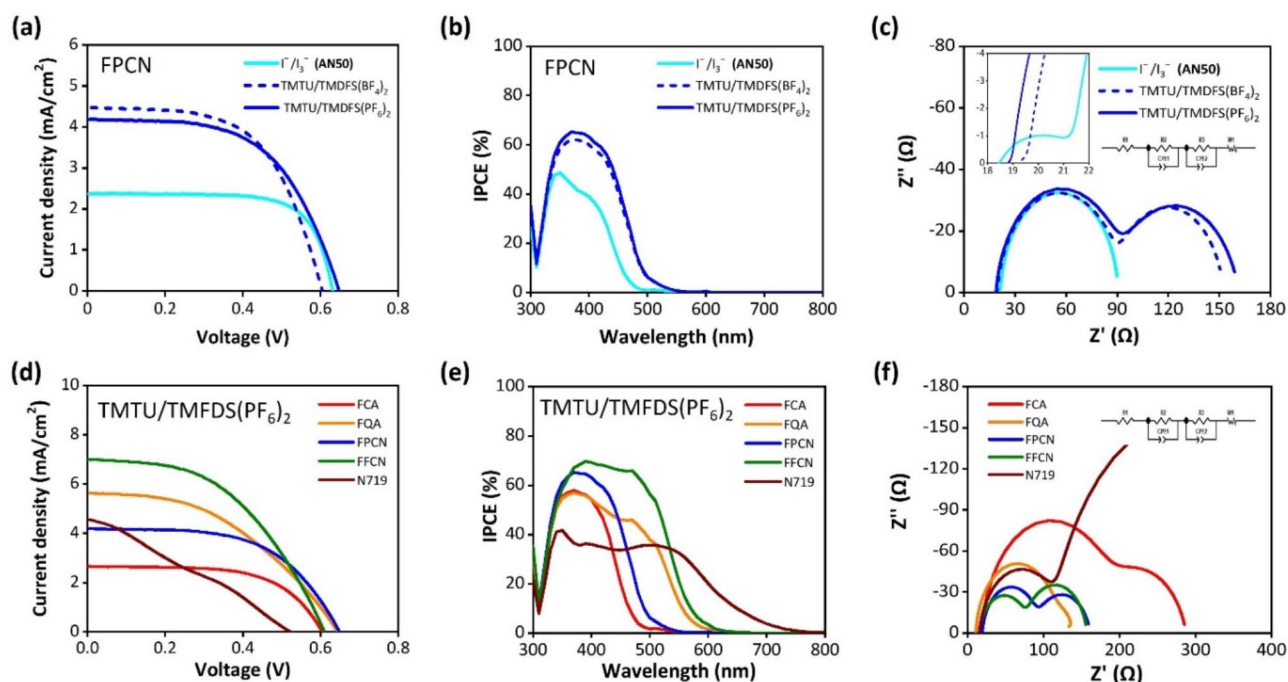


Fig. 4. (a) J-V curves, (b) IPCE spectra, and (c) Nyquist plots of FPCN-sensitized solar cells using I^-/I_3^- (AN-50) and TMTU/TMFDS²⁺ electrolytes. The inset in (c) shows the equivalent circuit used for impedance modeling. (d) J-V curves, (e) IPCE spectra, and (f) Nyquist plots of DSSCs using TMTU/TMFDS(PF₆)₂ electrolyte with various dyes (FCA, FQA, FPCN, FFCN, and N719). The inset in (f) depicts the equivalent circuit for the impedance measurements.

	TMTU/TMFDS(BF ₄) ₂		TMTU/TMFDS(PF ₆) ₂		AN-50	
	T_{avg} (%)	τ_{vis} (%)	T_{avg} (%)	τ_{vis} (%)	T_{avg} (%)	τ_{vis} (%)
FPCN	62.1	68.4	62.6	68.4	59.7	67.2
FCA	63.2	69.3	63.3	69.3	57.2	63.2
FFCN	56.3	60.0	51.8	55.2	55.3	62.5
FQA	57.4	60.1	60.9	65.0	56.0	62.6
N719	41.8	38.5	45.6	39.6	48.1	45.2

Table 2. AVT and VLT values for DSSCs sensitized with UV-absorbing small molecules.

dyes like N719, the electron transfer mechanism between I^- and the dye involves an inner-sphere electron transfer (ISET) process, which is influenced by the desolvation of I^- in the MeCN environment³⁸. Experimental evidence from transient absorbance spectroscopy (TAS) suggests that dye regeneration by I^- occurs faster than by TMTU²⁶. Consequently, a detailed investigation of interfacial charge transfer kinetics at the TiO₂ electrode is warranted. However, metal-free organic dyes, particularly UV-absorbing dyes, have shown significantly better regeneration efficiency with TMTU/TMFDS²⁺ electrolytes. These findings emphasize the importance of matching electrolyte properties to dye characteristics to maximize DSSC performance.

The color properties of light transmitted through the DSSCs were analyzed using the CIE 1931 (x, y) chromaticity diagram, as shown in Fig. 5. This analysis focused on evaluating how the TMTU/TMFDS²⁺ electrolyte affects key colorimetric parameters, including chromaticity coordinates (x, y), CCT, and Duv, as summarized in Table 4. The introduction of the TMTU/TMFDS²⁺ electrolyte led to lower |Duv| values compared to the I^-/I_3^- system, indicating that the transmitted light color is closer to the blackbody curve at a given temperature. A lower |Duv| value implies that the light is more balanced, appearing more neutral without significant green or purple tints. Notably, the DSSCs with FQA and FFCN dyes exhibited significantly reduced |Duv| values, meaning that the light transmitted through these devices is closer to white. The N719-sensitized solar cells showed slightly negative Duv values, indicating a slight purplish tint, as they are positioned slightly below the blackbody curve. Figure 5 shows chromaticity quadrangles that represent the ANSI C78.377–2017 standard for general lighting applications, which defines acceptable chromaticity regions for white light in the CCT range from 2700 K to 6500 K³⁹. DSSCs employing the TMTU/TMFDS²⁺ redox couple fall within the ANSI C78.377–2017 chromaticity tolerances, except for the FPCN device, which lies just outside the boundary.

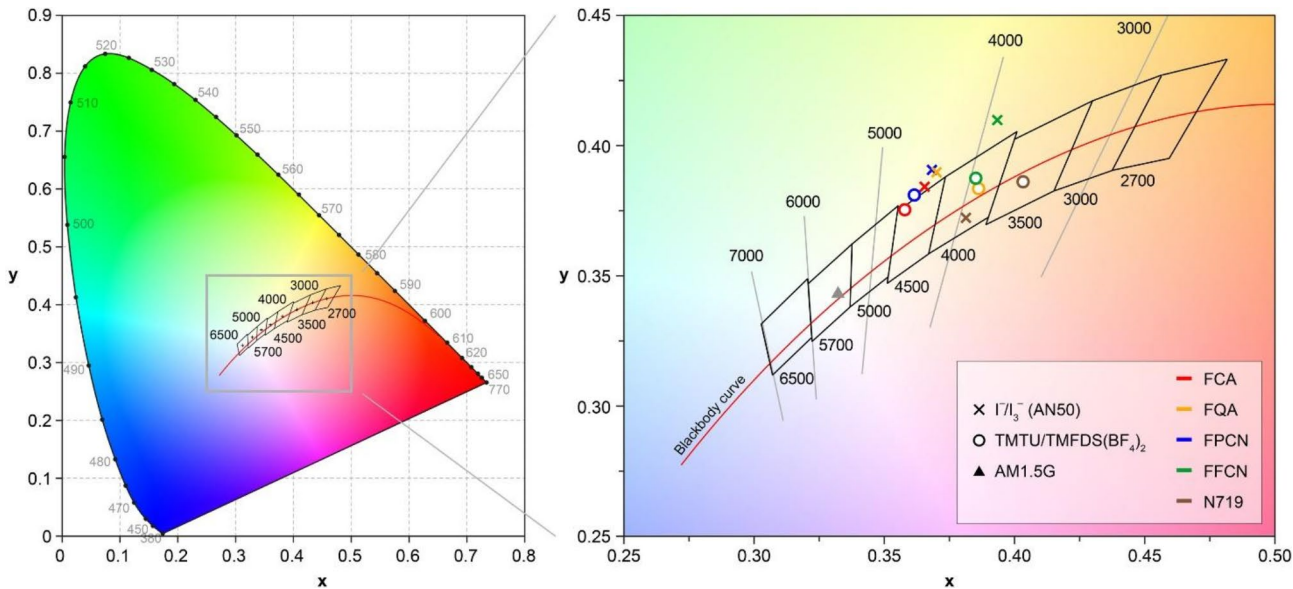


Fig. 5. Color coordinates of the I^-/I_3^- electrolyte (represented by crosses) and the TMTU/TMFDS(BF₄)₂ electrolyte (represented by circles). The reference light source AM 1.5G is included for comparison (represented by triangle). The solid black line represents the region defined by ANSI C78.377–2017.

Electrolytes	Dye	V_{oc} (V)	J_{sc} (mA/cm ²)	FF (%)	η (%)
AN-50	FPCN	0.619 ± 0.018	2.41 ± 2.49	72.1 ± 0.4	1.07 ± 0.08
	N719	0.699 ± 0.013	10.90 ± 0.40	70.9 ± 0.6	5.39 ± 0.10
TMTU-TMFDS(BF ₄) ₂	FCA	0.545 ± 0.013	2.70 ± 0.01	58.8 ± 0.6	0.92 ± 0.02
	FQA	0.588 ± 0.010	6.55 ± 0.12	47.7 ± 1.7	1.84 ± 0.06
	FPCN	0.623 ± 0.027	4.18 ± 0.30	56.7 ± 6.1	1.47 ± 0.12
	FFCN	0.620 ± 0.007	6.04 ± 0.05	38.4 ± 8.0	1.63 ± 0.24
	N719	0.509 ± 0.005	4.58 ± 0.05	22.1 ± 2.0	0.50 ± 0.03
TMTU-TMFDS(PF ₆) ₂	FCA	0.597 ± 0.010	2.68 ± 0.05	61.1 ± 0.4	0.98 ± 0.01
	FQA	0.634 ± 0.010	5.75 ± 0.18	38.0 ± 9.3	1.38 ± 0.33
	FPCN	0.655 ± 0.009	4.05 ± 0.26	53.8 ± 4.4	1.42 ± 0.12
	FFCN	0.607 ± 0.002	6.77 ± 0.20	39.4 ± 7.9	1.62 ± 0.38
	N719	0.532 ± 0.010	4.21 ± 0.57	24.2 ± 3.6	0.54 ± 0.11

Table 3. Photovoltaic parameters of DSSCs with different dye-electrolyte combinations under 1-sun illumination (AM 1.5G, 100 mW/cm²). Values are presented as averages with standard deviations, calculated from at least five devices for each condition.

In contrast, the UV-harvesting DSSCs using the I^-/I_3^- system fall outside the ANSI C78.377–2017 tolerance regions, implying that the transmitted light has a noticeable color deviation. These devices are positioned above the chromaticity quadrangles, suggesting that the light they transmit exhibits a greenish tint, making them less suitable for applications requiring high-quality white light.

Figure 6; Table 5 provide a comparative analysis of the CRI values for DSSCs using the I^-/I_3^- and TMTU/TMFDS²⁺ electrolytes. The CRI assesses how well colors are rendered by a light source compared to a natural or ideal reference. Higher CRI scores indicate more accurate color reproduction, while lower scores suggest more pronounced color distortions. For most of the devices, except those employing N719, the use of the TMTU/TMFDS²⁺ electrolyte improved both general CRI (R_a) and special CRIs (R_9 to R_{15}), indicating enhanced color rendering performance in DSSCs, particularly in UV-harvesting systems. The FFCN-based device exhibited the most pronounced enhancement, with an average CRI improvement of 5.63 across the special CRI values. This indicates superior color fidelity, which is especially relevant for applications requiring precise color rendering, such as retail lighting, museums, art galleries, photography, and professional filming. Specific improvements in the R_9 , R_{10} , R_{12} , R_{13} , and R_{15} values are particularly notable. The R_9 (red rendering) is crucial for medical settings where accurate tissue visualization is essential and for culinary displays where enhancing the appearance of food is desirable. The R_{13} and R_{15} (skin tone rendering) are significant for photography, broadcasting, and cosmetic

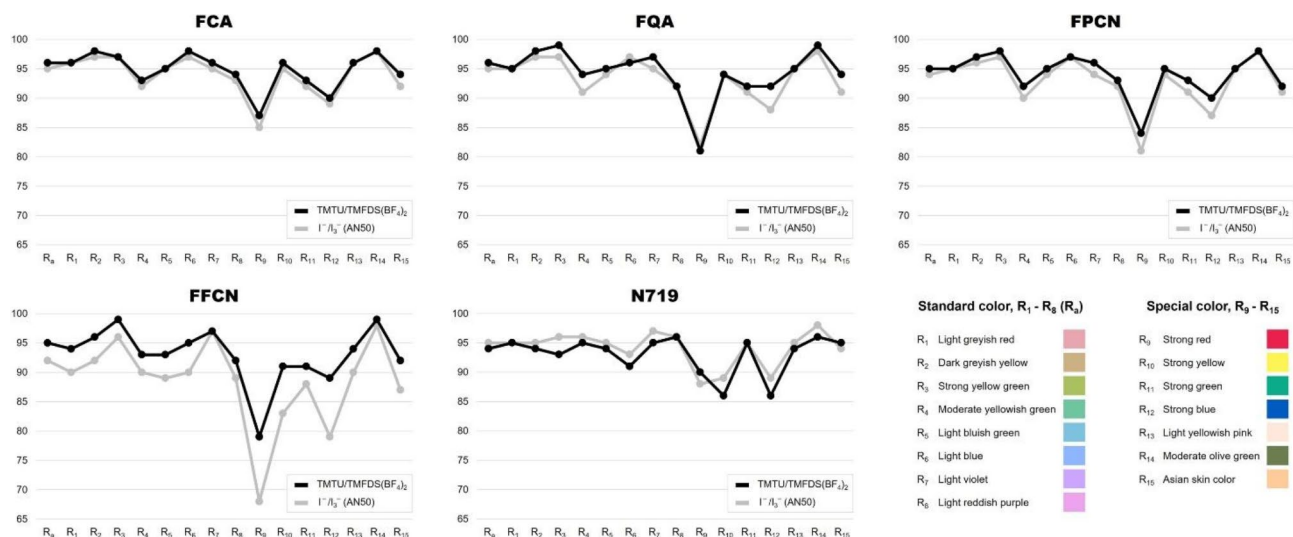


Fig. 6. Comparison of the color rendering indices (R_a , R_1 to R_{15}) between the I^-/I_3^- electrolyte (shown as a gray line) and the TMTU/TMFDS(BF_4)₂ electrolyte (shown as a black line).

Dye	R_a	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}
I^-/I_3^-								
FCA	95	85	95	92	89	96	98	92
FQA	95	82	94	91	88	95	98	91
FPCN	94	81	94	91	87	95	98	91
FFCN	92	68	83	88	79	90	98	87
N719	95	88	89	95	89	95	98	94
TMTU/TMFDS(BF_4) ₂								
FCA	96	87	96	93	90	96	98	94
FQA	96	81	94	92	92	95	99	94
FPCN	95	84	95	93	90	95	98	92
FFCN	95	79	91	91	89	94	99	92
N719	94	90	86	95	86	94	96	95

Table 5. General CRI (R_a) and special CRIs (R_9 to R_{15}) of the I^-/I_3^- and the TMTU/TMFDS(BF_4)₂ electrolytes.

industries, where accurate skin color reproduction is critical for natural and appealing visuals. The R_{10} and R_{12} are key in environments such as art studios and museums, where accurate color reproduction of artworks is vital³⁴.

While improving color rendering, it is also important to consider the trade-offs between CRI and photovoltaic efficiency. Although a CRI of 80 is generally acceptable for most applications, devices with CRI values above 90 are increasingly sought after to reduce color distortion and enhance visual comfort. Studies have shown that higher CRI values not only improve the appearance of objects but can also enhance visual acuity. These findings emphasize the significant role of color rendering in improving user experience, where changes in CRI can have a greater impact on satisfaction than variations in illuminance levels.

While striving for superior color rendering, it is vital to consider the trade-off with power conversion efficiency. A CRI of 80 is generally deemed adequate for most applications, though lamps with such a rating can sometimes render colors inaccurately. Consequently, manufacturers are increasingly aiming to produce lamps with CRIs above 90 to mitigate these issues. Studies have shown that higher CRI values not only improve the subjective preference for object appearances but may also enhance visual acuity, emphasizing the significant impact of color rendering on user experience^{40,41}. Changes in color rendering often influence user satisfaction more than variations in illuminance⁴¹, underscoring the importance of optimizing color fidelity in lighting applications to enhance the overall quality of the visual environment.

Conclusion

This study highlights the successful integration of UV-absorbing, metal-free organic dyes with non-iodine-based electrolytes to fabricate DSSCs with exceptional visible light transparency and color rendering. The FPCN dye, in

Dye	x	y	CCT	Duv
I^-/I_3^-				
FCA	0.3655	0.3838	4468	0.0080
FQA	0.3701	0.3894	4366	0.0090
FPCN	0.3683	0.3902	4422	0.0100
FFCN	0.3935	0.4094	3903	0.0109
N719	0.3814	0.3718	3935	-0.0026
TMTU/TMFDS(BF ₄) ₂				
FCA	0.3578	0.3749	4657	0.0065
FQA	0.3864	0.383	3890	0.0012
FPCN	0.3617	0.3806	4563	0.0078
FFCN	0.3853	0.3869	3946	0.0033
N719	0.4033	0.3856	3502	-0.0018

Table 4. CIE 1931 (x, y) chromaticity coordinates, correlated color temperature (CCT), and Duv of the I^-/I_3^- and the TMTU/TMFDS(BF₄)₂ electrolytes.

combination with the TMTU/TMFDS²⁺ electrolyte, offered high transparency (68.4%) alongside a competitive PCE of 1.58%. This combination outperformed the conventional I^-/I_3^- electrolyte system by providing clearer aesthetic and improved color rendering, as confirmed by CIE chromaticity and CRI analysis. The aesthetic and functional advantages make these cells ideal for photovoltaic windows and curtain walls, where transparency and minimal color distortion are paramount. This work establishes a foundation for future exploration into transparent DSSC technologies.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information file. The raw data are available from the corresponding author on reasonable request.

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Author contributions

M.A.M., K.C. and J.H. wrote the main manuscript text. M.A.M., S.L. and J.H. prepared Figs. 1, 2 and 3; Table 1, and 2. M.A.M., G.M.A., I.N.P.P. and J.H. prepared Fig. 4; Table 3. K.C. and J.H. prepared Figs. 5 and 6; Table 4, and 5. All the authors discussed the results and commented on the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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