

Classification and Mechanisms of Electrochromic Materials: Advances and Prospect

Yuejiao Qu*

Faculty of Mathematical and Physical Sciences, University College London, London, United Kingdom

*Corresponding author: yuejiao.qu.23@ucl.ac.uk

Abstract. Electrochromic (EC) materials have emerged as promising materials for energy-efficient smart windows and adaptive optical devices due to their ability to reversibly modulate optical properties under electrical stimuli. However, a lack of systematic comparison across different EC materials often leads to ambiguous understanding of their performance trade-offs. To bridge this gap, this paper classifies EC materials (ECs) into four categories: inorganic ECs, organic ECs, hybrid nano-enhanced ECs, and emerging functional ECs, the latter of which include three subcategories: fluorescent ECs, three-layer PANI-based ECs, and dual-band ECs. Each category is discussed in terms of its working mechanism: Inorganic ECs rely on ion insertion/extraction into transition metal oxides, organic ECs involve redox-active conjugated systems and hybrid ECs enhance performance via nanostructuring and interfacial effects, while emerging ECs introduce functionalities such as fluorescence, lateral ion migration, or VIS–NIR dual modulation. By comparing these systems, this paper identifies trade-offs among durability, switching speed, coloration efficiency, and spectral response. Inorganic ECs offer high stability, while organic ECs allow molecular tunability. Hybrid and emerging ECs push the boundaries of performance and multifunctionality. This review highlights the importance of mechanistic understanding to guide material design for next-generation EC technologies.

Keywords: Electrochromic materials; Conjugated polymers; Ion insertion; Smart windows; Hybrid nanostructures.

1. Introduction

Electrochromic (EC) materials have emerged as a promising class of smart materials capable of reversibly changing their optical properties, particularly color or transparency, under the influence of an external electric field. Their energy-efficient operation, low power consumption [1], and design flexibility make them ideal for a wide range of applications. These include commercial products like smart windows [2, 3], monitors [4], and anti-glare mirrors [5], as well as emerging technologies in wearables [6, 7], sensors [8], and adaptive camouflage [9]. EC materials also play a crucial role in promoting environmental sustainability by enabling dynamic control of solar radiation, which can thus reduce energy consumption for lighting, heating, and cooling. Their application in smart windows and optical devices mentioned above can lower building energy use by over 30% compared to conventional glazing [10]. The ability of electrochromic materials to switch between colored and transparent states while maintaining their adaptability and structural integrity renders them particularly advantageous for the advancement of energy-efficient and adaptive technologies, establishing them as promising candidates for next-generation materials in architecture, transportation, and electronics.

Over the past decades, extensive research has demonstrated the versatility and practicality of EC materials across multiple applications. “Smart windows” represent one of the most commercially established EC technologies, which can automatically regulate indoor lighting and thermal environments by adjusting transmittance in response to sunlight, thus reducing the demand for artificial lighting and air conditioning. P. M. Martin examined the internal structure and working principle of electrochromic devices (ECDs), such as smart windows, and also the electrochromic effect in inorganic materials, highlighting the dual injection or ejection of ions (M^+) and electrons (e^-)

[11]. Tungsten oxide (WO_3) is widely discussed as the most promising inorganic EC material for EC window coatings, owing to its high stability and excellent optical modulation properties [10-12]. R. J. Mortimer talked about the various organic EC materials and their corresponding mechanisms in depth [13]. A. V. Shchegolkov et al. studied the origins of internal and external size effects in the modification of WO_3 electrochromic films utilizing nanomaterials, specifically GO/rGO nanomaterials [14]. There are also many researchers analyzing the potential practicability of cutting-edge functional EC, such as fluorescent electrochromic (FEC) materials [15, 16], a novel self-structuring ECD based on a single layer of multicolor polyaniline (PANI) [17], and dual-band EC systems [18]. These achievements reflect the growing significance of EC materials in enabling sustainable and user-interactive technologies.

Despite considerable progress, most existing reviews focus either on specific material types (e.g., WO_3 or conjugated polymers) or on narrow application domains, lacking a comprehensive comparison across material systems and their working mechanisms. Additionally, emerging types of electrochromic materials (ECs), such as fluorescent ECs, self-structuring ECs with PANI single-layer arrangement, and dual-band ECs, remain underrepresented in the current literature. This review seeks to address these limitations by systematically classifying EC materials into four main categories: inorganic, organic, hybrid/nano-enhanced, and functional ECs (including emerging types mentioned above). For each category, this paper will analyze the underlying electrochromic mechanisms (e.g., ion intercalation, redox reaction, VIS/NIR modulation), compare their respective advantages and drawbacks, and discuss their suitability for different applications. Industrial challenges will also be highlighted, such as cycling stability, color richness, and scalability, while offering a forward-looking perspective on future research opportunities and commercialization pathways.

2. Classification of Electrochromic Materials

Electrochromic (EC) materials are primarily classified in two mainstream ways: by chemical structure and by solubility in redox states [14]. The first, more traditional approach divides EC materials into inorganic and organic categories based on chemical composition and structure [14]. Inorganic ECs include transition metal oxides (TMOs) such as WO_3 , TiO_2 , and MoO_3 , which are well-known for their chemical stability and long cycle life. Organic ECs, on the other hand, comprise viologens, conjugated conductive polymers (e.g., PEDOT, PANI), and phthalocyanines, offering faster switching speeds and richer color variability. Table 1 shows the general categorization of ECs.

Table 1. General classification of ECs [14]

Category	EC Class	Chemical Name	Application
Inorganic	Transition metal oxides (TMOs)	WO ₃ , MoO ₃ , V ₂ O ₅ , TiO ₂ , Nb ₂ O ₅ , Ir(OH) ₃ , NiO et al.	Smart Windows, antiglare mirrors
	Prussian blue (PB)	Prussian brown (C ₆ Fe ₂ N ₆), Prussian blue (C ₁₈ Fe ₇ N ₁₈)	Smart Windows
Organic	Conductive polymers	PEDOT (where EDOT = C ₆ H ₆ O ₂ S), PT (where T = thiophene = C ₄ H ₄ S), PANI (where ANI = aniline = C ₆ H ₄ S)	Smart Windows, flexible displays
	Viologens	N,N'-disubstituted bipyridinium salts	Antiglare coatings and displays
	Metal phthalocyanines (Pc)	[Lu(Pc) ₂] being Pc = C ₃₂ H ₁₈ N ₈ et al.	Displays
	Transition metals and lanthanoids	poly [Ru ²⁺ (vbpy) ₂ (py) ₂]Cl ₂ (py = pyridine = C ₅ H ₅ N)	Smart mirrors

The second classification method, proposed by I.F. Chang et al. [19] in 1975, sorts EC materials based on their solubility in different redox states (Types I–III), but this system is less commonly adopted in practice and will only be briefly mentioned in this paper. In this classification, Type I materials are soluble in both their reduced and oxidized states, allowing for reversible color changes in homogeneous solution systems. Type II materials are only soluble in the reduced state, but upon oxidation, they deposit a solid film on the electrode surface, which enables electrochromic function. Type III materials (e.g., TMOs, conductive polymers, and Prussian blue) remain solid and insoluble in both redox states, typically forming a thin film on the electrode.

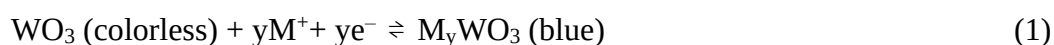
In this review, the author primarily adopts the chemical structure-based classification, further expanded into four categories: inorganic, organic, hybrid/composite, and emerging functional EC materials. Each category is characterized by its unique EC mechanism, even if some differences are subtle. The discussion of their individual working principles and recent developments will follow this order—from conventional systems to more innovative and multifunctional designs.

3. Electrochromic Mechanisms

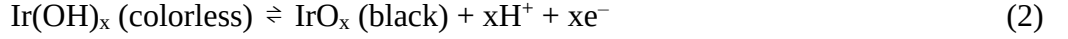
3.1. Inorganic EC Materials

Inorganic electrochromic (EC) materials, including transition metal oxides (TMOs), such as WO₃, MoO₃, IrO₂, TiO₂, NiO, and Nb₂O₅, and Prussian blue (PB), represent a well-established class due to their superior chemical stability, high coloration efficiency, and long cycling life. These materials undergo color changes through ion-electron injection and extraction [11], which alters their optical properties. The electrochromic effect arises from the redox-induced insertion (cathodic) or extraction (anodic) of ions (e.g., H⁺, Li⁺, Na⁺) and electrons (e[−]) into or from the oxide matrix.

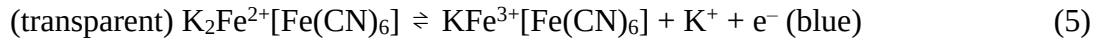
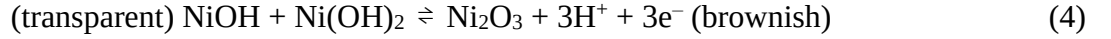
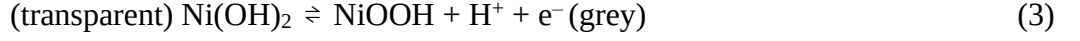
A typical cathodic reaction involves tungsten trioxide (WO₃), where M⁺ (where M is H⁺, Li⁺, Na⁺, Ag⁺, etc.) and e[−] are inserted to form M_yWO₃ (blue colored):



In contrast, anodic reactions like that of iridium hydroxide $\text{Ir}(\text{OH})_x$ involve ion and electron removal:



Movement to the right induces coloration or darkening, while movement to the left leads to bleaching [11]. In addition to WO_3 , several other EC materials such as NiO and PB have been extensively studied [3]. These materials also rely on reversible redox or intercalation reactions for electrochromism. For example, NiO undergoes a reversible oxidation to NiOOH in alkaline electrolytes, while PB , i.e. $\text{K}_3\text{Fe}(\text{CN})_6$, exhibits color changes based on ion insertion [3]. The corresponding reactions are as follows:



In this mechanism, electron–ion separation causes transition metal ions to change oxidation states, altering d-electron configurations and light absorption properties. TMOs like WO_3 are cathodically coloring, while IrO_2 and NiO are anodically coloring.

TMOs typically show a band gap within 1–5 eV, positioning them as intermediate materials between semiconductors and insulating material [20]. The electrochemical behavior is dependent upon the structure of TMOs, and, for instance, amorphous Nb_2O_5 shows a brown color when reduced, while crystalline Nb_2O_5 appears blue [14]. Structural and impurity defects also directly influence the properties, especially the physicochemical properties, of the examined ECs. The insertion of ions with high diffusion coefficients improves coloration efficiency. Furthermore, optimal band gap (E_g) tuning (e.g., from 3.62 eV to 3.30 eV in WO_3) influences conductivity and response speed [14]. Specifically, the varying band gap indicates that the conductivity of the WO_3 film improves as E_g decreases, while the enhanced conductivity accelerates the electrochromic response time.

A typical inorganic EC coating (e.g., “smart window”), shown in Figure 1 and 2, consists of 5 multi-functional layers that collaboratively enable reversible optical modulation. The top and bottom layers are transparent conductive electrodes (commonly indium tin oxide, ITO), which allow electrical current to pass while injecting electrons into the electrochromic layer [11, 21]. The electrochromic layer, usually made from materials like WO_3 or NiO , undergoes reversible redox reactions upon electron/proton injection, resulting in visible color changes due to altered light absorption. The ion transport layer (electrolyte), typically composed of immobile solvents, ionic glasses, or open-channel metal oxides (e.g., perovskites), facilitates proton transport [11]. These protons are sourced from the counter electrode or ion storage layer, which balances charge and supports ion exchange. The entire system is activated by applying an external voltage across the electrodes, inducing ion/electron motion and color change. Remarkably, the coloration can persist even after power is removed, and the system returns to its original state by reversing the polarity [1].

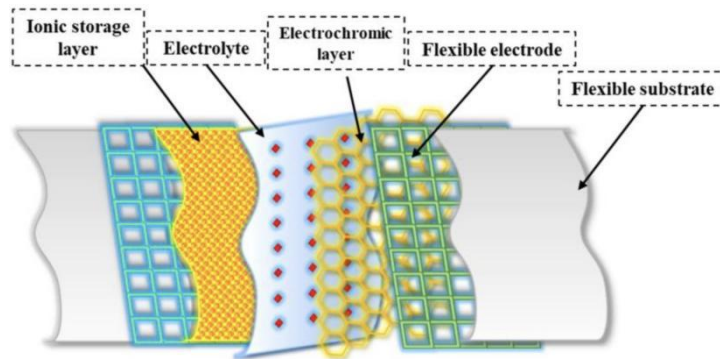


Fig. 1 Fundamental design of flexible EC materials [21]

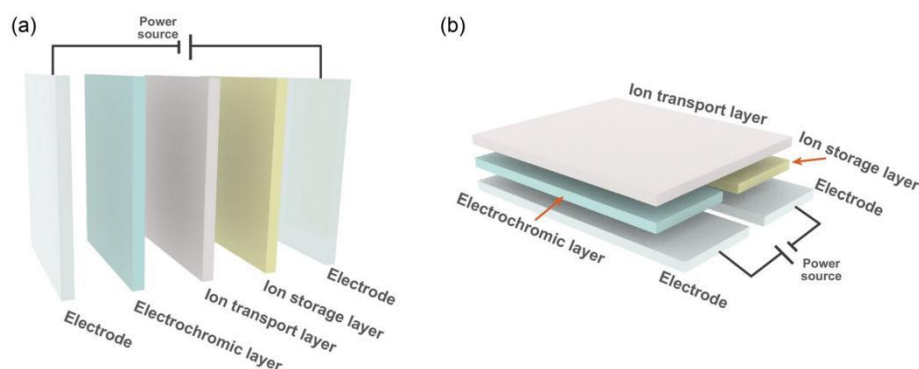


Fig. 2 Configurations of the traditional (a) **layered** and (b) lateral ECD featuring five functional layers, comprising two electrodes, an ECL, an ITL, and an ISL [22]

3.2. Organic EC Materials

Organic electrochromic (EC) materials, including conjugated polymers such as polyaniline (PANI) and poly(3,4-ethylenedioxythiophene) (PEDOT), as well as viologens (e.g., 1,1'-di-substituted-4,4'-bipyridinium salts), exhibit reversible color changes driven by redox reactions that modulate their visible-light absorption. These materials differ fundamentally from inorganic ECs such as TMOs, where coloration typically arises from ion intercalation into the crystal lattice, thus altering the material's electronic structure and optical properties. In contrast, organic EC materials primarily operate through molecular-level electron transfer, involving π -conjugated systems or redox-active centers [13].

Viologens (1,1'-di-substituted-4,4'-bipyridinium salts) are the most widely studied organic EC compounds. Their redox process involves three states as shown in Figure 3:

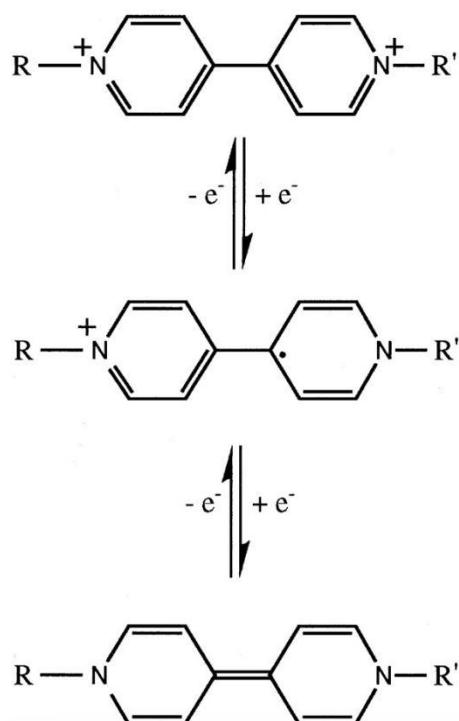


Fig. 3 The three typical redox states of viologen [13]

Viologens exhibit three typical redox states: the dication form (colorless), the radical cation (deeply colored, often appearing blue or violet), and the neutral form (also colorless). Upon reduction, viologens form radical cations, which are intensely colored due to strong optical charge transfer between the formally 0 and +1 valent nitrogen atoms. These radical cations are stabilized through π -electron delocalization, and their color can be tuned by modifying substituents. For instance, alkyl

groups yield blue/violet hues, while aryl groups like 4-cyanophenyl shift the color to green. In contrast, di-reduced viologens appear faint due to the lack of visible-range optical transitions. A unique feature of viologen radical cations is their ability to undergo dimerization [13], forming diamagnetic dimers with distinct spectral properties. For example, methyl viologen (MV) radical-cation monomers in water are blue, whereas their dimers are red (with absorption bands at ~550 and 900 nm). This process is influenced by the molecular structure and medium, and although dimerization can slow bleaching [13], it also provides access to multi-color transitions, which is a property exploitable in future design.

Viologen-based organic electrochromic systems, especially in solution form, are used in devices like rear-view mirrors [13] and smart windows [14]. Through reversible redox reactions, they enable dynamic color changes under voltage. These systems offer tunable colors, low power consumption, and fast switching, making them ideal for adaptive light control and energy-efficient applications.

3.3. Nano-enhanced Hybrid EC Materials

EC performance is strongly influenced by interfacial electron/ion transfer rates, which benefit from increased surface area [22]. Nanostructures enhance redox activity by offering more active sites due to their high specific surface area. Strategies include combining EC materials with nanomaterials or directly fabricating nanostructured EC films [22]. For instance, PEDOT-coated ZnO nanowire arrays prepared via seed-growth hydrothermal methods display dramatically increased Li^+ diffusion ($\sim 2.01 \times 10^{-4} \text{ cm}^2 \cdot \text{s}^{-1}$), achieving switching speeds under 2.2 ms. Additionally, tungsten-bronze-like $\text{Nb}_{18}\text{W}_{16}\text{O}_{93}$ nanomaterials synthesized via sol-hydrothermal routes [23] exhibit outstanding dual electrochromic and energy-storage capabilities, which overcome the ion diffusion limitations of typical inorganic EC materials like WO_3 and Nb_2O_5 by leveraging favorable crystal structures: optical modulation up to 93% at 633 nm (better than WO_3 and Nb_2O_5) and high energy storage capacity ($151.4 \text{ mAh} \cdot \text{g}^{-1}$ at $2 \text{ A} \cdot \text{g}^{-1}$), with excellent cycling stability (~ 6000 cycles) [23]. GO/rGO modification of WO_3 films is also a promising strategy to optimize film morphology and enhance electrochromic performance [14]. In addition, MOF-templated hierarchical porous $\text{NiO}@\text{C}$ electrodes address the drawbacks of conventional NiO by facilitating ion transport and boosting conductivity via porous frameworks and carbon doping. They exhibit rapid switching ($\sim 0.46 \text{ s}$ coloration/ 0.25 s bleaching) and retain $\sim 90\%$ performance after 20000 cycles [23], making them suitable for smart eyewear and potentially scalable for smart windows. Overall, these nanostructured hybrid strategies effectively overcome ion-diffusion constraints, enabling faster, more efficient, and durable EC devices suitable for energy-efficient smart glazing.

3.4. Emerging Functional EC Materials

3.4.1. Fluorescent Electrochromic (FEC) Materials

Fluorescent electrochromic (FEC) systems represent an emerging class of functional EC systems, as they integrate reversible fluorescence modulation with electrochemical stimuli, offering multifunctionality beyond conventional absorption-based electrochromic. FEC systems operate by integrating redox-active units with fluorophores, allowing external voltage to modulate the fluorescence output. The applied potential triggers reversible redox reactions, which alter the electronic states or quenching environment of the fluorophore, resulting in fluorescence enhancement or suppression without requiring optical excitation changes. In one study, J. Sun et al. developed FEC thin films via in-situ electro-polymerization of donor-acceptor monomers, forming interchain charge-transfer complexes (CTCs) with strong intermolecular interactions [15]. These CTCs produced redshifted orange fluorescence ($\sim 600 \text{ nm}$) with high contrast ($T = 33.6\%$, $I_{\text{on}}/I_{\text{off}} = 28.3$) and fast switching performance: coloring in 1.25 s, fading in 0.53 s, and good cycling stability (1.2% fluorescence decay after 2 h without power supply achieved by the improved spin delocalization of bis-carbazole radical cations through CTCs) [15]. Meanwhile, the 2019 study by J. Sun et al. [16] introduced a self-powered electrofluorochromic device (EFCD), constructed using a Mg/POM battery and powered by perovskite solar cells (PSCs). The fluorescence of Rh6G was modulated via a POM-based electrochromic layer, where switching between “ON” and “OFF” states was achieved

through POM redox reactions and associated fluorescence quenching upon charge/discharge cycles [16]. When sunlight was available, perovskite solar cells (PSCs) recharged the system, oxidizing the fluorophore and restoring fluorescence. This redox-based switching cycle operated without any external power supply, demonstrating a sustainable pathway for smart windows. Compared to conventional EC systems (e.g., WO_3 , PEDOT), FECs add fluorescent-state tunability, enabling new functions for low-energy, dual-mode optical devices.

3.4.2. Simplified Three-Layer PANI ECDs

Recent studies have proposed a novel self-structuring electrochromic device (ECD) that integrates a single multicolor polyaniline (PANI) film, breaking from the conventional five-layer architecture of symmetric ECDs [21]. This three-layer configuration, which comprises a PANI electrochromic layer, a quasi-solid-state gel electrolyte, and a conductive substrate, enables multicolor and gradient pattern displays with high transmittance contrast ($\sim 60\%$ at 630 nm) upon horizontal current application [17]. Unlike traditional redox-based coloration mechanisms driven by vertical ion migration, this system operates via a horizontal ionic redistribution mechanism [17]. Specifically, the applied horizontal current induces a magnetically-driven lateral migration of anions within the PANI layer, resulting in self-patterned optical changes across the film. This dynamic variation, adjustable by tuning the direction and intensity of the current, achieves rapid response (~ 16 s) [17] and excellent cycling stability. Such a mechanism not only simplifies the device structure but also offers a new approach for developing high-performance, programmable multicolor EC devices suitable for smart fabrics, camouflage, and display technologies.

3.4.3. Dual-band EC systems

Most EC materials only target visible light, but since nearly 50% of solar energy lies in the near-infrared (NIR) range, which greatly impacts indoor heat, controlling NIR has become critical for energy-efficient thermal regulation in buildings. Dual-band electrochromism addresses the challenge of regulating both visible (VIS) and near-infrared (NIR) light independently, which is crucial for energy-efficient smart windows and thermal control. For example, WO_3 -based dual-band EC materials achieve this via redox-induced ion intercalation/extraction, modulating optical absorption in both spectral regions [18]. The NIR response is attributed to localized surface plasmon resonance (LSPR) influenced by oxygen vacancies and doping, while VIS modulation is primarily due to polaronic absorption linked to charge transfer and structural transitions [18]. Moreover, N. Wu et al. developed dual-band ECDs using triazine-centered viologen analogues (TPPT and TPBT) paired with ferrocene (Fc) as the electron mediator, achieving high contrast modulation in both VIS and NIR regions, rapid switching (< 28 s), and notable coloration efficiency ($> 170.23 \text{ cm}^2 \text{ C}^{-1}$) in the NIR region [24]. Conducting polymers like PEDOT, PTs, and PANI have also been explored for EC applications. PEDOT shows dual-band behavior with VIS and NIR modulation, while PANI offers excellent stability and conductivity, so combining PEDOT with PANI enhances dual-band performance, highlighting the potential of organic materials in dual-band ECDs [18].

4. Performance Comparison: Advantages & Limitations

Electrochromic materials exhibit varied performance depending on their categories. Inorganic EC materials, such as TMOs (e.g., WO_3 , NiO), offer high chemical stability, long cycling life, and strong coloration efficiency. However, they often suffer from slow switching speeds due to limited ion diffusion and require high-temperature processing [22]. Organic EC materials, like PEDOT and viologens, show flexible processing, bright tunable colors, and faster switching in small molecules, but their small sizes and weights often result in unexpected thermal diffusion. Therefore, they usually lack long-term stability and can degrade under ambient conditions [21, 22]. Hybrid nano-enhanced ECs combine the benefits of inorganic and organic systems, improving ion mobility, optical modulation, and cycling stability. Despite their promise, they face challenges in synthesis complexity, cost, and uniform scalability.

Functional EC systems can be further divided into three subtypes: (1) Fluorescent ECs introduce dual-mode optical control (color + fluorescence) but face issues with photostability and device integration. Specifically, FEC materials face limitations such as poor cycling stability, polymer dissolution, and reduced fluorescent/optical contrast over time. Furthermore, they exhibit slow brightening speeds and require precise voltage control for consistent performance [15]; (2) Three-layer PANI ECs enable lateral ion redistribution and programmable displays compared to the conventional 5-layered ones, but they require precise structural tuning. Also, the transmittance contrast decreased after long-term cycling. For example, after 150 cycles, the transmittance contrast in the deep blue region dropped to 76% of its initial value, indicating performance degradation with increased cycling, especially under higher current density [17]; (3) Dual-band ECs uniquely allow independent VIS/NIR modulation, which is critical for energy-efficient smart windows. However, achieving simultaneous high performance in both bands remains difficult. Firstly, dual-band EC devices face unresolved trade-offs between switching speed, optical contrast, and cycle stability due to limited redox potential windows and the viscosity of electrolytes. Moreover, fully independent VIS and NIR regulation within a single device remains difficult, as achieving high NIR modulation without compromising VIS performance is unlikely to be realized. Also, variability in electrolyte composition and ion mobility further complicates reproducibility and scaling [18].

Overall, each category presents trade-offs between speed, efficiency, durability, and functionality, guiding material choices for tailored applications for the industrial applications.

5. Conclusion

This review systematically categorizes electrochromic (EC) materials based on their working mechanisms, offering a comparative understanding of their electrochemical behaviors, advantages, and limitations. The classification spans four major types: inorganic ECs, organic ECs, nano-enhanced hybrid ECs, and emerging functional EC systems, such as fluorescent ECs, simplified PANI structures, and dual-band ECs. Through comparative analysis, the author provides a clear overview of how material composition and structure influence coloration performance, switching dynamics, and application potential.

Inorganic ECs, such as WO_3 and NiO , function via redox-driven ion intercalation and offer reliable long-term cycling stability and mature processing. However, they often face limitations in switching speed and color range. Organic ECs, including conjugated polymers and viologens, leverage molecular-level electron transfer for faster switching and broader color tunability but suffer from poor long-term stability. To balance these trade-offs, nano-enhanced hybrids have emerged, incorporating nanostructures like nanowires or nanoporous films to enhance conductivity, flexibility, and switching dynamics. Emerging functional ECs further expand capabilities: fluorescent ECs enable reversible luminescent switching for dual-mode optical outputs; simplified PANI systems offer multicolor programmability; and dual-band ECs address a critical gap in energy efficiency by simultaneously regulating both visible (VIS) and near-infrared (NIR) light, which is essential for thermal control in architectural applications.

Despite significant advancements, there are still some big problems, such as slow response in certain systems, degradation of organic materials, and fabrication complexity. Future research should therefore focus on improving electrochemical durability, optical modulation flexibility, and scalable manufacturing. Ultimately, by understanding the mechanistic foundations and trade-offs of each EC category, material scientists and engineers can better design multifunctional and high-performance EC devices tailored for energy-saving buildings, flexible electronics, and adaptive display technologies.

References

- [1] J. S. E. M. Svensson and C. G. Granqvist. Electrochromic coatings for ‘smart windows’. *Solar Energy Materials*, 1985, 12(6): 391–402.

- [2] S. Macher et al. Large-Area Electrochromic Devices on Flexible Polymer Substrates with High Optical Contrast and Enhanced Cycling Stability. *Advanced Materials Technologies*, 2020, 6(2): 2000836.
- [3] R. Baetens, B. P. Jelle, and A. Gustavsen. Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. *Solar Energy Materials and Solar Cells*, 2010, 94(2): 87–105.
- [4] Y. Li et al. Colorful Electrochromic Displays with High Visual Quality Based on Porous Metamaterials. *Advanced Materials*, 2023, 35(23): 2300116.
- [5] T. A. Ranney, L. A. Simmons, and A. J. Masalonis. The Immediate Effects of Glare and Electrochromic Glare-Reducing Mirrors in Simulated Truck Driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 2000, 42(2): 337–347.
- [6] H. Fan et al. Wearable electrochromic materials and devices: from visible to infrared modulation. *Journal of Materials Chemistry C*, 2023, 11(22): 7183–7210.
- [7] G. Fu, H. Gong, T. Bai, Q. Zhang, and H. Wang. Progress and challenges in wearable electrochromic devices: a review. *Journal of Materials Science Materials in Electronics*, 2023, 34: 1316.
- [8] S. Ranjbar, A. H. Salavati, N. A. Astani, N. Naseri, N. Davar, and M. R. Ejtehad. Electrochromic Sensor Augmented with Machine Learning for Enzyme-Free Analysis of Antioxidants. *ACS Sensors*, 2023, 8(11): 4281–4292.
- [9] H. Fu, L. Zhang, Y. Dong, C. Zhang, and W. Li. Recent advances in electrochromic materials and devices for camouflage applications. *Materials Chemistry Frontiers*, 2023, 7(12): 2337–2358.
- [10] A. V. Shchegolkov, E. N. Tugolukov, and A. V. Shchegolkov. Overview of Electrochromic Materials and Devices: Scope and Development Prospects. *Advanced Materials & Technologies*, no. 2(18): 066–073.
- [11] P. M. Martin. OPTICAL MATERIALS | Smart Optical Materials. *Encyclopedia of Modern Optics*, 2005, 9–16.
- [12] C.G. Granqvist. *Handbook of Inorganic Electrochromic Materials*. Elsevier eBooks, 1995, 1–15.
- [13] R. J. Mortimer. Organic electrochromic materials. *Electrochimica Acta*, 1999, 44(18): 2971–2981.
- [14] A. V. Shchegolkov, S.-H. Jang, A. V. Shchegolkov, Y. V. Rodionov, A. O. Sukhova, and M. S. Lipkin. A Brief Overview of Electrochromic Materials and Related Devices: A Nanostructured Materials Perspective. *Nanomaterials*, 2021, 11(9): 2376.
- [15] J. Sun et al. In-situ electro-polymerization of fluorescent electrochromic thin films based on charge-transfer complexes. *Chemical Engineering Journal*, 2021, 428: 132625.
- [16] J. Sun, Y. Li, J. Sun, Z. Zhu, Y. Zhai, and S. Dong. Reversible self-powered fluorescent electrochromic windows driven by perovskite solar cells. *Chemical Communications*, 2019, 55(80): 12060–12063.
- [17] H. Gong, K. Zhou, Q. Zhang, J. Liu, H. Wang, and H. Yan. A self-patterning multicolor electrochromic device driven by horizontal redistribution of ions. *Solar Energy Materials and Solar Cells*, 2020, 215: 110642.
- [18] Y. Zhai et al. Recent Advances on Dual-Band Electrochromic Materials and Devices. *Advanced Functional Materials*, 2022, 32(17): 2109848.
- [19] I. F. Chang, B. L. Gilbert, and T. I. Sun. Electrochromic Systems for Display Applications. *Journal of the Electrochemical Society*, 1975, 122(7): 955-962.
- [20] P. Ashrit. *Transition Metal Oxide Thin Film-Based Chromogenics and Devices*. Elsevier, 2017, 376.
- [21] G. Nuroldayeva and M. P. Balanay. Flexing the Spectrum: Advancements and Prospects of Flexible Electrochromic Materials. *Polymers*, 2023, 15(13): 2924.
- [22] C. Gu, A.-B. Jia, Y.-M. Zhang, and S. X.-A. Zhang. Emerging Electrochromic Materials and Devices for Future Displays. *Chemical Reviews*, 2022, 122(18): 14679–14721.
- [23] G. Cai et al. Tunable Intracrystal Cavity in Tungsten Bronze-Like Bimetallic Oxides for Electrochromic Energy Storage. *Advanced Energy Materials*, 2021, 12(5): 2103106.
- [24] N. Wu, L. Ma, S. Zhao, and D. Xiao. Novel triazine-centered viologen analogues for dual-band electrochromic devices. *Solar Energy Materials and Solar Cells*, 2019, 195: 114–121.