Perspective

Carbon Future

Bridging the gap between theoretical design and practical performance of environment-adaptive multi-band regulation smart windows

Ya Huang[1,#], Kangkang Wang[1,#], Zhenyu Guo[1,#], Siming Zhao[1], Zhuojing Zhao[1], Fan Lan[1], Ruina Liu[1], Linan Feng[1], Weiyin Su[1], Shuang Tao[1], Ying Wang[1], and Rufan Zhang[1,2] ✉

[1] *Beijing Key Laboratory of Green Chemical Reaction Engineering and Technology, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China*
[2] *State Key Laboratory of Chemical Engineering and Low-carbon Technology, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China*

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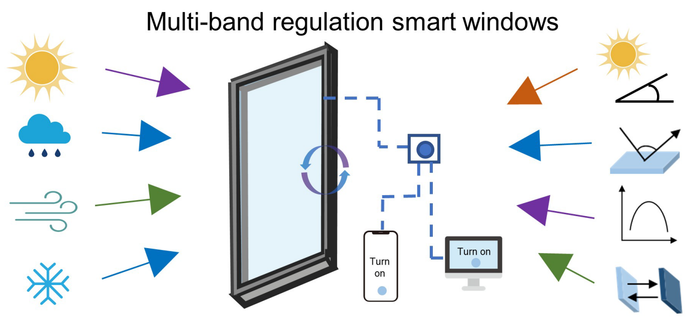
ABSTRACT: Smart windows have emerged as promising building-envelope technologies that could reduce energy consumption by dynamically regulating solar radiation and thermal exchange. Recent advances have extended smart window design from single-band optical modulation to multi-band control across the visible, near-infrared, and mid-infrared regions, creating an opportunity to coordinate daylight utilization, solar heat gain, thermal insulation, and radiative cooling within a single integrated glazing system. However, most reported multi-band regulation smart windows (MBRSWs) have been evaluated under idealized optical and thermal conditions, including normal solar incidence, standardized spectral inputs, simplified boundary environments, and small-area devices. These assumptions often obscure the fact that an operating window is exposed to continuously changing solar angles, weather conditions, sky radiation, indoor loads, and device-level heat transfer. In this perspective, we argue that next-generation MBRSWs should be designed as environment-adaptive thermodynamic interfaces rather than isolated optical films. Key design principles for materials and devices are discussed, including temperature-dependent spectral selectivity, angular dependence, device architecture, scalable manufacturing, durability, and realistic evaluation approaches. We further propose that the field should shift from maximizing peak modulation under ideal conditions to climate-weighted, operationally relevant performance in realistic use scenarios.



KEYWORDS: Smart windows, building energy efficiency, real-world operation, spectral selectivity

1 Introduction

Buildings account for a substantial fraction of global energy consumption and carbon emissions, with a significant portion attributable to heating, cooling, and lighting[1]. Windows are among the most critical components of the building envelope because they simultaneously mediate daylight admission, solar heat gain, conductive heat transfer, and long-wave radiative exchange between indoor and outdoor environments[2, 3]. Therefore, the role of windows is not only limited to optical transparency, but also extends to serving as a thermal boundary whose function depends on how different spectral bands are transmitted, absorbed, reflected, and emitted. Solar and thermal radiation provide a natural basis for spectral design. Visible (VIS) light transmission supports daylighting and visual comfort, near-infrared (NIR) radiation can be selectively blocked or transmitted to manage solar heat gain, and mid-infrared (MIR) emissivity determines long-wave heat exchange and the potential for radiative cooling through the atmospheric transparency window from 8 to 13 μm[4, 5]. Conventional smart windows have mainly focused on VIS modulation or combined VIS and NIR regulation[6–8]. More recent multi-band regulation smart windows (MBRSWs) have sought to coordinate VIS, NIR, and MIR responses in one device, thereby connecting lighting

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✉ Address correspondence to Rufan Zhang, zhangrufan@tsinghua.edu.cn

[#] Ya Huang, Kangkang Wang, and Zhenyu Guo contributed equally to this work.

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control, solar heating, thermal insulation, and radiative heat dissipation[9, 10]. In summer, an ideal MBRSW would maintain appropriate visible transmittance for daylighting and visual comfort, suppress NIR heat input, and enhance MIR emission to release absorbed heat. In winter, the window would maximize daylighting, allow useful solar heat gain, and reduce MIR heat loss to maintain indoor warmth.

Despite these advances, multi-band regulation smart windows (MBRSWs) still face two central problems. First, a large modulation range in isolated spectral measurements did not necessarily lead to large building energy savings. Optical spectra were often measured at normal incidence under standard solar inputs (e.g., Air Mass 1.5). In contrast, thermal performance was frequently assessed without fully resolving convection, conduction, sky radiation, and indoor radiation. In real buildings, solar incidence changes continuously with time of day, season, orientation, and geographic location[11]. Thermal environment around windows is also dynamic, governed by ambient temperature, wind speed, humidity, effective sky temperature, surrounding surfaces, and indoor load profiles. Solar angle mainly affects the effective transmittance and reflectance of angle-sensitive structures, including interference coatings, photonic resonators, scattering layers, and anisotropic optical systems[12, 13]. Temperature changes the material state, switching threshold, and thermal-radiation balance, while wind modifies convective heat transfer at the window surface. In addition, surrounding thermal radiation from the sky, ground, and nearby buildings can alter the net long-wave radiative exchange of vertical windows. Therefore, the same spectral state may produce different heating or cooling effects under different environmental conditions. These variables could shift the optical response, alter the window temperature, and change the balance between solar gain and thermal loss. Second, the gap between material performance and building performance became more pronounced after device integration. Generally, an MBRSW is not simply an active layer attached to glass but is usually a laminated glazing system, including multiple functional components such as substrates, interlayers, protective coatings, and sealing structures, which collectively determine its final optical and thermal performance. However, these components may attenuate solar transmission, increase haze, disrupt the intended spectral selectivity, suppress MIR radiative exchange, or redirect heat flow through conduction and convection. At a large scale, additional constraints arise from coating uniformity, layer adhesion, mechanical reliability, weather sealing, color consistency, optical clarity, and manufacturing yield.

In this perspective, we advocate for a shift from idealized, material-centric optimization toward environment-adaptive and system-level design principles for MBRSWs (**Fig. 1**). We first examined the key limitations of current approaches and identified critical environmental factors that influenced real-world performance. We discussed emerging strategies for incorporating angular dependence, spectral-thermal coupling, and multi-physics considerations into materials and device design. Finally, we outlined the need for standardized, realistic testing protocols and proposed future directions to bridge the gap between laboratory innovation and practical application.

2 Environment-adaptive materials design

MBRSWs should be designed not only to achieve substantial optical modulation performance under laboratory conditions, but also to maintain reliable spectral and thermal regulation under changing outdoor conditions. In practical operation, smart windows were simultaneously influenced by solar spectrum fluctuations, angle-dependent incident irradiation, ambient thermal exchange, and dynamic weather conditions, which imposed new requirements on materials design.

One important direction was the development of materials with spectral selectivity coupled to thermal management. Radiative

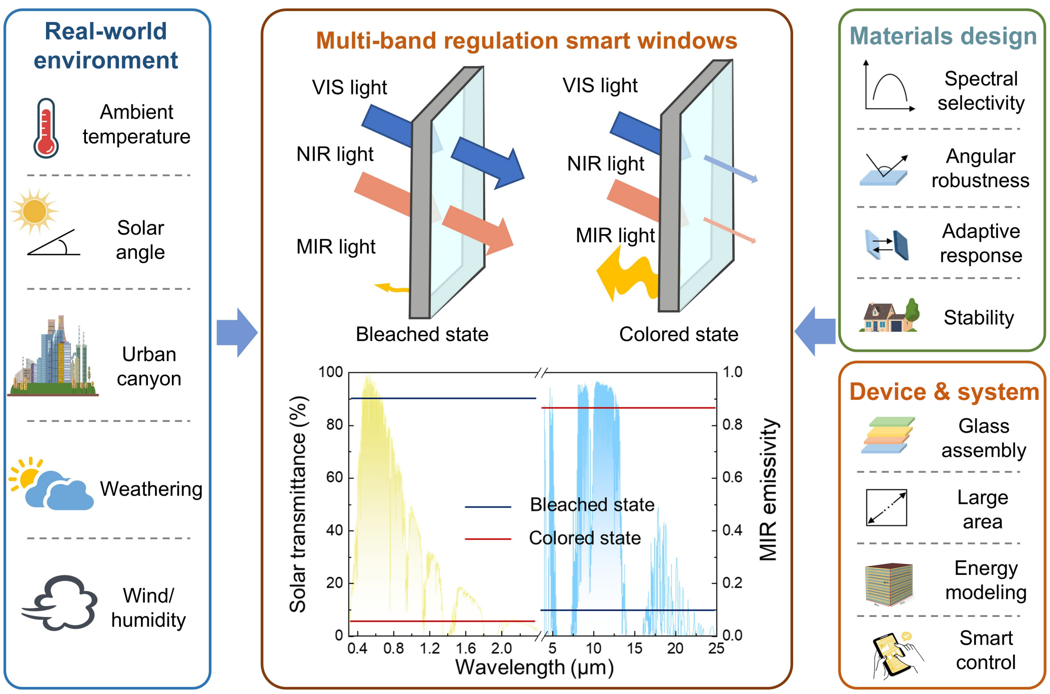

Fig. 1. Concept of environment-adaptive multi-band smart windows.

cooling studies have often emphasized MIR spectral selective emitters with high emissivity within the atmospheric transparency window from 8 to 13 μm because such emitters can reduce equilibrium temperature under ideal sky-facing conditions[14, 15]. However, recent studies have suggested that broadband emitters might provide higher net cooling power when the surface temperature is close to or higher than ambient temperature, particularly under realistic outdoor environments[16]. This finding indicated that the optimal emissivity spectrum may strongly depend on operating conditions rather than following a fixed optimal design principle. For smart windows, this insight is especially important because the window surface temperature can rise due to solar absorption and can also fall or rise depending on indoor and outdoor heat transfer[17]. Adaptive radiative emitters provided a useful design direction. Tang *et al.* demonstrated an infrared self-adaptive radiative cooling approach that dynamically switched between selective and broadband emission by leveraging a bilayer structure of microporous SiO_2 fiber and thermo-responsive hydrogel (**Fig. 2**a(i))[18]. Through temperature-driven directional transport of water within the hydrogel, the emitter reversibly transitioned from an atmospheric window-selective emitter (MIR emissivity = 0.85) under sub-ambient conditions to a broadband emitter (MIR emissivity = 0.92) under above-ambient conditions. This adaptive spectral regulation enabled optimized radiative cooling across fluctuating temperatures, outperforming static emitters[19].

A second requirement is to evaluate and design the angular response. Most MBRSW spectra were measured at normal incidence, but facade windows received direct sunlight over a broad range of angles. Optical interference coatings, photonic structures, multilayer resonators, anisotropic liquid crystal systems, and scattering media could also display strong angular dependence[20–22]. Under oblique illumination, the spectral response might shift, the VIS appearance might change, and the solar modulation calculated from normal incidence spectra might no longer represent daily performance[23]. Recently, Ryu *et al.* reported an angular-dependent energy-saving smart window based on a structured VO_2 array-Fabry–Pérot resonator, which simultaneously responded to seasonal variations in solar zenith angle and temperature, enabling dual modulation of solar transmission and broadband thermal

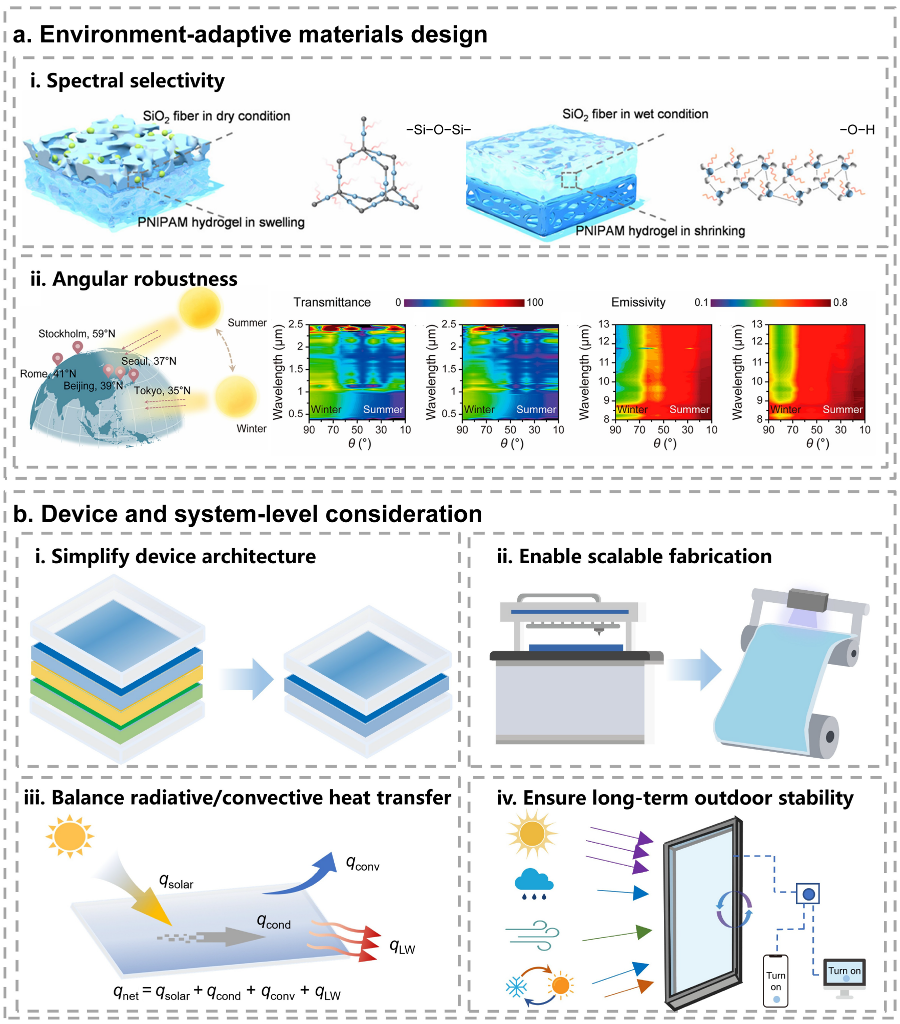

Fig. 2. Environment-adaptive materials design and device-level considerations for MBRSWs. a, Materials-level design emphasizes (i) spectral selectivity[18] and (ii) angular dependence under realistic environmental fluctuations[11]. Reproduced with permission from Ref[18], © Royal Society of Chemistry, 2024. Reproduced with permission from Ref[11], © American Chemical Society, 2025. **b,** Device-level implementation requires (i) simplified architectures, (ii) scalable fabrication, (iii) balanced heat-transfer pathways, and (iv) long-term outdoor durability to bridge material functionality and practical building application.

emissivity (Fig. 2a(ii))[11]. Through precise structural modulation of the resonator's angular selectivity, the device could better match the seasonal change in solar incidence, rather than treating oblique illumination as an optical loss factor. Moreover, it demonstrated that the performance of MBRSWs should be evaluated under coupled environmental variables, where spectral response, incident angle, and thermal state jointly determine the actual energy-saving behavior.

A third requirement is the long-term spectral stability. Common materials for MBRSWs have included thermochromic hydrogels[24], liquid crystals[25], electrochromic oxides[26], and hybrid photonic structures[27], which could provide dynamic regulation of VIS, NIR, and MIR spectra. However, their long-term outdoor performance was strongly affected by water retention, ion transport stability, electrode compatibility, ultraviolet resistance, interfacial adhesion, and mechanical integrity. For example, hydrogels could offer large optical contrast and passive temperature response, yet dehydration, freezing, leakage, and interfacial adhesion might limit their outdoor durability[28–30]. Electrochromic materials could provide continuous and reversible modulation at low voltage, but ion trapping, electrode degradation, and nonuniform switching might emerge during repeated cycling[31–34]. These issues determine whether the material could maintain its designed spectrum after months or years of exposure. Overall, this field should move beyond maximum modulation under ideal conditions and focus on spectral functions that remain beneficial across temperature variation, angular dependence, weather exposure, and cycling. A high-performance material should be judged by the persistence of its useful response within the operating envelope of buildings, not only by the magnitude of its initial optical contrast.

3 Device and system-level considerations

While smart materials provide the fundamental foundation for dynamic spectral regulation, the practical performance of MBRSWs was ultimately determined by how these materials were assembled into complete windows and operated in real building environments. A material with excellent VIS, NIR, or MIR modulation did not necessarily result in an energy-efficient window because the final device must simultaneously satisfy optical, thermal, mechanical, economic, and durability requirements. Therefore, device-level considerations were essential for understanding the gap between material functionality and practical application.

The first challenge was that multi-band regulation usually required more complex device architectures than conventional single-band smart windows (Fig. 2b(i)). Taking multi-band electrochromic smart windows as an example, to independently manipulate VIS light, NIR heat, and MIR radiation, many systems relied on multilayer stacks, including transparent electrodes, electrolytes, encapsulation layers, photonic structures, low-emissivity coatings, or radiative cooling layers[5, 35–37]. However, these components could strongly modify the optical and thermal behavior of the active material. For example, transparent electrodes and substrates might introduce parasitic absorption in the solar spectrum, while encapsulation layers and adhesives might reduce MIR emissivity or block radiative cooling channels. Multilayer interference could also shift the spectral response under oblique incidence. As a result, the performance of a complete smart window might significantly differ from that measured from an isolated material film.

The second challenge concerns large-scale manufacturability (Fig. 2b(ii)). MBRSWs often involve expensive materials, precise coating processes, patterned structures, or multiple functional layers. Although such designs could demonstrate impressive spectral accuracy at a small scale, their practical value depended on whether they could be fabricated over square-meter areas with acceptable cost, yield, and uniformity. For electrochromic or other electrically driven systems, large-area scaling further introduces nonuniform electric potential distribution, increased electrode resistance, slower ion transport, and edge-related failure, which could cause spatially uneven coloration, delayed switching, and reduced optical contrast[38, 39]. Therefore, high device performance must be balanced with fabrication simplicity, material availability, and compatibility with existing glazing manufacturing processes[40, 41].

The third challenge came from heat transfer coupling. In real operation, the window temperature was governed by the balance among solar absorption, transmitted solar radiation, thermal emission, convection, conduction through the glazing, and radiative exchange with the sky and indoor surfaces (Fig. 2b(iii)). A simplified heat-balance relationship can be written as:

$$q_{\mathrm{net}} = q_{\mathrm{solar}} + q_{\mathrm{cond}} + q_{\mathrm{conv}} + q_{\mathrm{LW}}$$

$$q_{\mathrm{solar}} = \tau_{\mathrm{sol}} G_{\mathrm{sol}}$$

$$q_{\mathrm{LW}} = q_{\mathrm{LW,in}} + q_{\mathrm{LW,out}} + q_{\mathrm{LW,sky}}$$

$$q_{\mathrm{net}} = \tau_{\mathrm{sol}} G_{\mathrm{sol}} + q_{\mathrm{cond}} + q_{\mathrm{conv}} + q_{\mathrm{LW,in}} + q_{\mathrm{LW,out}} + q_{\mathrm{LW,sky}}$$

where q_{net} represents the net heat flux associated with the window, q_{solar} represents the transmitted solar heat flux, τ_{sol} is the solar-spectrum-weighted transmittance of the window, and G_{sol} is the incident solar irradiance. q_{cond} and q_{conv} represent conductive and convective heat transfer. q_{LW} describes long-wave radiative exchange with indoor surfaces ($q_{\mathrm{LW,in}}$), outdoor surroundings ($q_{\mathrm{LW,out}}$), and the sky ($q_{\mathrm{LW,sky}}$). If the window absorbs considerable solar energy, the absorbed heat may offset the benefit of MIR emission. Similarly, under strong wind or large indoor-outdoor temperature differences, convective and conductive heat transfer may dominate over radiative heat exchange. Therefore, the device design must consider the competition between convective heat gain or loss and radiative heat dissipation, rather than treating MIR emissivity as an isolated parameter.

The fourth challenge was linked to weatherability and maintenance (Fig. 2b(iv)). Windows are continuously exposed to ultraviolet irradiation, humidity, oxygen, temperature cycling, dust, pollutants, rain, and mechanical cleaning[42, 43]. These factors could degrade active materials, corrode electrodes, weaken encapsulation, change haze, or cause leakage in electrolyte-containing devices. For MBRSWs, surface contamination from dust or water films could adversely affect their optical properties, especially solar reflectance[44]. Besides, for thermochromic and electrochromic systems, repeated switching might lead to fatigue, ion trapping, delamination, or irreversible color change. Thus, a practical MBRSW must maintain not only initial spectral modulation but also optical clarity, sealing integrity, switching reversibility, and thermal function over long-term outdoor exposure. The fifth challenge was operational complexity, which further affected practical deployment. Passive thermochromic windows could respond automatically to temperature, but their transition temperature and spectral state

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might not always match actual heating or cooling demand[45]. Active electrochromic devices offered greater controllability, but they required a power supply, wiring, sensors, control logic, and sometimes connection to building management systems. These additional components increased installation cost and maintenance requirements.

Taken together, the application of MBRSWs was limited not only by material performance but also by device architecture, cost, durability, heat-transfer coupling, and operational complexity. Therefore, practical smart windows should be understood as integrated thermodynamic components rather than isolated optical films. Their real value depended on whether multi-band spectral regulation could be achieved in a scalable, stable, and economically viable device while maintaining a favorable balance among solar gain, radiative exchange, convection, and indoor thermal comfort.

4 Realistic evaluation and future metrics

To bridge laboratory research and practical deployment, evaluation methods should transition from discrete optical parameters to scenario-driven energy performance metrics. Conventional indicators such as luminous transmittance, solar modulation ability, haze, color rendering, mid-infrared emissivity, switching time, and cycling stability remain necessary because they allow comparison among materials. However, these basic indices should be complemented by angle-resolved spectra testing, temperature-dependent spectral characterization, full device thermal measurements, long-term outdoor tests, and whole-building energy consumption simulation. The central aim is to determine whether a spectral function remains useful when the window is exposed to realistic climate and operation scenarios.

First, angle-resolved characterization should become routine for structures that rely on interference, resonance, scattering, or anisotropic alignment. Reporting only normal-incidence transmittance could hide large performance changes at realistic solar angles. Measurements at several incidence angles, such as 0, 30, 45, and 60 degrees, would allow researchers to estimate daily and seasonal performance more accurately. In addition, vertical facade windows differ fundamentally from horizontal radiative-cooling surfaces[46]. Their long-wave radiative exchange is not directed only toward the cold sky, but is distributed among the ground, neighboring facades, and indoor surfaces. Therefore, the effective MIR cooling or heating contribution depends strongly on the sky view factor, surrounding surface temperature, and urban geometry. In dense urban canyons, a reduced sky view can weaken radiative heat dissipation to the sky, while warm ground and nearby building surfaces may increase long-wave radiative heat input to the window[47, 48]. Moreover, facade windows receive both direct and diffuse solar radiation. Under cloudy conditions or in dense urban environments, diffuse sky radiation and multiple reflections from surrounding surfaces can become important components of the total solar input[49]. For angle-sensitive coatings, photonic structures, multilayer resonators, and anisotropic systems, the response measured under a single direct incident angle may therefore not represent the effective performance under mixed direct and diffuse irradiation.

Second, thermal evaluation should include coupled heat-transfer pathways. A window exchanges energy through transmitted solar radiation, absorbed solar radiation, mid-infrared emission, convection, conduction through the glazing, and radiation with indoor and outdoor surfaces. Measuring only surface temperature under outdoor sunlight may be misleading because the result strongly depends on wind, mounting configuration, back insulation, and sky conditions. Future research should provide boundary conditions clearly, including ambient temperature, wind speed, humidity, solar irradiance, sample tilt, sky condition, and indoor-side heat-transfer assumptions[50]. If possible, experiments should be paired with heat-transfer models or building-energy simulations.

Third, a useful future metric could be climate-weighted energy performance. Instead of reporting only the modulation value, a comprehensive evaluation across representative weather files and orientations should be conducted. The output would include annual or seasonal heating, cooling, and lighting energy change relative to a reference glazing. This approach would reveal whether a material is broadly useful or only effective under a narrow range of conditions.

Fourth, a fairer comparison between passive and active devices should be made, because active devices may have better adaptability but require power, sensors, and control systems. Standardized durability and safety tests are also needed. Studies should specify cycling number, voltage window, temperature range, humidity exposure, ultraviolet dose, haze change, color shift, leakage risk, and failure mode. These practical metrics are essential for translating prototypes into deployable building components.

5 Conclusions and outlook

MBRSWs offer a promising route to reduce building energy use by coordinating VIS daylighting, NIR solar heat regulation, and MIR thermal radiation control. The field has moved beyond simple tinting toward sophisticated optical and thermal functions. However, the next step should no longer be merely to pursue greater modulation magnitudes under ideal laboratory testing conditions. Further challenges were in maintaining stable and dependable performance during practical operation, where solar irradiance, ambient temperature, wind speed, air humidity, atmospheric sky radiation, building facade orientation, and user thermal demands dynamically fluctuate. Therefore, we emphasized an environment-adaptive design framework for MBRSWs. At the materials level, smart windows should combine spectral selectivity, angular dependence, adaptive emissivity, and long-term stability. At the device level, multilayer coupling, large-area uniformity, encapsulation, switching control, and durability should be considered from the beginning. At the evaluation level, normal-incidence spectra should be supplemented by angle-resolved, temperature-dependent, outdoor, and climate-weighted tests. Looking forward, the value of MBRSWs will depend not only on material novelty but also on how intelligently they respond to local climate and building operation. By connecting materials innovation with realistic environmental evaluation, next-generation smart windows can contribute more effectively to low-carbon buildings and global energy sustainability.

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Data availability

Not applicable.

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Author contributions

Y. H. conceived the main idea of this perspective. Y. H., K. W., and Z. G. wrote the paper. S. Z., Z. Z., F. L., R. L., L. F., W. S., S. T., and Y. W. carried out the data collection. R. Z. supervised the project. Y. H., K. W., and Z. G. contributed equally to this work.

Competing interests

The authors declare that they have no competing interests.

Use of AI statement

None.