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Literature review of solar control smart building glazing: Technologies, performance, and research insights

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ABSTRACT

Conventional glazing, typically exhibits poor performance characterized by high thermal losses, overheating and potential glare, thereby compromising both building energy efficiency and occupants' comfort. In response, the scientific community has been actively engaged in researching and developing innovative glazing solutions capable to adapt to environmental conditions and even produce energy, such as smart glazing. This paper provides a comprehensive literature review of the performance of solar control smart glazing solutions installed on building façades. First, the smart glazing technologies covered in this review are introduced: photochromic, thermochromic, phase change, gasochromic, electrochromic, suspended particles and liquid crystals. Subsequently, research studies on these technologies are carefully analyzed to identify the type of glazing, climate and energy and comfort performance outcomes. The studies covered include tropical, arid, temperate and continental climates. The findings highlight that electrochromic and thermochromic glazing solutions are the most extensively studied, achieving notable energy savings and improvement of indoor comfort. Photochromic, suspended particles and liquid crystals glazing increase visual comfort, while studies on gasochromic glazing are scarce, though they report energy savings. Finally, this review identifies research gaps and emphasizes the need for future studies that holistically assess the energy, comfort, economic and environmental aspects of these glazing solutions under different climates.

1. Introduction

The significant increase of the global energy demand in the last decades [1], driven by the sharp growth of the world's population [2], underscores the necessity of the implementation of green strategies necessary to promote a sustainable and efficient energy use.

Buildings are a key sector (Fig. 1a) for reducing energy consumption and mitigate climate change, since they are accounted for a large fraction of global energy consumption and CO_2 emissions [3]. This sector comprises the energy used for construction, HVAC, lighting, appliances and equipment installed in residential and non-residential buildings.

Building façades, which act as an interface between the indoor and outdoor environments [4,5], ensure support, control of heat and mass transfer, aesthetics and occupant's health and safety. However, most existing buildings are equipped with passive façade systems exhibiting a poor energy performance [6,7] because of higher heat losses during cold months and heat gains during hot months that place excessive demand on climatization systems to achieve thermal comfort. As a result, research has increasingly focused on developing new façade systems [8,9] and materials with a more flexible behavior aimed at achieving nearly zero buildings' net energy consumption while promoting indoor comfort and urban sustainability.

Glazed elements allow buildings benefiting from daylight and a view towards the outdoor, thereby reducing the demand for artificial lighting and enhancing occupants' wellbeing [10,11]. However, conventional glazed elements are usually responsible for higher heat exchanges than opaque elements and can cause glare discomfort due to excessive illuminance levels [12–15]. Traditional shading systems such as blinds,

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louvers, and shutters can mitigate these issues but often lack adaptability to environmental stimuli, resulting in suboptimal energy and daylighting performances. Dynamic shading systems, which are more flexible, can overcome this drawback but often depend on complex control mechanisms thar can be susceptible to operational inefficiency and/or user dissatisfaction. Furthermore, both types of shading systems obstruct outdoor view, may require significant space for installation and interfere with the aesthetic of the building.

Considering that highly glazed façades are promoted by worldwide architectural trends, it is crucial to improve building glazing properties [16]. As a result, the investigation and development of modern and highly innovative glazing technologies [17,18] with a better performance than conventional glazing have been promoted in recent decades, with smart glass market projections showing a continuous and sharp growth in the future (Fig. 1b). These modern technologies [19,20] can control the light and radiation levels that pass through the glazing, adapting to environmental conditions and even at times offering new functions such as energy transformation [21], self-cleaning [22], heat storage [23] and anti-reflection [24]. However, challenges such as high costs, complex installation, technical performance limitations, climate suitability, environmental impact and market acceptance remain critical barriers to their widespread adoption.

This review aims to address these challenges by collecting and analyzing existing research studies on the performance of solar control smart glazing to help characterize the performance of established technologies. While numerous studies have explored this topic, organizing and synthesizing the available knowledge is essential to better understand these technologies' performance and identify research gaps to guide future research.

This work presents a literature review of the performance of solar control smart glazing installed on building façades which consists of: i) a brief overview of the evolution from conventional glazing to smart glazing; ii) an introduction and characterization of the smart glazing technologies covered in this review; iii) an extensive literature review of existing studies that analyze the performance of smart building control smart glazing; iv) a discussion of the methodology and results of the reported studies; v) and, at last, the main conclusions with recommendations for future studies on the subject. The scope of this review focuses on smart glazing technologies that are specifically designed for solar control purposes, excluding shading systems solutions.

The added value of this work lies in its critical analysis of existing research focused on assessing the performance of solar control smart glazing when integrated into building façades, including a comparison of research approaches, climate and smart glazing solutions covered, and energy and comfort performance outcomes. Specifically, this review addresses the following research questions: i) "How do different types of solar control smart glazing technologies perform in terms of energy savings, visual comfort, and thermal comfort?"; ii) "What are the

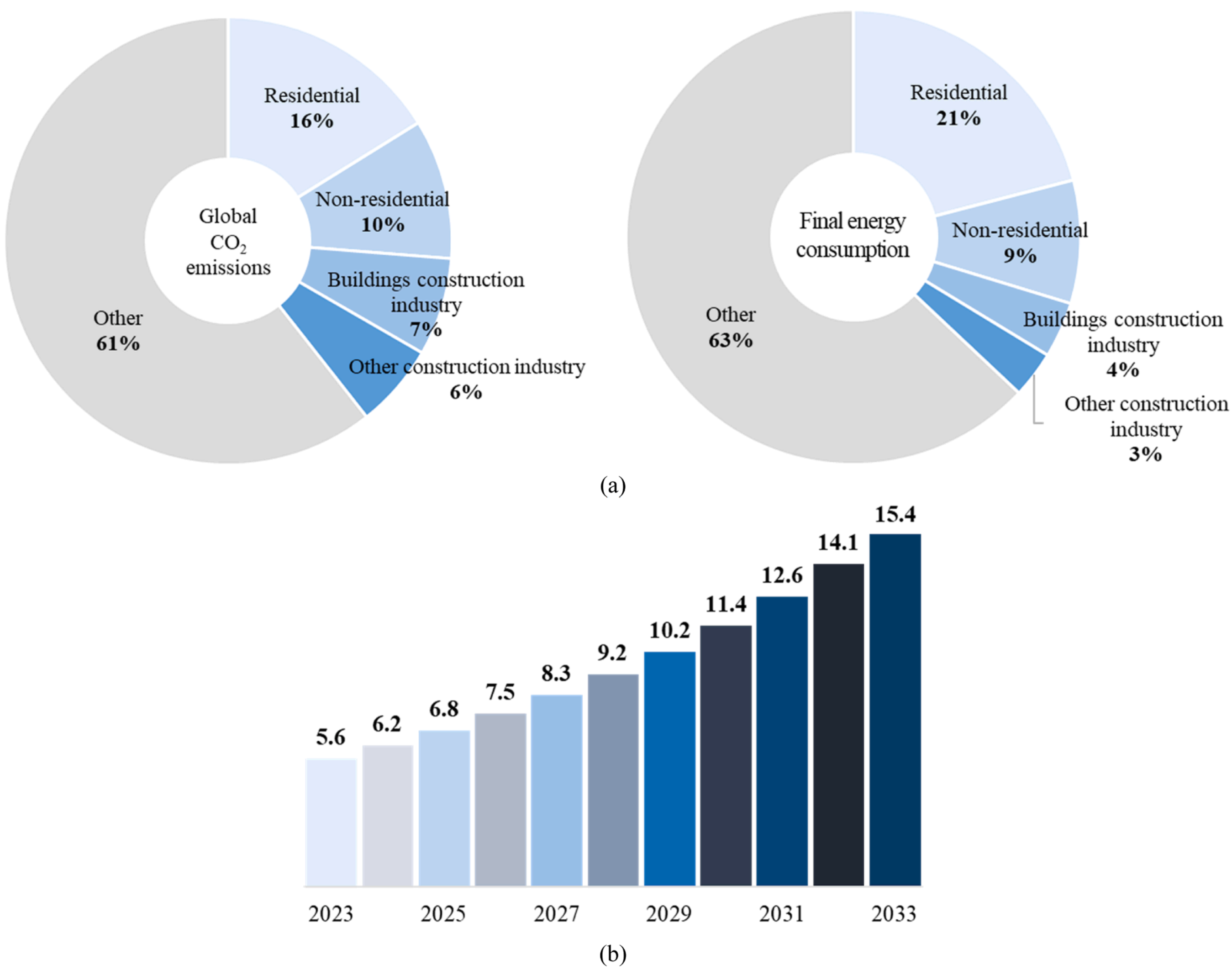

Fig. 1. (a) Share of buildings, in percentage, in the total final energy consumption (left) and global CO_2 emissions (right) relative to other sectors in 2022 (data from IEA [25]); (b) Global smart glass market size projection, in USD billion, from 2023 to 2033 (data from Precedence Research [26]).

advantages and disadvantages of each technology?"; iii) "What are the most common methodology approaches to assess the performance of solar control smart glazing technologies?"; iv) "What are the existing research gaps and the future research directions needed to improve the state of knowledge?".

2. From conventional glazing to smart glazing

This section sets up a quick overview of the evolution of building glazing, from conventional glazing to smart glazing. The building glazing industry has experienced a constant evolution with multiple and important breakthroughs in materials, functionalities and technologies. Fig. 2 shows a simplified timeline of the evolution of building glazing.

In primitive times, windows were just holes in walls that were later covered with materials such as cloth, wood or paper [27]. With the aim of providing daylight, a view towards the outdoor and an aesthetic appeal, while protecting occupants from extreme environmental conditions, the incorporation of glass in architectural design of building windows was promoted. The Romans used cast glass windows in Alexandria in the second century AD [28]. Until de 17th century, large disks of crown glass were cut to produce window glass. Larger window glass sheets were produced by blowing large cylinders that were initially cut and flattened, and then cut into panes. In the early 19th century, window glass was usually manufactured through the cylinder method, which limited the width of the produced glass panes and resulted in windows that were divided by transoms into rectangular panels [29]. A continuous ribbon of flat window glass formed between rollers was patented in 1848 by Engineer Henry Bessemer [30] and was the early advances in automated window glass production. Nevertheless, the process was considered expensive as the glass surfaces needed polishing. Attempts to manufacture flat window glass were made by using a molten tin bath or by casting a large puddle of glass into an iron surface, but these processes were considered unworkable and costly [27]. The first successful commercial application to manufacture a continuous ribbon of glass was developed in the mid-20th century by Sir Alastair Pilkington and Kenneth Bickerstaff [31] by using a molten tin bath where the glass flows unhindered under the influence of gravity and is flattened by its own weight. The development of this float process led to the rapid growth of the production of high-quality window glass and is the standard glass production method until nowadays.

In the early stages of building glazing application, single-pane clear uncoated glazing was predominant in building construction [29]. However, while this type of glazing is effective in providing daylight due to its high visible transmittance, it presents a deficient thermal insulation that often results in discomfort conditions and an inefficient use of energy. Nowadays, the use of this type of glazing is limited to low-cost solutions or to cases of retrofitting of historical buildings with window frames not thick enough to accommodate double glazing systems.

During the glass production process, metal components can be added to clear glass to produce colored glazing (most common: cobalt – blue, green, pink; selenium – pink, red; iron – green, brown, blue). The ratio of these coloring components affects the color and optical properties of the glazing, aiming to reduce its visible and solar transmittances by increasing its solar absorption [32]. These increase of the solar absorption of the glazing results in a high solar heat gain coefficient since the absorbed radiant energy by the glass is transformed into heat, raising the glass temperature, and then is reemitted towards the indoor environment. As a result, colored glazing does not have a high performance. Other than providing solar control, colored glass can also be an important architectural element for the aesthetical appearance of building façades.

The absorption of solar radiation by glazing increases its temperature and results in reradiation of heat (infrared wavelength) towards the indoor environment, which is typically undesired. This heat exchange can be avoided by applying a low-emissivity (low-e) coating to a clear glazing during the manufacturing process. Low-e coatings can be made of doped metal oxides (hard-coat low-e) or metal-based stacks (soft-coat low-e) [32,33]. Doped metal oxides are less expensive and can be deposited onto the glazing by spray pyrolysis after the float process, being more suited for thermal insulation in cold climates. Metal-based stacks are more expensive and comprise thin film stacks whose deposition onto the glazing requires advanced equipment for the production (like sputtering with high vacuum) and thickness control, being more versatile and suited for solar control or thermal insulation. Hard-coat low-e coatings promote higher energy savings than soft-coat low-e [32]. The optical properties of low-e coatings are adjusted so the coating presents a high reflectance of infrared radiation and a high transmittance of visible radiation, while maintaining very low emissivity. If the transition from high transmittance to high reflectance of a low-e glazing occurs at wavelength $\lambda \approx 0.7$ μm, the coating is intended for solar control, as it aims to reject the solar infrared spectrum [27]. Conversely, if the transition occurs at $\lambda \approx 1.2$ μm to transmit the solar infrared, the coating is intended for thermal insulation [27]. Low-emissivity glazing is suitable for temperate climate conditions where solar gains are desirable but heat losses through the glazing must be minimized. When considering a double-glazed unit, the low-e coating is usually applied to the exterior surface of the interior pane to optimize solar gains or applied to the interior surface of the exterior pane to be more efficient on reflecting solar radiation towards the outdoors [16].

Other types of solar control coatings can be applied to clear glazing during the manufacturing process such as reflective or spectrally selective coatings [34,35]. Reflective coatings usually consist of a thin layer of metallic or metal oxides that give a mirror-like appealing appearance to the glazing (typically with metallic colors such as silver, bronze, and gold). Reflective coatings based on noble metals must be added to the internal glass surfaces in contact with the air gap to be protected by sealing in cavity, while others are more durable and resistant and can be added on exposed glass surfaces [27]. Reflective glazing aims at reducing excessive solar radiation levels transmitted through the glass by reflection, preventing indoor over-heating and potential glare. However, similar to colored glazing, the transmittance of reflective glazing decreases more significantly than its solar heat gain coefficient. The incorporation of this type of glazing into façades is limited by the sun mirror effect that can cause disturbances on buildings, roads and people in the surrounding area [36–38]. In addition, highly reflective glazing systems are not suitable for spaces where daylighting is desirable [39]. Spectrally selective coatings are recommended for these cases since they aim at reducing excessive solar gains, while maintaining high transmittance levels of visible radiation [16]. Contrary to low-e coatings that aim at reducing heat exchanges through the glazing by reflecting infrared radiation, reducing the U-value and increasing thermal insulation, reflective coatings aim at reducing solar gains by reflecting

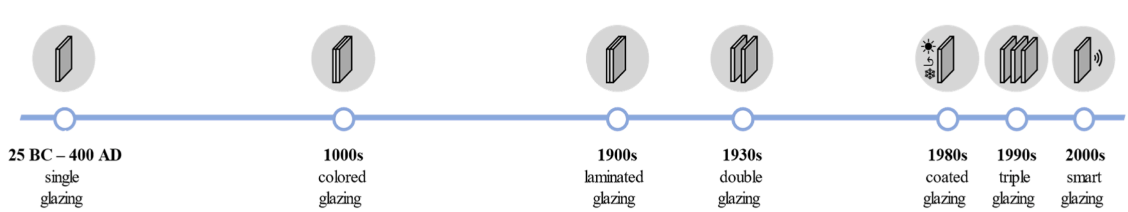

Fig. 2. Timeline of building glazing.

visible and near infrared radiation, reducing the solar heat gain coefficient of the glazing. These coatings also differ in terms of appearance, since low-e coatings are usually near transparent while reflective coatings have a metalized appearance. Regarding climate conditions, low-e coatings are more suitable for cold or temperate climates where both heating and cooling energies efficiency is needed, while reflective coatings are suitable for hot climates where the reduction of cooling energy needs is a priority.

The combination of multiple glass layers, usually double or triple glass panes, separated by sealed cavities that are filled with air or inert gases (typically argon, krypton, or xenon) presents a better thermal performance than single glazing, with improved thermal insulation and desirable transmittance and heat gains [40,41]. Spacers, which act as sealants of air and moisture in the sealed cavities, are developed to accommodate the thermal stress and differential expansion of the multiple glass panes [42]. The reduction of heat transfer through a glazing cavity can be achieved by thermal conductance of the air/gas in case of a narrow gap or by convection in case of a larger gap. The use of inert gases promotes larger relative changes in the thermal transmittance coefficient, when compared to air filled cavities. However, the retention of these gases can be challenging since they tend to diffuse through the seals and microcracks in the sealing materials when ageing and degradation of the window starts to occur [42], strongly depending on the design and construction quality, on the used materials and on the assembly techniques. A double clear glazing presents a significantly reduced thermal transmittance coefficient (approximately 50 %) and a slightly reduced solar heat gain coefficient (approximately 10 %), when compared to a single clear glazing [27]. If a greater reduction of solar gains is desired, colored, and reflective glass panes can be utilized. A double low-e glazing presents a halved thermal transmittance coefficient compared to double clear glazing. However, in heating-dominated climates, double glazing systems often prove insufficient to mitigate thermal losses adequately, leading to the incorporation of triple (or quadruple) glazing systems that have significantly low thermal transmittance values (down to 0.6 W/m2 K [27]). In triple or quadruple glazing systems, gases such as krypton or xenon are utilized as filling gases to reduce the total width of the window assembly, since these gases allow positioning the glass panes at shorter distances from each other.

Fig. 3 shows the transmittance spectra of typically used single (clear, colored, and reflective) and double (clear, colored, low-e, and selective low-e) glazing systems, as generated by Optics [43] software. The transmittance of the clear glazing systems is high across all spectrum regions (UV, visible and infrared), apart from the dip at approximately 1 µm due to the presence of iron oxide (Fe_2O_3) in the glass. In contrast, the transmittance of the low-e double glazing systems exhibits high transmittance values in the visible range but lower transmittance in the infrared region. This decrease of transmittance of thermal radiation is more significant for the selective low-e glazing. The reflective glazing shows the lowest visible transmittance, as illustrated in Fig. 3.

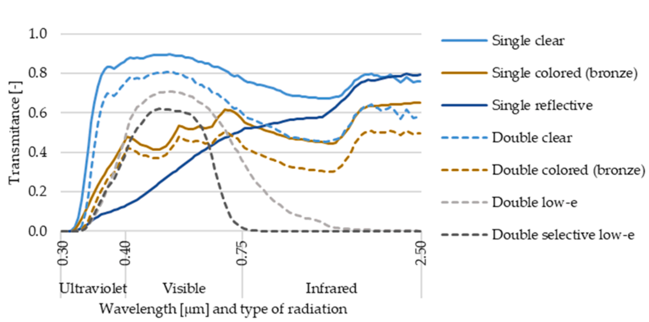

Fig. 3. Transmittance spectra of single (clear, colored, reflective) and double (clear, colored, low-e, selective low-e) glazing systems (6mm thickness glass and 12 mm thickness air gap) commonly incorporated into building façades. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The desire of achieving a balance between multiple performance requirements in a single glazing solution has promoted the development of smart glazing systems that integrate smart materials [44]. Smart materials can have intrinsic or extrinsic control mechanisms that sense stimulus and respond by adapting to transient environmental conditions, reverting to their original state when the stimulus or control is removed [45–47]. Contrary to traditional materials, smart materials present the following characteristics: immediacy, since they respond in real time to stimuli; transiency, since they respond to various environmental states; self-actuation, since their ability to react to stimuli is internal to the material itself; selectivity, since their reaction is discrete and predictable; directness, since their reaction is internal to the stimuli triggering it [44].

Depending on the type of reaction to stimuli, these materials can be divided in property-changing and energy-exchanging materials [44]. Property-changing smart materials autonomously and reversible change one or more of their (mechanical, chemical, optical, electrical, magnetic or thermal) properties, with no extrinsic control needed, in response to a stimulus. Energy-exchanging smart materials are able to convert input energy into another form of energy in accordance with the first law of thermodynamics, in a direct and sometimes reversible way (bidirectional energy-exchanging smart materials).

According to the type of reaction control, smart materials can be classified in passive or active materials [48]. Passive materials independently respond to environmental stimuli. This type of materials can have as drawback the absence of control by the user since they have an intrinsic control. Active smart materials can be directly controlled by the users, responding to their needs, or be part of a computerized building management system, where they rely on an energy source to respond to variations in environmental stimuli (Fig. 4).

Smart materials exist at the micro and nanoscale [49]. The integration of smart materials into building glazing to change the glass properties improves the chemical, physical and mechanical performance of the glazing, since the combination of smart materials can be used to form a system able to satisfy multiple purposes, such as thermal comfort, visual comfort and energy efficiency [50]. Although there is a large variety of smart materials, not all can be applied to building glazing (smart glazing technologies). The most common types of smart glazing materials [20,48,51,52], grouped by type of reaction to stimuli and respective stimulus and reaction, are presented in Table 1.

The optical and/or thermal properties of property-changing smart glazing technologies can be actively or passively modulated. Gasochromic, electrochromic, suspended particles and polymer dispersed liquid crystals smart glazing technologies show an active type of reaction control. On the other hand, photochromic, thermochromic and phase change smart glazing technologies have a passive type of reaction control. This property modulation alters the levels of daylight and solar heat gains that are transmitted indoors by responding to a specific stimulus such as temperature, solar radiation, electric tension, and gas concentration [20].

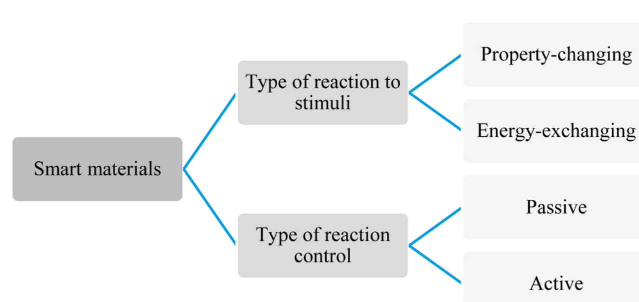

Fig. 4. Classification of smart materials.

Table 1
Most common types of smart glazing materials and corresponding stimulus and reaction.

Type of reaction to stimuli Smart glazing material	Stimulus		Reaction	
Property-changing				
Photochromic		Solar radiation	■⇔□	Color change
Thermochromic		Temperature	■⇔□	Color change
Phase change		Temperature	⇔□	Phase change
Gasochromic		Concentration of pumped gas	■⇔□	Color change
Electrochromic		Electrical tension	■⇔□	Color change
Suspended particles		Electrical tension	■⇔□	Color change
Polymer dispersed liquid crystals		Electrical tension	■⇔□	Color change
Energy-exchanging				
Photovoltaic		Solar radiation		Electrical tension

In the case of photochromic, thermochromic, gasochromic, electrochromic, suspended particles and polymer dispersed liquid crystals smart glazing technologies, the reaction to stimuli manifests as change in color. These smart glazing technologies can be referred as chromogenic and can reversibly switch between a transparent/clear state and a (absorptive or reflective) colored/dark state, and sometimes intermediate states [53,54]. A high dynamic spectral modulation, consisting of the ratio between the transmittance values of the clear and dark states, is usually considered desirable for chromogenic glazing technologies, providing a more flexible dynamic control and being associated with a higher ability of the glazing to alter its properties and meet the occupants' desired conditions [55]. It is important to note that the dynamic coloration of these glazing technologies can result in the overheating of the glazing due to a higher solar absorption, and in the extreme cases, it may lead to thermal breakage. Due to the chromatic change, chromogenic glazing technologies greatly affect the spectra of visible radiation transmitted towards indoors, negatively affecting color rendition and promoting a desaturated color appearance, particularly in dark states (lower transmittance) [56]. The kinetics of the modulation of chromogenic glazing technologies is expressed by its response time, which is representative of the time required to activate the transition between different states, usually varying between 10 s to 5 min [55].

Energy-exchanging smart glazing technologies, such as photovoltaic, are able to convert solar energy into electricity. Photovoltaic glazing, which has solar cells laminated between two glass panes, can be installed in buildings to harvest solar energy, aiming to reduce the energy consumption and emissions of the building [18].

Smart glazing technologies have different characteristics and performances, making each of them suitable for specific applications. Fig. 5 shows the main smart glazing technologies organized by their purpose, type of reaction to stimuli and type of reaction control.

The focus of this review is on established smart glazing technologies aimed at providing solar control, such as photochromic, thermochromic, phase change, electrochromic, gasochromic, suspended particles and polymer dispersed liquid crystals, all described in detail in the next section.

3. Solar control smart glazing

Solar control smart glazing aims at reducing cooling loads during hot months, increasing passive solar heat gains during cold months, improving daylight exploitation and reducing potential glare, while maintaining an unobstructed view of the outdoor environment. This section consists of a description of the established main solar control smart glazing technologies for installation on building façades with passive control (photochromic, thermochromic, phase change materials) or active control (gasochromic, electrochromic, suspended particles, polymer dispersed liquid crystals), represented in Fig. 6 and Fig. 7, respectively.

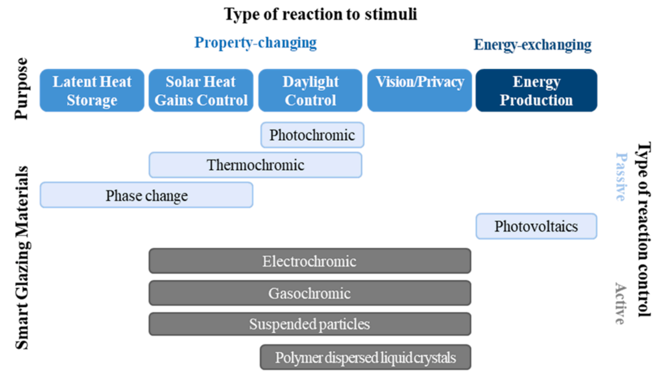

Fig. 5. Main smart glazing technologies organized by type of reaction to stimuli, purpose and type of reaction control.

3.1. Photochromic

Photochromic (PC) glazing (Fig. 6a) autonomously reacts mainly to ultraviolet (UV) radiation due to the incorporation of photosensitive crystals [57,58], which appear colorless in their inactivated form, in the photochromic layer. These inorganic crystals, which allow easy color control of the glazing by changing light intensity [51], are generally embedded into host matrices such as polymers or ceramics [59]. UV radiation breaks down the molecular structure of the photosensitive crystals, altering it into an excited state, and thus increasing the absorption of visible radiation, darkening the glazing [60,61]. The darkening process occurs in seconds to a few minutes. The chromatic transition is reversed in the absence of UV radiation, taking a longer time than the transition from clear to dark.

Different transition times, potential presence of shading and rapid and frequent changes in outdoor radiation intensity can originate visual problems with this type of glazing such as uneven areas of shadow and light in the indoor environment. It is also important to note that, due to the increase of absorption of the glazing in its colored state, intense solar radiation levels can cause an overheating phenomenon and lead to glass rupture because of thermal shock. An efficient PC glazing should present a high dynamic spectral modulation, a fast reversible darkening process, and an acceptable photochemical stability [51,59]. PC glazing may not be suitable for four-seasoned climates since it could impede solar heat gains through the glazing in its dark state during winter.

Currently, PC glazing is rarely used in architecture because of the lack of ability of control by the user, the manufacturing cost and the difficulty in achieving a uniform distribution of the photochromic material in the glass pane [20]. The gradual loss of the reversibility of the chromatic change over time is also a major drawback of this smart glazing technology. The market for this solar control smart glazing technology in building applications is limited with few manufacturers, such as ICESUN Vacuum Glass Ltd. that manufactures PC vacuum glass solutions. Additionally, it is possible to install PC window films for retrofitting existing glazing systems, with companies like CoolVu [62] and SolarScreen [63] providing different film options.

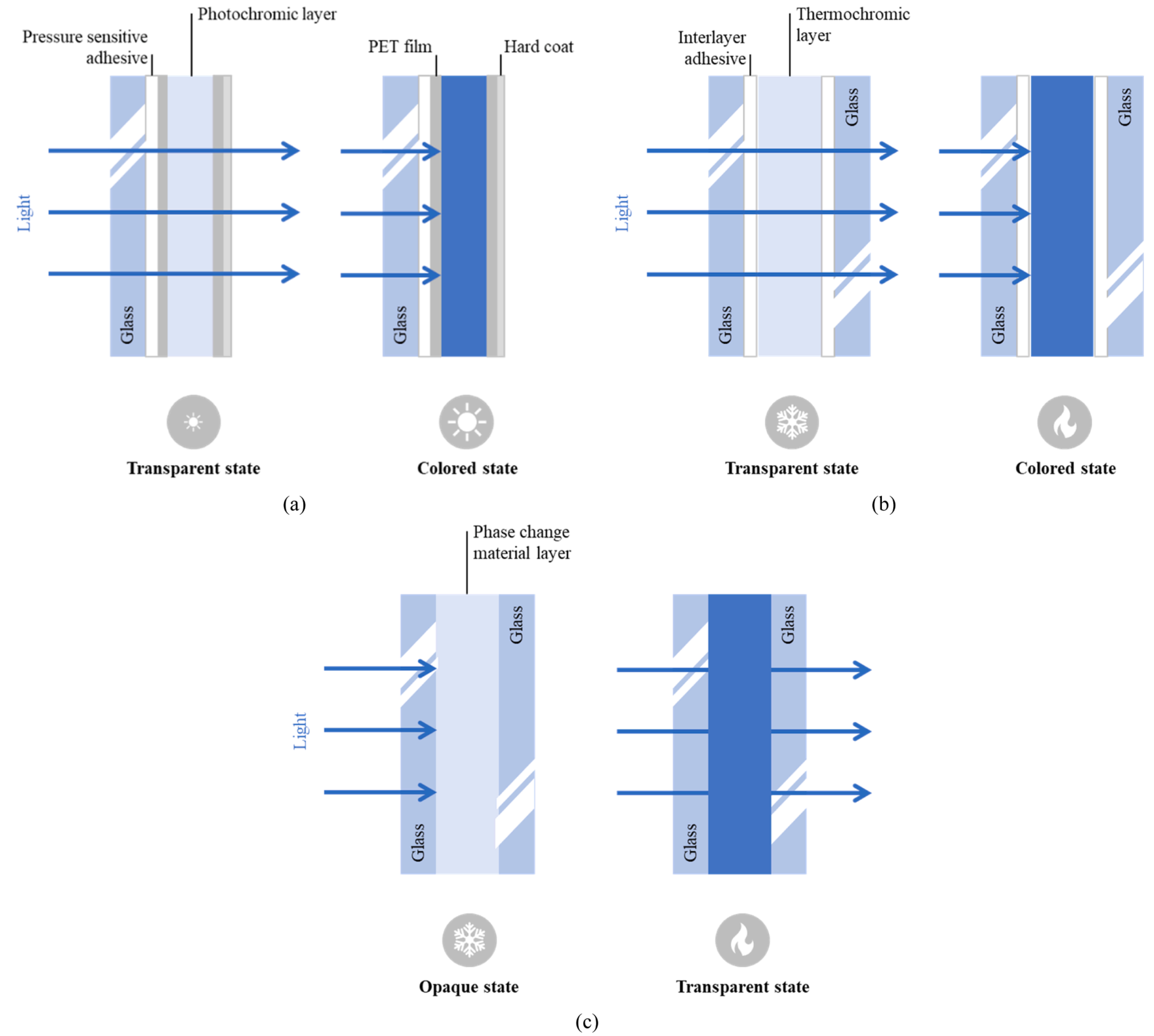

Fig. 6. Schematic illustration (dimensions not in scale) of the main passive smart glazing technologies: (a) Photochromic; (b) Thermochromic; (c) Phase change materials.

3.2. *Thermochromic*

Thermochromic (TC) glazing (Fig. 6b) autonomously alters its optical properties due to the temperature variation of a thin layer of a TC material laminated between two glass panels [64,65]. When the TC material reaches temperature values higher than a specific critical (transition) temperature, a chemical reaction is induced that increases the tinted state of the glazing, changing the TC glazing transmittance properties and reducing solar heat gains through the window [27,66]. If the temperature values are lower than the transition temperature, the TC glazing is visually and infrared transparent [20,66]. Between the totally clear and totally dark states, the glazing transmittance varies continuously [67].

TC materials for smart windows, which can be organic or inorganic [68], have undergone rapid development, with several types being successfully applied such as: vanadium dioxide (VO2); hydrogels; ionic liquids; liquid crystals; and perovskites [51,69]. Vanadium dioxide is the most studied and common TC material used in glazing solutions, which exists under six crystallographic structures and undergoes a reversible crystal phase transition of first order at the transition temperature of, approximately, 68 °C from monoclinic to tetragonal phase [70]. This transition, which occurs in 10 to 12 s [68], results in an increase of the absorbance in the near infrared, but negligible alteration in the ultraviolet and visible spectrum. In order to reduce the transition temperature and increase the visible transmittance and solar modulation of planar VO2 films, various methods have been developed [51]: inclusion of dopants; introduction of porosity or multilayer structures; incorporation of nanoparticles in nanocomposites; preparation of biomimetic or griding structures. Tungsten is the most effective dopant to reduce transition temperature [71].

The dynamic behavior of TC glazing helps minimizing solar heat gains and glare problems, maximizing daylighting and increasing occupants' comfort [20,64]. The fact that TC glazing is purely materials-driven, not requiring an additional control system is usually considered as an advantage [51]. Nevertheless, for cases where control by occupants is desirable, it acts as a disadvantage to wider acceptance.

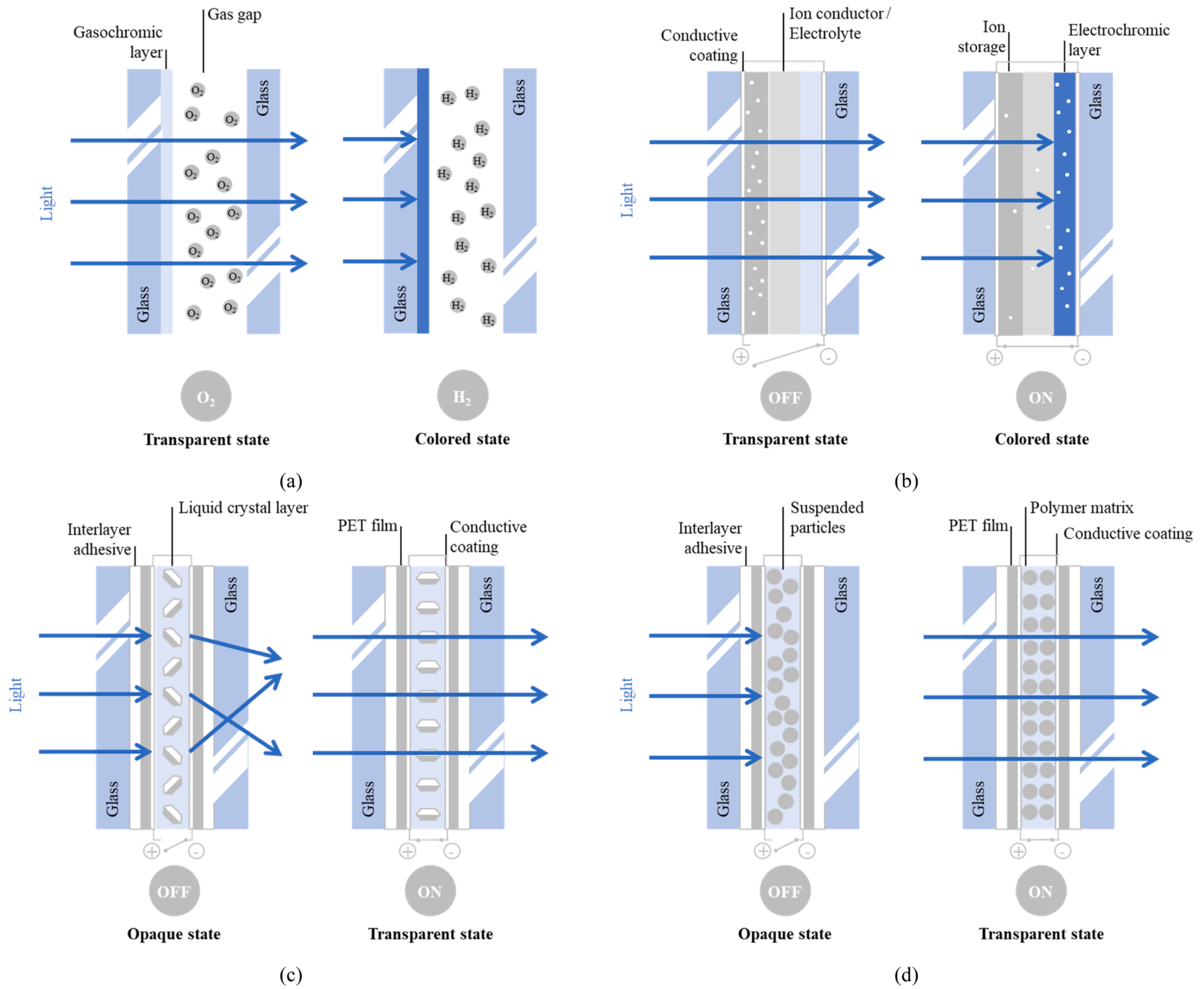

Fig. 7. Schematic illustration (dimensions not in scale) of the main active smart glazing technologies: (a) Gasochromic; (b) Electrochromic; (c) Polymer dispersed liquid crystals; (d) Suspended particles.

Manufacturers such as Suntuitive by Pleotint [72] and RavenWindow [73] offer commercially available TC glazing products that have been installed in more than 500 residential and commercial buildings, in 36 countries, to enhance energy efficiency and occupant comfort.

3.3. Phase change materials

Phase change materials (PCMs) can absorb, store and release latent heat in an endothermic/exothermic process, changing their physical state between solid and liquid [20,74]. In the solid state PCMs are opaque, becoming transparent in the liquid state [68]. The melting temperature of PCMs used in glazing solutions should be close to occupants' thermal comfort conditions [20]. The solar heat gains transmitted through a glazing system filled with PCMs (Fig. 6c) are reduced since the absorption of solar heat gains by the PCMs incorporated between two glass panes provides the latent heat necessary for the phase change (transition from opaque to transparent) [75]. When in the liquid state, PCM glazing has the potential to store considerable amounts of energy [76,77], releasing the stored heat when temperatures drop (usually at nighttime). The increase of the latent heat capacity and reduction of the phase transition temperature have a positive impact on the thermal performance of PCM glazing [78,79].

PCMs incorporated into building glazing can be organic (such as paraffin), inorganic (such as metallics and salt-hydrates), or eutectics (mixture of organic and inorganic PCMs), and be categorized as integrated or micro and macro encapsulated [80]. Among multiple PCMs, paraffin has become a relevant option because of its affordability, high latent heat capacity and wide phase transition temperature ranges [74,77]. PCM glazing with paraffin wax in the sealed cavity has been developed and assessed, presenting a nominal melting temperature of 35 °C and a heat storage capacity of 170J/g, considering a temperature range between 26 °C and 41 °C [81,82]. The ultraviolet and infrared transmittance of PCM glazing with paraffin is significantly reduced, while keeping a satisfactory visibility [77]. The phase state of paraffin strongly affects the optical properties (visible transmittance in liquid state: 90 %; visible transmittance in solid state: 40 % [83]) and the energy transmittance of the PCM glazing, consequently influencing its thermal performance [77,83,84]. PCM glazing solutions currently available on the market comprise salt hydrates completely sealed in a clear polycarbonate and claim to reduce average indoor air room temperature by 5 °C to 9 °C [85].

PCM glazing working principle makes it possible to shift the peak energy demand from midday, when solar heat gains are usually higher, to afternoon/night period [68]. Reduction of the interior surface temperature of PCM glazing has also been reported [86,87]. However, it presents the following disadvantages [20]: risk of overheating, possible paraffin leakage and phase segregation impeded by salt hydrates.

PCM glazing is primarily in the research and development phase, with commercial products not yet prevalent. However, GlassX [88] is a PCM glazing developed by the Swiss company GlassX AG and manufactured by Saint-Gobain that is available is various configurations and has been installed in at least 25 buildings (such as multi-family housing, retirement homes, offices).

3.4. Gasochromic

Gasochromic (GC) glazing (Fig. 7a) usually consists of a double-glazed unit (DGU) with a pane of glass coated with a thin gasochromic layer that changes its properties when exposed to a specific gas. Monocrystalline, polycrystalline, and amorphous GC layers are available, with amorphous films showing the best GC properties [89]. The gasochromic layer (less than 1 μm thick [90]), usually made of tungsten oxide (WO3) coated with a catalyst (usually platinum or palladium [68]) layer that breaks down H2 into H+ ions, undergoes a chemical reduction transforming into tungsten bronze (HWOx) and darkens when exposed to a low concentration of diluted hydrogen gas (mixed with argon or nitrogen gas to stabilize the compound and improve thermal insulation [90]) that is injected into the gap of the DGU [91,92]. Alternative gasochromic materials such as nickel oxide (NiO) and magnesium alloys can also be used in the gasochromic layer [50]. The transparency of the glazing varies according to the thickness of the gasochromic layer and to the volume of hydrogen that is injected [93,94]. The chromatic transition can be reversed by injecting a low concentration of oxygen into the cavity, restoring the glazing to the clear state.

Sol-gel, chemical vapor deposition, physical vapor deposition and spray pyrolysis processes are viable application methods of the GC layer, with odd-line glass treatment being preferable because of the high annealing temperature associated with online production that can alter the crystal phase and microstructure of tungsten oxide and prejudice the performance and operation of the GC glazing [90]. Improved transition times can be achieved through the optimization of the stoichiometric reaction or through the increase of the GC layer porosity. By doping tungsten oxide with silica, via a sol-gel dip-coating process, a nanoporous composite film with significantly lower transition time for coloring (from 35.21 s with WO3 to 6.75 s) and bleaching (from 13.93 s with WO3 to 2.27 s) can be obtained [95]. GC glazing is inherently stable due to its chemical operation mechanism, not requiring an electric power input to maintain a colored state, being sufficient to stop the supply of gas [90]. The hydrogen and oxygen necessary for the chemical reaction can be produced by an electrolyser with an average consumption of 12.5 W that can power multiple GC glazing systems at a time [90].

Even though the manufacturing and assembly of this smart glazing technology is simpler and cheaper than others (mainly electrochromic glazing), GC glazing implicates a more complex control. The gases are injected through a gas supply unit consisting of a pump and an electrolysis unit connected by pipes to the DGU. The electrolysis unit decomposes water that circulates in a closed cycle while the pump is working. Then, the gases are reconstituted as water in the presence of a catalyst.

Both the solar and visible transmittances of a GC glazing are approximately 76 %, in the clear state, and 5 % in the dark state, considering a typical thickness of 500 nm for the gasochromic layer and a hydrogen concentration of 1 % (far below the combustion limit of 3 %) [93]. Visible transmittance and solar heat gain coefficient of GC glazing solutions available on the market vary between 15 %–54 % and 0.28–0.65 [90], respectively. GC glazing presents a high capacity of exploiting solar heat gains during winter and a low solar protection during summer, making this smart glazing technology suitable for colder climates with warm (but not too hot) summers. Moreover, GC glazing presents a transition 10 times faster than electrochromic glazing, however, its narrower dynamic spectral modulation acts as a limitation that needs to be overcome [96].

Ongoing research is aiming at addressing challenges related to performance, durability and integration into building façades, with no recognized manufacturers currently present in the market of gasochromic windows and applications primarily limited to laboratory testing.

3.5. Electrochromic

Electrochromic (EC) glazing (Fig. 7b) can reversibly change its optical properties in the presence of an electrical stimulus (DC voltage) that promotes a modification of the visible and near-infrared transmittance of the EC device incorporated in the glazing [55,97]. Usually, this EC device is made of multiple layer coatings [90] constituted by an ion storage layer, an ion conductor layer (or electrolyte) and an electrode (EC material) layer laminated between two outer conductive coating layers made of transparent conductive oxides. The electrolytes can be in a liquid, gel, or solid state. The ions moving through the electrolyte are usually lithium or hydrogen or, more rarely, sodium. The EC materials are mainly transition metal oxides or organic materials, with tungsten trioxide (WO3) being the most widely used. The voltage applied between the electrical conductors, creates an electric field that moves coloration ions reversibly between the ion storage film through the ion conductor layer and then into the EC layer, promoting a change of color of the glazing from clear to dark in the electrode layer (cathodic coloration) or in the storage layer (anodic coloration) [55,90]. By combining cathodic and anodic coloration, coloring intensity and modulation can be enhanced, and it is possible to obtain EC glazing solutions with a neutral appearance in their tinted state [90]. In absence of the electrical stimulus, coloring ions are extracted from the EC layer, making the glazing clear again [55]. The optical modulation in EC glazing is usually associated with an increase of the absorption of the glazing, rather than reflectance [55].

The position of the EC device in double and triple glazing units can have serious implications on the thermal performance of the window [55]. In double glazing windows, the EC device should be placed in the outer pane facing the air cavity to prevent secondary heat gains and glass overheating. The EC device can also be laminated between two glass panes.

The transition time of EC glazing varies depending on the size of the glass panel, with small glass panes of 0.1 x 0.3 m taking 5 min, and larger glass panes of 1.2 × 0.8 m darkening in 12 min and bleaching in 8 min [90]. Apart from panel size, the transition time also depends on the glass temperature, increasing in the presence of lower temperature values, and differs between darkening and bleaching processes, with the bleaching process usually occurring faster. EC glazing can be controlled by occupants, in an interactive way, according to their needs, or controlled automatically by integration in the building energy management system [98].

This solar control smart glazing technology has seen significant commercial development with multiple manufacturers worldwide. View Inc. and SageGlass are the main manufacturers of electrochromic windows to be installed in buildings (mainly offices, airports, educational and cultural institutions), with the largest installation of electrochromic windows being of, approximately, 18,500 m^2 of SageGlass Harmony in an office building in India [99] to promote employee wellness and sustainability.

3.6. Suspended particles

Suspended particles (SP) glazing (Fig. 7c) comprises two glass panels within which is a thin layer of SP immersed in an organic fluid and located between two clear thin plastic films that act as electrical conductors [100]. Particles with optical properties dependent on polarization, such as polyhalite particles [20], are initially randomly oriented in the absence of electric power (AC voltage), presenting an opaque appearance that significantly reduces daylight through absorption. When electric power is applied, the SP align with the electric field, giving a clear appearance to the glazing and, consequently, making it possible to increase daylight transmission through the glass. Therefore, the transparency level of SP can modulate the transmittance of daylight and solar heat gains through the SP glazing. A typical SP glazing presents a visible transmittance and solar heat gain coefficient varying between 0.5 % (clear) to 65 % (opaque) and 0.06 (clear) to 0.57 (opaque), respectively [101]. Extremely quick transition times of 1 to 3 s, needing about 100 V AC, characterize SP glazing [20].

SP glazing, when compared to EC glazing, allows continuous control rather than a discrete one, meaning that the transmittance of the SP glazing can be tuned at multiple levels in function of the AC voltage applied. As a drawback, SP glazing requires an ongoing voltage supply to maintain the clear state, which usually translates in a higher energy consumption to control the glazing than EC.Research and development in SP glazing technology are ongoing, with widespread commercial adoption and real-world applications currently limited since few companies are exploring its potential. Gauzy SP glazing [102] has been recently launched onto the market.

3.7. Polymer dispersed liquid crystals

Polymer dispersed liquid crystals (PDLC) glazing (Fig. 7d) consists of a laminated glazing with two panes that contain a PDLC device composed of a polymer matrix thin film placed between two clear thin plastic films that act as electrical conductors. Liquid crystals (LC) spheres present in the polymer matrix film have a diameter of the same order of magnitude as the visible radiation wavelength (500 nm [18]). The LC spheres are in a random and unaligned state in the absence of electric power (AC voltage), scattering daylight and giving a translucent appearance to the glazing that provides privacy. In the presence of an electric stimuli, the LC spheres align in the same direction as the electric field, slightly increasing direct light transmittance and making possible the view in both directions [103]. Visible transmittance of PDLC glazing usually varies between 50 % (translucent) and 70 % (clear) [20].

Even though PDLC glazing can scatter daylight, it transmits most of the incident daylight in a diffuse way and, consequently, does not significantly reduce heat gains (0.39–0.53 [20]). As a result, this smart glazing technology is often installed indoors for privacy purposes, such as office glazing partitions.

The use of intermediate transparency states is not possible with PDLC glazing [90]. Similar to SP glazing, a constant voltage input is necessary to maintain PDLC glazing in the clear state, consuming on average 5–10W/m^2 of glazing surface, which is significantly higher than the energy use of EC and SP glazing technologies [20].This solar control smart glazing is available on the market, with companies like Polytronix [104] and Smartglass International [105] offering a selection of PDLC solutions with multiple designs.

4. Existing studies on the performance of solar control smart glazing

The scientific engineering databases Scopus [106], Science Direct [107], and Google Scholar [108] were searched to compile existing studies that analyze the performance of solar control smart glazing technologies applied to building façades. The following keywords were used in the literature search: “smart windows”, “energy performance”, “visual comfort”, “thermal comfort”, “photochromic glazing”, “electrochromic glazing”, “thermochromic glazing”, “PCM glazing”, “gasochromic glazing”, “liquid crystals glazing”, “suspended particles glazing”. The search focused on studies published between 2002 and early 2024. Priority was given to peer-reviewed journal articles on the performance of solar control smart glazing technologies in buildings, while conference papers on the same topic were also considered. To ensure relevance, studies focused exclusively on material development, production processes or without application in building façades were excluded. Additionally, the gathered studies were filtered based on their contributions to assessing energy performance and occupants comfort assessment. Articles that lacked sufficient data or did not explicitly address these criteria were omitted from the review. A total of 73 relevant studies were collected, which are briefly described in Table 2.

A network visualization map, generated with VOSviewer [177] software, of keyword co-occurrence is shown in Fig. 8 to help quickly identify research trends and conceptual relationships between the keywords of the gathered research studies. It is important to note that this network visualization map depends on the criteria adopted in the literature search, being a tool to understand relationships between topics of the selected studies, rather than representing the entire research field. A higher occurrence of “smart windows”, “electrochromic windows” and “visual comfort” keywords can be observed. The secondary focus of keywords like “daylighting”, “thermal comfort”, “energy savings” and “building energy efficiency” highlights the interdisciplinary nature of the topic and reflects the relevance of the selected smart glazing technologies on energy-saving strategies and occupants’ comfort.

This section presents the main findings of these studies in terms of the luminous, thermal, energy, environmental and economic performance of the focused smart glazing technologies.

4.1. Photochromic

Despite a considerable number of studies [57,178] focusing on the scientific investigation of the incorporation of PC materials into building glazing at a material scale, studies [109–111] assessing the feasibility of installing this glazing technology in buildings are scarce in the literature.

Cannavale et al. [110] evaluated the visual comfort and energy performance of a PC glazing against three static glazing systems (clear non-selective; intermediate selective; selective dark), using a dynamic simulation in EnergyPlus [179] of a multi-story office building under the climates of the cities of Brindisi (hot-summer Mediterranean climate [180]) and Milan (humid subtropical climate [180]). Cooling energy consumption was significantly reduced with the PC glazing, achieving 4079 kWh (Brindisi) and 4238 kWh (Milan) savings on the south façade, when comparing to static glazing. Moreover, artificial lighting demand reduced 3711 kWh annually with the PC glazing, compared to the static selective glazing systems. Regarding the visual comfort assessment, increases between 2 and 20 % of useful illuminance levels were obtained with the PC glazing, when compared to the static glazing solutions. The benefit of installing PC glazing is highlighted on the south façade, except when comparing to the selective dark glazing because of the spectral similarity between these two solutions. Illuminance difference was higher for the city of Milan, which has lower global horizontal radiation levels. According to the findings of the glare performance analysis, the PC glazing significantly reduced “just uncomfortable” glare levels by 12–38 % compared to static glazing, except for the selective dark glazing that was more effective than the PC glazing on glare reduction, in both cities.

Tällberg et al. [109] assessed the energy performance of a PC glazing against a static clear glazing through a dynamic simulation model of an office room, in IDA ICE software [181], under the climates of three different cities (Trondheim – continental sub-artic climate; Madrid – cold semi-arid climate; Nairobi – temperate oceanic climate [182]). The lighting and heating energy use increased with the photochromic glazing when compared to the clear glazing under all climates. With the exception of the hot climate of the city of Nairobi, the solar control capacity of the photochromic glazing promoted the reduction of the cooling energy use, when compared to the clear glazing. In terms of total energy use, a slight increase was obtained with the photochromic

Table 2
. Brief description of the existing studies on the performance of solar control smart glazing technologies applied to building façade.

Glazing technology[1]	Climate[2]	Building/ space	Solar orientation[3]	Research approach[4]			Performance assessment[5]					Comfort assessment[6]		Ref.
				Analyt.	Exp.	Sim.	Therm.	Lum.	Energy.	Environm.	Econ.	Therm.	Vis.	
PC; TC; EC	Bsk, Cfb, Dfc	Office room	S			✓			✓					[109]
PC	Cfa, Csa	Office building	E, S, W		✓	✓			✓				✓	[110]
PC	Csa	Test-room	S		✓	✓		✓	✓				✓	[111]
PC	Aw, Bwh, Cfa, Cfb, Csa	Office room	S			✓		✓	✓				✓	[112,113]
PC	Dfa	Office room	N, E, S, W			✓		✓					✓	[114]
PC	Csa	Office room	SW		✓		✓	✓				✓	✓	[115]
TC	Bwh, Cfa, Cfb, Csa, Dfb	Office room	S		✓	✓			✓					[116,117]
TC	Csa, Cfb, Dfb	Office room	SE		✓	✓	✓	✓	✓			✓	✓	[64]
TC	Bsk, Cfa, Cwa, Dfa, Dwa	Office building	N, S		✓	✓	✓		✓					[118]
TC	Cfa, Dwa	Test-room / residential	S		✓	✓			✓					[119]
TC	Cfa, Cfb	Office room	N, E, S, W		✓	✓			✓					[120]
TC	Cfa, Cfb, Cwb, Dwa	Office room	S			✓	✓	✓	✓			✓	✓	[121,122]
TC	Cfa, Cfb, Csa	Office building	N, E, S			✓	✓	✓	✓			✓	✓	[123]
TC	Aw	Office room	1°N intervals			✓	✓	✓	✓			✓	✓	[124]
TC	Cfb	Single room	N, E, S, W			✓		✓					✓	[125]
TC	Bwh, Cfa, Dfb	Office room	S		✓	✓		✓	✓				✓	[126,127]
TC	Cfa, Dfa	Test-room / office building	N, E, S, W		✓	✓	✓	✓	✓					[128]
TC	Cfa, Dfa	Office building	N, E, S, W				✓		✓					[129]
TC	Bsk, Bwh, Csa	Office building	N, E, S, W			✓			✓					[130]
PCM	Bsk	Office room	E		✓		✓	✓	✓			✓	✓	[131]
PCM	Cfa	Test-room	S	✓	✓		✓		✓					[86,87]
PCM	Dwa	Scale model	S	✓	✓		✓							[132,133]
PCM	Csa	Scale model	S		✓		✓					✓		[134]
GC	Cfa, Cwb, Dwa	Office room	S			✓		✓	✓				✓	[135]
GC; EC	Cfa, Dwa	Office building	N, E, S, W			✓			✓					[94]
GC; EC	Bwh, Cfb, Cfc, Csb	Residential building	22.5°N intervals			✓			✓					[136]
GC; EC; TC	Bwh	Office room	N, E, S, W			✓		✓	✓				✓	[137]
EC	Csa, Cfb, Dfb	Office room	SE		✓	✓	✓	✓	✓			✓	✓	[97]
EC	Bwh, Cfa, Dfa	Office building	E, S, W			✓			✓	✓	✓			[98]
EC	Csb	Office room	S			✓		✓	✓				✓	[138]
EC	Am, Cfa, Cfb, Csb, Dfa, Dfb, Dwb	Office building	N, E, S, W			✓	✓	✓	✓			✓	✓	[139]
EC	Cfa, Dfa	Office building	N, E, S, W			✓		✓	✓				✓	[140]
EC	Dwa	Office building	N, E, S, W			✓	✓		✓		✓			[141]
EC	Csb	Office room	E, S, W			✓			✓		✓			[142]
EC	Am, Bwh, Bwk, Cfa, Csa, Csb, Dfa, Dfb	Office building / apartment	N, E, S, W			✓			✓		✓			[143]
EC	Am, Bsk, Dfb	Office building	N, E, S, W			✓			✓					[144]
EC	Bsh, Bsk, Bwh, Csa	Office building	E, S, W			✓			✓					[145]
EC	Bwh, Cfb, Csa	Office rom / building	E, S; W			✓		✓	✓				✓	[146,147]

(continued on next page)

Table 2 (*continued*)

Glazing technology[1]	Climate[2]	Building/ space	Solar orientation[3]	Research approach[4]			Performance assessment[5]					Comfort assessment[6]		Ref.
				Analyt.	Exp.	Sim.	Therm.	Lum.	Energy.	Environm.	Econ.	Therm.	Vis.	
EC	Cfb, Csa	Scale model /single family house	N, E, S, W		✓	✓	✓	✓	✓				✓	[148–151]
EC	Cfb	Scale model	S		✓	✓	✓	✓				✓	✓	[152]
EC	Cfb	Test-room	N, S		✓			✓					✓	[153]
EC	Af	Test-room	W		✓		✓	✓	✓			✓	✓	[154,155]
EC	Cfa	Office room	W		✓	✓	✓		✓			✓		[156]
EC	Csb	Test-room	S		✓		✓	✓	✓					[157]
EC	Csb	Office room	SE		✓				✓				✓	[158]
EC	Csa	Test-room	SW		✓		✓		✓		✓			[159]
PDLC, EC	Dwa	Office building	E, S, W			✓		✓	✓				✓	[160,161]
PDLC, EC	Bwh	Single family house	N, E, S, W			✓			✓	✓				[162]
PDLC	Cfb	Scale model	S	✓	✓			✓					✓	[163]
PDLC	Aw, Bwh, Cwa	Office building	45°N intervals	✓	✓			✓	✓		✓			[164]
PDLC	Bwh, Cfb	Office building	N, E, S, W			✓		✓	✓				✓	[165]
PDLC	Bwh	Scale model / office building	N, E, S, W		✓	✓		✓	✓	✓			✓	[166]
PDLC	Bwh, Cfb, Csa	Test-room / office room	N, E, S, W		✓	✓	✓	✓	✓				✓	[167]
PDLC	Csa	Test-room / office building	E, S, W		✓	✓	✓		✓	✓				[168]
SP	Cfb	Scale model	S	✓	✓		✓	✓	✓	✓			✓	[169,170]
SP	Cfb	Scale model	S		✓		✓	✓				✓	✓	[171,172]
SP	Bwh	Office building	N, E, S, W			✓		✓	✓				✓	[173]
SP	Cfa, Dwa	Office building	n.a.			✓			✓					[174]
SP	Dwa	Test-room/ office room	N, E, S, W		✓	✓			✓					[175,176]

[1] Glazing technology: PC – photochromic; TC – thermochromic; EC – electrochromic; PCM – Phase change material; GC – gasochromic; PDLC – polymer dispersed liquid crystals; SP – suspended particles.

[2] Climate (Köppen-Geiger classification [165]): Af – tropical rainforest; Am – tropical monsoon; Aw - tropical savanna; Bsh - hot semi-arid; Bsk – cold semi-arid; Bwh – hot desert; Cfa – humid subtropical; Cfb – temperate oceanic; Cfc – subpolar oceanic; Csa - hot-summer Mediterranean; Csb – warm-summer Mediterranean; Cwa – monsoon-influenced humid subtropical; Cwb – subtropical highland; Dfa – hot-summer humid continental; Dfb – war-summer humid continental; Dfc – subartic climate; Dwa - monsoon-influenced hot-summer humid continental.

[3] Solar orientation: N – north; E – east; S – south; SE – southeast; W – west.

[4] Research approach: Analyt. – Analytical; Exp. – Experimental; Sim. – Computer simulation.

[5] Performance assessment: Therm. – Thermal; Lum. – Luminous; Environm. – Environmental; Econ. – Economical.

[6] Comfort assessment – Therm. – Thermal; Vis. – Visual.

glazing under all climates.

The energy performance and visual comfort of a test-room with a PC glazing were assessed by Nicoletti et al. [111] using a numerical simulation model constructed in EnergyPlus [179] and calibrated with experimental data. The performance of the dynamic glazing was compared against clear and low-e double glazing systems, under the climate of the city of Rende (hot-summer Mediterranean climate [180]) and considering different window sizes. Annual energy savings up to 9 % and 4 % were obtained with the PC glazing, comparing to clear and low-e glazing, respectively. However, for the smallest window-to-wall ratio (WWR) of 15 %, the low-e glazing is the best solution from an energy performance point of view. The presence of PC glazing made it possible to improve useful illuminance levels up to 2 % against clear glazing, and 6 % against low-e glazing, when considering small WWRs. However, for larger WWRs, the low-e glazing proved to be more effective on providing useful illuminance levels. This can be explained by the fact that the PC glazing has a low visible transmittance when incident radiation is high, which reduces excessive daylighting when it is caused by high radiation levels, however, the room becomes significantly bright when the window is too large, even at times with medium solar radiation levels, making the PC glazing a poor shield against incoming light.

The energy performance and visual comfort of an office room with five different commercial PC films installed on the glazing were assessed by Khaled et al. [112,113], using a dynamic simulation model constructed in EnergyPlus [113] and Ladybug/Honeybee tools [183]. The clear double glazing without film was used as reference. Six representative cities of a diverse range of climate types (Miami – tropical savanna; Dubai – hot desert; Houston and Tokyo – humid subtropical; Rome – hot-summer Mediterranean; Vancouver – temperate oceanic [180]) were selected by the authors. Findings showed that the PC films exhibited excellent cyclic stability and color-rendering, and quick switching times. Considering small WWRs, annual energy savings of 1–4 % were obtained with the PC films, achieving 10–14 % savings with an entirely glazed wall facing south in cooling-dominated climates with lower latitudes. In desert, tropical and subtropical climates, energy consumption was reduced by 1–14kWh/m2, whereas in temperate, subtropical climates energy consumption was reduced by 1–8kWh/m2. The lowest energy saving was obtained for Mediterranean and oceanic climates, achieving a maximum of 6kWh/m2. This high performance was obtained with the PC film with the largest spectral modulation. PC films decreased daylight autonomy, nevertheless, useful illuminance levels were improved close to the window, resulting in a more uniform

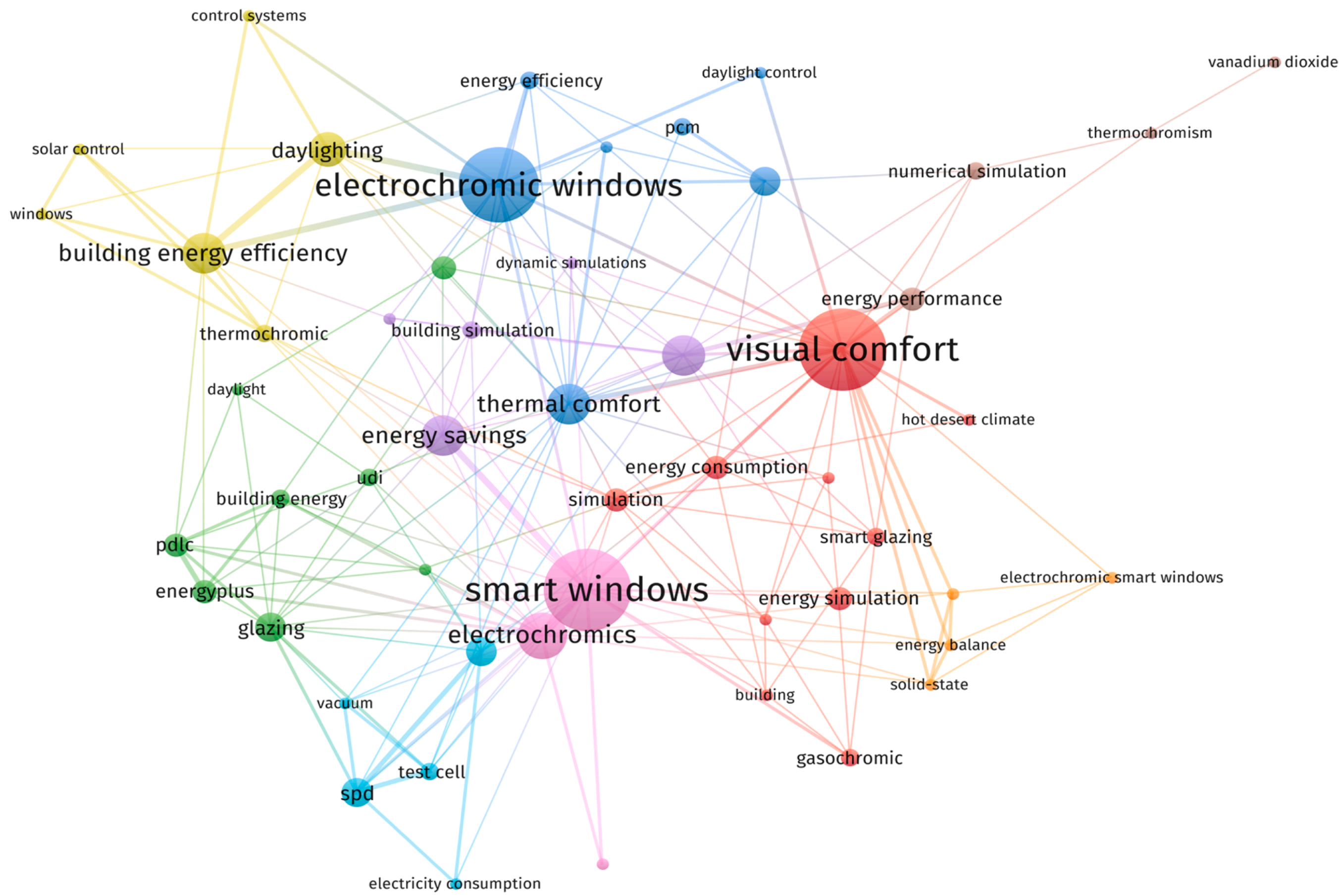

Fig. 8. Network visualization map of keyword co-occurrence for the collected studies.

distribution of light in the space. Glare autonomy increased by up to 4 % with the PC films.

The effect of nine PC coatings with different colors on the visual comfort of occupants was evaluated by Matin et al. [114], through a simulation model constructed in Rhinoceros [184] software with the Grasshopper [185] and Honeybee Legacy [183] plug-ins. Three window types (clear single, clear double, low-e double) were coated with the different PC coatings and assessed under the climate of the city of Michigan (hot-summer humid continental [180]). PC coatings with combinations of medium blue color showed the highest percentage of useful illuminance levels. The yellow PC coating has a similar performance to uncoated glass. PC red and medium blue coatings, and its combinations, had the largest impact on the reduction of discomfort glare. Considering both illuminance and glare performance, coatings with combinations of red, medium blue and yellow had shown the best performance.

4.2. Thermochromic

Existing research studies that evaluate the performance of TC glazing using a computer simulation approach [64,109,116–130,137], singly or in combination with an experimental approach [116–120,126,128, 137], usually conclude that this glazing technology is more suitable for warm and hot climates. Some of these studies investigate the performance of TC glazing solutions with theoretical or prototypal thermochromic layers, while others consider glazing solutions available on the market. The simulation models mainly consist of typical buildings generally located in cities on the northern hemisphere.

Most studies tend to focus on the energy performance of TC glazing [64,109,116–120,122–124,126–130,137]. Aburas et al. [186] concluded that the type of climate has a more significant influence on the annual energy savings of buildings compared to the type of TC glazing, based on comparisons across different research studies. Existing studies have demonstrated significant reductions of excessive solar gains with TC glazing and, as a result, decreased cooling energy demand compared to static clear glazing, with a higher impact in hot climates with significant solar radiation. It was also concluded that low outdoor temperatures in cold climates negatively affected the performance of TC glazing because it could not reach its darker states effectively in order to control excessive solar heat gains.

Apart from the energy performance, some studies also investigated the impact of TC glazing on thermal [121,123,124] and/or visual [122–124,126,127] comfort conditions. Accordingly, TC glazing can optimize visual comfort when compared to static clear glazing [122–124,126,127], increasing between 5 % (higher latitudes) and 20 % (lower latitudes) daylight exploitation and reducing between 10 % (higher latitudes) and 50 % (lower latitudes) glare levels [126,127]. When evaluating the illuminance spatial distribution inside an office room, Liang et al. [122] concluded that desired illuminance levels significantly reduced with the increase of the distance from the glazing, mainly with higher solar altitude angles. Thermal comfort in the presence of TC glazing is poorly explored by existing studies [123,124], which tend to use the indoor operative temperature levels to assess thermal conditions.

4.3. Phase change materials

The performance of PCM glazing has been investigated in several experimental studies [132] [133] [86] [87] [134,187] [180] [131].

Liu et al. [132] experimentally investigated the thermal performance of a PCM glazing when exposed to radiation from a solar simulator. Results show that PCM thickness has a vital role in the optical performance of the glazing. However, a higher thickness was associated with an increase of the temperature delay, achieving a peak temperature difference of about 30 °C between the surface top (liquid state) and bottom (solid state) temperature of the glazing with a PCM thickness of 16mm. When assessing the influence of PCM thickness and melting temperature on the thermal performance of PCM glazing, using test-rooms located in humid subtropical climate, Liu et al. [133] recommended a PCM thickness of 12–30 mm and a melting temperature of 14–16 °C.

In an experimental study, Li et al. [86] assessed the thermal performance of a PCM glazing against a hollow glazing during summer, using a test-room in a humid subtropical climate. A temperature time lag of 3 h was observed with the PCM glazing, resulting in an interior surface temperature of the glazing of approximately 10 °C lower than the hollow glazing. The heat transfer was reduced by almost 40 %, which resulted in a reduction of 41 % of the annual energy consumption of the HVAC system. In another experimental study using the same test-room, Li et al. [87] experimentally and numerically evaluated the thermal performance of a triple PCM glazing against a triple-glazed hollow glazing. A reduction of about 6 °C of the interior surface peak temperature, during a sunny day in summer, was obtained with the triple PCM glazing, compared to the hollow triple glazing, and a reduction of about 3 °C compared to the double PCM glazing of the previous study [86]. During a sunny day in winter, a reduction of about 5 °C and 1 °C of the interior surface peak temperature was obtained with the triple PCM glazing, compared to the hollow triple glazing and the double PCM glazing [86], respectively.

The energy performance and thermal comfort of a PCM glazing against a clear glazing, in the hot-summer Mediterranean climate, was experimentally investigated by Goia et al. [134,187] using a test-cell. The PCM glazing reduced energy gain in summer by 50 %. Under clear sky with moderate radiation during summer, PCM glazing reduces by 20 % thermal discomfort floor area. However, for high radiation levels, the discomfort floor area is very similar between glazing systems during summer, but a significant improvement can be observed with PCM glazing during winter. Under cloudy sky, PCM glazing provides thermal comfort conditions in almost all the floor area. Risk of overheating can occur with clear sky during summer on clear sky days if the transition temperature is not carefully optimized.

The impact of a PCM glazing on the energy performance and visual and thermal comfort of an office room located in a semiarid climate [180] was experimentally evaluated by Uribe et al. [131]. An adjacent office room with a clear double-glazing was used as reference. A reduction of about 20 % of the total cooling energy in summer was obtained with the PCM glazing. Thermal comfort increased during winter and mid-season with the PCM glazing. During summer, too hot temperature levels decreased with the PCM glazing. In terms of visual comfort, the PCM glazing was more effective on providing comfort glare levels during winter.

4.4. Electrochromic

Existing research studies that investigate the performance of EC glazing through a computer simulation approach [94,98,109,137–145,147,160,161], experimental testing approach [146,148,149,153–159], singly or in combination [151,152,156,159], found that this technology promotes the reduction of cooling energy needs and glare levels, being more suitable for hot climates.

Most studies tend to focus on the energy performance of EC glazing [98,138–145,147,151,154,156–159], showing that significant energy savings and reduction of peak energy demand are obtained, compared to clear and low-emissivity glazing systems, mainly during summer months in hot climates. Due to the low visible transmittance of the tinted states of EC glazing, an increase of the energy consumption for artificial lighting was observed.

Some studies investigate the impact of EC glazing on thermal comfort through the computation of the predicted mean vote or predicted percentage of dissatisfied [139,154,156] or through the analysis of the indoor operative temperature levels [152,155,156], concluding that thermal comfort increased compared to clear glazing. Visual comfort was assessed through the analysis of discomfort illuminance [138,139,146,152,153,155] or glare levels [138,140,146,148,149,152,153] and existing studies concluded that illuminance and glare reduction is possible without compromising daylighting, thus promoting visual comfort. However, the combined assessment of energy performance and indoor comfort in the same study remains scarce [139,140,152,154].

4.5. Gasochromic

Even though there is a significant number of research publications on gasochromic technologies from the mid-2000s onwards [136], the number of existing studies [94,135–137] on the performance of GC glazing in buildings is very limited, primarily focusing on energy performance analyses of commercial building/spaces.

A research group in China conducted an energy analysis [94] of a commercial building with a metal-oxide GC window under the climate of cities with humid subtropical (Shanghai and Guangzhou) or monsoon-influenced hot-summer humid continental (Beijing, Harbin and Changchun) climates (Köppen-Geiger climate classification [180]), using the eQUEST building simulation program. The performance of the GC glazing was compared against the performance of multiple static glazing solutions (single – clear, solar control, low-e, colored; double – clear, solar control, low-e, colored) and a TC glazing. Results indicate that hot summer and cold winter regions are best suitable for employing GC glazing, which decreased annual HVAC loads in Shanghai by, approximately, 28 % and 12 % when compared to clear and colored double-glazing systems, respectively. Compared with the clear single-glazing, annual HVAC loads were reduced by 25 %–35 %, in all cities.

In order to assess the performance of a magnesium yttrium (Mg-Y) GC glazing versus a metal-oxide (WO3) GC glazing, Liang et al. [135] conducted a simulation analysis of the energy performance and visual comfort of an office room under the climate of five different cities in China (humid subtropical climate [180] – Hangzhou and Guangzhou; subtropical highland climate [180] – Kunming; monsoon-influenced hot-summer humid continental climate [180] – Harbin, Beijing), using EnergyPlus [179] software. A conventional double-glazing system was used as reference. Although energy efficiency increased by 11 % (Guangzhou) and 25 % (Kunming) in cooling-dominated cities with the Mg-Y GC glazing, when compared to the clear glazing, energy efficiency was lower with this GC glazing in heating-dominated cities. The WO3 GC glazing present energy savings in all cities. Useful daylight illuminance levels increased up to 20 %, in the presence of the Mg-Y GC glazing, when compared to the WO3 GC glazing. Improving the transmittance modulation of the Mg-Y GC glazing, the authors concluded that energy efficiency is improved, particularly in climates with both heating and cooling requirements. Outdoor temperature values and cooling loads proved to be effective control strategies of Mg-Y GC glazing under different climates, while solar radiation control is best suitable for extreme hot climates without heating demand.

The impact of a GC glazing on the energy performance and visual comfort of office rooms in the hot desert climate [180] was evaluated by Nageib et al. [137]. The GC glazing performance is compared against clear and colored glazing (blue, green, brown), TC glazing and EC glazing, considering different window to floor area ratios (8 %, 16 %, 24 %, 32 %). Lighting energy savings were similar between the GC glazing and the EC glazing. Cooling energy consumption was reduced by 22–41 % in the presence of the GC glazing, comparing to clear glazing. However, this reduction was surpassed by the EC glazing.

Morrey et al. [136] assessed the energy performance of a GC glazing against static single and double-glazing systems, and a dynamic EC glazing. A residential building located in Birmingham (temperate oceanic climate [180]) was used as case study. Findings showed that the GC glazing was the most effective in reducing HVAC loads, with 65 %, 20 % and 13 % reductions when compared to single-glazing, double-glazing and EC glazing, respectively. This high performance lays on the fact that the GC glazing exhibited the lowest heat losses due to its low thermal transmittance, and that its larger solar heat gain coefficient made it possible to increase solar heat gains during winter months. When optimizing the switching criteria, the authors found the best performance results when considering an indoor temperature of 24 °C as set-point, which was under the cooling set-point of the HVAC system, always tinting the window when the building cooling was on. With this switching criteria, HVAC loads were reduced by 5 % against to the scenario with the GC window always in the clear state. The impact of the climate location (Birmingham - temperate oceanic; Abu Dhabi – hot desert; Cape Town - warm-summer Mediterranean; Reykjavik - subpolar oceanic [180]) of the building with the optimized switching criteria was also assessed by the authors, achieving significantly higher HVAC loads in cities with extreme climates (cold and hot).

4.6. Suspended particles

Research works [169,173–176] focusing on the performance of SP glazing in buildings are scarce. Nevertheless, they cover both experimental [169,175] and simulation [173,174,176] studies conducted under different climates.

Min et al. [174] conducted a preliminary simulation study (TRNSYS software [188]) of the energy performance of office buildings with SP filmed glazing, in humid continental (Seoul) and subtropical (Gwangju) climates [180] in South Korea. The performance was compared to the one of conventional glazing systems using virtual models and trends in heating/cooling loads of the SP glazing according to the glazing specifications. The thermal transmittance of the glazing reduced in the presence of the SP film (0.77W/m2 K), which resulted in a decrease of up to, approximately, 30 % of cooling and heating energy consumption. The findings of this study were limited by the reference of comparison being clear glass and by the absence of real-time control of the SP film.

In addition, in the humid continental climate [180] of Seoul in South Korea, Ko et al. [175,176] evaluated the energy performance of SP glazing systems, varying the solar heat gain coefficient, solar orientation and WWR ratios. An experimental test-room and a simulation model in TRNSYS software [188], calibrated with the experimental data, were used. With a WWR of 40 %, cooling consumption decreased by 30 % with SP glazing, while heating consumption increased by 16 %. For high WWR (70 %), an increase of about 17 % of total energy (heating + cooling) savings was obtained with the simulation model. For smaller WWRs, higher and smaller solar heat gain coefficient ranges are more suitable for providing heat gains and decrease heating consumption (up to 5 % total energy savings). For larger WWRs, lower and larger solar heat gain coefficient ranges are more suitable for providing shade and decrease cooling consumption (up to 12 % total energy savings).

An experimental study to investigate the heat transfer and cooling reduction of a SP glazing in the temperate oceanic climate [180] of Dublin, was conducted by Ghosh et al. [169]. A reduction of 6 kWh of the cooling load was obtained for the test-cell volume (0.34 3m3) with the SP glazing in opaque state, compared to clear state. Using the same test-cell, Ghosh et al. [170] evaluated the thermal and daylight performance of the SP glazing against double clear glazing. During a sunny day, the maximum illuminance level of 10klx with clear glazing was reduced to 0.64klx with the SP glazing in opaque state. Under overcast sky, SP glazing should be in the transparent state to provide useful illuminance levels. SP glazing in clear state was unable to provide comfortable glare levels. Carbon dioxide emission savings of 1m2 of SP glazing were calculated by the authors for different cities, achieving reductions of 100–400KgCO2 per square meter of SP glazing.

By combining the SP device in an evacuated glazing, Ghosh et al. [171,172] experimentally analyzed its thermal and daylight performance using the same test-cell located at Dublin. A low thermal swing range from 6 °C to 11 °C was obtained by the authors, which is advantageous to reduce heating and cooling energy consumption. Even though the SP glazing promoted useful illuminance levels for a clear sunny day, it increased insufficient illuminance levels under overcast sky conditions, not providing comfortable conditions. All states of the SP glazing (off, intermediates, and on) provided comfortable glare levels.

Mesloub et al. [173] evaluated the energy performance and visual comfort of an office room with a SP glazing (with and without an automated control) in the hot desert climate [180], through a simulation model constructed with EnergyPlus [179] and Diva-for-Rhino [189] software. Net energy was reduced for all solar orientations by up to 58 % with the SP glazing, compared to low-e double glazing, except for north orientation. The SP glazing with automated or always on control showed a significant decrease of excessive illuminance levels, with a maximum of 10 % of excessive illuminance levels for all solar orientations. SP glazing with automated control eliminated intolerable glare levels, resulting in imperceptible glare levels for the majority of time.

4.7. Polymer dispersed liquid crystals

Although PDLC glazing can have positive impacts on buildings performance, studies focused on this topic are scarce in the literature, focusing on its energy and luminous performance.

Ghosh et al. [163] experimentally evaluated the luminous performance of a PDLC glazing under solar radiation, using a test cell in Dublin. Despite that the opaque state significantly decreased illuminance levels under all sky conditions (clear, intermittent cloudy and overcast), when compared to transparent state, excessive illuminance levels were almost constantly observed under clear sky. Glare reduction with the opaque state was similar under all sky conditions, with uncomfortable levels under clear sky.

Oh et al. [160] analyzed the energy performance and visual comfort of an office building with different PDLC films against clear double-glazing, under the humid continental climate in South Korea. The PDLC films reduced by 19–22 % the energy consumption, compared with the original clear glazing. The discomfort illuminance time ratio was reduced to 38–60 % with the PDLC films, when compared to the original clear glazing (66 %). Similarly, the installation of PDLC films also had a positive impact on indoor glare, reducing from 43 % to 8–34 % the discomfort glare generation time. Using the same building and climate as case study, Oh et al. [161] assessed the energy performance of the PDLC film with the lowest visible transmittance against low-e double glazing and a EC glazing. The PDLC glazing promoted energy savings of 25 %, being surpassed by the EC glazing that achieved savings of 32 %, when compared to the low-e glazing. The PDLC and the EC glazing systems exhibited an increase of about 150 % of the comfort illuminance time ratio. Moreover, the PDLC glazing was more effective on glare control, reducing by 79 % the discomfort glare ratio time.

Iluyemi et al. [162] evaluated the energy performance of a family house with a PDLC glazing under the hot desert climate [180] of the city of Oman, using a simulation model in EnergyPlus [179]. The performance of the PDLC glazing was compared to the one of single and double clear glazing systems, and of an EC glazing. PDLC glazing reduced the total energy consumption by 17–22 % against single glazing, being slightly surpassed by the EC glazing, which achieved energy savings of 23–24 %. Carbon dioxide emissions decreased by more than 8000KgCO2e. Daylight control proved to be a more effective control type in terms of energy performance than glare control, for both dynamic glazing systems.

The HVAC cost-saving potential of different colored PDLC glazing systems was assessed by Shaik et al. [164] using a numerical model. The results were computed for the climate of the cities of Jodhpur (hot desert [180]), Mumbai (tropical savanna [180]) and New Delhi (monsoon-influenced humid subtropical [180]). White PDLC glazing achieved the highest annual cost savings of about 102$/year, and respective payback period of almost 13 years, for the southeast orientation under the hot desert climate.

The energy performance and visual comfort of an office building with PDLC glazing against clear double-glazing was investigated by Hemaida et al. [165] under hot desert and temperate oceanic climates, using EnergyPlus [179] software. When controlled by outdoor solar radiation levels, the PDLC glazing reduced annual energy consumption up to 8 % and 3 % under hot desert and temperate oceanic climate, respectively, when compared to the clear glazing. When controlled by outdoor air temperature levels, the PDLC glazing reduced annual energy consumption up to 8 % and 2 % under hot desert and temperate oceanic climate, respectively, when compared to the clear glazing. PDLC glazing increased useful illuminance by up to 15–17 %, and reduced discomfort glare by up to 3–24 %.

Mesloub et al. [166] assessed the energy performance and visual comfort of an office building with PDLC glazing under the hot desert climate, using a test cell to collect data for calibration of a simulation model build in EnergyPlus [179] and ClimateStudio [190] software. The impact of the WWR and solar orientation was analyzed. The PDLC glazing achieved annual energy savings of 5–32 %, which resulted in a reduction of carbon dioxide emissions up to 33–89KgCO2e/m2. Excessive illuminance was observed with higher WWRs for all solar orientations. Useful illuminance levels were reduced from 41 to 93 % with the PDLC on transparent state, to 0–49 % on opaque state.

An experimental and simulation study on the thermal, luminous and energy performance of a PDLC glazing during summertime was conducted by Ruggiero et al. [167]. A test-room located in Benevento, Italy, was used to collect experimental data, which was used to calibrate the simulation model in EnergyPlus [179]. Experimental data showed an increase of 18 % of useful illuminance with the PDLC in opaque state, when compared to the transparent state. The simulation analysis was made for different climates in the north hemisphere (hot-summer Mediterranean, hot desert and temperate oceanic), solar orientations, WWR and switching control types. For the lowest WWR (18 %), the PDLC glazing always on opaque state showed the best energy performance for west, east and north orientation, being surpassed by the PDLC glazing controlled by illuminance for south orientation, under all climates. For the highest WWR (100 %), the PDLC glazing always on opaque state showed the best energy performance for all solar orientations, under the different climates.

Ciampi et al. [168] investigated the thermal and energy performance of an office building with a PDLC glazing, using a test-room and a simulation model (TRNSYS [188]). The PDLC glazing on opaque state reduced indoor air temperature by about 1 °C during summer, according to experimental data. The cooling energy demand was reduced up to 41 % with the PDLC glazing, against a low-e double-glazing. The maximum reduction of carbon dioxide emissions (2.6 %) was achieved with the PDLC glazing controlled by the highest vertical radiation threshold.

5. Discussion of existing studies on the performance of solar control smart glazing

Comparing and analyzing the results of existing research studies on the performance of solar control smart glazing solutions, it becomes evident that the performance of these glazing systems strongly depends on multiple conditioning factors such as: building type and geometry; smart glazing technology type, control and dimension; solar orientation of the glazed façades; local climate conditions; existing shading systems; type and efficiency of the climate control systems. These conditioning factors are briefly discussed in this section along with the research approach and performance assessment of the research studies previously reported in the literature review. A simple statistical analysis is also presented in this section to categorize the research studies based on the building type, geometry, orientation, type of smart glazing, type of reference glazing, climate, research approach and performance assessment they analyze. In the case of a single study investigating multiple glazing technologies (or climate or other aspect), each case was counted separately to accurately reflect the distribution of the existing research. This approach ensures that the reported percentages represent the relative frequency of each case within the reviewed literature, instead of the number of articles.

5.1. Building type, geometry and orientation

The high variation in terms of wall materials, building type and geometry, and construction regulations among studies complicates the task of comparing findings.

In terms of building type (Fig. 9a), the majority (65 %) of studies were based on the performance of smart glazing when installed in office buildings (33 %) or office rooms (32 %), which can be justified by the common highly glazed façades of this typology of buildings that are usually linked to overheating and glare problems. The scarce (7 %) performance investigation in residential buildings may be explained by the fact that they usually have restricted occupancy levels during the day and low climatization (heating and/or cooling) and artificial lighting energy demand. Nevertheless, studies have reported the benefits of the installation of solar control smart glazing in residential buildings [119,136,143,151,162]. Some research studies (28 %) used scale models or test-rooms to assess the glazing systems performance. These test spaces are usually suited to assess prototypes or glazing samples with reduced dimensions under specific real weather conditions.

The higher solar heat gains and daylight levels incident on south façades (in the north hemisphere) justifies the larger percentage (34 %) of studies that assessed south-facing windows (Fig. 9b). The percentage of studies that considered east (21 %) and west-facing (19 %) windows is similar and was chosen by the authors to better assess the glazing performance with lower solar angles. Despite north-facing windows receiving low incident solar radiation, the performance in this solar orientation was assessed to better assess the limitations of installation (usually an increase of artificial lighting and heating demand), particularly in whole building scenarios where a homogenous perception of all façades is desirable.

The percentage distribution of WWR assessed by existing studies is shown in Fig. 9c. Highly glazed spaces (WWR>50 %) were preferred by the majority of studies (53 %) to conduct the performance assessment. Spaces with reduced glazing areas (WWR<25 %) correspond mainly to scale models.

5.2. Type of smart glazing technology and control

The percentage distribution of each type of solar control smart glazing technology evaluated in the reported studies is shown in Fig. 10a. The most studied technology was EC (37 %), followed by TC (23 %). Other glazing technologies are less investigated, particularly GC (4 %) and PC (7 %), which have the lowest number of associated studies. This trend can be explained by the differences in development and potential benefits between technologies, with EC and TC being the most established ones.

The type of control (manual or automatic) of active smart glazing technologies (GC, EC, SP, PDLC) strongly influences the performance of the glazing. Different, and sometimes personalized, switching control parameters can be used in automatic control by connecting the glazing system(s) to sensor(s) and a control panel that can be programmed to manage the tinted states. Existing studies mainly consider active glazing systems controlled by outdoor/indoor temperature, solar radiation and/or illuminance levels.

The majority of existing studies compares the performance of smart glazing to static glazing solutions, using them as reference (Fig. 10b). This approach enables the evaluation of performance differences between the dynamic glazing solutions and conventional glazing. Single-

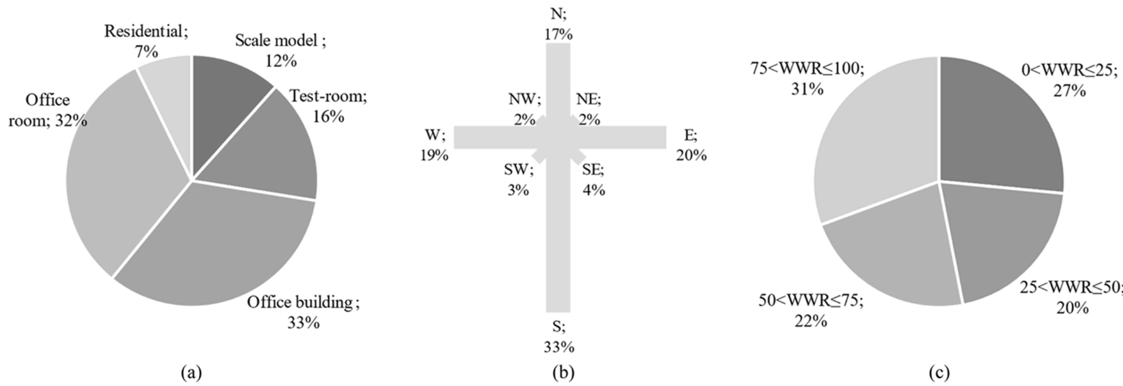

Fig. 9. Percentage distribution of (a) the building type, (b) solar orientation of the glazing systems and (c) window-to-wall ratio assessed by existing studies.

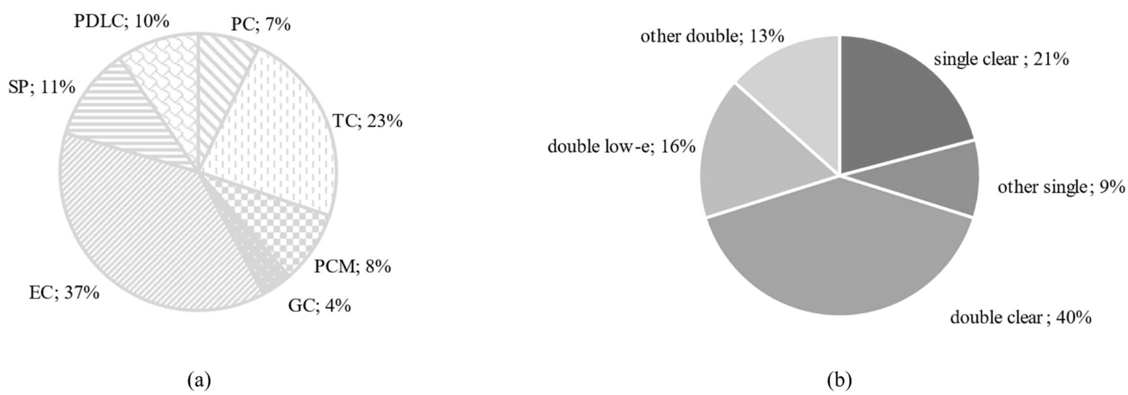

Fig. 10. Percentage distribution of (a) the type of smart glazing technology and (b) the reference glazing system assessed by existing studies.

glazing (30 %), particularly single clear (21 %), is usually used to represent the worst performance solution because of its high thermal and visual transmittance. Most reference glazing systems considered consist of double-glazing (69 %), particularly double clear (40 %), which is a commonly installed glazing in the existing building stock, including as an energy retrofitting measure. Double low-e is also a preferred option for some authors to represent a glazing solution with a good thermal performance.

5.3. Climate

The large majority of case studies is located in the north hemisphere, with only five locations in the south hemisphere, and considers temperate climate conditions (Fig. 11a). Case studies are mainly concentrated in European countries, in the United States of America and in China. The glazing performance for locations other than those covered in existing studies can be roughly inferred from the findings obtained under the same climate and latitude, where weather and incident solar radiation levels are similar, along with analogous conditioning factors.

Fig. 11b shows the percentage distribution of studies that consider each main climate group (A – tropical; B – arid, C – temperate, D – continental) and each specific climate type, in accordance with the Köppen-Geiger climate classification [180]. Temperate climates are assessed by a higher number of studies (56 %), followed by continental climates (22 %). Regarding specific climate types, humid subtropical (Cfa) is the most studied (22 %), followed by temperate oceanic (Cfb), hot-summer Mediterranean (Csa) and hot desert (Bwh).

The smart glazing technologies assessed under each climate group (A, B, C and D) are shown in Fig. 11c. PC, TC and EC glazing systems have been assessed under all four climate groups and are the only tested technologies in tropical climate group (A) along with PDLC. EC (20 %) and TC (15 %) were the most tested solutions under temperate climates (group C). Focusing on arid climates (group B), the EC technology was the most studied, closely followed by TC technology. However, under continental climates (group D), TC technology shows a slightly higher percentage than EC technology.

Even tough solar control smart glazing technologies were initially developed and advised for installation in hot climates with high solar radiation levels, existing studies proved them to be effective under multiple climate types.

5.4. Research approach

Reported studies used analytical, experimental or computer simulations, singly or in combination, as research approaches to evaluate the glazing systems performance. The percentage distribution of each type of research approach is shown in Fig. 13a.

Analytical studies, which are more time consuming than computer simulations and are more suited for less complex case studies, are the scarcest (8 %). This research approach was used in combination with experimental tests by Ghosh et al. [169,170] when assessing SP solutions (1 %), by Ghosh et al. [163] and Shaik et al. [164] when evaluating PDLC solutions (2 %), and by Li et al. [86,87] and Liu et al. [132,133] when investigating PCM solutions (5 %).

Experimental studies (35 %) cover experimental campaigns conducted in small test-cells, test-rooms, as well as in spaces used by occupants under real occupation and operating conditions. In both outdoor and indoor environment, the following variables are commonly measured and collected: solar radiation; illuminance; air and surface (opaque elements, glazing, shading system) temperatures; heat flows through glazed and opaque elements; air speed; relative humidity; electricity consumption. The collected data can be used to calibrate computer simulation models. The most experimentally assessed glazing

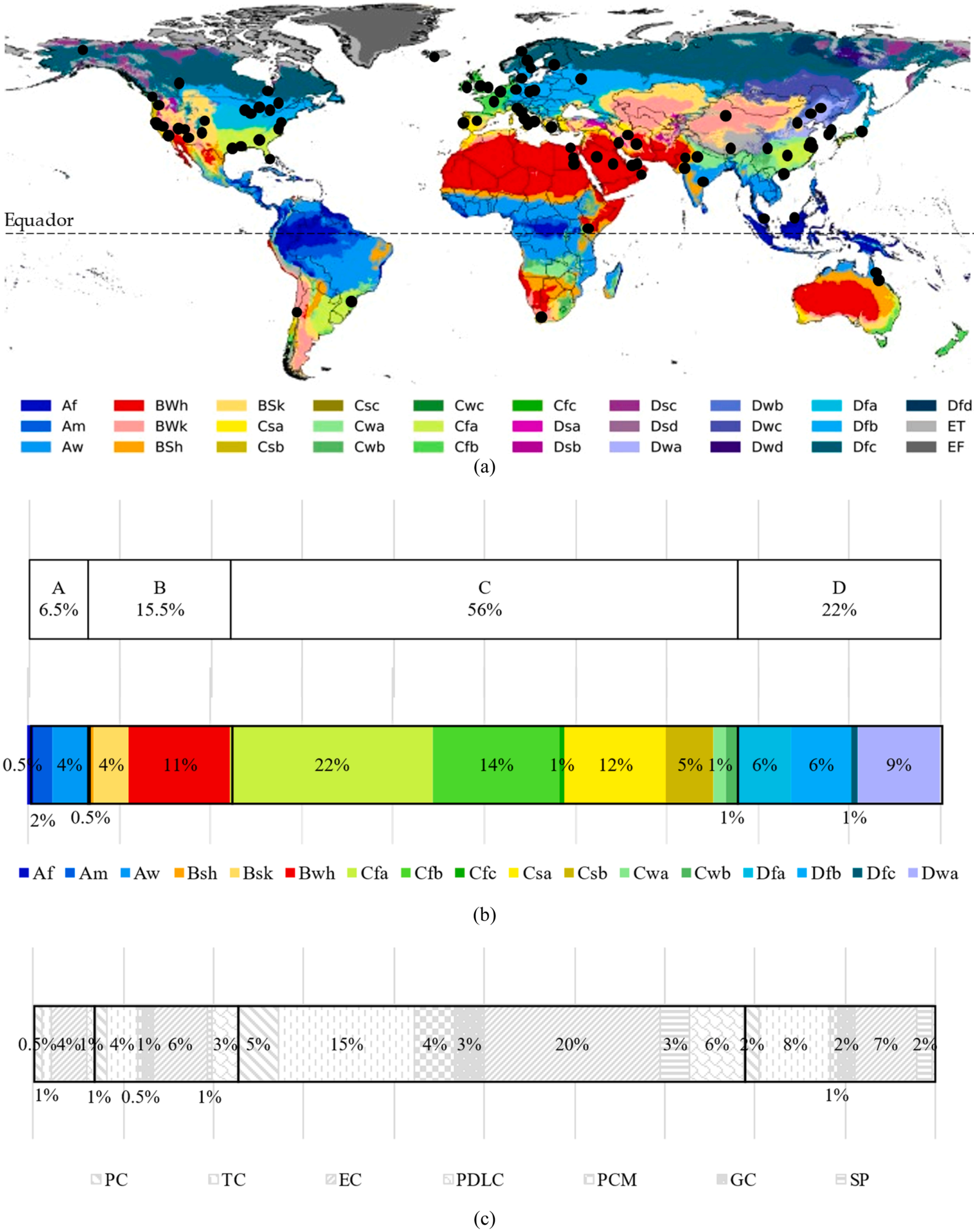

Fig. 11. (a) Geographical location of existing studies and climate zones, (b) percentage distribution of the evaluated climate types and (c) percentage distributions of the smart glazing technologies assessed under each climate group, in accordance with the Köppen-Geiger climate classification [180].

technologies are EC (9 %), TC (8 %), PCM (7 %) and PDLC (6 %).

Research studies with computer simulations usually focus on EC (20 %) and TC (18 %) glazing solutions. The 3D model of the simulated rooms/buildings was usually constructed using SketchUp [191] or DesignBuilder [192]. The optical and thermal properties of the simulated glazing solutions were numerically computed, experimentally measured in laboratory or computed using Optics [43] and Window [193] software. Multiple software options were used by the authors of the reported studies to perform the dynamic simulations (Fig. 12b). EnergyPlus [179] was by far the most used building simulation software, followed by eQUEST [194] and TRNSYS [188]. Some studies used Radiance [195] and Daysim to perform daylighting and lighting simulations. Few studies used Rhinoceros [184] plug-ins such as Grasshopper [185], Honeybee/Ladybug [183], Diva [189] and ClimateStudio [190]. Others (9 %), less used simulation software, includes BuildingEnergy, Winsel, ESP-r [196], Matlab [197] and IDA ICE [181].

The simulation models of existing studies mainly consist of standard buildings and few calibrated models [64,111,167,168]. For the calibration, statistical parameters such as the coefficient of determination [111], the mean absolute error [168], the mean bias error [111,167], the normalized mean bias error [64], the root mean square error [111, 168], the normalized root mean square error [111] and the coefficient of variation of the root mean square error [64,167], were used to quantify the error between experimental and simulated data. Indoor air temperature, opaque or glazing surface temperatures, heat fluxes through walls/roof, illuminance and thermal power were considered as calibration variables.

5.5. Performance assessment

The percentage distribution of the type of performance assessment (thermal, luminous, energy, economic and environmental) of existing studies is shown in Fig. 13a. Energy performance is the most assessed (43 %), followed by the luminous (27 %) and then the thermal (21 %) performances. Only a small percentage of studies evaluate the economic (4.5 %) and environmental (4.5 %) performance.

In order to evaluate the thermal performance of the glazing systems, existing studies usually analyze the indoor air temperature and exterior/interior glazing surface temperature levels. In some cases, the heat flux through the glazing is also measured. Due to the low solar transmittance

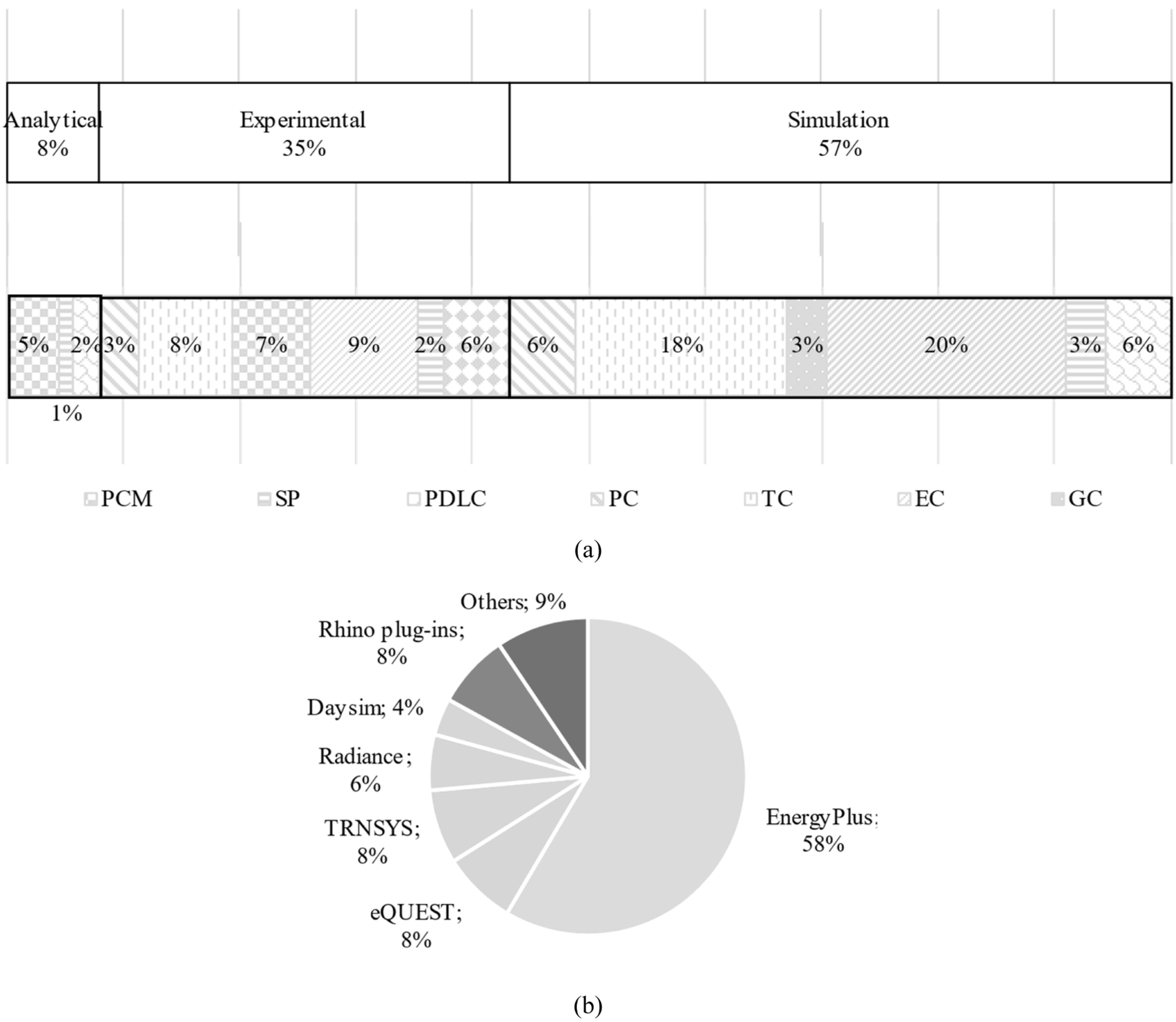

Fig. 12. Percentage distribution of (a) the type of research approach with the respective smart glazing technologies assessed and (b) simulation software used by existing studies.

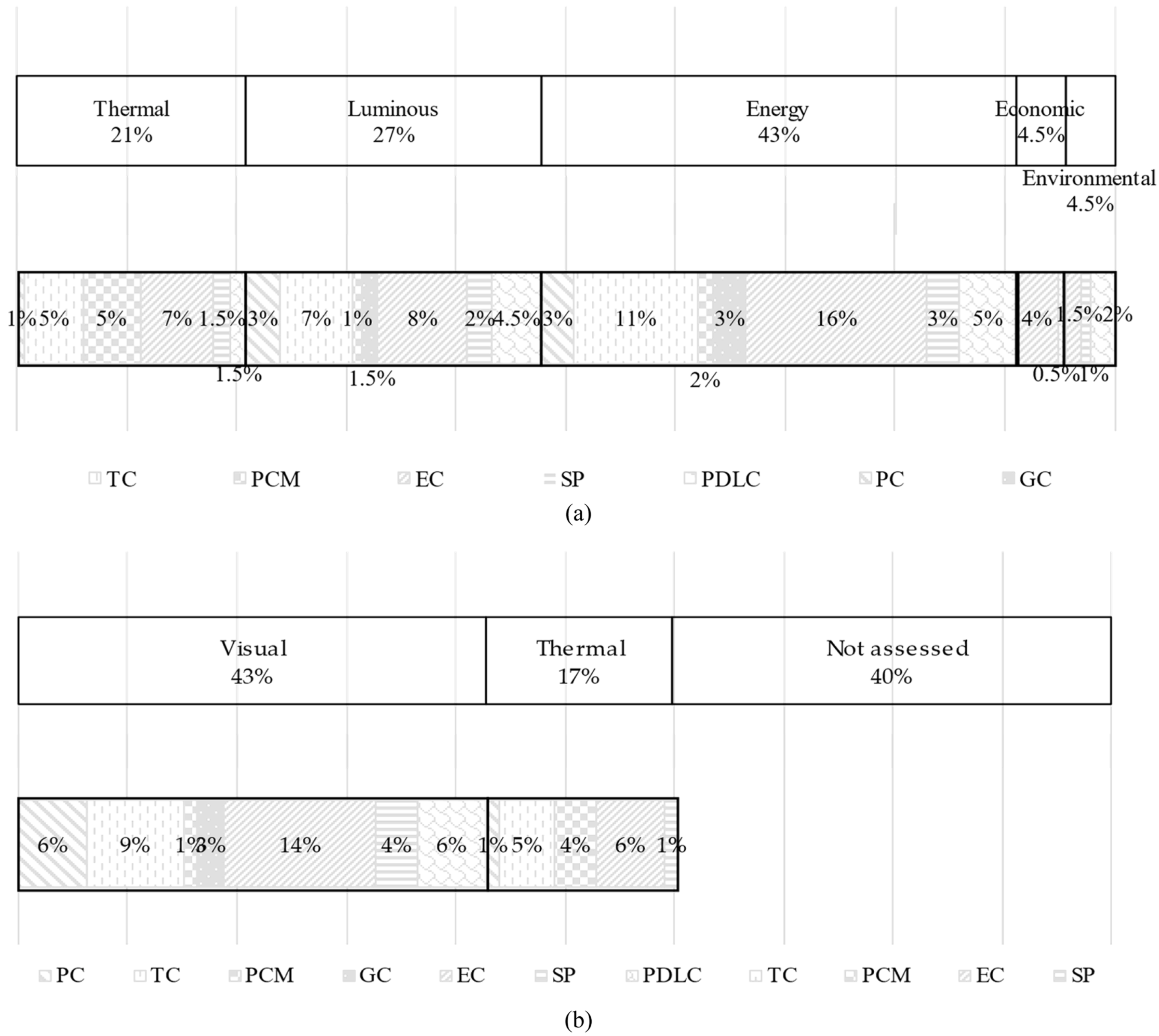

Fig. 13. Percentage distribution of (a) the type of performance assessment and (b) the type of comfort assessment with the respective smart glazing technologies assessed by existing studies.

or phase change of smart glazing, its impact on spaces thermal behavior can be noticed by a reduction of the indoor air temperature. Glazing technologies that block solar radiation by absorption exhibited higher surface temperatures. Thermal performance assessment was mostly conducted with EC (7 %), TC (5 %) and PCM (5 %) solutions.

The analysis of vertical and horizontal illuminance levels on the indoor space with smart glazing and its comparison against outdoor levels and/or indoor levels with static glazing is used by existing studies to assess the luminous performance. Some studies investigate the impact of sky conditions (clear, intermittent cloudy and overcast) on the luminous performance. The indoor horizontal distribution of illuminance levels, which is of high importance for large area spaces such as open plan offices, is explored by some studies in literature. EC (8 %), TC (7 %) and PDLC (4.5 %) were the most considered glazing solutions in luminous performance.

Regarding energy performance, reported studies assess energy needs, energy consumption and peak values in the presence of the smart glazing solutions and, sometimes, compare them to scenarios with static or other dynamic glazing systems. Air conditioning (heating and cooling) is the most analyzed energy use in existing studies. This can be explained by one of the main purposes of these smart glazing technologies: control of solar heat gains. The comparison between studies is difficult due to the discrepancy between the type of climate control and respective efficiency and setpoints. Due to the low visible transmittance of some smart glazing systems, some studies also assess its impact on the artificial lighting consumption. Energy performance assessment covers all types of glazing technologies, with higher incidence on EC (16 %) and TC (11 %) solutions.

Few studies [98,141–143,159,164] cover the economic aspect, simply by conducting a simple analysis that consists of the computation of the cost of the energy consumed, or energy savings comparing different glazing solutions, using cost values of local energy suppliers. The economic performances carried out by existing studies [98, 141–143,159] focused on EC glazing.

The environmental performance, investigated by scarce studies [98, 162,166,168,170], consisted of the computation of carbon dioxide emissions resulting from the energy consumed, or energy savings comparing multiple glazing systems.

Fig. 14 illustrates the energy performance distribution of solar control smart glazing technologies (PC, TC, PCM, GC, EC, SP, PLDC), in terms of energy savings comparing to static glazing (negative values correspond to an energy increase), across different climate groups in accordance with Köppen-Geiger climate classification [180], based on data extracted from the collected studies. For climate group A, only data of PC and EC glazing technologies are available, with EC showing a slightly better energy performance. For climate group B, SP showed the highest potential for energy savings, though with significant variability, followed by EC, PCM and TC glazing technologies. For this group, small energy increases were reported with PDLC glazing. For climate group C, TC and EC are associated with the highest energy savings, though exhibiting high dispersion. Lastly, for climate D, SP and PDLC glazing technologies exhibit highest average energy savings, though the significant variation associated with the performance of SP suggests that its efficiency depends on specific conditions. Since the data presented in Fig. 14 is based on a synthesis of the collected studies, it is important to state its limitations because the energy performance of each glazing technology depends significantly on the case study conditions and methodological choices made by each research work. Additionally, data availability is not uniform across all climate groups, leading to potential biases when comparing. Thus, while Fig. 14 offers a useful overview of energy performance trends, it does not necessarily reflect absolute real-world performance results.

Fig. 13b shows the percentage distribution of the type of comfort assessment conducted by existing studies. People spend a significant time indoors [198], so the assessment of the impact of glazing systems on indoor thermal and visual comfort is of extreme importance. Most studies investigate the impact of the smart glazing technologies on indoor comfort (60 %). However, the percentage of studies that do not address this aspect is high (40 %).

Reported studies that assess visual comfort (43 %) mainly use the useful daylight illuminance [199,200] metric to compute the floor area or percentage of working hours with useful illuminance (0.1–3.0klx). This assessment is usually performed for just one/two reference points in the indoor environment, resulting in rather limited results. Nevertheless, some studies [113,123,137,166] evaluate the spatial distribution of useful illuminance levels, providing a more complete analysis. The daylight availability metric is used by some studies [111,113,152,166,173]. Furthermore, the impact of smart glazing on glare levels is assessed by some studies, employing the subjective rating [149,172], daylight glare index [64,110,140,146–149,160,161,163,165,172] or daylight glare probability metric [113,114,131,152,153,173]. All glazing technologies were addressed in the visual comfort assessment, with a higher incidence for EC (14 %), TC (9 %), PC (6 %) and PDLC (7 %).

A significantly lower percentage of studies (16 %) addresses thermal comfort in the presence of smart glazing. Most of these studies [64,131,134,139,154,156,172] use the predicted mean vote and/or predicted percentage of dissatisfied indexes developed by Fanger [201]. Uribe et al. [131] and Goia et al. [134] used the modified predicted mean vote proposed by Sullivan, which takes into account the influence of the transmitted direct solar radiation on thermal comfort. Some studies [123,124,152,155] use operative temperature levels to evaluate thermal comfort. Adaptive thermal comfort models [64] are very scarcely used by existing studies. Thermal comfort assessment is focused on EC (6 %), TC (5 %), PCM (4 %), PC (1 %) and SP (1 %) technologies, with no existing studies on PDLC and GC.

Table 3 lists the advantages and drawbacks of each solar control smart glazing technology (PC, TC, PCM, GC, EC, PDLC, SP) and presents the best performance aspects, in terms of energy and comfort, achieved by existing studies.

6. Conclusions, research gaps and recommendations

Research studies that focus on the energy, thermal, luminous and comfort performance evaluation of solar control smart glazing technologies were collected and meticulously analyzed for the present literature review. This literature review does not cover studies of durability testing and life cycle assessment of these smart glazing technologies. As previously stated, these smart glazing technologies have gained interest from the community in recent years because of their potential benefits when installed in building façades. Depending on the glazing technology, these smart glazing systems can be considered either for rehabilitation or refurbishment. With the aim of increasing the glazing performance, in terms of energy consumption and occupant's comfort, these technologies are continuously under investigation and development by the scientific community.

There are numerous research studies on the performance of solar control smart glazing, showing significant heterogeneity in terms of methodology adopted, analyzed parameters, and performance and comfort indices considered, a fact which makes a direct performance comparison between solutions difficult. The performance of smart glazing technologies significantly depends on solar orientation, local climate, location (latitude and longitude), control strategy and existing obstructions on the surrounding environment.

The following research gaps have been identified:

- lack of studies conducted under tropical climates and are non-existent research for PCM, GC and SP technologies;
- lack of studies addressing the impact of smart glazing on thermal comfort and are non-existent research for PC, GC and PDLC technologies;
- lack of studies combining all performance assessments for each technology, since they tend to focus on TC and EC;
- existing studies assess individual spaces/buildings, without considering urban context.
- Future research efforts should focus on addressing the following analysis aspects to mitigate the identified research gaps:
- conducting deeper investigations of the energy, thermal and visual performance of solar control smart glazing solutions in tropical

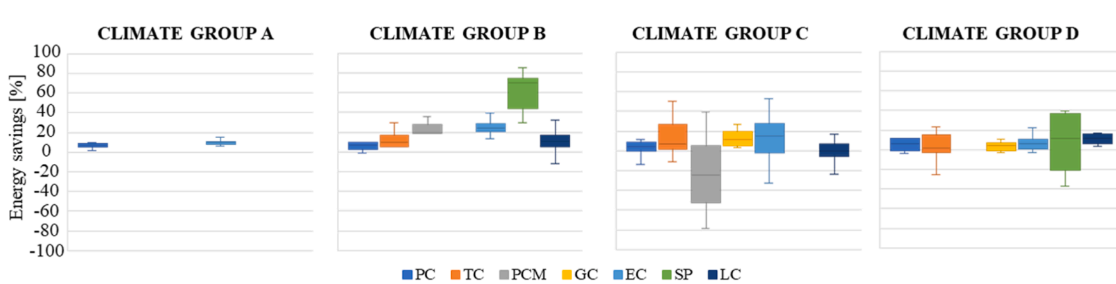

Fig. 14. Energy savings of each solar control smart glazing technology (PC, TC, PCM, GC, EC, SP and PDLC), across different climate groups (Köppen-Geiger climate classification [180]), based on data extracted from the collected studies.

Table 3
Advantages, drawbacks and performance of each solar control smart glazing technology considered in this review.

Glazing	Advantages	Drawbacks	Climate group* – Performance
PC	- Passive syystem - Thin coating - Multiple colors - Easy installation (film option) - Quick reaction time - Daylight control	- Lack of control - Potential uneven tinted areas - Risk of glass breakage - Difficult large-pane production - Gradual loss of chromatic change	A – Energy savings up to 11 % and increase of UDI up to 5 % [113] B – Energy savings up to 25 % [109] and increase of UDI up to 5 % [113] C – Energy savings up to 12 % [109] and increase of UDI up to 20 % [110] D – Energy savings up to 12 % [109] and increase of UDI up to 10 % [114]
TC	- Passive system - Gradual adaptability - Low cost - Solar heat gains and daylight control	- Lack of control - Potential uneven tinted areas - Lack of adaptability with cold temperatures	A – WWR has the highest impact on energy demand [124] B – Energy savings up to 30 % [117] C – Energy savings up to 50 % and increase of UDI up to 24 % [64] D – Energy savings up to 22 % [117]
PCM	- Passive system - Latent heat storage - Solar heat gains control - Satisfactory visibility	- Lack of control - Potential uneven areas - Possible material leakage - Risk of glass breakage	A – No data B – Heating/cooling energy savings up to 81/33 % and reduction of mean PMV and DGP up to 60 % and 10 % [131] C – Energy savings up to 41 % [86] and reduction of PMV up to 63 % [134] D – Reduction of transmitted solar energy by 86 % [133]
GC	- Active system - Gradual adaptability - Directly coated on glass - Cheaper production than other active technologies - Quick transition time - Solar heat gains and daylight control	- Requires an external power source - Potential gas leakage - Complex control system - Narrow spectral modulation	A – No data B – Cooling energy savings up to 41 % [137] C – Reduction of HVAC loads up to 28 % [94] and increase of UDI up to 52 % [135] D – Reduction of HVAC loads up to 35 % [94] and increase of UDI up to 35 % [135]
EC	- Active system - May be integrated into a building energy management system - Gradual adaptability - Solar heat gain and daylight control	- Requires an external power source - Glass temperature affects transition time - Long transition time - Ongoing voltage supply to maintain tinted state	A – Energy savings up to 19 % [154] B – Energy savings up to 50 % [98] and increase of UDI up to 38 % [147] C – Energy savings up to 48 % [156] and increase of UDI up to 38 % [147] D – Energy savings up to 56 % [98] and increase of UDI up to 6 % [147]
PDLC	- Active system - Provides privacy (opaque state) - Easy installation (film option) - Quick transition time	- Requires an external power source - Limited adaptability (on-off) - Ongoing voltage supply to maintain clear state	A – HVAC cost-savings up to 102$/year and DF lower than 2.1 % [164] B – Energy savings up to 32 % and CO_2 emission reduction up to $89 kgCO_2/m^2$ [166] C – Primary energy savings up to 4 % and CO_2 emission reduction up to 2 % [168] D – Energy savings up to 25 %, increase of UDI up to 165 % and reduction of discomfort DGI up to 80 % [161]
SP	- Active system - Gradual adaptability - Solar heat gains and daylight control - Quick transition time	- Requires an external power source - Ongoing voltage supply to maintain clear state - Low solar heat gains control	A – No data B – Energy savings up to 83 % and increase of UDI by 37 % [173] C – Energy savings up to 14 % [174] and DGI lower than 26 [172] D – Energy savings up to 14 % [174]

* Köppen-Geiger climate classification main groups [180]: A – tropical; B – arid, C – temperate, D – continental.

climates, particularly for PCM, GC and SP technologies to overcome the previously identified research gap;
- conducting thermal comfort assessments, considering free-float and air-conditioning regimes, in the presence of solar control smart glazing technologies (particularly PC, GC and PDLC identified in the research gaps), to better understand the impact of these glazing solutions on thermal comfort and climatization needs;
- undertaking holistic evaluation addressing both energy and comfort aspects in the presence of all solar control smart glazing technologies, considering multiple climates and façade design, to explore and optimize the selection and potential combination of glazing technologies to achieve sustainable buildings;
- conducting sensitivity analysis of the conditioning factors on the global performance of different solar control smart glazing solutions, to evaluate the impact of building construction and of solar-optical glazing properties;
- analyzing the impact of urban context on the global performance to quantify the potential benefits with large area application of solar control smart glazing and to explore the installation feasibility in various building and neighborhood types.

This literature review aims at highlighting the limitations of existing studies and at providing guidelines for future research on this topic.

CRediT authorship contribution statement

Henriqueta Teixeira: Writing – original draft, Methodology, Investigation. **A. Rodrigues Moret:** Writing – review & editing, Supervision, Methodology, Investigation. **Daniel Aelenei:** Writing – review & editing, Supervision, Methodology, Investigation. **M. Glória Gomes:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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