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Smart Glass as a Sustainable Solution for Improving Thermal Comfort in Indoor Spaces

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***Abstract*— The growing demand for energy-efficient and sustainable building solutions has intensified interest in advanced materials capable of enhancing indoor environmental quality. Smart glass, with its ability to modulate light and heat transmission, offers a promising approach to improving thermal comfort while reducing reliance on mechanical heating and cooling systems. This paper explores the application of smart glass technologies—such as electrochromic, thermochromic, and photochromic glazing—as sustainable interventions in building design. Through a review of current literature and case studies, the paper assesses the impact of smart glass on indoor thermal regulation, energy consumption, and occupant well-being. The findings highlight that smart glass not only contributes to significant energy savings but also enhances occupant comfort by dynamically responding to external climate conditions. The paper concludes with recommendations for integrating smart glass into modern architectural practices as part of a holistic strategy for sustainable and resilient indoor environments.**

***Keywords*— Smart Glass, Thermal Comfort, Energy Efficiency, Sustainable Architecture**

I. INTRODUCTION

The construction and building sectors represent nearly 30% of worldwide energy usage and contribute about 15% of global CO_2 emissions. Implementing energy-efficient building practices plays a crucial role in reaching carbon neutrality targets, while environmentally-certified commercial buildings additionally demonstrate increased market value and financial returns [1,2]. Human comfort is a fundamental goal in the architectural design process. Ensuring that building occupants are safe and healthy during use is a primary concern. Once these needs are met, providing a comfortable indoor environment becomes essential—particularly thermal comfort, which significantly influences not only occupants' happiness but also their productivity and social interactions [3]. Thermal comfort plays a crucial role in building design as it directly affects occupant satisfaction, operational efficiency, and overall energy performance. The growing emphasis on energy-efficient and sustainable architecture has brought advanced glazing technologies into focus. High-performance glazing systems (HPGSs), including smart glazing technologies, offer an innovative solution by adapting to dynamic environmental conditions, thereby enhancing thermal comfort and optimizing energy usage. Conventional glazing systems are often thermally inefficient, contributing to issues such as excessive heat gain during summer and considerable heat loss in winter. These inefficiencies increase reliance on heating, ventilation, and air conditioning (HVAC) systems, leading to higher energy consumption. In light of climate change, escalating energy costs, and the global movement toward net-zero energy buildings, addressing thermal performance through advanced solutions like smart glazing has become increasingly critical.

Fig. 1. :Sustainable Development Goals Targeted
Source: https://sdgs.un.org/goals

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This study will investigate how smart glass can enhance thermal comfort in indoor spaces. The study aims to improve energy efficiency, reduce cooling loads, and create more health-conscious environments especially in hot climates.

A. Research Problem

Despite the demonstrated potential of smart glass technologies (electrochromic, thermochromic, photochromic, and SPD) to enhance thermal comfort and energy efficiency in buildings, their widespread adoption remains limited by critical barriers. Current systems face challenges including high manufacturing costs (particularly for electrochromic and SPD glass), slow response times (in photochromic variants), energy consumption concerns (with SPD technology), and lack of adaptability to diverse climatic conditions. Furthermore, there is insufficient research on hybrid systems that could combine the advantages of multiple technologies while mitigating their individual limitations. The absence of comprehensive lifecycle assessments and real-world performance data across different climate zones creates uncertainty about long-term sustainability and cost-effectiveness. This research gap hinders the optimization of smart glass solutions for maximum thermal comfort improvement with minimal environmental impact. Addressing these limitations is crucial for developing accessible, efficient, and climate-responsive smart glass technologies that can significantly contribute to sustainable building design and operation

B. Research Objective

This study aims to develop and optimize smart glass technologies as sustainable solutions for improving indoor thermal comfort by comprehensively evaluating the performance, energy efficiency, and cost-effectiveness of electrochromic, thermochromic, photochromic, and suspended particle device (SPD) systems across diverse climatic conditions. The research will focus on overcoming current limitations through innovative approaches, including hybrid system development that combines multiple technologies, material enhancements to improve response times and durability, and manufacturing optimizations to reduce production costs. Additionally, the study will conduct lifecycle assessments to determine environmental impacts and long-term sustainability, while generating practical guidelines for technology selection based on building types, climate zones, and energy efficiency requirements. The ultimate goal is to advance smart glass solutions that effectively balance thermal comfort, energy savings, and economic viability for broader adoption in sustainable building design.

C. Research Hypothesis

This study hypothesizes that smart glass technologies—particularly optimized electrochromic systems and hybrid configurations—can significantly improve indoor thermal comfort while reducing energy consumption compared to conventional glazing solutions. It is anticipated that electrochromic glass will demonstrate superior adaptability and control, whereas hybrid systems (e.g., combining thermochromic and electrochromic layers) will achieve optimal balance between passive responsiveness and active adjustability. Further, material and manufacturing advancements are expected to lower costs and enhance durability, making these solutions more viable for widespread adoption. The research also posits that climate-specific smart glass implementations will outperform traditional windows in both thermal regulation and lifecycle sustainability, with hybrid designs showing the greatest potential for universal applicability across diverse building types and environmental conditions.

D. Research Methodology

A comparative study of smart glass and conventional glazing systems in terms of thermal performance, energy efficiency, cost, durability, and user comfort across various climate zones and building typologies.

II. THEORETICAL FRAMEWORK

A. Thermal Comfort

Thermal comfort factors are the elements influencing a person's perception of whether an indoor environment feels thermally comfortable. These factors can be divided into environmental and personal categories, as defined by standards like ASHRAE 55 and ISO 7730, as shown in tableI.

TABLE I. THERMAL COMFORT DIFFERENT DEFINITIONS

Source	Definition
ASHRAE Definition	The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as: "That condition of mind which expresses satisfaction with the thermal environment." This definition emphasizes the subjective nature of thermal comfort, which varies between individuals based on factors like metabolism, clothing, and personal preference.
ISO 7730 Definition	The International Organization for Standardization (ISO) in its standard ISO 7730 describes thermal comfort as: "The condition of thermal environment in which at least 80% of occupants feel thermally neutral (neither too hot nor too cold)." This definition introduces a quantitative aspect, focusing on statistical acceptability.
CIBSE Guide	Holistic Comfort: Thermal comfort is often described as a balance between heat production in the human body and heat exchange with the surrounding environment through mechanisms such as convection, conduction, radiation, and evaporation. Adaptive Model Perspective:
	Thermal comfort accounts for the ability of individuals to adapt to environmental changes through clothing, behavioral adjustments, and physiological acclimatization, particularly in naturally ventilated buildings.

Environmental Factors: Thermal comfort is significantly influenced by a range of environmental factors that determine the thermal interaction between the human body and its surrounding environment. These factors include air temperature, relative humidity, air velocity, and mean radiant temperature. Air temperature refers to the temperature of the air surrounding the occupant and is a primary determinant of thermal sensation. Relative humidity influences the body's ability to regulate heat through evaporation of sweat, with high humidity levels reducing evaporative cooling efficiency. Air velocity affects convective heat exchange and can enhance thermal comfort by promoting heat dissipation from the body, especially in warmer conditions. Mean radiant temperature represents the average temperature of surrounding surfaces and plays a crucial role in radiant heat exchange between the body and the environment. The combined effects of these variables must be carefully balanced in building design to ensure optimal thermal comfort, as shown in table II.

TABLE II. THERMAL COMFORT ENVIRONMENTAL FACTORS

Factors	Definition	Impact	Optimal Range
Air Temperature	The temperature of the air surrounding an individual.	Too high leads to overheating. Too low causes discomfort from cold.	Typically, 20–24°C in winter, 24–28°C in summer, depending on activity level and clothing.
Radiant Temperature	The heat emitted by surrounding surfaces (walls, windows, floors).	High radiant temperatures (e.g., from a sunny window) can cause localized overheating. Low radiant temperatures (e.g., uninsulated walls) can cause discomfort.	Measurement: Mean radiant temperature (MRT) combines all surface temperatures.
Air Velocity	The speed of air movement around the occupant.	Low air velocity reduces heat dissipation, causing a stuffy feeling. High air velocity increases cooling, which can feel drafty.	0.15–0.5 m/s indoors; higher speeds may be acceptable in hot climates
Humidity	The amount of moisture in the air, usually expressed as relative humidity (%RH).	High humidity (>70%) reduces the body's ability to sweat, causing discomfort Low humidity (<30%) can cause dryness of the skin and respiratory issues	30–60% RH is generally comfortable.
Air Quality	Refers to the freshness and cleanliness of indoor air	Poor air quality (e.g., high CO_2 or pollutants) can affect perceived comfort, even if temperature and humidity are ideal	Ventilation and air purification systems are key

Personal Factors: These relate to individual characteristics or actions that influence how a person experiences thermal conditions:

TABLE III. THERMAL COMFORT PERSONAL FACTORS

Factors	Definition	Impact	Examples
Metabolic Rate (Activity Level)	The amount of energy a person generates through activity, measured in met units.	Higher activity levels increase heat production, requiring cooler environments for comfort. Lower activity levels require warmer conditions.	Sitting quietly: ~1.0 met. Walking: ~2.0–3.0 met. Heavy work: ~5.0+ met.
Clothing Insulation (Clo)	The insulating value of clothing, measured in clo units.	High insulation (e.g., winter wear) retains body heat, suitable for colder environments. Low insulation (e.g., summer wear) allows more heat dissipation.	Light summer clothes: ~0.5 clo. Winter clothes: ~1.5 clo or more.
Adaptation	The ability of individuals to adapt to their environment over time.	People accustomed to a specific climate may tolerate higher or lower temperatures better. Behavioral adjustments like opening windows or changing clothing can enhance comfort.	

Thermal comfort is a key consideration in designing buildings, as it directly impacts occupant satisfaction, productivity, and energy efficiency.

B. Smart Glass

There are two types of intelligent glass, differentiated by their operation: active-controlled (user-adjustable) and passive-controlled (automatically adapting).

1) Passive Dynamic Glazing

Passive smart glass technologies operate without electrical stimulation, responding automatically to environmental conditions such as light (photochromic windows) or heat (thermochromic and thermotropic windows). Unlike active systems, these solutions are easier to install and more durable, though they lack on-demand user control

a) Photochromic glazing

Photochromic glass adjusts its transparency in response to incoming light intensity. This functionality stems from organic or inorganic compounds—such as silver halides (chloride or bromide) or light-sensitive polymers—embedded in the glass during manufacturing. These materials act as "optical photosensitizers," reacting to ultraviolet (UV) radiation or specific light wavelengths.

When exposed to sunlight, the glass undergoes a reversible color change due to shifts in light absorption between the glass and its embedded materials. While the transition to a tinted state takes a few minutes, reverting to transparency takes twice as long. This delayed response can be problematic in environments with rapidly fluctuating light, potentially causing uneven shading or glare.

Moreover, photochromic glass absorbs rather than reflects light after darkening, increasing the risk of overheating and thermal stress fractures under intense sunlight [4].

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Fig. 2. Photochromic glazing
Source: https://smartglassnordic.com/

b) Thermo-chromic glazing

Thermochromic (TC) glazing autonomously adjusts its optical properties in response to external temperature changes, driven by either biochemical processes or phase transitions. Below the transition temperature, the material stays transparent, but it becomes opaque (milky) as temperatures rise. The transition typically occurs between 10°C (maximum opacity) and 65°C (minimum opacity). This thermochromic behavior is found in various organic, inorganic, and metal oxide materials—such as vanadium dioxide (VO_2)—which undergoes a semiconductor-to-metal phase transition. This shift triggers a strong infrared (IR) reflectance response, making it particularly effective for thermal regulation. The most advanced method for implementing thermochromic tinting involves embedding thermochromic materials within a 1.2-mm-thick polyvinyl butyral (PVB) interlayer. Since PVB is already widely used in laminated safety and acoustic glazing, this approach optimizes manufacturing efficiency while ensuring high-quality output at a reduced cost. When integrated with glass panels, this system enables rapid switching (within seconds) between transparent and opaque states. This transition dynamically modulates daylight transmission and thermal mass, enhancing energy efficiency [4].

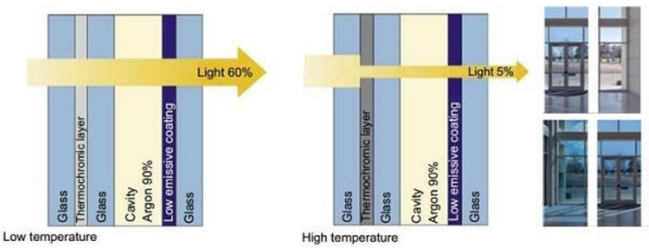

Fig. 3. Thermo-chromic glazing
Source: https://www.glassonweb.com/

2) Active Dynamic Glazing

Active dynamic glazing systems allow precise control over transparency and thermal properties in response to both external conditions (sunlight and heat) and internal factors (artificial lighting, thermal loads, or user preferences). These systems can be manually adjusted or automated, enabling real-time modulation of visible light and infrared .radiation transmission. When integrated with photovoltaic technology, such glazing can achieve energy self-sufficiency. Advanced features include remote operation via smartphones, independent control of individual window segments, and future potential for interactive touch-screen display capabilities [5].

a) Electrochromic Devices (EC)

Electrochromic glazing utilizes specialized coatings that dynamically modify solar radiation transmission, absorption, and reflection in response to an applied electrical voltage. These coatings undergo reversible optical changes through the insertion or extraction of ions—when an electric field is applied, ion migration triggers chemical reactions that alter the material's coloration. An electrochromic device consists of: two transparent conductive layers (electrodes), an electrochromic film (ion storage layer), and an ion-conducting electrolyte sandwiched between them When voltage is applied across the conductive layers, ions migrate from the storage layer through the electrolyte into the electrochromic coating, inducing a visible color change. This process is reversible, allowing precise control over light and heat transmission. Unlike conventional tungsten oxide-based electrochromic materials, which typically transition from transparent to blue, modern electrochromic glazing systems generally exhibit green or blue coloration. These advanced systems offer precise control over transparency levels, with adjustable states ranging from completely clear (when deactivated) to fully tinted. The light transmission capabilities vary significantly across this spectrum - achieving approximately 60% visible light transmission in the clear state and dropping to as low as 1% in the fully darkened state. This wide dynamic range allows for optimal balance between daylighting and solar heat gain management while maintaining visibility when desired. Electrochromic glass technology holds significant potential for advancement through several key improvements: enhancing the number of control modes and transition speed, increasing opacity in tinted states for better privacy, and substantially reducing the already minimal power consumption. These technological developments would expand functionality while optimizing energy efficiency, making electrochromic systems more versatile and sustainable for architectural applications.

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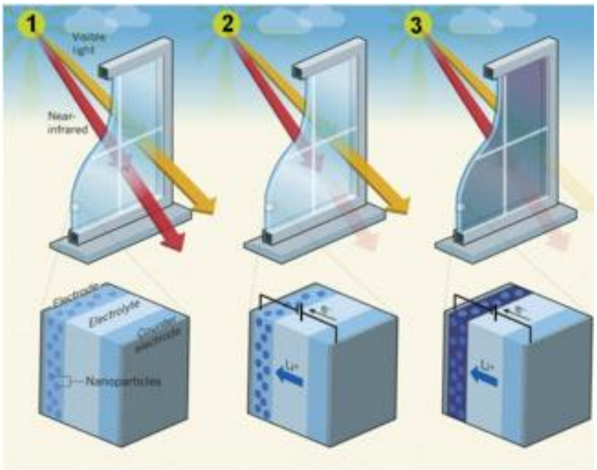

Fig. 4. Electrochromic Devices (EC)
Source: https://www.sciencedirect.com/

b) Suspended Particle Devices (SPDs)

SPD technology consists of a dual-pane glass system with a laminated layer of microscopic rod-shaped nanoparticles suspended in a liquid matrix, sandwiched between two conductive transparent plastic layers. When an electrical current is applied, these particles align to allow light transmission, rendering the window transparent. Conversely, when deactivated, the particles randomly disperse, blocking light and tinting the glass to a dark blue, gray, or black hue. This dynamic operation enables precise control over sunlight penetration by adjusting voltage levels, with the ability to block up to 99% of visible light when fully darkened. Notably, SPD glass maintains UV protection regardless of its operational state [5]. The system requires approximately 100 V AC to transition from opaque to transparent and can stabilize at intermediate tint levels. Power consumption is relatively efficient, with a continuous operational demand of 0.55 W/m² and a switching requirement of 5 W/m². However, despite its promising functionality, widespread adoption faces challenges due to unverified long-term durability, limited market availability, and high costs.

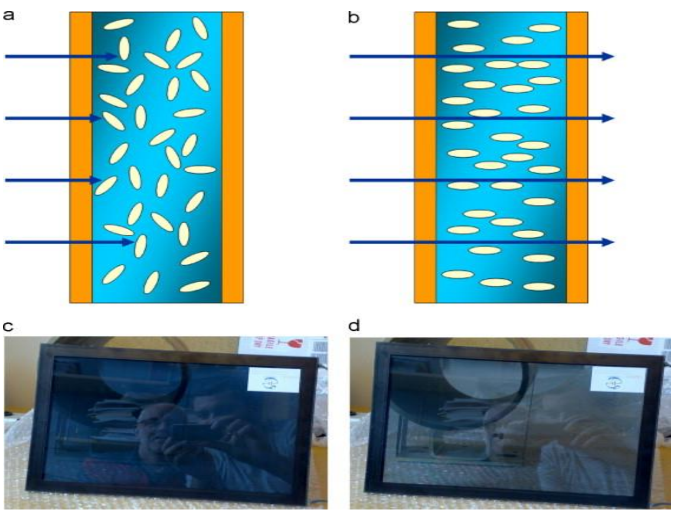

Fig. 5. Suspended Particle Devices (SPDs)
Source: https://www.sciencedirect.com/

III. CONCLUSION

The comprehensive comparison of smart glass technologies reveals that each type offers unique advantages for enhancing thermal comfort sustainably in indoor spaces. Electrochromic glass stands out as the most balanced solution, combining adjustable control, energy efficiency, and long-term durability, making it ideal for dynamic environments where both user preferences and energy savings are priorities. Thermochromic glass provides an excellent passive alternative for climates with consistent temperature fluctuations, operating without energy input while automatically responding to thermal changes. Photochromic glass, though limited by its slower response and UV-dependence, remains a cost-effective option for residential applications. Suspended Particle Devices (SPD) deliver unmatched speed and light-blocking capabilities but are hindered by high costs and energy demands, restricting their use to premium projects.

To advance these technologies, future research should focus on improving energy efficiency, reducing manufacturing costs, and enhancing material durability. Hybrid systems that combine the strengths of multiple technologies could revolutionize smart glass performance, while real-world testing in diverse climates will ensure practical reliability. By addressing these challenges, smart glass can become a more accessible and effective solution for sustainable building design, ultimately optimizing indoor thermal comfort while minimizing environmental impact. The optimal choice depends on specific project requirements, but continued innovation will expand the possibilities for smarter, greener architectural solutions

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TABLE IV. SMART GLASS TECHNOLOGIES: COMPARATIVE ANALYSIS FOR SUSTAINABLE THERMAL COMFORT

Feature	**Electrochromic (EC)**	**Thermochromic (TC)**	**Photochromic (PC)**	**SUSPENDED PARTICLE (SPD)**	
Activation Mechanism	Electric voltage	Temperature changes	UV/visible light exposure	Electric voltage	Precise control: EC, SPD
Transition Speed	5–15 minutes	1–10 minutes	2–10 minutes (slower reversal)	<1 second	Speed: SPD
Light Transmission	60% (clear) → 1% (tinted)	10–65% (varies with temp.)	50% → 10% (UV-dependent)	60% → <1%	Darkening range: SPD
Energy Efficiency	Low power (0.5–5 W/m^2)	Passive (no energy needed)	Passive (no energy needed)	Moderate (0.55 W/m^2 standby; 5 W/m^2 switch)	Passive: TC, PC
User Control	Adjustable (manual/automated)	None (automatic)	None (automatic)	Adjustable (manual/automated)	Customization: EC, SPD
UV/IR Blocking	Yes (in tinted state)	Partial (depends on material)	Partial (UV-triggered)	Yes (99% in dark state)	UV protection: EC, SPD
Cost	High (100 – 100–200/sq. ft)	Moderate (50 – 50–150/sq. ft)	Low–Moderate (40 – 40–100/sq. ft)	Very High (200 – 200–400/sq. ft)	Affordability: PC, TC
Durability	High (10–20 years)	Moderate (5–15 years)	Low–Moderate (5–10 years)	Moderate (under testing)	Longevity: EC
Sustainability	Renewable energy compatible (PV integration)	Passive, zero energy use	Passive, zero energy use	Higher energy demand	Eco-friendly: TC, PC, EC

IV. RECOMMENDATIONS

For future research, priority should be given to: developing hybrid smart glass systems that combine the strengths of multiple technologies, optimizing manufacturing processes to reduce production costs, particularly for EC and SPD glass, enhancing material formulations to improve response times and durability, and conducting comprehensive lifecycle assessments to evaluate long-term environmental impacts. Additionally, field studies across diverse climatic conditions would provide valuable data on real-world performance and user satisfaction. These research directions will be crucial for advancing smart glass technologies toward more sustainable, efficient, and accessible solutions for thermal comfort management in buildings.

The continued development of smart glass technologies holds significant potential to revolutionize building energy efficiency while improving occupant comfort. By addressing current limitations through targeted research and innovation, these solutions can play a pivotal role in sustainable architecture and the creation of more responsive, energy-conscious built environments.

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