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Smart Glazing Systems vs Conventional Glazing: A Comprehensive Study on Temperature Control, Daylighting, and Sustainability

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ABSTRACT

Glazing systems play a significant role in managing the interaction between indoor and outdoor temperatures within a building. This research was conducted in a laboratory at Najran University in Saudi Arabia, focusing on six different glass samples, including two conventional (double low-E glass and vacuum clear glazing) and four smart glazing configurations (PDLC and SPD in both ON & OFF states), aiming to analyze their impact on indoor-outdoor temperature interaction, solar radiation control, and visual comfort. Key findings include SPD-OFF's superior temperature control (limiting increase to 24.28℃ compared to 10.53℃ for double low-E), PDLC-ON's optimal daylight illumination (2901.43 lux), and its higher energy efficiency (97.97 W/m² heat gain) compared to 44.8 W/m² for double low-E. The study also highlighted cost and environmental differences, with double low-E being the most cost-effective ($1.43/m²) and PDLC-ON the most eco-friendly (14.5 kg CO_2/m²), despite higher operating costs. Overall, smart glazing systems, particularly the PDLC configuration, demonstrated notable advantages in thermal and visual comfort management.

1. INTRODUCTION

Transportation, Buildings, and Industry stand as the primary economic sectors driving energy consumption on a global scale [1]. Among these sectors, buildings have experienced a significant surge in energy consumption, making them one of the fastest-growing contributors [2]. Collectively, buildings account for nearly half of the world's energy consumption [3-5]. While carbon dioxide (CO_2) emissions remain a central environmental concern, other aspects of energy usage must also be addressed to ensure a sustainable energy future with minimal ecological impact [1]. Notably, over 33% of global carbon emissions are attributed to energy consumption within the building and construction sectors [6]. This surge in building energy use has played a pivotal role in the steady increase of greenhouse gas and carbon dioxide emissions worldwide [7]. The Kingdom of Saudi Arabia (KSA) presents a unique case, characterized by a substantial demand for energy within the building sector, particularly during the scorching summer months when air conditioning needs are exceptionally high due to soaring exterior temperatures, even at night [8]. A study conducted in KSA revealed that residential buildings alone consume approximately 50% of the country's total electricity [7]. In the city of Dhahran, KSA, residential buildings account for over 52% of the city's electricity consumption, irrespective of the building type [9]. KSA boasts a well-established power regulation structure and is renowned for its heavy reliance on fossil fuel energy sources [10]. Notably, KSA consumes more than a quarter of the oil it produces, a significant portion of which is used for electricity generation [11]. This situation not only intensifies the country's dependence on local energy resources but also impacts its revenue from oil exports [12]. To mitigate the strain on these finite natural resources, effective energy management practices in buildings must be established to save both energy and costs [13]. This necessity highlights the urgency of addressing the global concern of building energy consumption, with a specific focus on the unique challenges faced by Saudi Arabia.

Efforts to conserve energy have led to the study and development of various strategies in critical areas like insulation, airtightness, and solar radiation management. These strategies are of utmost importance because a building's envelope, comprising walls, ceilings, floors, and windows, plays a pivotal role in determining the energy required for cooling, heating, and lighting [7]. The initial step in designing energy-efficient buildings is to minimize heat sources, including solar exposure and high temperatures [7]. The building envelope, consisting of these structural elements, offers more than just structural support—it can be instrumental in creating a secure and comfortable interior environment [7]. Among the components of the building envelope, glazing, or windows, significantly influences energy consumption within the building [14, 15]. Investigating the thermal behavior of walls and windows is crucial to reducing heat gain in structures [16]. Factors like exterior wall and roof insulation, window shading, window size, and the type of glazing all have a notable impact on a building's energy efficiency [7]. The performance of a structure and the comfort of its occupants are both adversely affected by heat ingress and loss through the glass surfaces [17, 18]. Clear glass windows, due to their higher solar transmittance and U values, allow more solar radiation to enter, impacting both thermal and visual comfort within the building's interior [19]. The energy efficiency of glazing is also significantly influenced by the "dead band," which represents the range of cooling and heating setpoints [20, 21]. Several types of glazing, including vacuum glazing [22], and low emissive (low-E) thin film coatings [23], have been investigated, and it has been observed that these options can lead to improved energy savings and enhanced thermal performance in buildings. Vacuum glazing is characterized by its thin glazing unit, high visual transmittance, and low heat loss [24, 25]. The application of low-E coatings to the surfaces of glass panes facing the void in vacuum glazing can reduce heat transmission through radiation by up to 20% [24, 26].

To reduce heating and cooling demands while optimizing natural light utilization, switchable glazing systems offer the ability to alternate between transparent and translucent states with a simple switch [27, 28]. Various coatings, including polymer-dispersed liquid crystal (PDLC), electrochromic (EC), thermochromic (TC), and photochromic (PC), have been developed for integration into smart glass products [29]. In regions with warm climates, an excessive amount of glass in buildings can lead to significant heat gain and visual discomfort. Consequently, current commercial smart glazing systems like polymer-dispersed liquid crystal (PDLC) [30], electrochromic (EC) [13], and suspended particle device (SPD) [31] glazing are deployed to enhance indoor thermal and visual comfort. Compared to low-emissivity (low-E) double glazing, SPD smart windows have the potential to reduce net energy consumption by up to 58% [31]. In SPD glazing, particles are randomly dispersed, creating a dark blue hue in the absence of an AC voltage, effectively blocking light. Transparency is achieved by applying an alternating current voltage, causing the randomly dispersed particles to align and render the glazing see-through [32]. The degree of transparency in SPD glazing can be adjusted, enabling it to transition from clear to translucent, depending on the amount of light and heat it allows through. At its most transparent, SPD glazing typically has a visible transmittance (VT) of 65% and a solar heat gain coefficient (g-value) ranging from 0.06 to 0.57 at its most translucent [33], Notably, SPD glazing exhibits rapid switching times, typically in the range of 1 to 3 seconds [34]. One of the key advantages of SPD glazing is its ability to continuously adjust transparency, rather than being limited to discrete levels based on the supplied voltage, as seen in conventional glass. Liquid crystal (LC) glazing represents another electroactive medium where the glass appears translucent when the power is off and completely transparent when turned on. LC glazing consists of a polymer matrix sheet sandwiched between two transparent plastic electrical conductors [35]. In the absence of applied voltage, liquid crystals scatter light due to their non-alignment [36]. However, when voltage is applied, the liquid crystals reorient, allowing light to pass through [37]. According to the study, switchable glazing solutions can result in significant energy savings of between 20% and 28% [38]. This dynamic response to voltage changes results in varying levels of transparency for LC glazing, with light transmittance typically around 50% in the opaque state and less than 70% in the active state [39]. Additionally, smart glass may be utilized to create climate-adaptive building shells that offer benefits including privacy, resistance to harsh weather, natural light adjustment, visual comfort, UV and infrared blocking, decreased energy usage, and thermal comfort [40].

The Kingdom of Saudi Arabia (KSA) has set a modern vision to encourage building systems that actively reduce energy consumption, subsequently leading to a decrease in CO_2 emissions. Among the fascinating solutions to address this challenge are smart buildings, which offer efficient responses to this critical issue. Both commercial and residential buildings in KSA are undergoing extensive consideration to enhance their energy efficiency and ensure that occupants experience both thermal and visual comfort. Given the extreme temperature ranges often recorded in KSA, the implementation of energy-efficient glazing in educational institutions is a crucial consideration. Indoor environmental quality (IEQ) in educational facilities significantly impacts the health, comfort, and productivity of students and teachers. This aspect has become a top priority in school design and construction [41-43]. Factors like the absence of sufficient daylighting and issues related to glare have a direct bearing on the IEQ of any building [44, 45]. These factors can lead to visual discomfort and even affect the eyesight of the building's occupants [46, 47]. In light of these considerations, the Saudi Building Code has recommended that buildings do not exceed a 50% window-to-wall ratio [48].

This underscores the importance of integrating daylighting considerations into building design and envelope planning. Moreover, the window-to-wall ratio has a direct influence on both thermal and visual comfort within the building. Based on a review of various studies, it becomes evident that controlling heat gain and incorporating daylighting features should go hand in hand to achieve energy-efficient buildings. By doing so, it is possible to minimize energy consumption while reducing heat gain through natural daylighting. This research focuses on examining a range of glazing options, including double low-E clear glazing, vacuum clear glazing, vacuum clear glazing with PDLC (ON and OFF states), and vacuum clear glazing with SPD (ON and OFF states). The major reasons for the above considerations are constraining the glares, improvising thermal comfort and natural daylighting. All the glazing which are studied have better performance than the conventional glazing i.e., clear glass but the feasibility of the glasses among the evolving glazing systems have been studied. The vacuum glazing and double low E have good performance capability but not as good as switchable glazing like SPD and PDLC. Among SPD and PDLC, it has been observed that PDLC performs better in its switch ability speed and in its cost. Field measurements and experimental investigations were carried out to assess the visual comfort and heat gain in a lecture room equipped with an intelligent façade. The study was conducted at the College of Engineering, Najran University, Saudi Arabia, which maintains a 50% window-to-wall ratio. This research seeks to provide insights into how energy-efficient glazing and intelligent building features can enhance both environmental sustainability and the quality of the educational experience in Saudi Arabian institutions.

2. MATERIALS AND METHODOLOGY

2.1 Materials and methodology

An aluminum cube with dimensions of 30 cm long, 30 cm wide, and 30 cm high was used in the experiment at a 1:10 size. Polystyrene insulation board was 5 cm thick around the cube to improve insulation. The room temperature was 25℃ throughout the studies. Glazing was attached to the aluminum cube to simulate a wall and window. The building model has 50% windows-to-walls. The glass for this configuration was 24 cm long and 24 cm high, with thicknesses differing per kind. Figure 1 illustrates the construction of the aluminum cube for the experimentation.

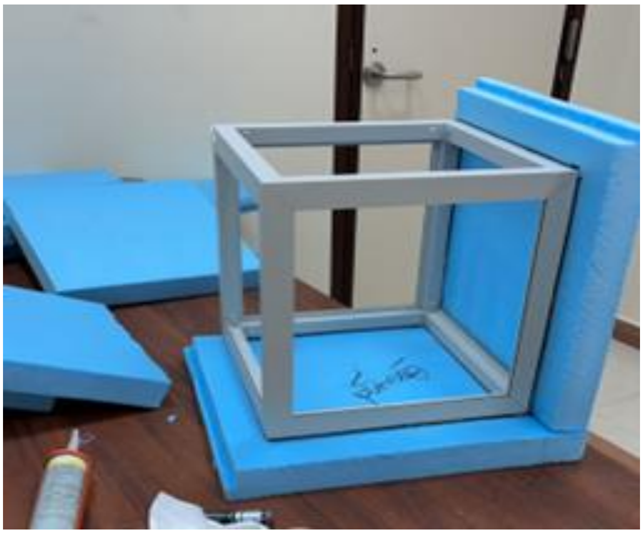

Figure 1. Aluminum cube arrangement

Six different types of glass were examined in this study, each with its unique characteristics and performance:

- Double Low-E Glass: This glass features a double-pane construction, with one of the glass layers coated on both sides with low emissivity (low-E) coatings. Low-E coatings are transparent but effectively reflect heat that falls on the glass.
- Vacuum Clear Glass: This type of glass is designed for optimal clarity and transparency. It does not have any special coatings or treatments, making it a standard glass option.
- SPD ON with Vacuum Glass: Utilizing Suspended Particle Device (SPD) technology, this glass has the capability to switch between clear and tinted states when an electrical current is applied. In the ON state, it allows visibility, while in the OFF state, it becomes opaque.
- SPD OFF with Vacuum Glass: Similar to the previous option, this glass employs SPD technology, but in the OFF state, it remains in a non-tinted, clear condition.
- PDLC ON with Vacuum Glass: Polymer Dispersed Liquid Crystal (PDLC) technology is incorporated in this glass, allowing it to transition between transparent and translucent states when an electric current is applied. In the ON state, it is transparent, while in the OFF state, it becomes opaque.
- PDLC OFF with Vacuum Glass: This glass, like the previous one, features PDLC technology. However, in the OFF state, it remains non-tinted and clear.

Having understood the evolution of smart glazing has motivated to select and compare the performance with efficient conventional type of glazing. These different glass types were studied to evaluate their thermal and daylight performance and to determine their suitability for various building applications, with the aim of achieving energy efficiency and visual comfort.

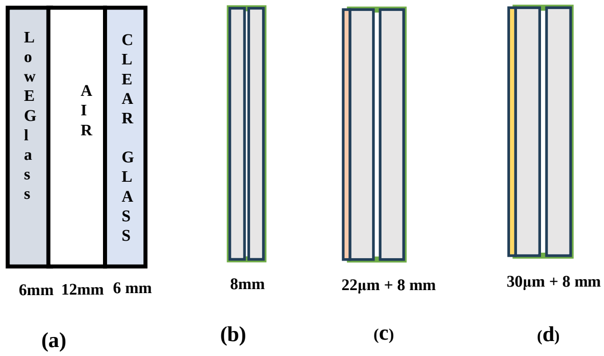

Figure 2. Various glass systems studied with its thickness

Low-E and transparent glass are 6mm thick. Figure 2(a) shows a 12 mm air gap between the panes. The vacuum glazing is only vacuum between two 8 mm panes. Figure 2(b) shows that vacuum between glasses is insignificant. Smart polymer dispersed liquid crystal (PDLC) glazing changes from clear to opaque in the voltage ON and OFF stages. Figure 2(c) depicts a 22 µm PDLC film mounted to 8mm vacuum glazing. PDLC film is confirmed, economical and efficient in its thin form which means its thickness is directly proportional to its cost of the film [49]. The experiment is done in transparent and opaque film states using ON and OFF voltages. The films in suspended particle devices allow light to flow through when electricity passes through and vice versa. Figure 2(d) shows a 30 µm film mounted to 8 mm vacuum glazing. Brief differences between PDLC and SPD are discussed in Table 1.

Table 1. Difference between SPD and PDLC

Parameters	SPD	PDLC
Privacy blind presentation	Weak to moderate	Strong
Heat block efficiency	High	Moderate
Opaque level adjustment	High	High
Transparency	Moderate	High
Switching speed	Several seconds	Milliseconds
Cost	High	Moderate

2.2 Materials and methodology

The experimental arrangement featured an affordable solar simulator that included a 150 W Osram metal halide lamp, which emitted a warm-white glow and maintained a color temperature of 4000 K. The lamp was positioned at 100 mm from the glass, as indicated in Figure 3. To monitor temperature changes, temperature-detecting sensors were strategically arranged on both the inside and outside surfaces of the glass. The readings of it have been recorded by surface thermocouple probe of type 'J' which has standard limit of error ±2.2℃ which can measure up to 750℃. This setup allowed for the measurement and analysis of temperature variations under different glazing conditions, helping to assess the thermal performance of the various glass types.

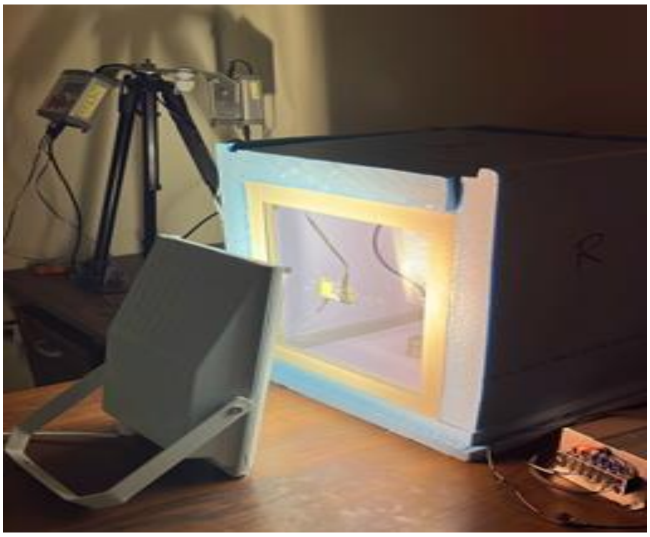

Figure 3. Experimental setup with 150 W Osram metal halide lamp

The temperature on the surface of the glass has been identified and the heat gained through the glass. The operating cost of the glass has been estimated considering the place, Najran, Saudi Arabia falls under hot and humid region, hence only cooling cost has been calculated. The heat gain which is calculated is also helpful to determine the carbon emission mitigation for the respective glass studied. The illumination has been recorded by using fluke light meter which measures up to 20,000 lux has been arranged inside the setup to evaluate the illumination passing through the glazing which has precision limit of ± 3%.

3. RESULTS AND DISCUSSION

3.1 Temperature absorption and daylight illuminance

The experimentation is carried out by considering the room temperature and the device introduced to give the artificial sunlight. The outside and the inside temperatures are recorded including the temperature at the face of the glass. The results obtained have been discussed in Table 2.

Figure 4 reveals that the temperature measurements recorded on the external and internal surfaces of different types of glass demonstrate their heat absorption capabilities and the extent of heat transfer through the glass. The data indicates that the SPD-OFF state glass has the highest heat absorption, with a temperature increase of approximately 24.28℃, while the Double low-E glass exhibits the lowest heat absorption among the glasses tested, with an increase of about 10.53℃. The order of the glasses which absorb the heat in descending order are SPD-OFF, SPD-OFF, PDLC-OFF, PDLC-ON, Vacuum clear glass and Double low-E glass. The minimum recommended daylight illumination is 200 lux [50]. Figure 5 shows the light transmission capacity of glass by depicting the illumination of light as it passes through the material. From the studied glasses the Vacuum clear glass has the highest illumination of 5895.27 lux, which may lead to the glare through the glazing which leads to thermal and visual discomfort whereas SPD-ONhas the least 121.18 lux, but the amount of daylight allowed by SPD-ON is not sufficient for the average commercial or residential building. The PDLC-ON & OFF states satisfy the daylighting requisites by providing the necessary amount of light through the glass. A substantial amount of energy can be wasted if the PDLC film is handled incorrectly [51].

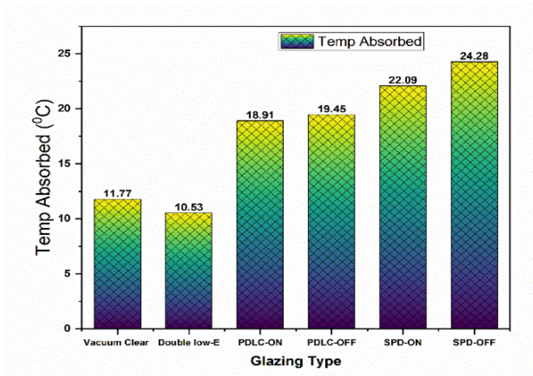

Figure 4. Temperature absorbed by glass

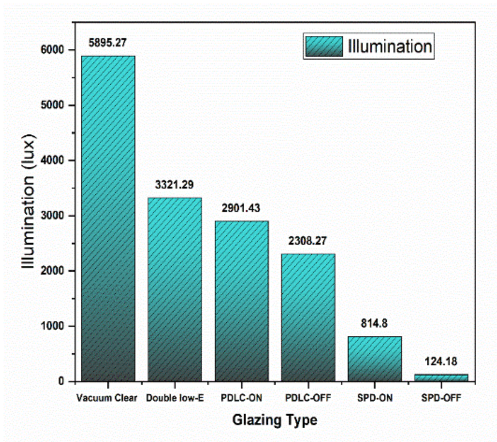

Figure 5. Daylight illuminance of the glass

Table 2. Temperature and illumination

No.	Glass	Time		Temp-SVR-Face (Ć)		Temp. Diff. (Ć)	Illumine (lux)
		Start	End	Inside	Outside		
1	**PDLC-ON**	10:05	11:05	32.15	51.06	18.91	2901.427
2	**PDLC-OFF**	11:50	12:50	32.10	51.55	19.45	2308.272
3	**Vacuum Clear**	1:15	2:15	37.32	49.09	11.77	5895.269
4	**Double Low-e glass**	2:30	3:30	34.09	44.62	10.53	3321.285
5	**SPD-OFF**	9:50	10:50	31.17	55.45	24.28	814.7962
6	**SPD-OFF)**	12:05	1:05	31.63	53.72	22.09	124.1769

The thickness of the glazing system, the total transmittance (U) and Solar Heat Gain Coefficient (SHGC) values of double low-E, SPD and PDLC glazing effects the efficiency of the glazing in terms of solar heat gains as well as the operating costs. The above parameters are the most influencing parameters for the glazing systems.

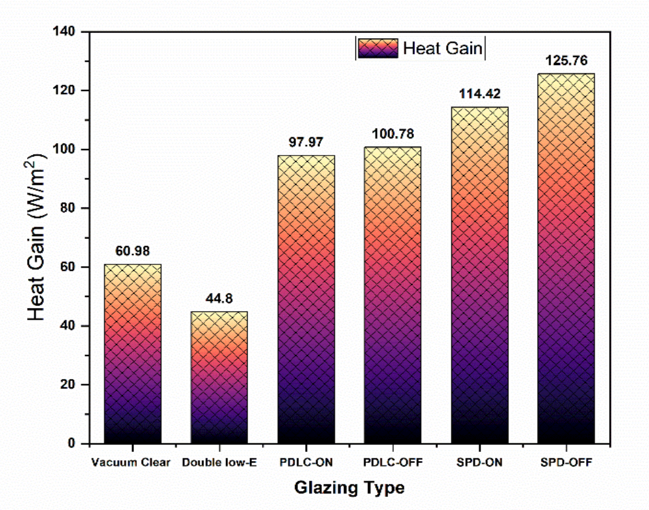

Figure 6. Heat gained by the considered glass

3.2 Heat gain from the glass

The heat gain calculations are the very important parameters to assess the credibility of the glass. The dimension of the glass holds an important role in understanding the amount of heat gained through the glass. The considered various types of glasses hold an area of 0. 0576 m^2. The thickness of the glass is 0.024 m, 0.008, (22 μm + 0.008 m) and (30 μm + 0.008 m) for Double low-E glass, Vacuum clear glass, (PDLC+ Vacuum glass) and (SPD + Vacuum glass) respectively. The heat gain has been measured for the samples considered is shown in Figure 5 and the heat gain calculations per unit area are also calculated and the readings were noted. The heat gains verses glasses bar graph has been presented in the image mentioned below. The heat gain calculations have been done per the considered area of glass and per unit area. For the considered area of the glass SPD-OFF state allows heat gain of 100 W through it and double low-E allows least i.e., 23.54 W. In terms of unit area considerations, SPD-OFF allows 126.78 W of heat and the double low-E glass allows up to 44.8 W.

Figures 6 and 7 show the heat gain through the glass area and per unit areas respectively. It has been observed that double low-E glass has much less heat gain among all the studied six glass samples and SPD -ON has more heat gain through it. The descending order of the heat gain among the six glass samples is SPD-OFF, SPD-OFF, PDLC-OFF, PDLC-ON, Vacuum clear glass and Double low-E glass. The same order is observed for considered unit area calculation too.

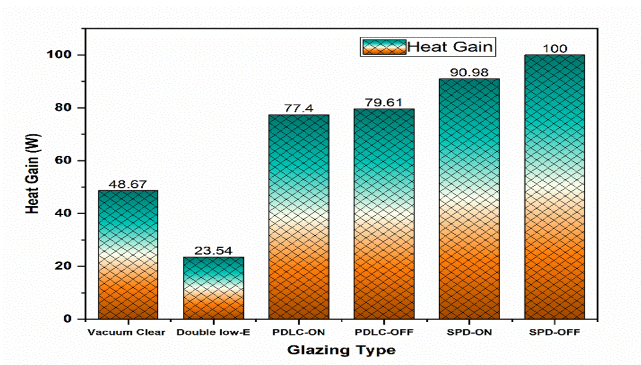

Figure 7. Heat gained by the glass per unit

3.3 Operating cost of the glass

The heat gain is also responsible for the operating cost of the glass. Najran, Saudi Arabia, a region which the study has been carried out falls under hot and dry conditions. Being a hot and dry region, the average temperature of any month shows the dominance of cooling environment than heating. Hence, the cooling cost is considered as the operating cost of the considered glass.

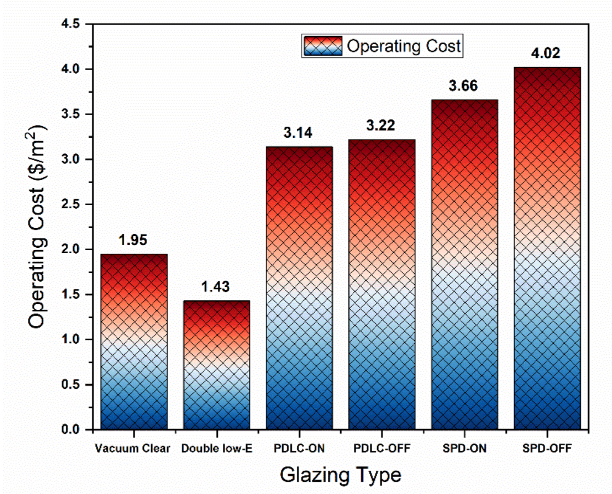

Figure 8. Operating cost of the glass per unit area

The operating cost at which the smart glazing is high and it affects the initial cost of the material but the maintenance cost of the buildings will be very less when compared to the conventional glazing systems. Among all the considered glass samples, Double low-E glass has the lowest operating cost among all, which is 1.43 \$/m^2 the glass samples and SPD-OFF has highest operating when it is calculated per unit area which is 4.02 \$/m^2. The descending order of the operating cost among the glass samples is SPD-OFF, SPD-OFF, PDLC-OFF, PDLC-ON, vacuum clear and Double low-E glass as it is shown in Figure 8. In terms of operating cost low-E glass gives out least operating cost but lacks in the adaptability to the exterior temperatures but the smart glazing achieves it.

3.4 Carbon emission mitigations

Despite widespread demands for carbon reduction strategies, construction sector GHG emissions continue to climb worldwide. A large portion of the carbon emissions that cause global warming and other climatic changes came from the energy used in buildings (almost a third). Most nations have policies and programs in place to cut down on greenhouse gas emissions and energy use in buildings. In buildings, the number of sources used for cooling/heating results in the consumption of electricity or natural gas which in turn is responsible for carbon emissions. The efficient glazing is responsible for the mitigation of carbon emissions. The mitigations have been calculated by considering Vacuum glazing as the reference. Having known that the SPD and PDLC as the evolving and smart glazing among all the samples, these smart glazing have been attached to the vacuum glazing and the emissions mitigation study has been done. In Saudi Arabia, the winter months considered are negligible and thus the study has been carried out on the summer months where cooling is implemented. The smart glazing contributes to carbon emissions mitigation by the means of restricting the electricity in its maintenance. Thus, it contributes to the sustainability of the building. In summer, for electricity, the annual average emission factor is 0.98 kg-CO_2/kWh. Among all the smart glazing, SPD-OFF state has more mitigations around 25.39 kg-CO_2/kWh and the least has with the PDLC-ON state, which is 14.5 kg-CO_2/kWh. The descending order of the Carbon Emission mitigations by the glass is SPD-OFF, SPD-OFF, PDLC-OFF and PDLC-ON. The calculations are shown in Figure 9.

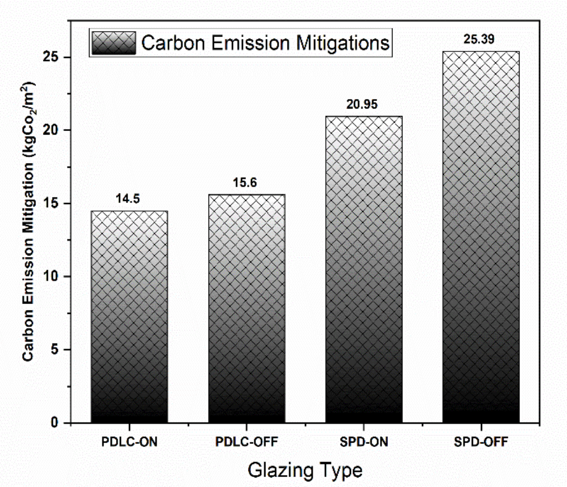

Figure 9. CO_2 emissions mitigation per unit area

4. CONCLUSION

In this comprehensive study, six different glass samples were examined, including Vacuum Clear, Double Low-E, SPD-ON, SPD-OFF, PDLC-ON, and PDLC-OFF. The research encompassed experimentation, numerical calculations, and analyses across various parameters, leading to the following key findings and conclusions (Figure 10).

- Effectiveness of Smart Glazing: The study revealed that all glass samples exhibited varying levels of efficiency across different parameters. However, it was evident that smart glazing systems outperformed traditional glazing arrangements in terms of energy efficiency and visual comfort.
- Heat Absorption and Daylighting: Among the glass samples, SPD-OFF and SPD-ON states absorbed more heat than the other types, but they allowed very little natural illumination. In contrast, PDLC-ON and PDLC-OFF states absorbed less heat while facilitating the desired daylighting.
- Heat Gain: Double low-E coated glass proved to have the least heat gain among all the glass samples. Among the non-conventional glass options, PDLC-ON and PDLC-OFF states exhibited lower heat gain compared to SPD-OFF and SPD-ON states.
- Operating Cost Efficiency: Calculations indicated that among the non-conventional glazing options, PDLC-ON and PDLC-OFF states had lower operating costs than SPD-OFF and SPD-ON states.
- Carbon Emissions Mitigation: The study found that SPD-OFF state led to greater carbon emissions mitigation compared to the other glazing types. PDLC held the third position, with a difference of 10 kg-CO_2/kWh.
- Recommendation: Based on the findings, PDLC film integrated vacuum glazing was suggested as the more favorable option when considering aspects such as heat gain, operating costs, and daylight illumination. In contrast, SPD glazing was found to be less effective in providing adequate daylighting, which limited its overall effectiveness.
- These results emphasize the advantages of smart glazing technologies, particularly PDLC, in achieving energy efficiency, visual comfort, and environmental sustainability in building design and construction.

The low-E glass, SPD and PDLC play important roles. In obstructing the sun rays through the glazing which in turn controls the solar radiation through it. The double low -E glass has performed in terms of obstructing the solar radiation which in turn results in effectiveness in heat gain as well as the operating cost. This is due to low U and SHGC values. The switch ability and smartness in glazing makes some difference in the conventional than the smart glazing.

PDLC-integrated facades can adjust to weather or optimize daylighting. This can aid energy-efficient city planning. PDLC-based switchable windows might reduce urban light pollution. Smart windows in buildings may be encouraged by public policy to improve night sky conditions.

Building codes and energy laws may use PDLC technology to achieve tougher energy efficiency demands for new and retrofitted buildings. Public health policies may recommend PDLCs in schools and hospitals to increase occupant comfort and well-being by controlling natural light and privacy. To meet sustainability goals and lessen dependency on traditional lighting and HVAC systems, government regulations should promote or subsidize PDLCs in building projects.

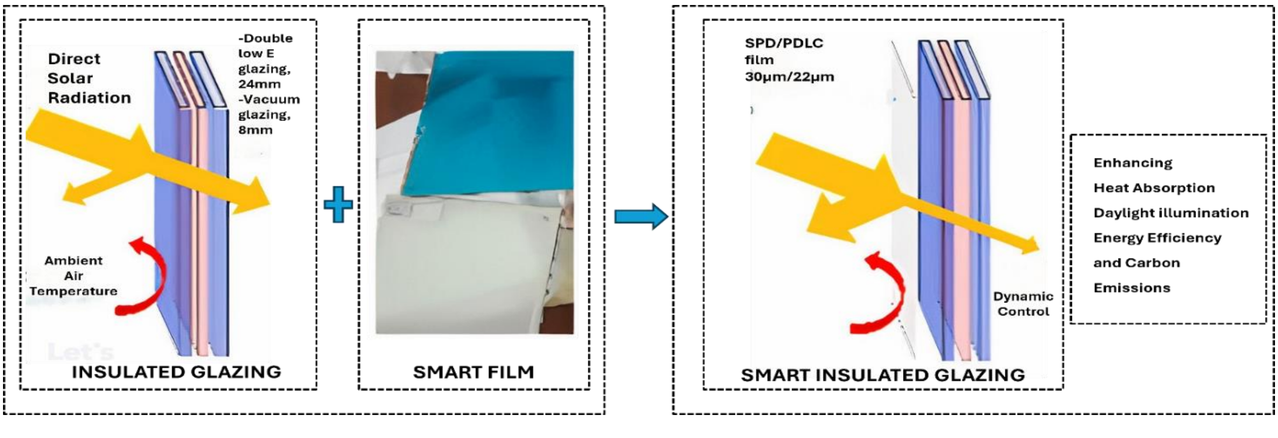

Figure 10. Overview of designed parameters, key findings, and conclusions from research analyses

5. APPLICATIONS AND FUTURE SCOPE

- The installation of smart glazing like PDLC would be really interesting in residential homes, commercial and office where there is a need of privacy and controlled natural light.
- The confidential places where the information is protected like ATMs will enhance the natural light but restrict the transparency.
- In hospitals, near patient partitions and to staff of hospital to monitor patients visually with a switch ability.

In the study, PDLC has been controlled by a switch and changed its state to complete ON and OFF. It has not been varied in terms of transparency and by voltage by which it can be responsive with respect to the external atmosphere of the glazing. For future studies, it can be extended to control the transparencies of the PDLC to make it adaptive with respect to the external climate. It can also be controlled by temperature and external light. The studies can also be extended to dynamic applications like in automotives. It can also pave the way for interdisciplinary collaborations with engineers, researchers, and architects for efficient building design for a sustainable future.

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