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Energy Savings and Carbon Emission Mitigation Prospective of Building's Glazing Variety, Window-to-Wall Ratio and Wall Thickness

Saboor Shaik [1,*], Kirankumar Gorantla [2], Aritra Ghosh [3,*], Chelliah Arumugam [1] and Venkata Ramana Maduru [1]

[1] School of Mechanical Engineering, Vellore Institute of Technology, Vellore 632014, India; chelliah.1985@gmail.com (C.A.); mvr.mec@gmail.com (V.R.M.)
[2] Department of Mechanical Engineering, Sasi Institute of Technology and Engineering, Tadepalligudem 534101, India; gorantla.kirankumar@gmail.com
[3] College of Engineering, Mathematics and Physical Sciences, Renewable Energy, University of Exeter, Cornwall TR10 9FE, UK
* Correspondence: saboor.nitk@gmail.com (S.S.); a.ghosh@exeter.ac.uk (A.G.)

Abstract: Strategic selection of glazing, its window-to-wall ratio, and wall thickness of building reduce the energy consumption in the built environment. This paper presents the experimental results of solar optical properties of five glasses: clear, tinted bronze, tinted green, bronze reflective, and polymer dispersed liquid crystal glasses. Laterite room models were modeled with four different thicknesses and four different glasses using Design Builder, and thermal simulation tests were carried out using Energy Plus. The energy savings and carbon emission mitigation prospective of a building's glazing variety, window-to-wall ratio (WWR), and wall thickness were investigated. The results revealed that among the five window glasses studied, the polymer dispersed liquid crystal glazing window (PDLCGW) was found to be the most energy-efficient for low heat gain in laterite rooms. The laterite room with 0.23 m wall thickness and 40% PDLCGW WWR reduced 18.9% heat gain in comparison with the laterite room with 0.23 m wall thickness and 40% clear glass WWR. The laterite room of 0.23 m wall thickness with PDLCGW glazing of 40% WWR enhanced cooling cost savings up to USD 31.9 compared to the laterite room of 0.08 m wall thickness with 40% PDLCGW. The laterite room of 0.23 m wall thickness with PDLCGW glazing of 40% WWR also showed improved carbon mitigation of 516 kg of CO_2/year compared to the 0.23 m wall thickness laterite room of 40% WWR with clear glass glazing. The results also showed that the laterite room with 0.23 m wall thickness and 100% clear glass WWR increased heat gain by 28.2% in comparison with the laterite room with 0.23 m wall thickness and 20% clear glass WWR. The results of this article are essential for the strategic design of buildings for energy saving and emission reduction.

Keywords: window-to-wall ratio; wall thickness; laterite rooms; energy-efficient glasses; annual cooling cost-saving; annual carbon emission mitigation

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1. Introduction

Globally, the building industry is liable for a total energy intake of 40%, and the energy requirement for its operation and repair will continue to rise in the coming years. The air conditioning load of heating and cooling absorbs about 60% of the overall electricity use of homes and is the greatest portion of energy usage [1]. In India, building sectors are accountable for significant power usage of about 33%, with an almost steady growth of 8% over the coming years [2,3]. In hot climatic regions, the cooling demand for residential and commercial buildings is a major concern for its practical requirement and preserving thermal comfort. Building energy consumption will begin to increase unless effective steps to boost energy quality are taken quickly due to urbanization, rising total built-up area, and living standards. Solar passive buildings with energy-efficient systems architecture use about 30% less electricity than traditional buildings [4]. Building elements such as glazing, floors, walls, and roofs are accountable for heat intake. The building envelope is the most critical and fundamental energy-saving feature of passive building architecture. The design and selection of construction materials are crucial steps to reduce the energy usage of buildings. Optimization of construction materials and element design is an essential part of energy efficiency. These building enclosures aid to prevent or drop the heat gain. The energy consumption was studied for buildings of various glazing materials such as single pane, double low-E glazing, and photovoltaic windows in Malaysia [5]. Thermal analysis was carried out with smart switchable glazing systems such as PDLCs [6], SPDs, and evacuated glazing [7] for energy savings; in addition to that, effect of sky condition on transmittance was explored [8–11]. The solar spectrum characteristics of glasses have been altered to study heat transfer through Single Low-E and Double Low-E windows. The different windows were suggested to reduce solar radiation in summer and increase solar radiation in winter in an adiabatic space [12]. The optimal tilt angle to the vertical outside wall minimized the strength of solar radiation in houses [13,14]. Investigations found that the construction of inward tilting windows is an efficient and affordable strategy for eliminating solar heat gain in buildings under hot environmental conditions. Glazing temperature and solar heat gain due to global radiation were evaluated by a mathematical model [15]. The effect of different geometry of the roof design and glass window materials as the low-E glass was examined in detail using eQUEST for energy reduction in Taiwan [16].

The impact of the exterior wall thickness on the thermal stability of the building has been observed, and it has been stated that houses with thick walls would be comfortable all year round, as compared to houses with thin walls [17,18]. Radiation protection coatings added to the reflective outside surfaces of the house have indicated a decrease in solar gain. DOE simulations for hot climate areas showed a 60% reduction in cooling and heating loads. The reduced loads saved about 50 percent of the air conditioning costs [19]. Numerical studies of an industrial building in China, and in Australia with reflective coatings over external surfaces such as glazings, walls, and roofs, showed a minimum of 30% reduction in the cooling load. The research suggested that using reflective coatings as a passive mechanism to monitor the heat gain in buildings may theoretically save up to 25% of operational costs [20].

Numerous studies and simulations have been performed to minimize solar radiation by building materials. Taleb and Al-Watter built windows to limit incoming solar radiation in building enclosures and published analytical models to quantify solar radiation [21]. Specific statistical measurements have been documented to determine glazing properties such as solar coefficient of heat gain, overall heat transfer coefficient, and solar optical properties for various window structures under various climatic conditions [22]. Thermal insulation in building walls increases thermal resistance to heat gain and significantly decreases cooling and heating energy. More thermal insulation thickness decreases the cooling and heating load and enhances the energy-saving results [1,23]. Optimum economic insulation thickness of various building materials was determined on the basis of a detailed relationship with exterior walls, roofs, and windows with various window-to-wall ratios. The proposed mix of insulation thickness and optimum WWR demonstrated substantial energy savings [24]. Thermal insulation provided to the exterior walls, roofs, and floors reduces heat gain and improves the thermal performance of the built environment. Thermal insulation used on the exterior roofs, walls, and floors reduces heat gain and improves the thermal performance of the built environment [25,26]. Thermoeconomic research was carried out to maximize the insulation thickness of exterior walls in various climates of Turkey [27]. Super insulation-related Aerogel technologies have been studied for the optimal thickness of the insulation and the environmental effects to minimize greenhouse gases. Such insulating products displayed a decrease in cooling loads coupled with a decline in CO_2 and SO_2 [28].

The window-to-wall ratio (WWR) is specified as the ratio of the glazed area to the gross outer wall region. WWR is a significant parameter that affects the energy efficiency of the building. Window area has an impact on the building of heating load, cooling load, and natural daylighting. The effect of the window-to-wall ratio on visual and thermal comfort of the various interiors of the residential building analysed showed a considerable reduction in cooling and heating energy use in China's high summer and cold winter areas [29]. For a passive solar structure, the window area of the south-facing exterior wall section has been designed to obtain the best energy output in five different cities of Turkey [30]. Various climates need a different range of WWR; however, the optimal WWR relative range is between 0.3 and 0.45 [31]. Thermal study of numerous buildings and glass structures of varying WWRs has been carried out to achieve an optimum combination to reduce the cooling load in a house [32]. Simulation studies were carried out to find suitable single/double glazing, laminated glazing, and hydrogel glazing to reduce cooling and heating costs in buildings of various climatic conditions [33–36]. The effective usage of natural daylight for lighting or illumination shows a decrease in the energy use of artificial daylighting. Natural daylighting has been measured with the aid of various models for different climatic zones. The reflective glasses are retrofitted in single-pane glazing and double-pane windows to reduce the heat gain and cooling load [37]. In Turkey's climatic condition, double glazing with 40% of the glazing area reported 79%, 53.97%, and 61.41% reduction in the heating load for south, north, and west (or east) orientations compared to single glazing, respectively [38].

The literature mentioned above shows the value of regulating the building's heat gain through building elements. The building's heat gain depends on the thickness of the external walls, the window-to-wall ratio (WWR), and the form of window glazing. Therefore, the best mix of wall thickness and type of glazing with a specific WWR will optimize the building's heat benefit.

Previous research concentrated on the structural and thermal properties of laterite stone, which is the most popular for buildings in India's coastal regions. For the first time, the air-conditioning cost-saving potential of laterite stone houses was investigated in this paper. The current study quantified heat gains through laterite stone rooms with varying wall thicknesses, which aided in calculating air conditioning cost savings and carbon emission reductions. The paper also presents the solar-optical properties of tinted, reflective, and smart switchable glazing systems (PDLCs) in the visible (380–780 nm) and entire solar regions that were experimentally measured (300–2500 nm). At various window-to-wall ratios, the results of conventional glazing systems were compared to those of smart glazing systems. In addition, the colour rendering index (CRI) and correlated colour temperature (CCT) of clear glass, tinted bronze glass, tinted green glass, bronze reflective glass, and polymer dispersed liquid crystal glasses (smart glasses) were thoroughly evaluated in this paper. The daylight inflow (average daylight factor) through glazing systems was also investigated to determine whether certain glazing systems incur any artificial daylighting costs.

2. Materials and Methods

Laterite rock is a natural, environmentally friendly stone and cost-efficient south-western ferruginous construction material that is locally available in dark red, dark brown, and yellowish red colours [39,40]. Laterite rock is used to make the building walls in Mangalore (12.870 N, 74.880 E), a city in the Indian state of Karnataka. Laterite rock formation typically occurs in subtropical regions such as India, and its formation occurs in warm and wet areas [41]. Malabar laterite stone's physical and mechanical properties have been investigated and reported in the literature [42,43]. This paper selected laterite as building wall material, reinforced cement concrete (RCC) for the roof, and dense concrete for the floor. Thermo-physical properties of laterite stone, along with other building materials, are presented in Table 1. The five different types of glazing materials available in the Indian market were selected. The glazing materials selected are clear, tinted bronze, tinted green, bronze reflective, and PDLC glasses. The walls of various laterite thicknesses (0.08 m, 0.13 m, 0.18 m, and 0.23 m) and glazing of the different window-to-wall ratios (20%, 40%, 60%, 80%, and 100%) were considered in this work.

Table 1. Thermophysical properties of building materials [44].

Materials/Properties	k (W/mK)	C_p (J/kgK)	ρ (kg/m^3)
Laterite stone	1.3698	1926.1	1000
Dense concrete	1.74	880	2410
RCC	1.58	880	2288

3. Experimental Methodology

Solar gain by glazing was computed with the help of the solar optical properties of the glazing. The solar spectral properties of various glasses were obtained by striking light at a zero angle on a glass surface with the spectrophotometric method [45] in the Perkin Elmer spectrophotometer.

Figure 1 shows the integrating spectrophotometer integrated with the UV WinLab software used in the experiment. Solar spectral properties of four 6 mm thick glasses such as clear glass, tinted bronze, tinted green, bronze reflective, and PDLC glasses were measured in the light spectrum range of 320–2500 nm. These spectral properties of glasses were further reduced to obtain solar energy transmission and reflection in the British Standard [46,47].

Figure 1. UV–VIS–NIR Perkin Elmer (Lambda 950) spectrophotometer.

These spectral properties of glasses were further reduced to obtain solar energy transmission and reflection as per British Standard [46]. Spectral absorption of glasses was obtained from the summation rule. The glazings' spectral transmission and absorption properties are described in Figures 2 and 3, respectively. Solar energy transmission and reflection for single-pane glazing can be calculated using Equations (1) and (2). In Figure 2, the graph shows the lowest transmission (spectral) for PDLC glass and the highest transmission (spectral) for clear glass among five glasses.

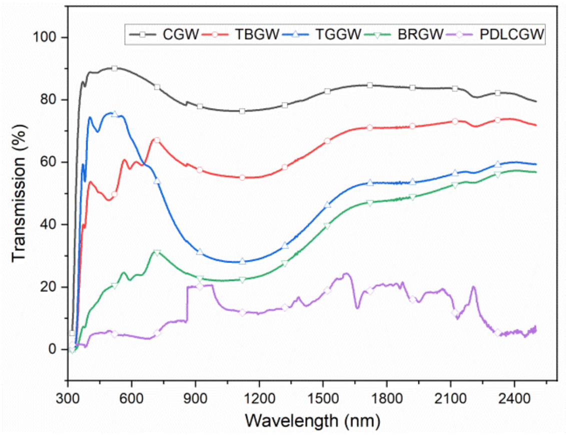


Figure 2. Spectral transmission of various glasses.

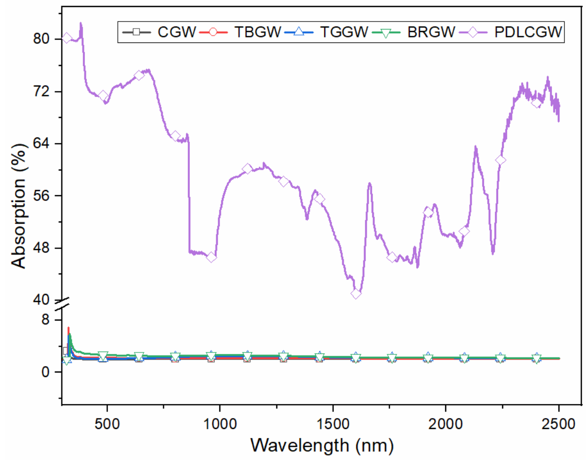


Figure 3. Spectral absorption of various glasses.

Solar transmission is a fraction of the solar radiation transmitted by glazing, which is calculated using the following formula (Equation (1)):

$$T_{SOL} = \frac{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \tau(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \Delta\lambda} \quad (1)$$

Solar reflection is a component of solar radiation reflected from glazing that occurs on glazing and is calculated using Equation (2):

$$R_{SOL} = \frac{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \rho(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \Delta\lambda} \quad (2)$$

Solar absorption can be calculated using Equation (3):

$$A_{SOL} = (100 - T_{SOL} - R_{SOL}) \quad (3)$$

In addition to the solar-optical properties, color rendering properties of glasses such as color rendering index (CRI) and correlated color temperature (CCT) of the glasses were calculated to assure the visual acceptability of the studied glazing systems as per British Standard [46]. Table 2 summarizes the experimentally measured solar optical properties and color rendering properties of various glasses. These thermo-physical and solar optical properties were used in the design of the model and thermal analysis of buildings, respectively. The calculated CRI values of the glazing systems were well above the minimum recommended level (80) for good color rendering in building interiors. The

CCT values of the glasses represent strong cool daylight through the studied glasses. The clear glass (CGW) reported the highest CRI of 95.7, and the tinted green glass (TGGW) reported the lowest CRI of 82.5.

Table 2. Solar optical and color rendering properties of glasses.

Window/Solar Properties	Abbreviation	Transmission, T_{SOL} (%)	Reflection, R_{SOL} (%)	Absorption, A_{SOL} (%)	CRI (−)	CCT (K)
Clear glass window	CGW	81.84	16.06	2.08	95.7	5188
Tinted bronze glass window	TBGW	58.66	39.08	2.24	84.8	5114
Tinted green glass window	TGGW	47.32	50.32	2.53	82.5	5240
Bronze reflective glass window	BRGW	27.22	70.17	2.60	85.1	5375
Polymer dispersed liquid crystals glass window	PDLCGW	11	27	62	86.8	5471

4. Design Methodology

Design Builder (embedded with Energy Plus V9.4) was used to design models and perform thermal analysis. The room models of measurements 5 × 5 m were designed with a ceiling height of 3.2 m from the ground. Four different thicknesses of the laterite walls were considered for the simulation 0.08 m, 0.13 m, 0.18 m, and 0.23 m. The buildings were designed using laterite for the walls, dense concrete for floors with a thickness of 0.15 m, and RCC for the roof with a thickness of 0.15 m. The room model with different wall thicknesses and different window-to-wall ratios of five different glasses was designed and thermally analyzed in the south orientation. The south orientation has been reported as the best orientation to place a window for minimum heat gain for the studied climate (Mangalore) in the northern hemisphere [48]. The glazing systems in the south have experienced the lowest and highest heat gain in the summer and winter, respectively, which is desired for the dominant cooling climates. Therefore, the analysis was carried out for the solar heat gains and cost savings while placing the glazing on the south wall [49].

A total of 100 room models (4 (wall thicknesses) × 5 (glasses) × 5 (window-to-wall ratios) = 100) were simulated for reducing cooling loads in buildings. The thermal analysis was conducted for the city of Mangalore, India (12.9141° N, 74.8560° E), which has a moderate climate [49]. This environment requires cooling for five months (April–August) and no cooling or heating during the other months (October–March), according to ASHRAE standards [50]. As a result, the analysis was conducted during the summer, when cooling requirements are greatest (April–August). During the simulation period, the sky conditions were clear most of the time, and thus the ASHRAE Clear Sky condition was assumed in the analysis to calculate heat gains [50]. The effect of sky conditions and shading devices were not considered in the present work to study the sole effects of various glazing systems, WWR, and wall thickness on energy savings. The wind speeds, radiative heat transfer coefficients, and emissivity of glazing surfaces were considered as per Chartered Institution of Building Services Engineers standard (CIBSE) [51]. Figure 4 shows building models designed for 20%, 40%, 60%, 80%, and 100% window-to-wall ratios.

Table 3 shows heat gain in laterite rooms with 0.23 m wall thickness with different WWR (20%, 40%, 60%, 80%, and 100%). Table 3 shows annual heat gain in building through building components such as walls, floors, roofs, and window glasses.

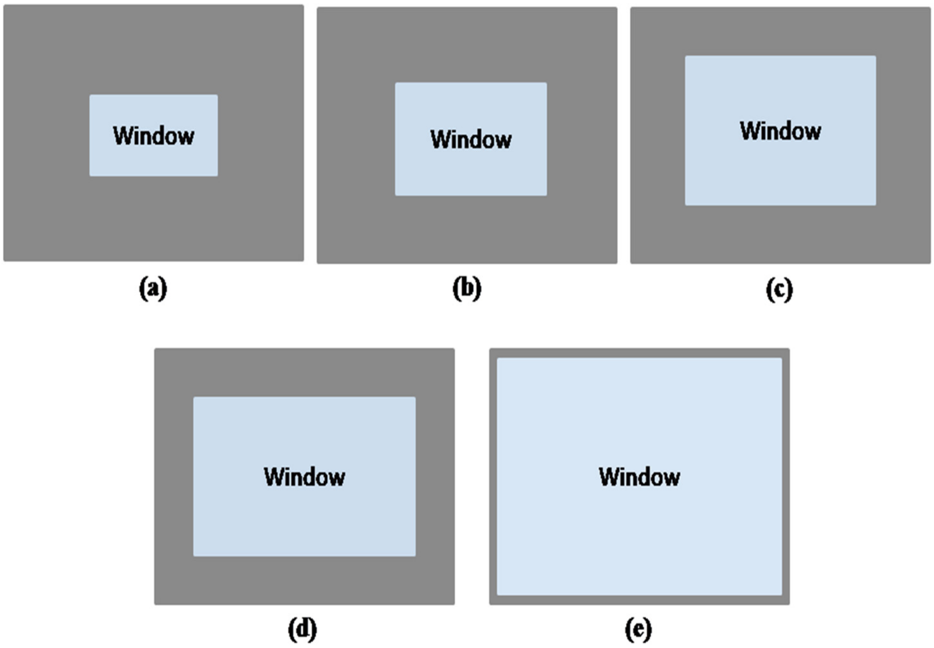


Figure 4. Building models: (**a**) with 20% WWR, (**b**) with 40% WWR, (**c**) with 60% WWR, (**d**) with 80% WWR, (**e**) with 100% WWR.

Table 3. Annual heat gain in 0.23 m wall thickness laterite rooms with different WWR.

	Enclosure	CGW (kWh)	TBGW (kWh)	TGGW (kWh)	BRGW (kWh)	PDLCGW (kWh)
WWR-20%	Walls	1551.2	1596.9	1619.7	1665.3	1520.8
	Floor	62.4	65.4	65.4	66.9	60.8
	Roof	1815.9	1840.2	1853.9	1881.3	1748.9
	Window	577.9	447.1	380.2	244.9	76
	Total	4007.4	3949.6	3919.2	3858.3	3406.6
WWR-40%	Walls	1371.8	1458.5	1504.1	1593.8	1444.8
	Floor	57.8	60.8	62.4	65.4	68.4
	Roof	1726.1	1777.8	1805.2	1858.4	1878.2
	Window	1190.8	921.6	783.2	504.9	132.3
	Total	4346.5	4218.8	4154.9	4022.6	3523.7
WWR-60%	Walls	1201.4	1326.2	1391.6	1522.3	1522.3
	Floor	51.7	56.3	59.3	63.9	68.4
	Roof	1634.9	1714	1753.5	1835.6	1878.2
	Window	1817.4	1406.8	1195.4	771.1	188.6
	Total	4705.4	4503.1	4399.7	4192.9	3657.6
WWR-80%	Walls	1049.4	1207.5	1289.7	1456.9	1475.2
	Floor	47.1	53.2	56.3	62.4	68.4
	Roof	1548.2	1651.6	1704.8	1812.8	1901
	Window	2442.4	1890.4	1606	1037.2	279.8
	Total	5087.1	4802.7	4656.8	4369.3	3724.5
WWR-100%	Walls	1026.6	1190.8	1274.4	1446.3	1444.8
	Floor	45.6	53.2	56.3	62.4	68.4
	Roof	1536	1642.5	1697.2	1809.8	1901
	Window	2538.2	1964.9	1669.9	1078.3	410.6
	Total	5146.5	4851.4	4697.8	4396.7	3824.9

5. Cost Assessment Methodology

Total heat gain (Q_T) in the laterite room during the summer days can be calculated using Equation (4) [50]:

$$Q_T = (Q_d \times 30)_{\text{April}} + (Q_d \times 31)_{\text{May}} + (Q_d \times 30)_{\text{June}} + (Q_d \times 31)_{\text{July}} + (Q_d \times 30)_{\text{August}} \quad (4)$$

where Q_T is the total heat gain during the summer season (kWh).

Annual cooling cost (Cc) is the cost incurred due to the total heat gain inside the building. It is given as Equation (5):

$$C_c = \frac{Q_T.C_e}{COP} \quad (5)$$

Annual energy saving (Q_{save}) is the yearly energy saving obtained by the difference between two different building heat gain values, and it can be calculated using Equation (6):

$$Q_{save} = Q_{T1} - Q_{T2} \quad (6)$$

Annual cooling cost-saving (C_s) is the cost savings that occurred for one building in comparison with another building [52], and it is given by Equation (7):

$$C_s = \frac{Q_{save}.C_e}{COP} \quad (7)$$

where C_e is the unit cost of electricity (0.082 USD/kWh) as per the Indian scenario, and COP indicates the cooling system's coefficient of performance (2.5).

Carbon emission mitigation (CO_2) is the carbon mitigated through annual energy saving [53], and it is given by Equation (8):

$$CO_2 = \frac{Q_{save}.m}{COP} \quad (8)$$

where m is the mass of carbon emission for producing unit electricity under coal power plant production (0.98×1.6 kg/kWh).

Design Builder simulation results were compared with the results obtained using the analytical model [36]. The simulated total solar heat gain (kWh) through the walls, roofs, floors, and clear glazing systems of 0.23 m wall thick and 40% WWR laterite room was 4346.5 kWh. The solar heat gain through the above building room was validated with the analytical findings of 4589 kWh as per the standard procedure. The Design-Builder simulation results were in good agreement with the analytical procedure results. The relative difference between the results was 5.3%. The building envelope characteristics, glazing properties, and parameters for the analytical procedure were considered to be similar to the Design Builder simulations.

Design Builder (embedded with Energy Plus V9.4) was used to calculate daylight inflow. The average daylight factor (DF) was simulated under CIE-overcast sky for a complete year. External shading was not considered in the analysis. Daylight inflow through glazing will significantly contribute to the indoor environment's ambience and reduce the demand and energy consumption for supplementary lighting. The average daylight factor (DF) of the space of interest is the ratio of internal to external lighting illuminance on the working plane under the overcast sky. The glazing should provide adequate illuminance levels throughout the day while avoiding discomfort, glare, and overheating from a daylight perspective. The minimum recommended average daylight factor (DF) for Indian dwellings is 0.625%, according to Indian standards [54]. One percent of DF metric is equal to 80 lux for a simultaneous 8000 lux outside illuminance.

6. Results and Discussions

6.1. Effect of Window Glasses and Their WWR on Heat Gain in Laterite Rooms of Various Wall Thicknesses

Figure 5 presents the heat gain in modeled laterite rooms in all enclosures with 20% WWR in the south orientation. Enclosures include walls, roofs, floors, and fenestration. From the outcomes of the study, we noted that the 0.08 m wall thickness laterite room with 20% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW was responsible for heat gain of 32.7, 32.4, 32.3, 31.8, and 29.2 kWh, respectively. The laterite room with 0.08 m wall thickness and 20% WWR of PDLC glass window was able to reduce 10.7% of heat gain as compared to the laterite room with 0.08 m wall thickness and 20% WWR of a clear glass window. It was also observed that the 0.13 m wall thickness laterite room with 20% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for heat gain of 29.2, 28.9, 28.7, 28.3, and 26.7 kWh, respectively. The laterite room with 0.13 m wall thickness and 20% WWR of PDLC glass window was able to reduce 8.5% heat gain as compared to the laterite room with 0.13 m wall thickness and 20% WWR of a clear glass window. The results also showed that the 0.18 m wall thickness laterite room with 20% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 27.3, 26.9, 26.7, 26.4, and 24.2 kWh of heat gain, respectively. The laterite room with a 0.18 m wall thickness and 20% WWR of PDLC glass window was able to reduce 11.5% heat gain as compared to the laterite room with a 0.18 m wall thickness and 20% WWR of a clear glass window. The significant reductions in the heat gains were due to the modulation in solar properties and g-values compared to clear glass. It was evident that the 0.23 m wall thickness laterite room with 20% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 26.2, 25.8, 25.6, 25.2, and 22.3 kWh of heat gain, respectively. The laterite room with 0.23 m wall thickness and 20% WWR of PDLC glass window was able to reduce 15.0% heat gain as compared to the laterite room with 0.23 m wall thickness and 20% WWR of a clear glass window.

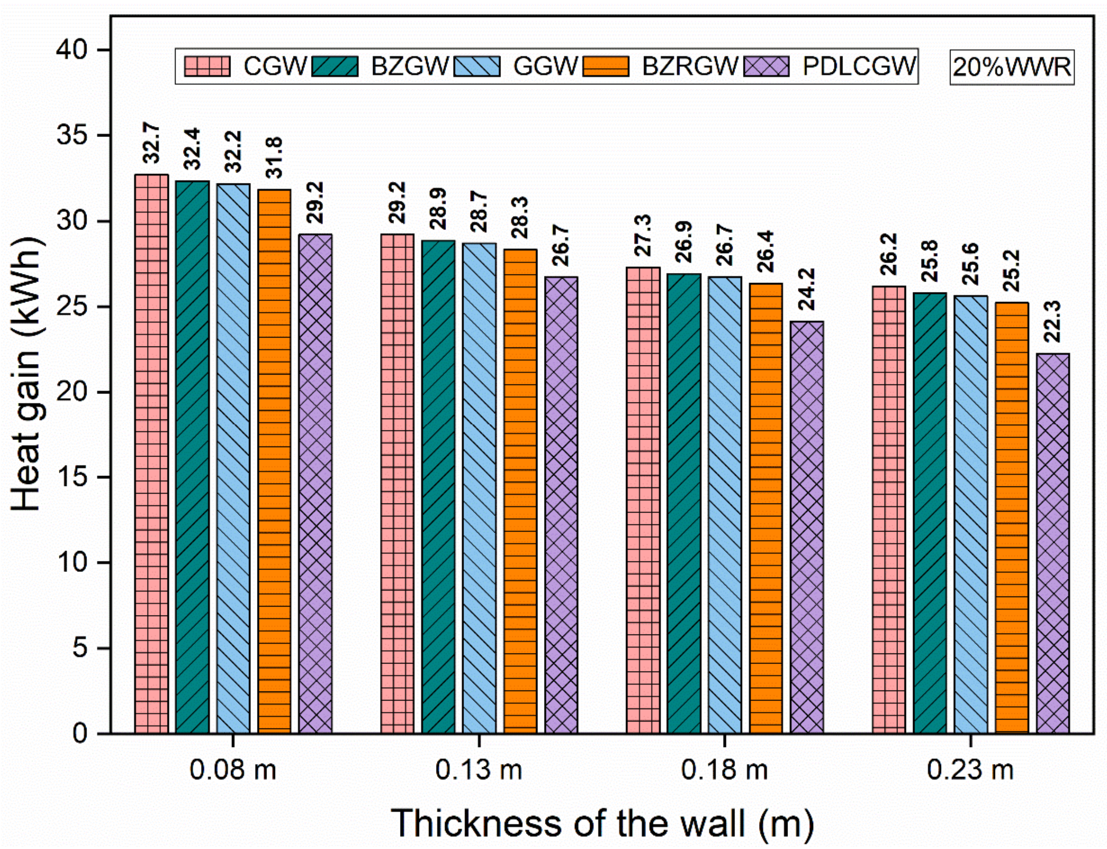


Figure 5. Heat gain in laterite rooms of different wall thicknesses of 20% WWR.

Figure 6 presents heat gain in laterite rooms through all enclosures with 40% WWR in the south orientation. The outcomes of the study noted that the 0.08 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW BRGW, and PDLCGW glazings was responsible for 34.5, 33.8, 33.4, 33.6, and 29.4 kWh of heat gain, respectively. The laterite room with 0.08 m wall thickness and 40% WWR of PDLC glass window was able to reduce 14.8% heat gain as compared to the laterite room with 0.08 m wall thickness and 40% WWR of a clear glass window. It was also observed that the 0.13 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 31.2, 30.5, 30.1, 29.3, and 26.8 kWh of heat gain, respectively. The laterite room with 0.13 m wall thickness and 40% WWR of bronze reflective glass window was able to reduce 14.1% heat gain compared to the laterite room with 0.13 m wall thickness and 40% WWR of a clear glass window. The results also showed that the 0.18 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 29.4, 28.6, 28.2, 27.4, and 24.4 kWh of heat gain, respectively. The laterite room with a 0.18 m wall thickness and 40% WWR of PDLC glass window was able to reduce 17% heat gain in comparison with the laterite room with a 0.18 m wall thickness and 40% WWR of a clear glass window. It was evident that the 0.23 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 28.4, 27.6, 27.2, 26.3, and 23.0 kWh of heat gain, respectively. The laterite room with 0.23 m wall thickness and 40% WWR of PDLC glass window was able to reduce 18.9% heat gain as compared to the laterite room with 0.23 m wall thickness and 40% WWR of a clear glass window.

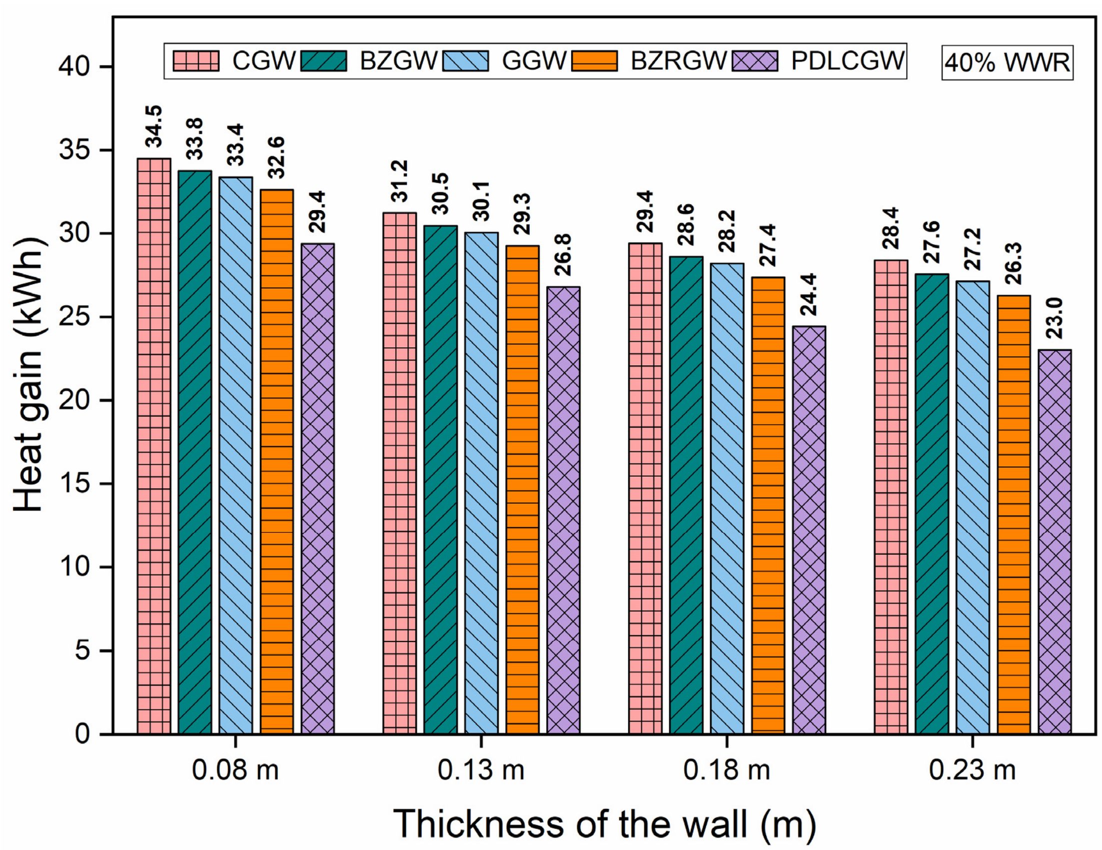


Figure 6. Heat gain in laterite rooms of different wall thicknesses of 40% WWR.

Figure 7 shows the total heat gain in laterite rooms through all enclosures with 60% WWR in the south orientation. From the outcomes of the study, we note that laterite rooms with 60% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings were responsible for 36.4, 35.3, 34.7, 33.5, and 30.0 kWh of heat gain, respectively. The laterite room with

0.08 m wall thickness and 60% WWR of PDLC glass window was able to reduce 17.8% heat gain compared to the laterite room with 0.08 m wall thickness and 60% WWR of a clear glass window. It was also observed that the 0.13 m wall thickness laterite room with 60% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 33.4, 32.1, 31.6, 30.3, and 26.9 kWh of heat gain, respectively. The laterite room with 0.13 m wall thickness and 60% WWR of PDLC glass window was able to reduce 19.5% heat gain as compared to the laterite room with 0.13 m wall thickness and 60% WWR of a clear glass window. The results also showed that the 0.18 m wall thickness laterite room with 60% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 31.7, 30.4, 29.8, 28.5, and 24.9 kWh of heat gain, respectively. The laterite room with a 0.18 m wall thickness and 60% WWR of PDLC glass window was able to reduce 21.3% heat gain in comparison with the laterite room with 0.18 m wall thickness and 60% WWR of the clear glass window. It was evident that the 0.23 m wall thickness laterite room with 60% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 30.8, 29.4, 28.8, 27.4, and 23.9 kWh of heat gain, respectively. The laterite room with a 0.23 m wall thickness and 60% WWR of reflective glass window was able to reduce 22.2% heat gain compared to the laterite room with 0.23 m wall thickness and 60% WWR of the clear glass window.

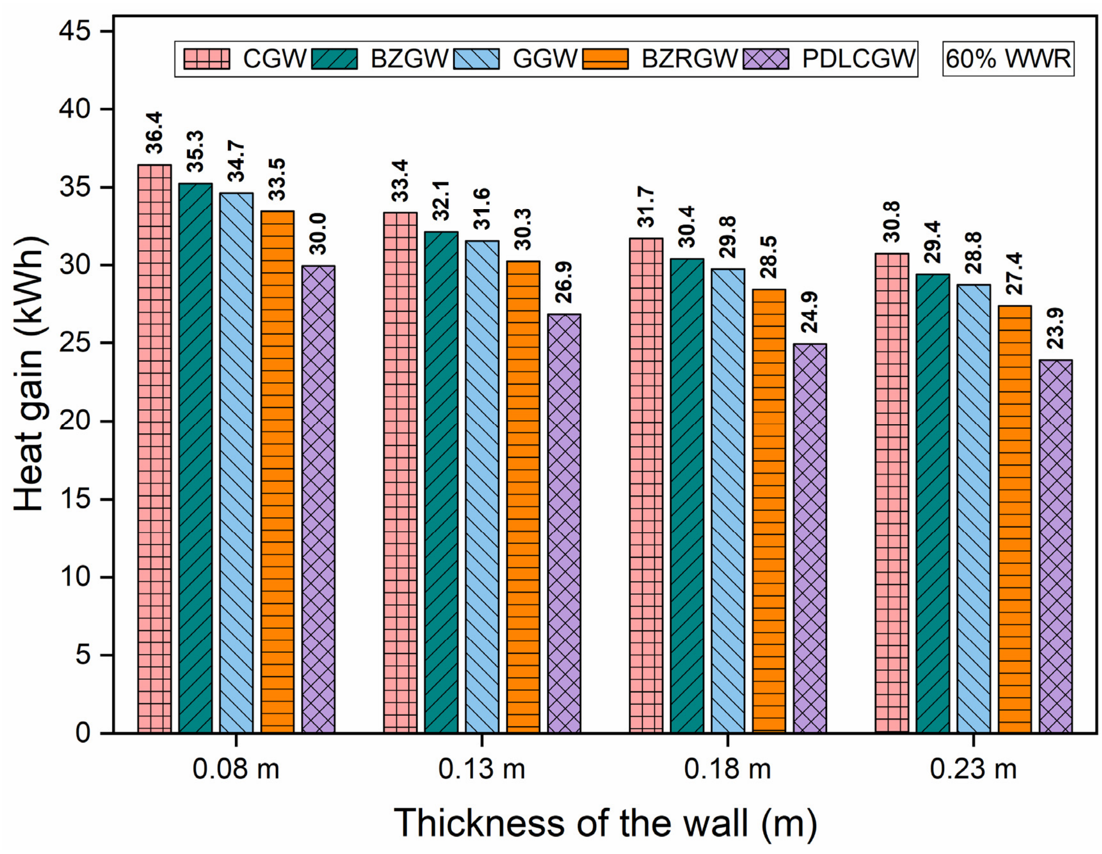


Figure 7. Heat gain in laterite rooms of different wall thicknesses of 60% WWR.

Figure 8 depicts the total heat gain in laterite rooms through all enclosures with 80% WWR in the south orientation. The outcomes of the study noted that the 0.08 m wall thickness laterite room with 80% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 38.5, 36.8, 36.0, 34.3, and 30.0 kWh of heat gain, respectively. The laterite room with 0.08 m wall thickness and 80% WWR of PDLC glass window was able to reduce 22.0% heat gain compared to the laterite room with 0.08 m wall thickness and 80% WWR of the clear glass window. It was also observed that the 0.13 m wall thickness laterite room with 80% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 35.6, 33.9, 33.0, 31.3, and 27.3 kWh of heat gain, respectively. The laterite room with 0.13 m wall thickness and 80% WWR of PDLC glass window was able to reduce 23.4% heat gain compared to the laterite room with 0.13 m wall thickness and 80% WWR of the clear glass window. The results also showed that the laterite room with 0.18 m wall thickness with 80% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 34.1, 32.3, 31.4, 29.6, and 25.2 kWh of heat gain, respectively. The laterite room with a 0.18 m wall thickness and 80% WWR of PDLC glass window was able to reduce 26.1% heat gain compared to the laterite room with 0.18 m wall thickness and 80% WWR of the clear glass window. It was evident that the 0.23 m wall thickness laterite room with 80% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 33.3, 31.4, 30.4, 28.6, and 24.3 kWh of heat gain, respectively. The laterite room with 0.23 m wall thickness and 80% WWR of PDLC glass window was able to reduce 26.8% heat gain compared to the laterite room with 0.23 m wall thickness and 80% WWR of the clear glass window.

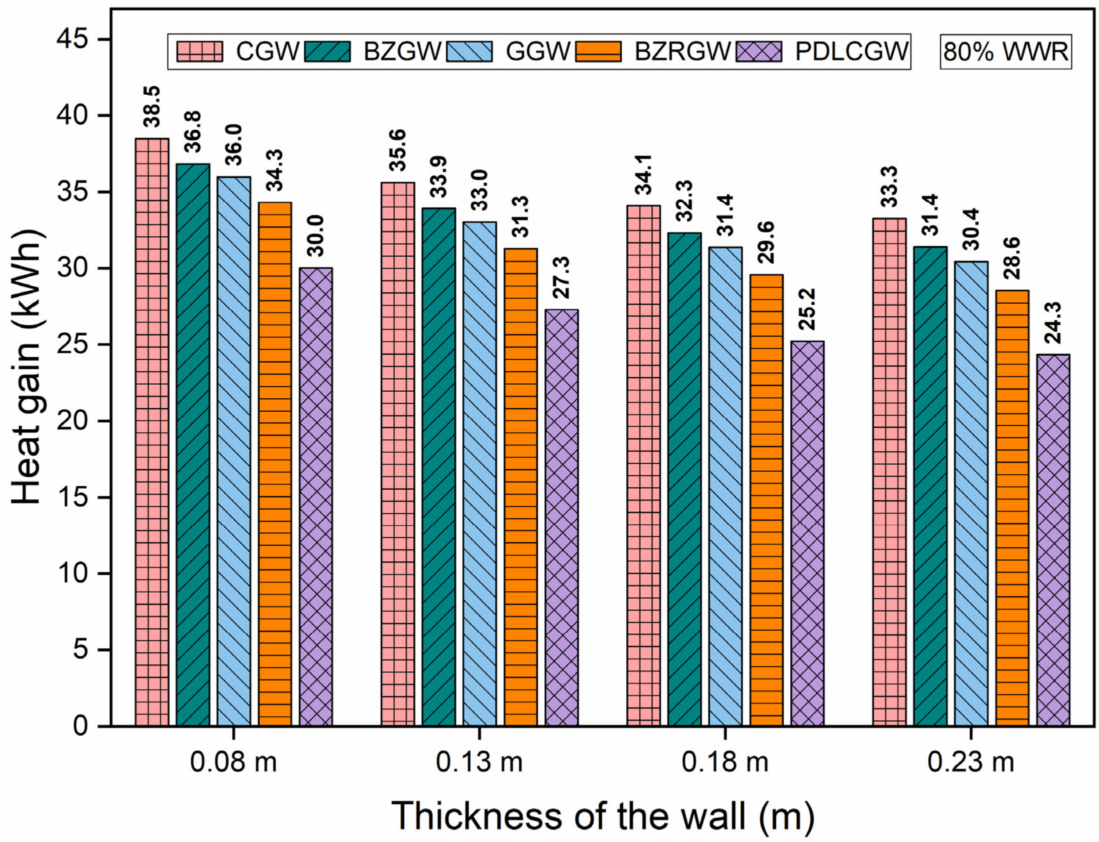


Figure 8. Heat gain in laterite rooms of different wall thicknesses of 80% WWR.

Figure 9 illustrates the total heat gain in laterite rooms through all enclosures with 100% WWR in the south orientation. The outcomes of the study noted that the 0.08 m wall thickness laterite room with 100% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 39.4, 37.5, 36.6, 34.7, and 30.4 kWh of heat gain, respectively. The laterite room with a 0.08 m wall thickness and 100% WWR of PDLC glass window was able to reduce 22.9% heat gain compared to the laterite room with 0.08 m wall thickness and 100% WWR of the clear glass window. It was also observed that the 0.13 m wall thickness laterite room with 100% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 36.4, 34.5, 33.6, 31.6, and 28.0 kWh of heat gain, respectively. The laterite room with 0.13 m wall thickness and 100% WWR of PDLC glass window was able to reduce 23.2% heat gain in comparison with the laterite room with 0.13 m wall thickness and 100% WWR of the clear glass window. The results also showed that the 0.18 m wall thickness laterite room with 100% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 34.7, 32.8, 31.8, 9.8, and 26.0 kWh of heat gain, respectively. The laterite room with a 0.18 m wall thickness and 100% WWR of PDLC glass window was able to reduce 25.1% heat gain compared to the laterite room with a 0.18 m wall thickness and 100% WWR of the clear glass window. It was evident that the 0.23 m wall thickness laterite room with 100% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazings was responsible for 33.6, 31.7, 30.7, 28.7, and 25.0 kWh of heat gain, respectively. The laterite room with 0.23 m wall thickness and 100% WWR of PDLC glass window was able to reduce 25.7% heat gain compared to the laterite room with 0.23 m wall thickness and 100% WWR of the clear glass window.

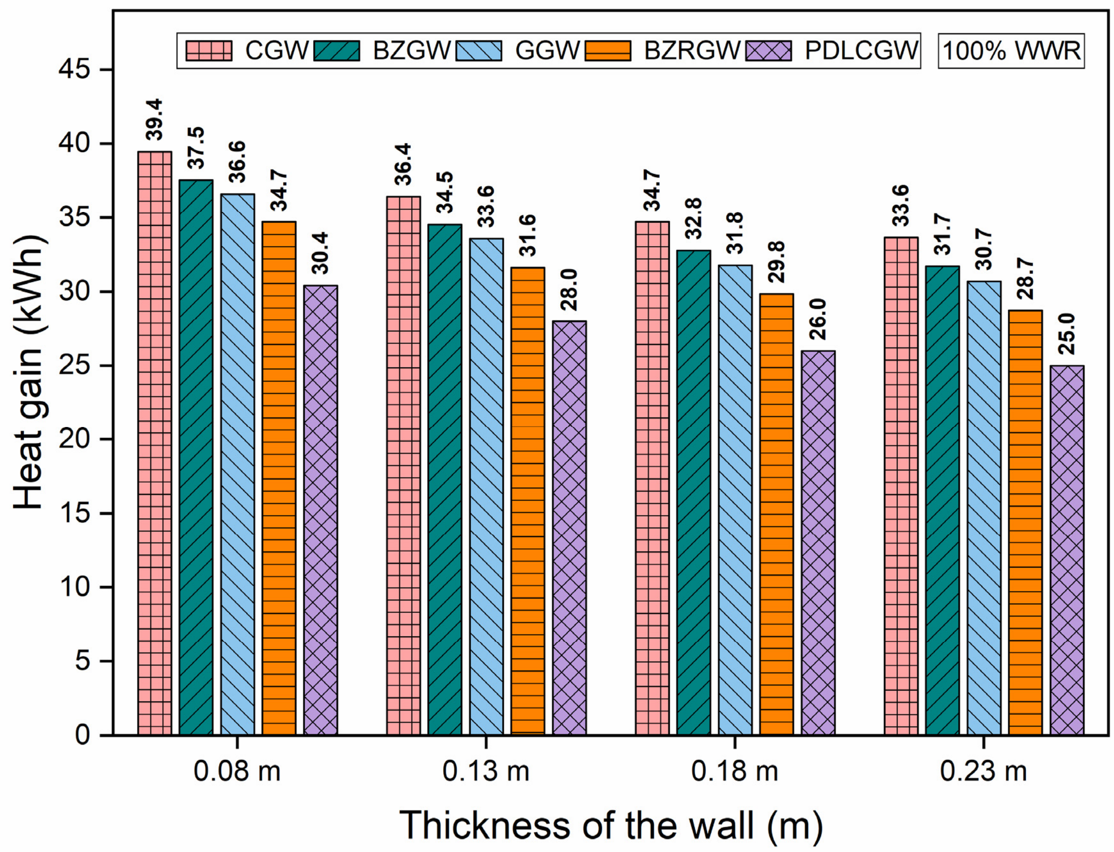


Figure 9. Heat gain in laterite rooms of different wall thicknesses of 100% WWR.

6.2. Influence of Window Glazing, Its WWR, and Wall Thickness on Cooling Costs of Laterite Rooms

Figure 10 shows that the cooling costs of the building increased with the increase in the WWR, and the cooling costs reduced with the increase in the wall thickness of the building. From Figure 10a, we can see that the 0.08 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazing showed annual cooling costs of USD 173.1, USD 169.4, USD 167.6, USD 163.8, and USD 147.5, respectively. From Figure 10b, we can observe that the 0.13 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazing gave annual cooling costs of USD 156.7, USD 152.8, USD 150.8, USD 146.9, and USD 134.6, respectively. From Figure 10c, we can see that the 0.18 m wall thickness laterite room with 40% WWR of CGW, TBGW, TGGW, BRGW, and PDLCGW glazing showed annual cooling costs of USD 147.7, USD 143.6, USD 141.6, USD 137.5, and USD 122.6, respectively. From Figure 10d, we can see that the 0.23 m wall thickness laterite room with 40% WWR CGW, TBGW, TGGW, BRGW, and PDLCGW glazing gave annual cooling costs of USD 142.6, USD 138.4, USD 136.3, USD 131.9, and USD 115.6, respectively.

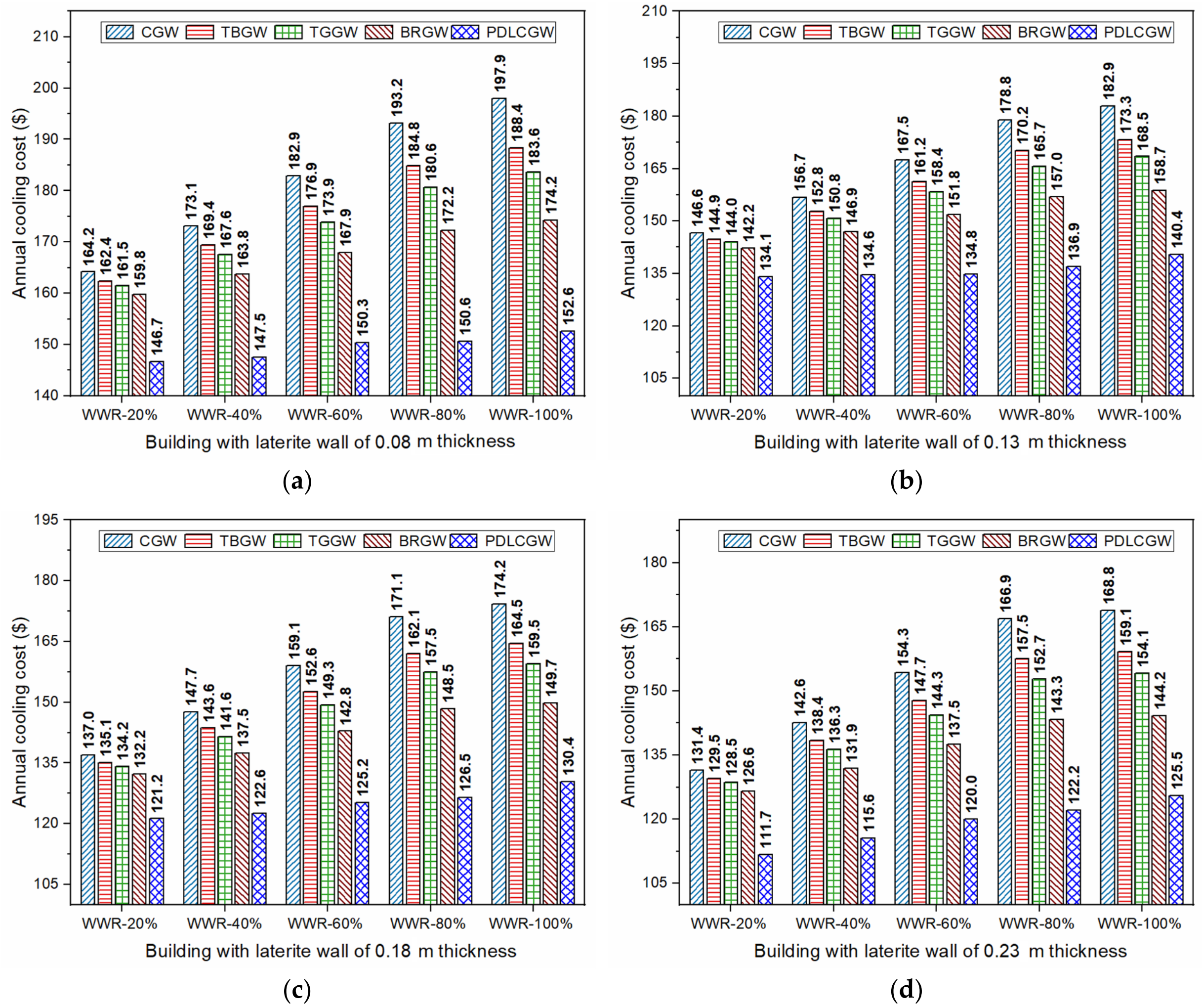
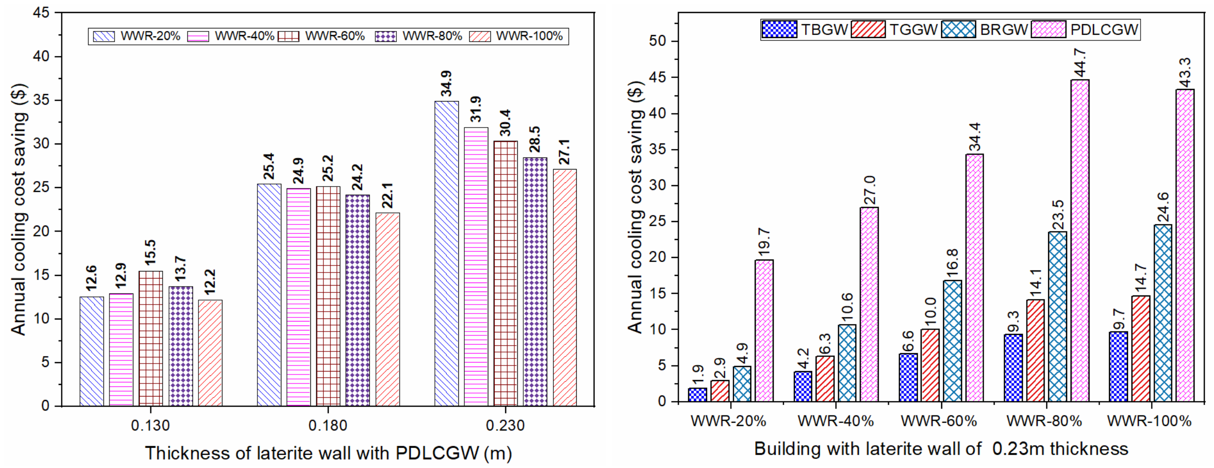


Figure 10. Influence of window glazing, its WWR, and wall thickness on cooling costs of laterite rooms (**a**) with 0.08 m thickness (**b**) with 0.13 m thickness (**c**) with 0.18 m thickness (**d**) with 0.23 m thickness.

The laterite room of 0.08, 0.13, 0.18 m, and 0.23 m wall thickness with PDLCGW glazing showed the lowest annual cooling costs of USD 147.5, USD 134.6, USD 122.6, and USD 115.6, respectively. Likewise, the laterite room of 0.23 m wall thickness with PDLCGW glazing gave the lowest cooling cost of USD 115.6.

6.3. Influence of Window Glazing, Its WWR, and Wall Thicknesses on Annual Cooling Cost Savings of Laterite Rooms

Figure 11a presents the cooling cost saving by the laterite room of 0.127 m, 0.18 m, and 0.23 m wall thickness with PDLCGW glazing of various WWR (20%, 40%, 60%, 80%, and 100%) as compared with laterite room of 0.08 m wall thickness and PDLCGW glazing of various WWR. It was observed that the laterite room of 0.23 m wall thickness with PDLCGW glazing of various WWR (20%, 40%, 60%, 80%, and 100%) gave the highest cooling cost savings of USD 34.9, USD 31.9, USD 30.4, USD 28.5, and USD 27.1, respectively, as compared to laterite room of 0.08 m wall thickness with PDLCGW glazing.



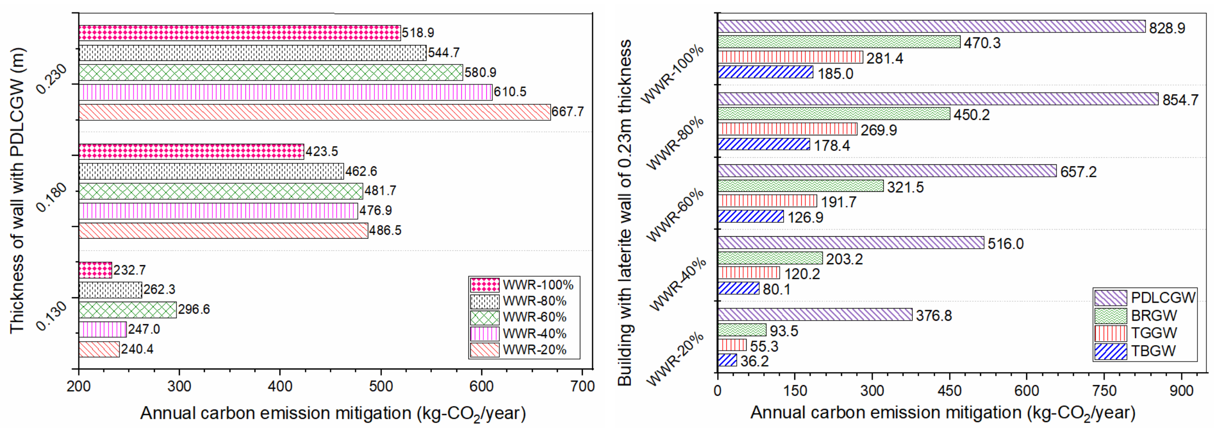
(**a**) (**b**)

Figure 11. Influence of window glazing, its WWR, and wall thicknesses on annual cooling cost savings of laterite rooms (**a**) Effect of various thicknesses of laterite walls (**b**) Effect of WWR on various glazing systems.

Figure 11b presents the cooling cost savings incurred by the laterite room of 0.23 m wall thickness with PDLCGW glazing and all WWR (20%, 40%, 60%, 80%, and 100%) in comparison with 0.23 m laterite wall thickness of various WWR of CGW glazing. It was observed that the 0.23 m wall thickness laterite room of 40% WWR with TBGW, TGGW, BRGW, and PDLCGW glazing gave cooling cost savings of USD 4.2, USD 6.3, USD 10.6, and USD 27.0, respectively, as compared to 0.23 m wall thickness laterite room of 40% WWR with clear glass glazing.

6.4. Influence of Window Glazing, Its WWR, and Wall Thicknesses on Carbon Emission Mitigation in Laterite Rooms

Figure 12a presents the carbon emission mitigation by the laterite room of 0.13 m, 0.18 m, and 0.23 m wall thicknesses with PDLCGW and all WWR (20%, 40%, 60%, 80%, and 100%) as compared with laterite room of 0.08 m wall thickness with PDLCGW of various WWR. The laterite room of 0.23 m wall thickness with PDLCGW glazing of various WWR (20%, 40%, 60%, 80%, and 100%) showed the carbon emission mitigation of 667.7, 610.5, 580.9, 544.7, and 518.9 kg-CO_2/year, respectively, as compared to the laterite room of 0.08 m wall thickness with PDLCGW glazing of various WWR.



(**a**) (**b**)

Figure 12. Influence of window glazing, its WWR, and wall thicknesses on carbon emission mitigation in laterite rooms (**a**) Effect of various thicknesses of laterite walls (**b**) Effect of WWR on various glazing systems.

Figure 12b presents the carbon emission mitigation by the laterite room of 0.23 m wall thickness with PDLCGW glazing and various WWR (20%, 40%, 60%, 80%, and 100%) compared to 0.23 m laterite wall of various WWR with CGW. For example, the laterite room of 0.23 m with 40% WWR with TBGW, TGGW, BRGW, and PDLCGW glazing shows the carbon emission mitigation of 80.1, 120.2, 203.2, and 516.0 kg-CO_2/year, respectively, as compared to the 0.23 m wall thickness laterite room of 40% WWR with clear glass.

6.5. Influence of Window Glazing and Its WWR on Daylight Inflow in Laterite Rooms

The modulation of solar-optical properties of glasses will influence the daylight inflow, as well as it demands for artificial daylighting. The daylight inflow investigations were conducted on the studied glazing systems to see whether they require artificial daylight energy. The DF metric will quantify the daylight inflow through the studied glasses. Figure 13 presents the average daylight factor metrics of studied glazing systems for various WWR (20%, 40%, 60%, 80%, and 100%). The laterite room with 40% WWR with CGW, TBGW, TGGW, BRGW, and PDLCGW glazing showed DF metrics of 7.88, 4.51, 6.1, 1.45, and 0.83, respectively. It was seen that the studied glasses could access minimum recommended daylight at all WWR for visual acceptability except PDLCGW at 20% WWR as per Indian building codes. The low DF metrics of PDLCs were due to their low visible transmittance of the PDLC in the visible region. The average daylight factor metric increased in proportion to the window-to-wall ratio. The simulated DF metrics of various studied glasses assured adequate daylight levels in building interiors to avoid artificial daylighting. We recommend adopting the optimal WWR for daylighting since the high WWR accessed the high daylight but caused a discomforting glare to occupants. The DF metric above 5.0 will cause discomfort glare and overheating of the space. The simulated DF metrics concluded that the studied glasses could access the recommended natural daylight for dwellings to avoid artificial daylighting. Thus, the lighting costs associated with daylight were not included in the cost analysis.

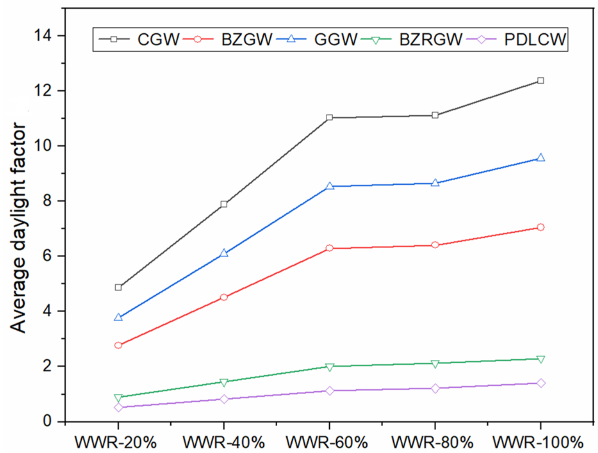


Figure 13. Influence of window glazing and its WWR on daylight factor in laterite rooms.

The modulated solar-optical properties of tinted, reflective, and smart switchable glazing systems were responsible for reducing solar heat gains and energy savings compared to clear glass. The color rendering properties of the studied glasses were well above the minimum recommended level as per the BS EN 410 standard. This revealed that the studied glasses could access the cool, strong daylight in the visible region for good color rendering in building interiors and uniform visible light transmittance in the visible region. The solar heat gains (kWh) were related to the WWR and indirectly proportional to the thickness of the wall. The simulated DF metrics were well above the minimum recommended level as per the CIE standard to avoid the need for artificial daylighting except for PDLCGW at 20% WWR. The PDLCGW requires a minimum of 40% WWR to access adequate daylight in building interiors to avoid artificial daylighting.

7. Conclusions

The laterite room models with different wall thicknesses of 0.08 m, 0.13 m, 0.18 m, and 0.23 m and with different window-to-wall ratios (20%, 40%, 60%, 80%, and 100%) of five different glazings (clear, tinted bronze, tinted green, bronze reflective, and PDLC) were designed and thermally analyzed in building models of Mangalore city in the Indian state of Karnataka. The solar optical properties of five different types of glazing systems were measured to study their thermal and visual performance studies.

- The laterite room of 0.23 m wall thickness with PDLCGW glazing of 40% WWR enhanced cooling cost savings up to USD 31.9 compared to the laterite room of 0.08 m wall thickness with 40% PDLCGW. In addition, the laterite room of 0.23 m wall thickness with PDLCGW glazing of 40% WWR also showed a better cooling cost saving of USD 27.0 compared to 0.23 m wall thickness laterite room of 40% WWR clear glass glazing.
- The laterite room of 0.23 m wall thickness with PDLCGW glazing of 40% WWR showed the enhanced carbon emission mitigation of 610.5 kg-CO_2/year compared to the laterite room of 0.08 m wall thickness with 40% PDLCGW. The laterite room of 0.23 m wall thickness with PDLCGW glazing of 40% WWR also showed improved carbon mitigation of 516 kg of CO_2/year compared to 0.23 m wall thickness laterite room of 40% WWR with clear glass glazing.
- The energy-efficient order of the glasses for windows was polymer dispersed liquid crystals (PDLCGW), bronze reflective (BRGW), tinted green (TGGW), tinted bronze (TBGW), and clear glass (CGW).
- The simulated daylight factor metrics allowed us to conclude that the studied glasses could access the minimum recommended daylight in building interiors to avoid artificial daylighting for window-to-wall ratios above 40%. The PDLCGW requires a minimum of 40% WWR to access adequate daylight in building interiors in order to avoid artificial daylighting. In addition, the evaluated color rendering properties of the studied glasses assured visual acceptability in the building interiors.

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