Concept and Performance Analysis of a Biodegradable Glass Film for Energy Efficiency and Daylighting Control

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ABSTRACT

Windows are essential building envelopes but often contribute to building energy consumption due to the direct solar heat gain. Retrofitting windows with glass films presents a simple yet effective energy-saving measure. However, conventional glass films pose environmental challenges post-disposal due to their non-biodegradability. In response to this issue, this paper proposes a degradable glass film utilising polylactic acid as the matrix material and incorporating pore and SiO_2 as fillers. Initially, through Mie theory, the film's microstructure was optimised. The results indicate that the film achieves optimal solar transmittance and mid-infrared emissivity of 0.661 and 0.955, respectively, at a thickness of 100 μm, with a pore diameter and porosity of 9 μm and 6%, and SiO_2 diameter and fill ratio of 10 μm and 20%. Subsequently, based on the optimised optical properties, the cooling load and daylighting performance post-application of this film were assessed. The calculations reveal a reduction in annual cooling load by 27%, with the percentages of time with acceptable glare level and illuminance uniformity increasing by up to 36% and 91%, respectively. The proposed concept opens new avenues for research of degradable glass films, presenting a promising direction for the advancement of sustainable building materials.

KEYWORDS Window films; Degradability; Mie theory; Building energy saving; Daylighting.

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1. Introduction

Driven by a growing emphasis on aesthetics and modern design, contemporary architecture has increasingly adopted transparent building envelopes. However, the high solar heat gain associated with glazing makes windows one of the primary contributors to a building’s energy consumption. Statistics suggest that windows can account for approximately 28% of a building's cooling consumption (Peng et al., 2019). A common method for retrofitting windows is through the application of glass films, offering advantages such as cost-effectiveness and simplicity of operation (Garlisi et al., 2020). By optimising the structure and materials of these films, it is possible to regulate solar heat gain and enhance passive radiative cooling. In recent years, research efforts have increasingly focused on developing advanced window films tailored to the energy and comfort requirements of buildings.

In regulating the solar heat gain, various types of electrochromic (Wu et al., 2023), thermochromic (Saju et al., 2024), and insulating films (Nur-E-Alam et al., 2024) have been studied. For achieving radiative cooling, glass films based on dispersed particles (Lv et al., 2022), and metamaterial structures (Huang et al., 2024a) have also been proposed. Despite the emergence of glass films with outstanding features, a critical limitation that has often been overlooked is their environmental sustainability. Most glass films are manufactured using polymers, such as PVDF, PDMS, and PET et al, which are not readily biodegradable. To enhance performance, they are often blended with particles which may pose environmental and health risks (Wang et al., 2021). While these films may offer energy benefits, their environmental impact increases recycling costs. To address this limitation, this paper proposes a biodegradable glass film composed mainly of polylactic acid (PLA), a harmless and degradable material (Ferreira et al., 2024), with the dispersion of pore and SiO_2 to enhance solar transmission performance for radiative cooling. Initially, the film’s thickness and microstructural parameters are analysed and optimised based on Mie scattering theory. Subsequently, the energy performance and daylighting impacts of the optimised film are evaluated using building simulations. The findings aim to advance research into biodegradable window films and offer new insights for the development of environmentally sustainable glazing technologies.

2. Research methodology

2.1. Structure of glass film

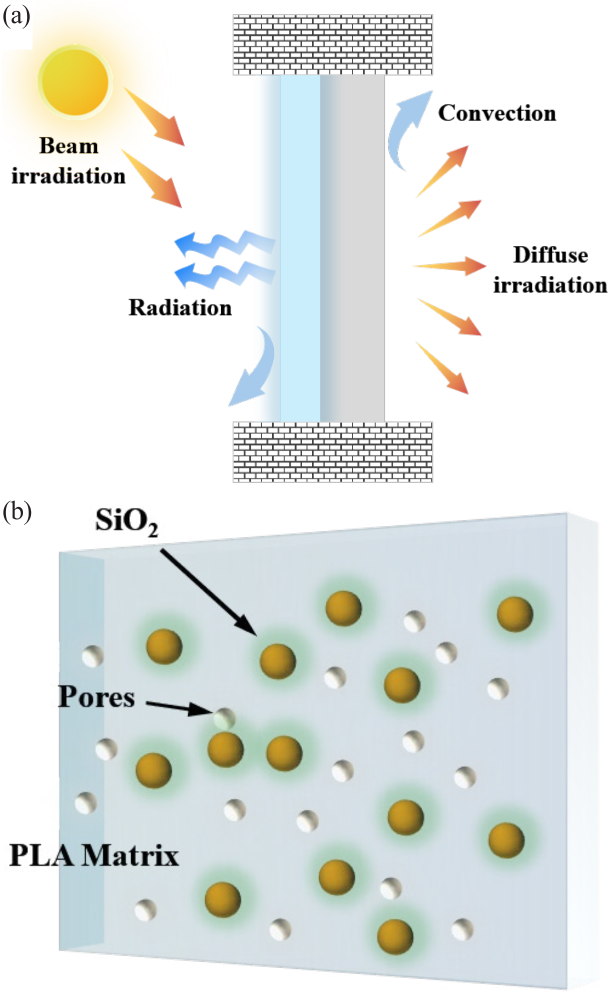


Figure 1. Schematic of a window with degradable glass film: (a) Illustration of heat transfer and solar radiation transfer across a windowpane covered with the proposed film; and (b) Microstructure of the degradable glass film. Transparent polylactic acid (PLA) with soil environmental protection is the same as the matrix of glass film. The randomly dispersed SiO_2 nanoparticles embedded in the PLA to enhance the radiative cooling performance and the pores are dispersed in the matrix to adjust the solar transmittance and daylighting performance.

Central to advanced glass films is not only the mitigation of energy consumption but also the enhancement of indoor environmental quality. The schematic shown in Figure 1 illustrates the integration of the proposed degradable glass film coated on a window, depicting its structure and working principle. As illustrated in Figure 1(a), the heat transfer dynamics across the window encompass convective heat exchange, radiative transfer, and solar radiation penetration. Upon the application of the proposed degradable film, its influence manifests primarily in the modulation of mid-infrared thermal radiation transmission and solar radiation. The film exhibits multiple beneficial attributes. First, characterised by high emissivity, it can emit substantial mid-infrared thermal radiation to the sky during both day and night. This emission reduces the glass substrate temperature and mitigates internal heat gain, thereby promoting a comfortable indoor thermal environment. Second, the film acts as an effective barrier against solar radiation by reducing its transmittance, which consequently lowers the building's cooling load. Furthermore, the film's optical properties induce scattering of incident visible light, diffusing its transmission into the interior space. This scattering leads to a more uniform distribution of daylight indoors and improves the quality of interior illuminance. Simultaneously, the film functions as a shading mechanism, enhancing indoor privacy while also improving architectural aesthetics.

The microstructural composition of the film is depicted in Figure 1(b). The PLA matrix is embedded with uniformly dispersed SiO_2 particles and pores, both of which play a key role in enhancing the functionality of the film. The air pores strategically scatter incident solar radiation, thereby attenuating solar transmittance and diffusing visible radiation within the interior. Concurrently, the high absorbance characteristics of SiO_2 in the mid-infrared spectrum amplify the film's mid-infrared emissivity, accentuating its thermal regulation capabilities. It should be emphasised that the composition of the film consists entirely of biodegradable materials, posing no biological hazards when disposed of in urban or soil environments. In comparison to conventional polymer-based optical films, the proposed degradable glass film not only champions energy conservation and daylighting management but also exemplifies a paradigm shift towards eco-conscious and biodegradable building technologies.

2.2. Simulation model

The present study conducts a theoretical investigation of the proposed degradable film using simulation-based methods. First, structural parameters including the film thickness, SiO_2 particle diameter and filling ratio, as well as pore diameter and porosity, were analysed and optimised based on coupled Mie scattering theory and the Monte Carlo method. When the size of the embedded particles is comparable to the wavelength of the incident radiation, wave phenomena must be considered based on electromagnetic theory. Mie theory provides an exact analytical solution for the scattering of incident radiation by spherical particles through direct resolution of Maxwell's equations. This has been widely applied and validated for analysing electromagnetic wave propagation in heterogeneous media (Huang et al., 2024b; Yalçın et al., 2020). After determining the scattering cross-section, extinction cross-section, and asymmetry factor of the particles using Mie theory, the radiative properties of the PLA composite film containing various particles were calculated by solving the radiative transfer equation using the Monte Carlo method (Yalçın et al., 2020). This method estimates the transmission and absorption of radiation at different wavelengths by statistically sampling a large number of photon paths through the composite medium. Subsequently, building upon the optimised film, EnergyPlus and Radiance simulation tools were employed to evaluate improvements in building energy efficiency and daylighting performance following the application of the proposed film. EnergyPlus, a widely adopted building energy simulation engine in both research and engineering applications, utilises detailed physical models to predict the energy performance of various building components by solving dynamic energy conservation equations for the building envelope. Specifically, EnergyPlus establishes heat balance equations for building elements such as walls, windows, and indoor air, and solves them using the transfer function method to obtain the hourly temperature distribution and corresponding cooling load of the building. Its reliability in simulating the thermal performance of building envelopes, especially glazing systems, has been extensively validated (Gennaro et al., 2023; Uddin et al., 2022; Wang et al., 2016). Radiance is state-of-the-art lighting simulation software developed for computing and visualising luminance distributions within indoor environments. It is particularly well suited for evaluating daylighting performance, including indoor illuminance, illuminance uniformity, and glare risk in spaces with complex fenestration systems. The core of Radiance’s calculation lies in a backward ray-tracing algorithm combined with the Monte Carlo method (Du et al., 2025). Rays are launched from the sensor point (e.g., the human eye or a measurement surface) and traced in reverse through the scene. When a ray intersects with a surface, its behaviour—reflection, transmission, or absorption—is determined based on the material's optical properties, such as reflectance and transmittance. The ray then recursively spawns new rays until the energy is sufficiently attenuated. The high precision of Radiance has been confirmed in numerous studies (Bian et al., 2023; Talaei & Sangin, 2024).

This study evaluated the impact of the proposed film on building energy consumption and indoor daylighting conditions using an office building as a case study. The building, with dimensions of 5 metres in width, 5 metres in length, and 3 metres in height, features a wall with a window-to-wall ratio of 90%, typical of many commercial office buildings. The office operates from 8:00 am to 6:00 pm. The material, thermal, and optical properties of the building envelope are detailed in Table 1. Weather data from a typical year in Hong Kong, Haikou, Singapore, and Manila served as the boundary conditions for the year-long simulation. For each city, scenarios with windows installed in four directions (east, west, south, and north) were analysed to strengthen the generalisability of the proposed membranes to improve building performance. The energy consumption calculations consider heat exchange with adjacent rooms for all walls except the south-facing one. The cooling setpoint indoors is assumed to be 26°C (Wang et al., 2024a), with no heating requirements considered due to negligible heating demands in the study area. To balance computational resources and time when conducting the daylighting calculation, the parameters in the Radiance software, including ambient bounces (ab), ambient divisions (ad), ambient super-samples (as), ambient resolution (ar), and ambient accuracy (aa), were set to 10, 1024, 2, 96, and 0.15, respectively, following the settings from a previous study (Tan et al., 2023).

Table 1. The materials and thermophysical properties of the building envelope.

	Material	Thickness *(m)*	Conductivity *(W/mK)*	Density *(W/m^3)*	Specific heat *(J/kgK)*	Solar reflectance	Emissivity	U value *(W/m^2K)*
Wall	Stucco	0.025	0.72	1856	840	0.7	0.9	0.22
	Concrete	0.20	1.79	2243	1858			
	Wall insulation	0.08	0.04	91	837			
	Gypsum board	0.016	0.16	800	1090			
Floor	Carpet pad	0.02	0.2	/	/	0.7	0.9	2.7
	Concrete	0.10	1.31	2240	836			
Roof	Roof membrane	0.0095	0.16	1121	1460	0.7	0.9	0.45
	Roof insulation	0.263	0.049	265	836			
	Metal decking	0.0015	45	7680	418			

2.3. Evaluation metrics

The performance of the proposed film in this study is evaluated based on its optical properties and its impact on the overall building performance after application. The optical properties under investigation include mid-infrared emissivity within the atmospheric window and solar transmittance. These properties are calculated by determining absorptance and transmittance using the optical simulation, integrating values over the blackbody radiation spectrum ranging from 8 to 13 *um* and the AM1.5 solar spectrum spanning from 0.3 to 2.5 *um* (Chen et al., 2021). The calculation equations for solar transmittance, visible transmittance, and mid-infrared emissivity are as follows:

$$T_{sol} = \int_{0.3um}^{2.5um} I_{solar}(\lambda)\tau(\lambda)d\lambda \,/\, \int_{0.3um}^{2.5um} I_{solar}(\lambda)d\lambda, \tag{1}$$

$$T_{vis} = \int_{0.38um}^{0.78um} I_{solar}(\lambda)\phi(\lambda)\tau(\lambda)d\lambda \,/\, \int_{0.38um}^{0.78um} I_{solar}(\lambda)\phi(\lambda)d\lambda, \tag{2}$$

$$\varepsilon_{mir} = \int_{0.3um}^{2.5um} I_b(\lambda)\tau(\lambda)d\lambda \,/\, \int_{0.3um}^{2.5um} I_b(\lambda)d\lambda. \tag{3}$$

where τ is the spectral transmittance of the proposed film; λ is the wavelength (um); I_{solar} is the solar spectral irradiance under AM1.5 conditions (W•m-^{2}•um-^{1}); I_b is the spectral radiance of a blackbody at ambient temperature (W•m-^{2}•um-^{1}); and ϕ is the CIE photopic luminous efficiency of the human eye. T_{sol} and T_{vis} represent the solar and visible transmittance, respectively, while ε_{mir} denotes the mid-infrared emissivity.

Building performance is primarily evaluated in terms of energy efficiency and daylighting quality. For energy performance, cooling load serves as the key metric. In the case study, the annual cooling load is directly obtained from EnergyPlus simulations. The energy-saving effect of the proposed film is quantified by the reduction in annual cooling load per unit area, as calculated by Eq. (4). In terms of daylighting performance, attention is paid to the illuminance uniformity and the glare values facing southward. The illuminance uniformity is assessed on a horizontal work plane located 1 metre above the floor, calculated as the ratio of minimum to average illuminance (Wang et al., 2022), as listed in Eq. (5). According to the literature (Liu et al., 2020), an indoor illuminance uniformity above 0.6 is considered acceptable for office buildings. Glare performance is evaluated using the Daylight Glare Probability (DGP), which is directly obtained from Radiance simulations. The DGP is calculated at the midpoint of the horizontal work plane, facing the window. DGP values range from 0 to 1, with lower values indicating reduced glare. Values below 0.4 are generally regarded as acceptable for occupant comfort (Wang et al., 2023).

$$\Delta E = (E_{without\,film} - E_{with\,film})/A, \tag{4}$$

$$U_o = L_{min}/L_{ave}. \tag{5}$$

where E represents the annual cooling load (*kWh*) and ΔE is the energy saving of proposed film per unit area (*kWh/m*^{2}); A is the area of the proposed film (*m*^{2}); L_{min} and L_{ave} are the minimum and average illuminance values (lux) on the work plane. U_o is the indoor illuminance uniformity.

4. Results and discussion

4.1. Structural analysis and optimisations

In this section, a comprehensive analysis and optimisation of the microstructural parameters of the proposed film are meticulously conducted. The influence of SiO_2 size and distribution on the film's solar transmittance is negligible, a finding substantiated by subsequent computational results. Thus, the study systematically first neglects the presence of SiO_2 and focuses on optimising the distribution of pores and the thickness of the films to achieve the desired solar radiation regulation. Building upon this groundwork, an additional optimisation is performed to enhance the mid-infrared emissivity by refining the distribution and size of SiO_2 particles.

The existing literature underscores the necessity for windows to exhibit a visible light transmittance exceeding 0.6 for optimal performance (Wang et al., 2024b). Within this study, adhering to this criterion, the optimisation objective prioritises minimising solar transmittance and maximising emissivity. Parameters governing the pores and film thickness are meticulously fine-tuned to achieve these objectives. The culmination of this optimisation effort reveals that an optimal configuration consists of a pore diameter of 9 *um*, a porosity of 6%, and a film thickness of 100 *um*, resulting in a visible transmittance of 0.66, a solar transmittance of 0.68, and an emissivity of 0.85. To delve deeper into the underlying optical mechanisms of the film, the study leverages these optimised parameters to investigate the impact of pore diameter, porosity, and film thickness on the film's optical properties. This analysis aims to unravel the intricate interplay between these structural parameters and the film's optical performance. Figure 2 shows the impact of thickness and pore parameter on emissivity and solar transmittance. Within Figure 2(a), the results reveal a reduction in solar transmittance with increasing thickness, a phenomenon stemming from two discernible factors. Firstly, the increased thickness of the PLA matrix extends the light propagation path. Secondly, a greater number of pores enhances light scattering. Additionally, the thicker PLA results in higher emissivity, primarily due to increased absorption of mid-infrared radiation. Figure 2(b) shows that solar transmittance declines significantly with increasing porosity. This effect stems from the strong refractive index mismatch between air and PLA, which induces scattering of incident solar radiation. A higher porosity enhances this scattering effect, thereby lowering solar transmittance. Conversely, porosity moderately increases emissivity due to the size similarity between air pores and mid-infrared wavelengths. According to Mie theory, this induces scattering of mid-infrared electromagnetic waves, thereby extending their propagation path within the PLA matrix and consequently enhancing absorption. However, the impact of porosity on mid-infrared emissivity is marginal, primarily because air has a zero imaginary component in its refractive index within this spectral range and thus does not absorb mid-infrared radiation. Figure 2(c) indicates that enlarging the pore diameter augments solar transmittance. This phenomenon arises because, under identical porosity conditions, larger pore diameters result in fewer pores, thereby reducing the occurrences of refraction. The influence of pore diameter on emissivity exhibits an initial increase followed by a decreasing trend. Similar to the impact of porosity, the variation in emissivity is minimal. Consequently, this study utilises SiO_2 to regulate emissivity effectively.

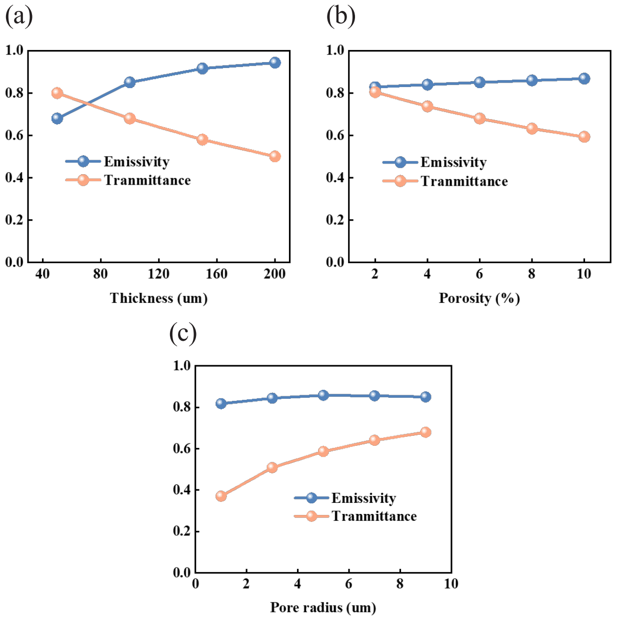


Figure 2. The impact of thickness and pore parameters on emissivity and solar transmittance: (a) Thickness of film (um); (b) Porosity (%); and (c) Pore radius (um).

Building upon the optimisations described above, a subsequent refinement is undertaken with a focus on maximising emissivity by optimising the diameter and filling ratio of SiO_2 particles. The optimised parameters for particle diameter and filling rate are determined to be 10 um and 20%, respectively. Similarly, utilising these optimised parameters as a foundation, the study systematically analyses the impact of particle diameter and filling ratio on emissivity and solar transmittance, with the results visually depicted in Figure 3. As shown in Figure 3 (a) and (b), variations in SiO_2 particle diameter and filling rate demonstrate negligible effects on the optical properties within the solar radiation spectrum. This phenomenon can be attributed to the approximate refractive index matching between SiO_2 and the polylactic acid matrix within the solar spectrum. According to Mie theory, significant scattering occurs only when there is a notable contrast in refractive indices between the particles and the surrounding medium. Within the mid-infrared spectrum, the presence of SiO_2 induces notable scattering of incident radiation, thereby extending the propagation path of mid-infrared electromagnetic waves within the film. Moreover, SiO_2 possesses a relatively high extinction coefficient in this spectral range, which substantially enhances absorption. As depicted in the figure, an increase in both particle diameter and filling rate leads to an elevation in emissivity, with the filling rate exerting a more pronounced influence on emissivity compared to particle diameter, ranging from 0.88 to 0.95.

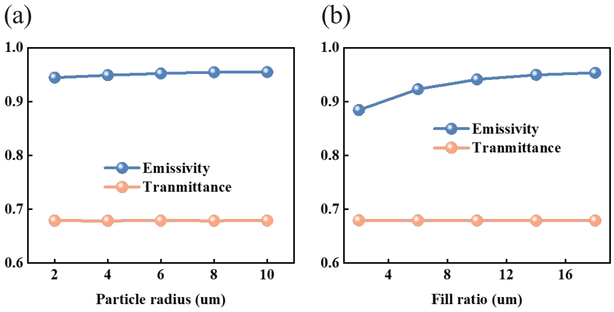


Figure 3. The impact of SiO_2 particle parameters on emissivity and solar transmittance: (a) Particle radius (um); and (b) Fill ratio (%).

Following optimisation, the spectral characteristics of the film in the mid-infrared and solar radiation spectra are illustrated in Figure 4(a) and (b). The emissivity in the atmospheric window consistently remains above 0.95, while the solar transmittance in the solar spectrum ranges between 0.6 and 0.8. Notably, the transmittance in the near-infrared spectrum surpasses that in the visible light spectrum, a phenomenon undesirable for glass films. Future research endeavours should explore alternative degradable particles capable of reflecting near-infrared radiation. Additionally, the optical properties of the optimised film at various incident angles are shown in Figure 4(c) and (d). It is observed that larger incident angles correspond to increased reflectance, resulting in reduced solar transmittance and mid-infrared emissivity. This phenomenon can be explained by Fresnel's Law (Malacara & Thompson, 2001), which indicates that the reflectance of electromagnetic waves at the interface between two media (PLA and air in this study) increases with the incident angle. Consequently, the optical performance of the film in both the solar and mid-infrared spectral ranges deteriorates at oblique angles. However, for incident angles below 60°, the solar transmittance and mid-infrared emissivity remain nearly constant, indicating that the film maintains stable optical properties under most practical conditions. In real-world applications, the energy of incident solar and thermal radiation at angles above 60° is significantly reduced due to cosine projection effects (Modest & Mazumder, 2021). Therefore, the film can be considered to exhibit favourable angular performance across a wide range of application scenarios.

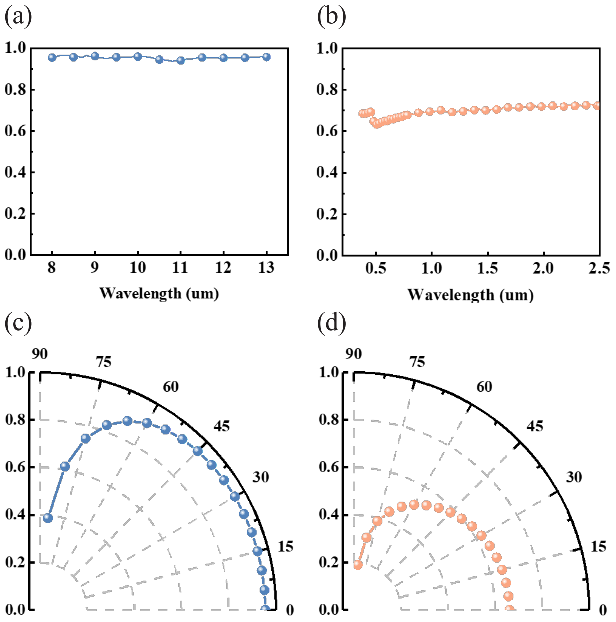


Figure 4. The optical properties of the proposed film with the optimised microstructure: (a) Emissivity spectrum in a mid-infrared wave; (b) Transmittance spectrum in a solar wave; (c) Emissivity at different incidence angles; and (d) Solar transmittance at different incidence angles.

4.2. Energy-saving and daylighting performance

In this section, the impact of the optimised film on building energy efficiency and daylighting performance is analysed. The analysis assumes that the film is applied to 3 mm transparent tempered glass, resulting in a visible light transmittance of 0.898, solar transmittance of 0.837, and an infrared emissivity of 0.84. The overall building performance with the film is evaluated by comparing it to that of a baseline case without the film. As shown in Figure 5, the application of the film leads to a reduction in annual cooling load across all studied locations and building orientations. The trend indicates a strong correlation between the total cooling load and the energy savings. In Hong Kong, the highest energy savings occur for south-facing façades, reaching 101 *kWh/m^2*. In Haikou, the maximum savings occur with west-facing façades at 89 *kWh/m^2*. For Singapore and Manila, the greatest savings are observed for east-facing façades, amounting to 134 *kWh/m^2* and 131 kWh/m^2, respectively. In contrast, for all studied regions, the lowest energy savings are associated with north-facing façades: 46 *kWh/m^2* for Hong Kong, 47 *kWh/m^2* for Haikou, 103 *kWh/m^2* for Singapore, and 92 *kWh/m^2* for Manila. Overall, across all cases, including variations in location and building orientation, the proposed window film reduces annual building energy consumption by approximately 27% to 35%.

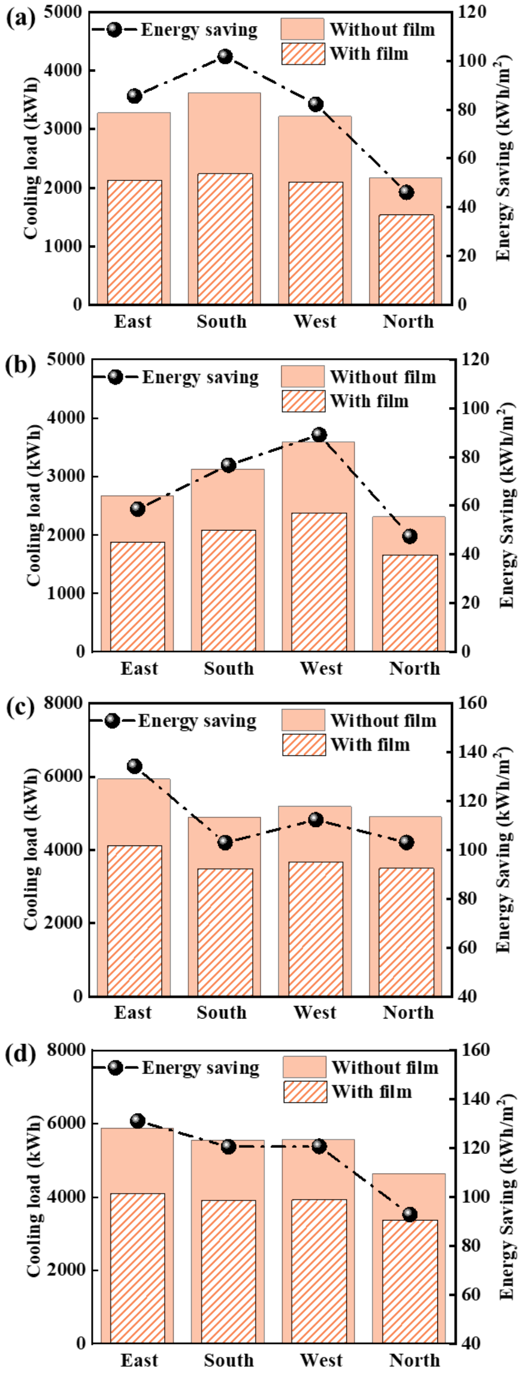
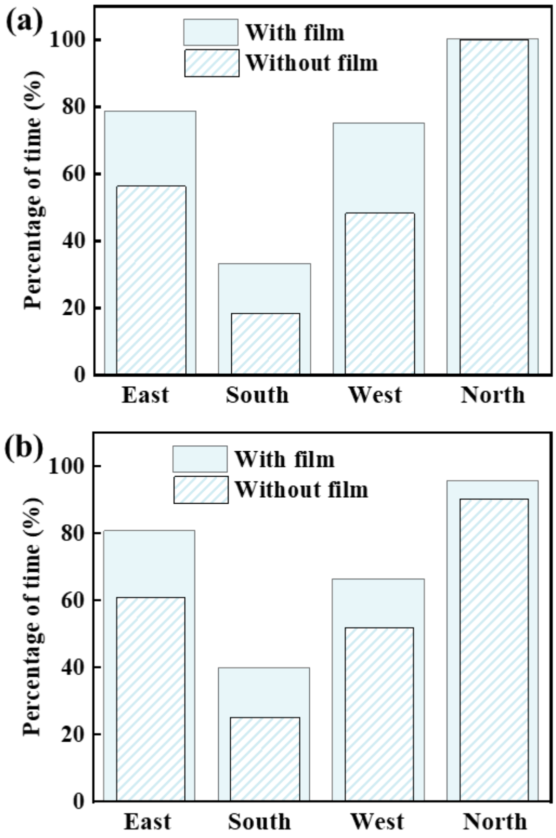


Figure 5. Comparison of energy performance between glass with and without the proposed glass film: (a) Hong Kong; (b) Haikou; (c) Singapore; and (d) Manila.

This study quantifies the proportion of time throughout the year during which indoor glare remains at a comfortable level (DGP < 0.4) across all the evaluated cases, as illustrated in Figure 6. Evidently, the application of the proposed window film significantly increases the percentage of time with acceptable glare levels. This improvement is particularly notable for east- and west-facing façades, while the effect is minimal for north-facing façades. The observed trend is attributed to variations in solar incidence angles. In east- and west-facing façades, lower solar elevation angles in the morning and afternoon lead to near-perpendicular sunlight penetration, which increases the probability of glare. Consequently, applying the proposed film to these orientations effectively reduces the duration of indoor glare. Specifically, the percentage of time without glare increases by 22–26% in Hong Kong, 14–19% in Haikou, 30% in Singapore, and 29–36% in Manila. In contrast, the north-facing façades experience minimal glare due to limited direct sunlight exposure, so the film has a negligible impact. For the four cities studied, the increase in the percentage of time without glare for north-facing façades is 0%, 5.1%, 13%, and 0.9%, respectively. For south-facing façades, the improvement is moderate, with increases of 14%, 14%, 15%, and 7%, respectively.



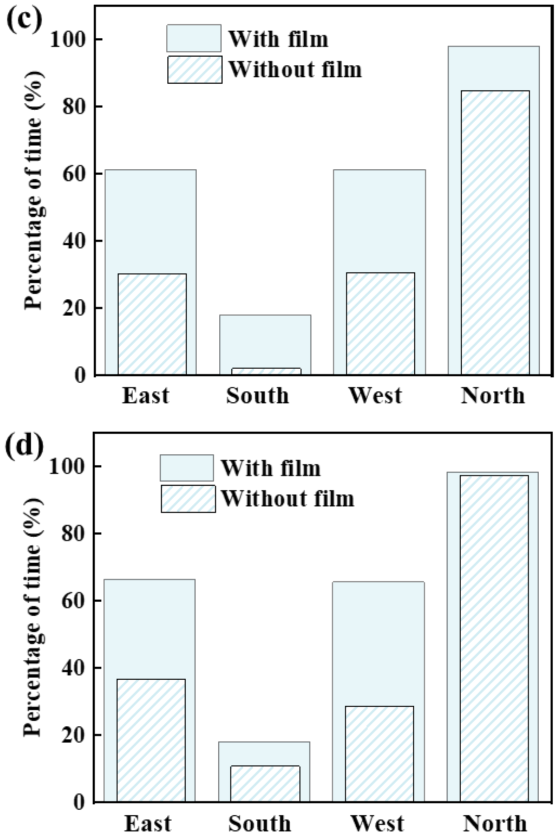
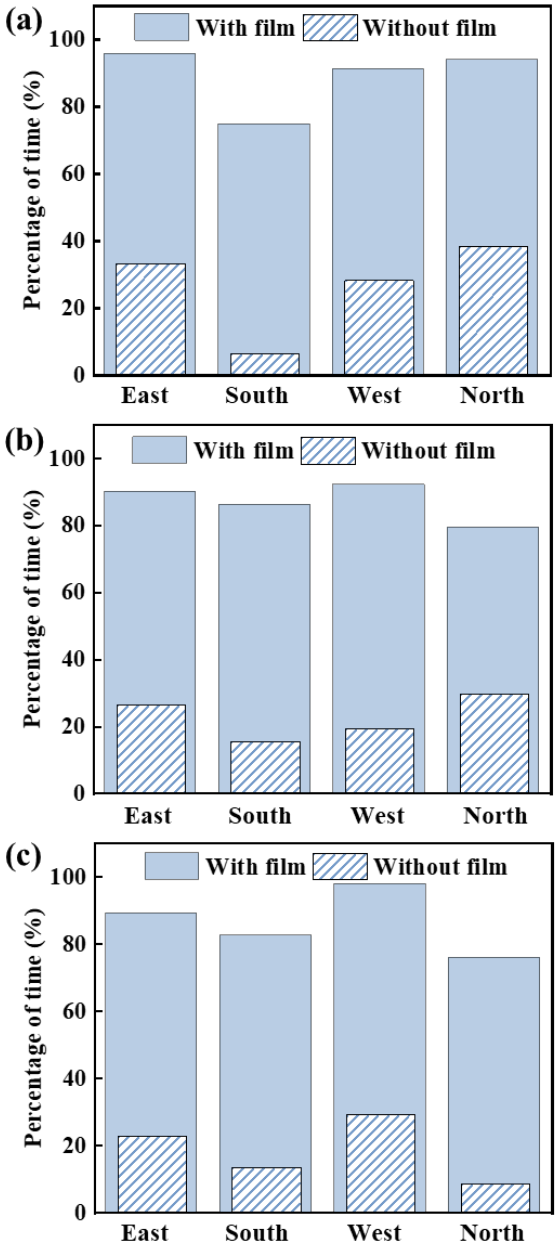


Figure 6. Comparison of time percentage with acceptable glare level: (a) Hong Kong; (b) Haikou; (c) Singapore; and (d) Manila.

Subsequently, this study quantifies the percentage of time throughout the year during which indoor illuminance uniformity remains at a comfortable level ($Uo > 0.6$) across all the evaluated cases, as shown in Figure 7. It is evident that the application of the proposed film significantly enhances indoor illuminance uniformity. According to the literature, merely reducing the transmittance of windows does not necessarily improve indoor illuminance uniformity (Wang et al., 2022). The improvement observed in this study is primarily due to the film's ability to alter the direction of incoming solar radiation, thereby converting direct radiation into diffuse radiation, which helps mitigate localised light spots and promote more even light distribution indoors. Across all the studied scenarios, the percentage of time with acceptable illuminance uniformity exceeds 80% in most cases. Compared to the baseline condition without the film, the proportion of time with uniform lighting increased by more than 50%. Due to the high solar elevation angles around noon, south-facing windows tend to produce strong light spots near the glazing, resulting in uneven indoor illumination. Therefore, the greatest improvements in uniformity are observed for south-facing façades, with increases of 68% in Hong Kong, 70% in Haikou, 69% in Singapore, and 91% in Manila. Even for façades facing other directions, notable improvements in illuminance uniformity are achieved. This is because the proposed film redirects incident light, enhancing illumination on work surfaces located farther from the window. Overall, the increase in uniform lighting time ranges from 55% to 91% across all evaluated cases.



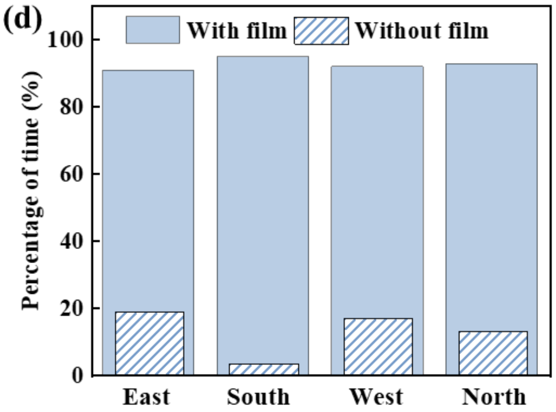


Figure 7. Comparison of time percentage with acceptable illuminance uniformity: (a) Hong Kong; (b) Haikou; (c) Singapore; and (d) Manila.

4.3. Comparison with other films

As demonstrated through the analyses in Section 4, the proposed film primarily reduces building cooling load by decreasing solar heat gain and enhancing radiative cooling. Additionally, the incorporation of pores enables the scattering of incident sunlight, thereby improving indoor daylighting performance, including illuminance uniformity and glare reduction. To contextualise these performances, the optical and thermal performance metrics of the proposed film are compared with those of the films in the published literature as well as commercial window films, as summarised in Table 2. It can be found that the proposed film exhibits particular strengths in terms of its biodegradability and its ability to enhance indoor daylighting quality. Its relatively high mid-infrared emissivity also contributes to its superior energy-saving performance. These features make the film especially attractive in the context of increasing environmental awareness and demand for sustainable materials. However, it is worth noting that the visible transmittance of the proposed film is slightly lower than its overall solar transmittance, which contrasts with the performance characteristics of most other window films. This phenomenon arises because the film exhibits slightly higher transmittance in the near-infrared (NIR) range than in the visible range, as shown in Figure 4(b). In cooling-dominated climates, windows are typically required to maintain high visible transmittance while effectively suppressing near-infrared transmission. Therefore, an ideal film should exhibit distinct spectral selectivity between the visible and near-infrared regions. However, most NIR-reflective films are generally non-biodegradable. In the future, the investigations will focus on identifying and incorporating sustainable nanoparticles as fillers of the proposed films to reduce NIR transmittance while preserving the film's environmental compatibility.

5. Conclusion and outlook

This study introduces a glass film designed to enhance building energy efficiency and the indoor daylighting environment. The film is primarily composed of a biodegradable polylactic acid (PLA) matrix embedded with air pores and SiO_2 particles. Its environmental friendliness and degradability distinguish it from conventional window films. Initially, through Mie scattering theory, the film's thickness and the size parameters of internal pores and particles were optimised. Subsequently, using an office building as a case study, the impact of the optimised film on building energy efficiency and daylighting performance was analysed across the different building orientations and cooling-dominated regions. The results indicate that the film exhibits optimal optical properties at a thickness of 100 um, with a pore diameter and porosity of 9 um and 6%, and SiO_2 diameter and filling ratio of 10 um and 20%, achieving solar transmittance and infrared emissivity of 0.66 and 0.95, respectively. After applying the film, the annual cooling load was reduced by 46~134 kWh/m^2, corresponding to average energy savings of 27%. In addition, the percentage of time with acceptable DGP increased by up to 36%, and indoor illuminance uniformity improved by 55%-91%.

Despite the encouraging outcomes, this study has limitations and areas for further exploration. Primarily, it remains a simulation-based study, although the models used have been widely validated. Future research will involve fabricating this film using solution methods and blade coating techniques, conducting experimental tests to validate its energy-saving and daylighting performance, and proving its biodegradability through extended outdoor testing. Additionally, as discussed in Section 4.3, one identified limitation is the relatively high NIR transmittance, which may compromise energy-saving performance. In cooling-dominated climates, effective suppression of NIR radiation is crucial. Future research will explore sustainable nanoparticle fillers that can enhance spectral selectivity by minimising NIR transmittance while maintaining the film's biodegradable characteristics. In summary, this study introduces a new pathway toward sustainable window retrofitting by combining energy performance optimisation with environmental responsibility. It is hoped that this work will inspire further research and practical advancements in biodegradable, high-performance window films for green building applications.

Table 2. Comparison between the present film and typical films in the published literature and market.

	Visible transmittance	Solar transmittance	Mid-infrared emissivity	Biodegradability	Daylighting improvement
Present film	0.63	0.66	0.95	✓	✓
NIRS film (Khaled & Berardi, 2025)	0.72	0.44	/	✕	✕
VANF film (Park et al., 2021)	0.9	0.8	/	✕	✕
PE composite film (Liu et al., 2025)	0.7	0.5	0.84	✕	✓
TRC film (Yi et al., 2021)	0.63	0.4	0.9	✕	✕
PDMS/ITO film (Pu et al., 2025)	0.86	0.8	0.96	✕	✕
SRP70 film in Hang Tai (Far East) Trading company	0.68	0.54	/	✕	✕
Prestige window film in 3M company	0.8	0.4	/	✕	✕

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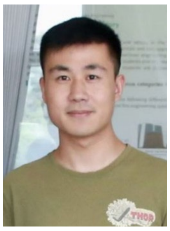

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