AUIQ Complementary Biological System
ISSN: 3007-973X
Journal homepage:
https://acbs.alayen.edu.iq

Manuscript 1014

Evaluating UV-Protective Low-Emissivity Window Films: Implications for Thermal and Visual Comfort in Luminous Office Buildings

Lina M. Shaker

AUIQ COMPLEMENTARY BIOLOGICAL SYSTEM 1 (2024) 46–60

Scan the QR to view
the full-text article on
the journal website

REVIEW

Evaluating UV-Protective Low-Emissivity Window Films: Implications for Thermal and Visual Comfort in Luminous Office Buildings

Lina M. Shaker

Al-Ayen Iraqi University (AUIQ), Nile St, Nasiriyah, Dhi Qar, 64001, Iraq

ABSTRACT

This review article explores the integration of thin window films and solar energy systems to enhance thermal comfort in luminous office buildings. Luminous office buildings, which prioritize natural lighting, often face challenges in maintaining thermal comfort for occupants. By integrating solar energy systems, such as photovoltaic (PV) and solar thermal systems, with thin window films, it is possible to optimize thermal comfort while harnessing sustainable energy sources. Thin window films act as a barrier against solar radiation, reducing heat gain while allowing therapeutic blue light (400–520 nm) transmission. The advantages of thin window films include improved thermal insulation, glare reduction, and harmful ultraviolet (UV) band protection. Case studies reveal that the integration of low emissivity (Low-E) films resulted in up to a 30% reduction in energy consumption for heating and cooling, while also enhancing indoor thermal comfort. Solar energy systems contributed to a 20% increase in energy efficiency by supplementing the building's energy needs. Furthermore, Low-E films support the public health and CO_2 emission reduction by cutting down the energy requirement of the buildings leading to lower greenhouse gas emission, better air quality, and more comfortable indoor environments. Through these influences, such thin films provide the efforts for improving environmental health and foster sustainable urban living.

Keywords: UV protective low-E films, CO_2 emissions reduction, Public health benefits, Luminous office building, Thermal comfort

1. Introduction

The concepts of luminous office building, characterized by abundant of natural lighting has gained wide attention in the recent years. With the growing awareness of natural light benefits for occupant well-being and architects and designers are getting important in case of the incorporation of large windows and transparent facades in the office buildings [1]. Luminous buildings aimed to create or establish a healthy environment in term of sufficient vitamin D synthesis and comfort in term of visual and thermal comfort, in addition to the luminous office buildings aims like the foster productivity, creativity, and the overall occupancy [2]. Natural light is desirable goal, which poses certain challenging cases particularly in terms of maintaining thermal and visual comfort. That increment then select penetration through extensive window can result in excessive heat gain during hot summer months. As a result, the occupant's discomfort would be a real problem and should be solved immediately. Balancing between harnessing the natural light and managing the heat transfer from the windows to the inner spaces in the building become crucial matter for creating sustainable uncomfortable work environments [3]. It is possible to optimize the energy efficiency and occupancy of well-being by combining the benefits of solar radiation and heat limitation by applying low emissivity (Low-E) window films the building's windows [4]. These thin

---

Received 6 October 2024; accepted 17 October 2024.

E-mail address: lina.mohammed99@alayen.edu.iq (L. M. Shaker).

https://doi.org/10.70176/3007-973X.1014

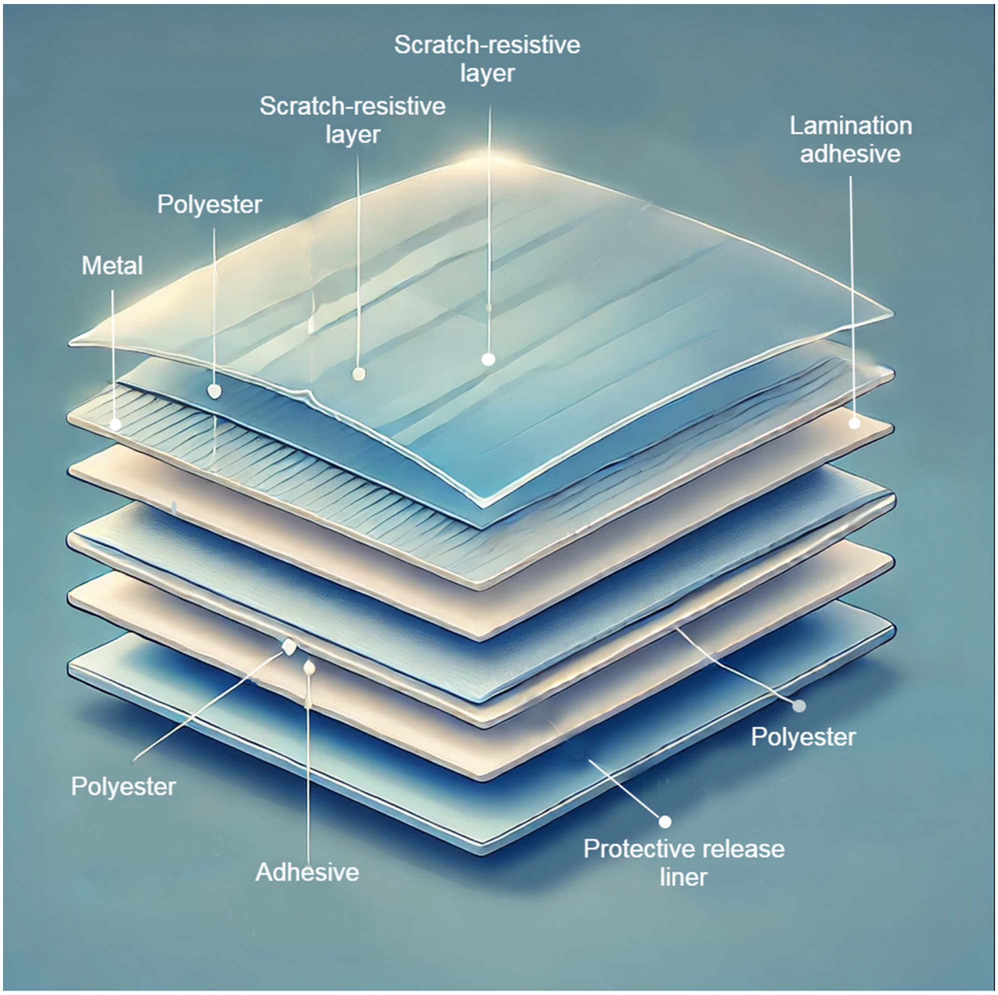

Fig. 1. In sequence the typical layers of thin window films. From the outer layer (top) to the inner layer (down).

films, according to Pereira et al. in 2020, are industrially made of 8 main layers; scratch-resistive layer, polyester [5], metal [6], lamination adhesive [7], UV resin is the sixth layer, adhesive, and protective release liner as shown in Fig. 1 [8].

Thin window films made of different compounds to achieve their distinctive functional characteristics. Mainly, Polyethylene Terephthalate (PET) due to its high transparency and durability, it is often used as the base material [9]. Sometimes, Polyvinyl Chloride (PVC) is used to make the films acquire more privacy characteristics, decorative applications, and flexibility. PVC thin films typically exhibit improved blocking performance, durability, and stability [10]. In their available various types, acrylic adhesives, ensure a strong bonding to glass surfaces without compromising visibility [11]. Metal oxides, like the Zinc oxide open embedded within the film matrix for UV protection properties [12]. On the other hand, Titanium dioxide or ceramic nanoparticles aid in heat rejection and CO_2 capturing [13]. Such like the latter metal oxides, Silver and Aluminum have antimicrobial properties and they are commonly incorporated in the Low-E window films [14], they are also used for enhancing the IR radiation reflection to reduce the heat transfer to the inner spaces [15]. To extend the lifespan of the thin films and preserving the clarity over time, UV stabilizers like Benzotriazole derivatives are integrated within the polymer matrix [16].

There is another benefit in addition to thermal comfort, is reducing the cooling loads which in turn minimize reliance on conventional energy grid [17]. This will acquire the office building a sustainable energy solution When it is integrated to solar thermal systems for water heating purposes and electricity generation solar energy systems like Photovoltaic (PV) systems [18]. By incorporating these technologies into the luminous office buildings, an abundance of sunlight would generate electricity without relying on the fossil fuel [19]. In summer, the insulation factor of thin window films would help in reducing the inner temperature [20]. The combination of Low-E films with solar energy systems leading to substantial energy saving and a decrease in carbon footprint [21]. These films are cost effective as they can be applied easily in any type or shape of the windows. Furthermore, these films selectively filter out the harmful UV rays' bands, allowing the useful blue rays (400–520 nm) to transmit, and reflect the IR radiation to the outer environment [22]. These examples serve the illustration of the benefits achieved by thin window films, including enhancement comfort, visual comfort, architectural design, improved energy efficiency, and increased occupants' satisfying [23]. Low-E window films are contributing to the achievement of the global sustainable development goals (SDGs); especially when they are aligned with SDGs 3 (Good health and well-being), SDGs 7 (Affordable and clean energy), SDGs 9 (Industry, innovation, and infrastructure), SDGs 11 (Sustainable cities and communities), SDGs 12 (Responsible consumption and production), and SDGs 13 (Climate action) [24]. Managing heat transfer while allowing sufficient light poses a complex challenge to designers, architects, and building professionals. The main issue is ensuring indoor environments remain comfortable while minimizing energy consumption. This challenge involves mitigating glare, managing temperature variability, and ensuring occupant comfort. This review article aims to explore the integration of Low-E films with solar energy production and heating systems in luminous office buildings, highlighting their role in maintaining indoor thermal comfort, energy efficiency, and the well-being of occupants. By examining real-world case studies, the paper delves into how these films balance natural light transmission and heat management, fostering energy-efficient environments without compromising public health. Furthermore, the biological aspect of the work includes an emphasis on the health benefits of properly managing indoor climates, particularly in relation to reducing glare, temperature-related discomfort, and potential long-term health impacts due to poor indoor environmental conditions. This review will also explore how such systems can enhance visual and thermal comfort, contributing to improved occupant well-being.

2. Importance of thermal comfort in office buildings

Thermal coverage plays a crucial role in the cognitive-related tasks of the individuals, public health, and overall well-being occupants in the office buildings as well as our houses. It refers to the conditions where the individuals feel satisfied with the environmental thermal conditions surrounding them, neither too hot nor too cold [25]. Continuing the optimal thermal comfort levels is necessary due to several reasons as listed below:

1. Occupant productivity: thermal comfort directly affects the individual performance and the productivity in both office and house settings. When the individuals are exposing to extreme temperatures or fluctuations, they're ability to focus and perform control cognitive tasks can be sufficiently affected [26]. Uncomfortable thermal conditions lead to destruction might use attention span and decrease the individual's cognitive-related performance; Oppositely, stable thermal environment promotes better focusing, good cognitive-related tasks productivity, and overall job satisfaction [27].
2. Health and well-being: thermal comfort has a substantial impact on the health and well-being of the office and houses occupants [28]. Exposing them to extreme temperatures weather excessively hot or cold can lead to various health issues. e.g., according to Pilcher el. al study, exposing a group of employers to 32.22°C in different durations negatively affect their performance by 14.88%, also, their performance has been affected negatively when exposing them to 10°C by 13.91% [29]. Hot environments may experience heat stress to the individuals, Dehydration, fatigue, and heat related illnesses [30]. On the other hand, cold environments contribute to discomfort respiratory problems and increased susceptibility to cold and viruses [31]. Preserving the optimal thermal comfort levels hello tune mitigate the risk of temperature degree to ensure the physical well-being of occupants [32].
3. Occupants' satisfaction: people are spending a significant portion of their time in the office buildings. When they feel satisfied in terms of temperature, they tend to have more positive performance and perception of their workspace, leading to overall positive performance as explained before. Oppositely, discomfort due to thermal issues lead to complaints and absenteeism due to heath issues [33].
4. Energy efficiency and sustainability: property rights managing thermal comfort in the office buildings contributes to sustainable energy production in high efficiency. People tend to use their personal cooling devices like fans or heating devices like heaters when they feel

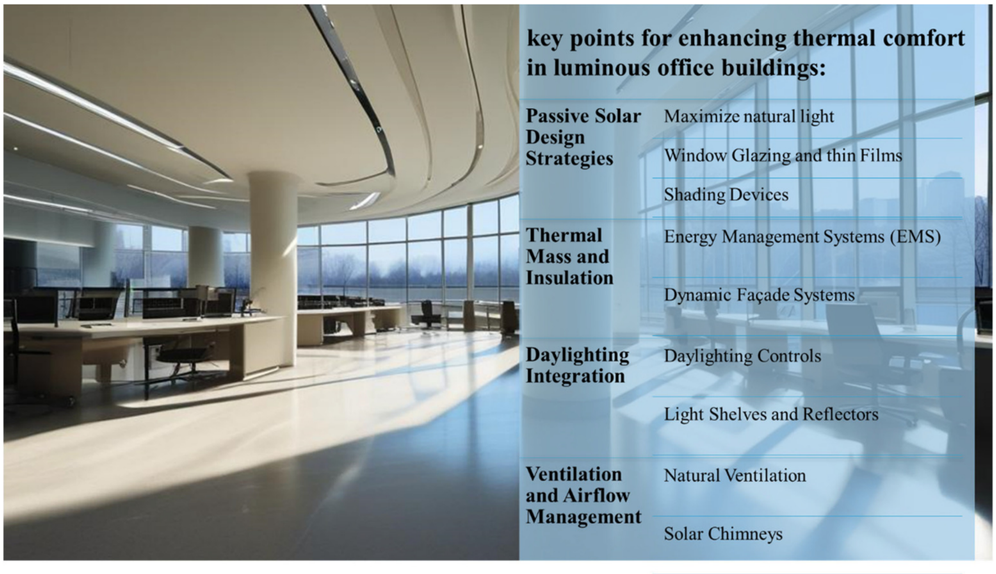

Fig. 2. Main key points used to enhance the inner spaces comfort in luminous office buildings through applying the passive solar strategies for thermal insulation and preserving the natural light transmission.

uncomfortable in office environments. These methods consume additional energy from the conventional grid. So, providing well-regulated and comfortable environment minimize the dependence of occupants on their personal heating or cooling devices then reducing the energy consumption and promoting the sustainability [34].

5. Compliance with the standards and regulations: compliance with the global regulations and standards regarding the indoor environmental quality, including thermal comfort, is essential for preserving the healthy and safe working environment. Failing to meet these regulations and standards expose the building owners and managers to legal consequences [35].

By prioritizing and optimizing the thermal comfort, office buildings environments will be conducted as supportive for the occupants, using to enhance the overall individual performance and preserving the health of well-being inside. Fig. 2 and Table 1 are summarizing the main key points to enhance the thermal comfort in luminous office buildings.

3. Challenges in achieving thermal and visual comfort in luminous office buildings: Balancing natural light and heat management

Achieving thermal and visual comfort in luminous office buildings presents several challenges due to the unique characteristics and design elements associated with these spaces. Low-E films are typically composed of layers of metallic or metal-oxide coatings that are thin enough to be transparent but engineered to selectively manage heat and light transmission [36]. The reduction of infrared and UV rays plays a critical role in improving indoor thermal comfort without causing the over-reliance on artificial lighting. Some of the key challenges include:

1. Heat Gain and Solar Radiation: Luminous office buildings typically feature extensive glazing, large windows, and transparent facades to maximize natural light. While this promotes a bright and inviting workspace, it also increases the potential for heat gain through solar radiation. Sunlight entering through windows can significantly increase the indoor temperature, leading to discomfort for occupants. Managing heat gain effectively without compromising the benefits of natural light is a major challenge [37]. These films work by reflecting a portion of the infrared (IR) spectrum while allowing visible light to pass through, thereby reducing solar heat gain while maintaining adequate natural light levels [38]. From a biological perspective, maintaining a balance between natural light and temperature control is crucial for occupant health and productivity. Natural light is vital for regulating circadian rhythms, which affect sleep, mood, and overall well-being [39].
2. Inconsistent Temperature Distribution: Due to the presence of large windows and extensive glazing, temperature distribution within

Table 1. Summary of the key points for enhancing thermal comfort in luminous office buildings through solar energy integration.

Strategies	Key points
Passive Solar Design Strategies	Maximize natural light, use window glazing and solar control films, incorporate shading devices to minimize heat gain and enhance thermal comfort.
Photovoltaic (PV) Panels for Energy Generation	Install rooftop solar panels or use Building-Integrated Photovoltaics (BIPV) to generate clean energy while maintaining natural illumination.
Solar-Assisted HVAC Systems	Implement solar-powered cooling systems like absorption chillers, and use hybrid HVAC systems to supplement heating and cooling needs.
Thermal Mass and Insulation	Incorporate thermal mass materials to maintain consistent indoor temperatures and improve insulation to minimize heat gain and loss.
Smart Building Technologies	Use energy management systems (EMS) and dynamic façade systems to optimize light and heat control and improve energy efficiency.
Daylighting Integration	Integrate daylighting controls and light shelves to balance natural illumination, reducing artificial lighting and heat generation.
Ventilation and Airflow Management	Use natural ventilation and solar chimneys to enhance airflow, improving passive cooling during warmer months.
Energy Storage Solutions	Use solar thermal storage to store excess heat for later use, and battery storage to capture excess photovoltaic energy.
Green Roofs and Solar Shading	Install green roofs to provide insulation and reduce heat gain, while integrating solar panels for shading and energy generation.

luminous office buildings can be uneven. Low-E coatings consist of multiple layers of thin, transparent metallic oxides, usually applied on or between glass panes [40]. These films reflect IR radiation, reducing the heat transfer from outside to inside the building during summer and minimizing heat loss during winter [41]. Direct exposure to sunlight can result in hot spots near windows, while areas farther from the windows may experience cooler temperatures [42]. This temperature variation can cause discomfort and make it challenging to maintain a consistent and comfortable thermal environment throughout the space [43].

3. Glare and Visual Discomfort: Excessive sunlight entering through windows can create glare, which is the excessive brightness or contrast that impairs vision and causes visual discomfort [44]. Glare can lead to eye strain, reduced visual acuity, and difficulty in reading or viewing screens. Balancing the desire for natural light with the need to minimize glare is a significant challenge in achieving optimal thermal and visual comfort in luminous office buildings [45]. Prolonged exposure to heat, on the other hand, can cause discomfort, fatigue, and reduced cognitive performance [46]. By using thin films to manage heat, we ensure that the biological benefits of natural daylight, such as its positive effects on mood and alertness, are retained while minimizing the adverse effects of excessive heat exposure. This creates a more comfortable and healthier indoor environment.
4. HVAC System Design and Control: The design and control of the heating, ventilation, and air conditioning (HVAC) system play a crucial role in achieving thermal comfort. However, in luminous office buildings, the presence of extensive glazing and sunlight penetration can significantly impact the HVAC system's performance. Proper HVAC system design, including equipment sizing, distribution, and control strategies, is essential to effectively regulate indoor temperatures and maintain thermal comfort [47]. (e.g., metal oxide coatings or multi-layered thin films) plays a major role in achieving this balance. These films often have low emissivity values (around 0.04 to 0.10), minimizing heat transfer through radiation while maximizing the passage of natural light [48].
5. Energy Efficiency Considerations: While maximizing natural light is desirable for energy efficiency and occupant well-being, it can pose challenges in maintaining thermal comfort without relying heavily on energy-consuming cooling systems. The trade-off between natural light and energy efficiency requires careful consideration to strike a balance that minimizes energy consumption while ensuring occupants' thermal comfort [49]. For example, photochromic film presents an attractive strategy for achieving more energy-efficient buildings and carbon neutrality to combat global climate change with a high luminous transparency of 91%, solar heat transmittance of 73%, and modulation of solar heat gain coefficient of 0.5 [38].
6. Retrofitting Existing Buildings: Retrofitting existing office buildings to improve thermal comfort poses additional challenges. Modifying the building envelope, including adding or replacing windows, integrating thin window films, or incorporating solar energy systems, requires

careful planning and implementation [50]. Retrofitting projects must address structural limitations, architectural compatibility, and cost considerations while achieving the desired thermal and visual comfort improvements [37].

Addressing these challenges requires a comprehensive and integrated approach. Solutions may involve a combination of architectural design strategies, such as optimizing window orientation and shading devices, using high-performance glazing materials, and implementing intelligent lighting controls. Additionally, advanced HVAC systems, such as zoned heating and cooling and adaptive controls, can help regulate temperature distribution and improve energy efficiency.

4. Solar energy integration in luminous office buildings

Incorporating solar energy systems in office buildings offers numerous benefits, ranging from environmental sustainability to cost savings and energy efficiency.

4.1. Benefits of incorporating solar energy systems

1. Renewable and Sustainable Energy: Solar energy is a clean, renewable source of energy that helps reduce reliance on fossil fuels and decreases carbon emissions. By harnessing sunlight to generate electricity or heat, office buildings can contribute to a more sustainable energy future and support environmental conservation efforts [51].
2. Cost Savings: Solar energy systems can lead to significant cost savings in the long run. Once installed, solar panels can generate electricity with minimal operational costs, reducing dependency on traditional energy grids and lowering utility bills. Additionally, solar energy systems may be eligible for government incentives, tax credits, and feed-in tariff programs, further enhancing the financial benefits [52].
3. Energy Independence and Resilience: By integrating solar energy systems, office buildings can enhance their energy independence and resilience. They become less reliant on external energy sources, reducing vulnerability to power outages and grid disruptions. This increased energy self-sufficiency provides a reliable and stable energy supply, enhancing the operational continuity of the building [53].
4. Positive Environmental Impact: Solar energy integration helps reduce greenhouse gas emissions and contributes to combating climate change. By utilizing clean and renewable energy, office buildings can lower their carbon footprint, promote environmental stewardship, and demonstrate corporate social responsibility [54].
5. Public Image and Green Building Certification: Incorporating solar energy systems enhances the public image of office buildings and organizations. Embracing renewable energy technologies showcases a commitment to sustainability and positions the building as an environmentally conscious entity. Moreover, solar energy integration can contribute to achieving green building certifications such as LEED (Leadership in Energy and Environmental Design), further validating the building's environmental credentials [55].

4.2. Solar energy integration strategies

1. PV Systems: PV systems convert sunlight directly into electricity using solar panels made of semiconductor materials. These systems are the most common form of solar energy integration in office buildings. PV systems can be installed on rooftops, facades, or even as standalone solar arrays [56]. The generated electricity can be used on-site to power various building functions or fed back into the grid through net metering arrangements. PV systems offer flexibility in terms of system size, design, and scalability, making them suitable for a range of building types and sizes [18].
2. Solar Thermal Systems: Solar thermal systems harness sunlight to generate heat for various purposes, such as space heating, water heating, and process heating. In office buildings, solar thermal systems can provide hot water for washrooms, showers, and kitchen facilities. These systems consist of solar collectors that absorb sunlight and transfer the captured heat to a fluid, which can then be used directly or stored for later use [57]. Solar thermal systems are particularly beneficial in regions with high heating demands and can significantly reduce reliance on conventional heating sources [58].
3. Hybrid Solutions: Hybrid solar energy systems combine both PV and solar thermal technologies to maximize energy production and efficiency. These systems capitalize on the strengths of both technologies, utilizing solar panels to generate electricity and solar collectors to capture heat.

The electricity generated can power the building's electrical systems, while the captured heat can be used for space heating, water heating, or other thermal applications. Hybrid solutions provide a holistic approach to solar energy integration, optimizing energy utilization and enhancing overall system performance [59].

Incorporating solar energy systems in office buildings offers a wide range of benefits, including renewable energy generation, cost savings, energy independence, environmental impact reduction, and enhanced public image. PV systems, solar thermal systems, and hybrid solutions are effective strategies for integrating solar energy. Each strategy provides unique advantages and can be tailored to suit the specific energy needs and requirements of the office building. By embracing solar energy integration, office buildings can embrace sustainability, reduce operating costs, and contribute to a greener future.

5. Low-E window films and vitamin D: Balancing efficiency and health

For adequate vitamin D synthesis, direct sunlight exposure [60], or alternative sources such as dietary intake or supplements, may be needed if Low-E films are used extensively in a living or working space [61]. Low-E thin window films can potentially reduce vitamin D production because they block a significant portion of UV radiation, particularly UVB rays, which are necessary for the skin to synthesize vitamin D [62]. While Low-E films are designed to minimize heat and UV transmission to enhance energy efficiency and protect indoor environments, this reduction in UVB exposure could limit the natural production of vitamin D for individuals who rely on sunlight through windows. The use of thin window films, particularly Low-E films, can significantly contribute to global public health and CO_2 emissions reduction by improving building energy efficiency. Here's how the relationship unfolds:

5.1. Reducing CO_2 Emissions

1. Lower Energy Demand: Low-E window films minimize heat gain in the summer and reduce heat loss in the winter [63]. This leads to a decrease in energy demand for heating and cooling, which are major contributors to a building's carbon footprint [64]. Reduced energy demand means lower fossil fuel consumption, thereby decreasing CO_2 emissions associated with power generation [65].
2. Climate Mitigation: By lowering greenhouse gas emissions, these films indirectly contribute to mitigating climate change [66]. Lessening the effects of climate change helps stabilize global temperatures, which is crucial for reducing the frequency and severity of climate-related health risks, such as heatwaves and respiratory issues due to pollution [67].

5.2. Public Health Benefits

1. Improved Air Quality: The reduction in energy consumption means fewer emissions from power plants, especially those burning coal, oil, or natural gas. This leads to improved air quality, as there are fewer pollutants like sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter [68]. Cleaner air reduces the incidence of respiratory diseases, asthma, and cardiovascular conditions.
2. Thermal Comfort and Well-being: By maintaining more stable indoor temperatures, Low-E films enhance thermal comfort in buildings [69]. Stable temperatures reduce stress on the human body, minimizing the risk of heat-related illnesses and improving overall well-being [70]. This is particularly important for vulnerable populations, such as the elderly and those with pre-existing health conditions.
3. Energy Security and Resilience: Lower energy demand can ease the burden on electrical grids, especially during peak times, thus reducing the likelihood of blackouts [71]. This resilience is crucial in maintaining healthcare facilities' operations and other essential services during extreme weather events.

5.3. Contributing to SDGs

1. By promoting energy efficiency, Low-E films contribute to several SDGs, particularly SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action) [72]. The alignment with these goals emphasizes the films' role in fostering healthier living environments and tackling climate change, thus promoting global sustainability and public health.

6. Working principle of reflective thin window films

Thin window films applied directly to the surface of existing windows or incorporated into new

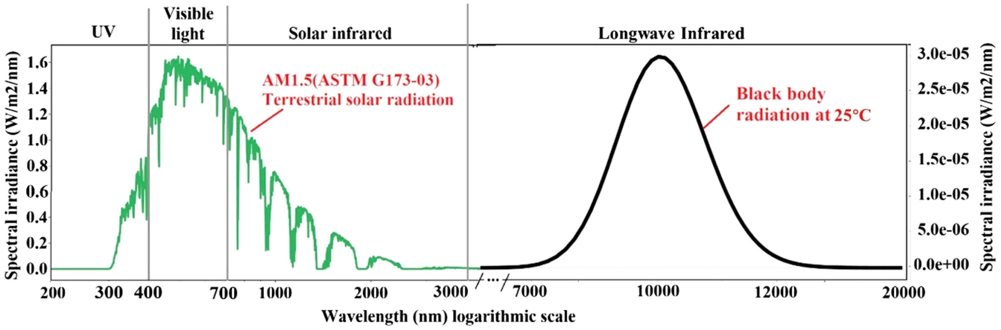

Fig. 3. Standard terrestrial reference spectrum and black body spectra at 25°C (It is calculated from Planck's Law).

window installations, provide enhanced control over solar radiation transmission and heat gain. This section introduces thin window films as a technology and explains their working principle and impact on the thermal performance of office buildings [73]. These films are designed to selectively modify the properties of the windows, improving their thermal performance, and controlling the transmission of solar radiation. By integrating thin window films into office buildings, architects and designers can effectively manage heat gain while allowing for ample natural light, creating a comfortable and energy-efficient indoor environment [74].

Thin window films operate based on two key principles: solar radiation control and thermal insulation [75]. In building energy studies, thermal radiation flux occurs across four key bands: UV radiation (100–400 nm), visible light (400–700 nm), solar IR radiation (700–3000 nm), and longwave radiation (3000–50,000 nm) as shown in Fig. 3 [76]. The standard terrestrial spectrum and black body radiation at 25°C highlight the importance of managing IR radiation in buildings. Low-E films play a vital role in reducing heat loss by reflecting indoor IR radiation, thus contributing to energy efficiency and indoor comfort, especially in climates with significant temperature variations [77]. Fig. 3 presents a comparison between the standard terrestrial solar reference spectrum and the black body radiation spectrum at 25°C (298K), calculated using Planck's Law [78]. This comparison is crucial for understanding heat transfer mechanisms in luminous office buildings, particularly concerning heat loss through radiation.

UV radiation, though a small part of the spectrum, can damage materials, but the use of UV-blocking window films and Low-E coatings helps mitigate this while improving insulation [79]. Visible light management, using advanced glazing systems like double glazing and smart windows, balances natural lighting with heat control. Solar IR radiation, a major contributor to heat gain, is addressed using Low-E glass, thermal films, and solar energy systems like photovoltaic panels [80]. Longwave radiation, typically from the building's interior or the environment, can cause heat loss, but this is minimized by high-performance insulation materials like spray foam, fiberglass, or aerogels [81]. The integration of these strategies, addressing radiation bands from 100 nm to 50,000 nm, creates a comprehensive approach to improving thermal and visual comfort, energy efficiency, and occupant well-being, with solar energy integration further enhancing sustainability by converting excess radiation into renewable power.

IR spectrum contains 45% of the sun's total energy as shown in Fig. 4. IR radiation that strikes an object produces heat as a direct result. The infrared radiation's heat-producing zone spans the wavelengths of 700 to 1100 nm. The surface is heated because of these radiations' absorption. In the summer, heat transfer through building envelopes makes up most of the load for indoor cooling. According to studies, using high reflectivity materials to coat outside walls of buildings is an efficient technique to lower heat gains from solar radiation and reduce cooling use.

1. Solar Radiation Control: Thin window films are designed to selectively control the transmission of solar radiation. They incorporate advanced coatings or layers that can reflect, absorb, or scatter solar energy. This control over solar radiation helps reduce the amount of heat and UV radiation entering the building through the windows, thereby minimizing heat gain and glare. By blocking a significant portion of solar radiation, thin window films reduce the cooling load on the HVAC system and contribute to energy savings [82].
2. Thermal Insulation: Thin window films also offer thermal insulation properties [83]. They create an additional layer of insulation on the windows, reducing heat transfer between the interior and exterior of the building. This

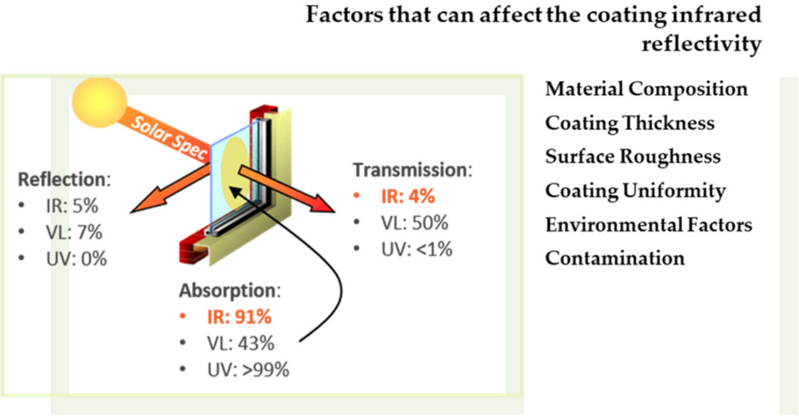

Fig. 4. interaction of solar spectrum components (IR, Visible, and UV) with thin window films.

insulation helps in maintaining a stable indoor temperature by minimizing heat loss during colder seasons and heat gain during warmer seasons. As a result, occupants experience improved thermal comfort and reduced reliance on mechanical heating and cooling systems.

3. IR Radiation Reflection: A reflective coating is a thin layer of material applied to a surface to enhance its ability to reflect light [84]. It is designed to minimize the absorption and transmission of light, resulting in increased reflectivity and reduced glare. Reflective coatings are commonly used in various applications, such as mirrors, optical devices, solar panels, and reflective clothing.

7. Impact on solar radiation transmission and heat gain

Thin window films have a direct impact on solar radiation transmission and heat gain in office buildings. The application of thin window films modifies the behavior of windows in the following ways [85]:

1. Solar Heat Gain Coefficient (SHGC) Control: Thin window films can effectively control the Solar Heat Gain Coefficient (SHGC), which measures the amount of solar heat transmitted through a window [86]. By selecting films with specific properties, the SHGC can be adjusted to limit the amount of solar heat entering the building. This helps in managing internal temperatures and reducing the cooling load on the HVAC system, leading to improved energy efficiency and thermal and visual comfort.
2. Glare Reduction: Thin window films also contribute to reducing glare caused by excessive sunlight entering the building. The films can selectively scatter or diffuse sunlight, minimizing the intensity of glare and creating a more visually comfortable environment for occupants [87]. Reduced glare improves visual comfort, minimizes eye strain, and enhances productivity.
3. UV Radiation Protection: Many thin window films are designed to block a significant portion of harmful UV radiation [83]. UV radiation can cause fading of interior furnishings, artwork, and flooring, as well as pose risks to human health. Thin window films with UV-blocking properties help protect occupants and preserve the longevity and aesthetics of interior elements.

8. Challenges of thin window films

1. Maintenance: Proper maintenance is essential to ensure the longevity and performance of thin window films. Films may require periodic cleaning using appropriate techniques and materials to prevent the accumulation of dirt or debris that could affect their optical properties [74]. Maintenance protocols should be established to ensure the films remain in good condition and continue to provide the desired benefits.
2. Installation Considerations: The installation of thin window films requires attention to detail and proper application techniques [88]. Improper installation can lead to aesthetic issues, such as air bubbles or creases, which may affect the visual quality and longevity of the films. Hiring experienced professionals for installation is recommended to ensure a high-quality and seamless application.
3. Potential Impact on Visual Aesthetics: While thin window films offer customization options, their presence can alter the visual appearance

of windows to some extent [89]. This may be a concern for buildings with specific architectural designs or for those aiming for a particular aesthetic appeal [90]. Careful selection of film types, colors, and transparency levels can help mitigate any potential impact on visual aesthetics.

4. Film Durability: The durability of thin window films can vary depending on the quality of the film and environmental conditions [91]. Exposure to harsh weather, UV radiation, or abrasive cleaning methods can potentially affect the longevity and performance of the films [92]. It is important to choose high-quality films that are specifically designed for long-term performance and consider their expected lifespan when incorporating them into office building designs.

Thin window films offer several advantages, including improved thermal insulation, glare reduction, UV protection, versatility, and cost-effectiveness. However, challenges related to maintenance, installation, potential impact on visual aesthetics, and film durability need to be carefully considered and addressed to ensure the effective and sustainable.

9. Case studies: Successful applications

Real-world examples of office buildings that have successfully integrated thin window films and solar energy systems showcase the positive outcomes and benefits achieved in terms of enhanced thermal and visual comfort, energy efficiency, and occupant satisfaction. The following case studies highlight notable projects where these technologies have been effectively implemented:

1. Colleen Boye et al. in 2010 showed that the application of selective UV-blocking window films to the museum surrounding windows achieved a balance between neutral and unobtrusive color appearance and protection the collections from harmful UV radiation [93]. Different types of window film were considered due to their ability for blocking most radiation below 380 nm, and their ability to transmit desirable visible light and color perception. 3M and L1umar lines window films were acceptable for museum uses according to the researchers. Who's that introduced noticeable tints like cyan or yellow were less desirable in their study, as they enter the visual experience of the artwork. The researchers found that all the tested forms blocked most radiation of UV band, though effectiveness and color naturality varied across the brands. 3M Prestige line performance was particularly good, blocked over 97% of UV light while maintaining the steep cutoff to prevent multiple killer shifts. The other films show more variability in UV blocking and caused visible color alteration making them less suitable for museum uses.
2. Amirkhani et al. in 2019 described in the document investigates the impact of Low-E window films on the energy consumption and CO_2 emissions of the Hilton Reading hotel in Berkshire, United Kingdom [94]. This study is motivated by the UK government's goal to reduce greenhouse gas emissions by 80% by 2050. The researchers employed building energy simulation software, EDSL TAS, to model the hotel's energy consumption with and without the application of 3M Thinsulate Climate Control 75 window film. The case study demonstrates that applying Low-E window films can achieve energy savings, with reductions of 3% in heating, 20% in cooling, and 2.7% in total energy consumption. Additionally, the study found annual CO_2 emissions and total energy costs decreased by 4.1% and 5.1%, respectively. The film's ability to retain heat during the winter and reduce solar heat gain in the summer contributed to these savings.
3. Pereira et al. in 2020, examined the window thin films on daylight illuminance levels in the inner spaces. The research focused on how much these window thin films affect both the illuminance and its distribution on the horizontal work plane after being applied to the glazing system [8]. Using a small-scale model oriented to the south in Lisbon, the field experiments involved 4 different thin window films and 6 mm clear glass under the condition of clear sky during summer and winter at 9h, 12h, and 15h. Their findings showed that the used thin films reduced the inner illuminance, and address the visual discomfort close by excessive daylight, and contributing to energy saving through reducing the cooling and artificial lighting demand.
4. Teixeria et al. in 2020 also focused in their study on the thermal and visual comfort, energy consumption and the environmental effects of the buildings [95]. This study was conducted in three adjacent offices located in the university building in Lisbon, then assimilation was called using the experimental data for comparison. The high reflection thin window films showed 16% of visible light transmission, solar heat gain coefficient of 0.15, and best thermal and visual comfort performance during 41% and 43% of working hours. Meanwhile Visible light

transmission of 63% and solar heat gain coefficient of 0.40 provided the best energy performance, reduced the annual energy consumption, and CO_2 emissions by 38%. This makes the selective thin window film as the best choice for energy savings and positively affect the overall environmental benefits.

5. Sedaghat et al. in 2021 examined the performance of thin window films when applied to the surrounding windows of the office buildings in Kuwait's hot climate [96]. In their study, they examined Neutral 20 and Neutral 70 from 3M window films brand. Over summer of 2019, data was collected to measure the temperature degree, humidity, and illumination in four offices. 3M Neutral 20 film reduced the energy consumption by 132.97 kWh and CO_2 emissions by 80–89 kg in June, but the effect of Neutral 70 film is almost negligible. The indoor temperature was reduced by 2–5°C and the humidity increased by 5–10%. The findings of simulations show that SOL 101 films could reduce the energy consumption by 1154.28 kWh and CO_2 emissions by 699.54 kg over the summer.

These case studies demonstrate the successful application of thin window films and solar energy systems in luminous office buildings. The integration of these technologies has resulted in notable outcomes, including enhanced thermal comfort, energy efficiency, reduced energy consumption, and positive occupant satisfaction. By leveraging the advantages of natural light and renewable energy, these buildings exemplify sustainable and forward-thinking design principles that prioritize both environmental stewardship and occupant well-being.

10. Future directions and opportunities

Thin window films technology is still under research, as is its integration in Building Integrated Photovoltaic (BIPV) solutions for solar energy generation. The field is evolving, so these emerging trends and technologies, though not yet mature, hold potential to grow or find niche applications, particularly in office buildings to improve comfort and energy efficiency. The section outlines several research areas and future directions that could shape the further development of these technologies:

1. Nanomaterials and Coatings: Through funding from the Building Technologies Office, researchers are investigating the addition of nanomaterials to thin window films for enhanced performance. These materials provide advanced optical properties with better angular dependence, improved solar control, and superior thermal insulation compared to traditional transparent materials. Using nanotechnology and advanced coatings can increase efficiency in transparent thin window films, offering greater solar radiation control and insulation.
2. Smart Window Films: Developing smart window films is a promising area of research with significant potential. These films can adapt to environmental conditions and adjust according to specific needs. For instance, they can switch between transparent, tinted, or reflective states depending on sunlight intensity or heat. This dynamic control allows for optimized solar radiation management and thermal comfort based on varying weather conditions and occupant preferences.
3. Building Automation Integration: Integrating thin window films and solar energy systems with building automation has great potential. When combined with intelligent controls, these systems can use real-time data (e.g., occupancy patterns, weather forecasts, and energy demand) to ensure optimal performance. For instance, cameras detecting an occupant entering a building could automatically control window film transparency, optimize solar energy use, and coordinate with the HVAC system for better energy efficiency and occupant comfort.
4. Energy Storage and Management: Adding energy storage solutions to solar technology and window films can mitigate the challenges posed by solar power's intermittent nature. Advanced batteries and thermal storage systems, for example, can store surplus solar energy during the day, providing a more consistent energy supply for buildings. By leveraging solar energy generation, coupled with energy storage and management, this approach can help meet energy demand while reducing reliance on the grid.
5. Innovative Design Approaches: Future research may explore innovative designs that combine thin window films, solar energy systems, and other building elements. This could include the use of shading devices like motorized blinds or external louvers, working in tandem with the films to further enhance energy performance and thermal comfort. Design considerations may also focus on maximizing daylight harvesting and optimizing building orientation to benefit from natural light and solar energy.
6. Human-Centric Design: Investigating the effects of thin window films and solar energy integration on occupant well-being, productivity, and

satisfaction is essential. Future developments should prioritize creating comfortable, aesthetically pleasing environments that promote health and performance by considering human-centric design principles. This may involve studying the impact of increased natural light, glare reduction, and customizable privacy features on occupant comfort through feedback and performance evaluations.

Looking ahead, integrating thin window films with solar energy systems presents exciting possibilities. Nanotechnology, smart window films, building automation, energy storage, advanced design tools, and human-centric principles show promise in enhancing thermal comfort, energy efficiency, and occupant satisfaction. Further research in these areas can help transform office buildings into greener, smarter, and more user-friendly spaces.

11. Conclusion

This review highlights the significant role that Low-E window films play in enhancing thermal comfort and energy efficiency in luminous office buildings. The integration of these films with solar energy systems proves to be an effective strategy for managing heat transfer, reducing reliance on conventional energy sources, and promoting sustainability. The main findings from the analysis demonstrate several key benefits:

1. Thermal Comfort: Low-E films provide enhanced thermal insulation by selectively blocking infrared radiation while allowing the transmission of visible light. This balance improves indoor temperature regulation, reducing the need for active heating and cooling systems.
2. Energy Savings: The application of Low-E films in conjunction with solar energy systems, such as photovoltaic panels, leads to substantial energy savings. Case studies demonstrate up to a 20% reduction in cooling energy consumption and a significant decrease in overall energy demand, contributing to a low-energy building designation.
3. CO_2 Emissions Reduction: By minimizing the energy required for heating and cooling, Low-E films contribute to a marked reduction in CO_2 emissions. This not only supports environmental conservation but also aligns with global sustainability goals.
4. Visual and Thermal Comfort: The films effectively reduce glare and UV radiation, while still allowing for sufficient natural light. This improves visual comfort for building occupants, while also protecting interior furnishings and reducing the risks associated with UV exposure.
5. Public Health and Well-Being: The improved thermal comfort and reduced reliance on fossil fuels contribute to better indoor air quality and occupant health. Stable indoor temperatures decrease the likelihood of heat-related illnesses, while the lower environmental impact benefits the broader public health agenda.

Overall, Low-E films, when combined with solar energy technologies, present a highly effective approach to balancing natural light and heat management in office environments. The results of this study provide a pathway towards more energy-efficient and healthier buildings, with long-term benefits for both public health and environmental sustainability.

Acknowledgments

The authors would like to express their sincere gratitude to Al-Ayen University (AUIQ) for providing the financial support through grant code TT-2023-018, which made this research possible.

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval

This study did not involve human or animal subjects.

Data availability

Data generated from this study will be made available upon request.

Funding

This research was conducted under the research agreement between Al-Ayen University (AUIQ) and Universiti Kebangsaan Malaysia (UKM), funded by grant code TT-2023-018.

Author contributions

All aspects of the research, including conceptualization, methodology, formal analysis, writing, and funding acquisition, were solely managed by Lina M. Shakir.

References

1. Lee ES, Matusiak BS, Geisler-Moroder D, Selkowitz SE, Heschong L. Advocating for view and daylight in buildings: next steps. *Energy Build*. 2022;265:112079. doi: 10.1016/j.enbuild.2022.112079.
2. Altomonte S, et al. Ten questions concerning well-being in the built environment. *Build Environ*. 2020;180:106949. doi: 10.1016/j.buildenv.2020.106949.
3. Azar E, et al. Simulation-aided occupant-centric building design: a critical review of tools, methods, and applications. *Energy Build*. 2020;110292. doi: 10.1016/j.enbuild.2020.110292.
4. Pode R. Organic light emitting diode devices: an energy-efficient solid-state lighting for applications. *Renew. Sustain. Energy Rev*. 2020;110043. doi: 10.1016/j.rser.2020.110043.
5. Baharu MN, Kadhum AAH, Al-Amiery AAA, Mohamad AB. Synthesis and characterization of polyesters derived from glycerol, azelaic acid, and succinic acid. *Green Chem Lett Rev*. 2015;8(1):31–38. doi: 10.1080/17518253.2014.991810.
6. Sasaki T, Takefuji Y. Inexpensive all-season passive thin metal film for energy savings in cities. *Energy Sustain Dev*. 2023;73:232–235. doi: 10.1016/j.esd.2023.02.010.
7. Kim H, Kim KH, Jeong YC. Direct coating of transparent and wear-resistant polysilsesquioxane on ultra-thin glass for flexible cover windows. *Prog Org Coat*. 2024;187:108162. doi: 10.1016/j.porgcoat.2023.108162.
8. Pereira J, Gomes MG, Rodrigues AM, Teixeira H, Almeida M. Small-scale field study of window films' impact on daylight availability under clear sky conditions. *J Facade Des Eng*. 2020;8(1):65–84. doi: 10.7480/jfde.2020.1.4785.
9. Xie Q, et al. Transparent flexible and stable polyethersulfone/copper-nanowires/polyethylene terephthalate sandwich-structured films for high-performance electromagnetic interference shielding. *Adv Eng Mater*. 2021;23(8). doi: 10.1002/adem.202100283.
10. Al-Amiery A, Yousif E, Rubaye A, Kadhum AAH, Mohamad AB. Stability of PVC films complemented with synthetic biolubricant. *Polym Degrad Stab*. 2015;d008. doi: 10.3390/ecsoc-19-d008.
11. Kim B, Yoo K, Kim S, Park JS, Seong DG, Yoon J. Self-adhesive thermotropic smart films for adaptive solar control under various climate conditions. *Chem Eng J*. 2022;443:136471. doi: 10.1016/j.cej.2022.136471.
12. Anuar SA, Ahmad KN, Al-Amiery A, Masdar MS, Isahak WNRW. Facile preparation of carbon nitride-ZnO hybrid adsorbent for CO_2 capture: the significant role of amine source to metal oxide ratio. *Catalysts*. 2021;11(10):1–12. doi: 10.3390/catal11101253.
13. Choudhuri B, Mondal A, Dhar JC, Singh NK, Goswami T, Chattopadhyay KK. Enhanced photocurrent from generated photothermal heat in indium nanoparticles embedded TiO2 film. *Appl Phys Lett*. 2013;102(23). doi: 10.1063/1.4811360.
14. Sulaiman GM, Mohammed WH, Marzoog TR, Al-Amiery AAA, Kadhum AAH, Mohamad AB. Green synthesis, antimicrobial, and cytotoxic effects of silver nanoparticles using Eucalyptus chapmaniana leaves extract. *Asian Pac J Trop Biomed*. 2013;3(1):58–63. doi: 10.1016/S2221-1691(13)60024-6.
15. Abundiz-Cisneros N, Sanginés R, Rodríguez-López R, Peralta-Arriola M, Cruz J, Machorro R. Novel Low-E filter for architectural glass pane. *Energy Build*. 2020;206:109558. doi: 10.1016/j.enbuild.2019.109558.
16. Sankaran A, Kamboj A, Samant L, Jose S. Synthetic and natural UV protective agents for textile finishing. In: Innovative and Emerging Technologies for Textile Dyeing and Finishing. Wiley; 2021:301–324. doi: 10.1002/9781119710288.ch11.
17. Elrayies GM. Prophylactic architecture: Formulating the concept of pandemic-resilient homes. *Buildings*. 2022;12(7):927. doi: 10.3390/buildings12070927.
18. Mahdi AS, Shaker LM, Al-Amiery A. Recent advances in organic solar cells: materials design and performance. *J Optics (India)*. 2023. doi: 10.1007/s12596-023-01262-2.
19. Franco A. Balancing user comfort and energy efficiency in public buildings through social interaction by ICT systems. *Syst*. 2020;8(3):1–16. doi: 10.3390/systems8030029.
20. Carriço JGL, Duarte B, Zemero BR, Souza ACD, Tostes MEL, Bezerra UH. Building information modeling approach to optimize energy efficiency in educational buildings. *J Build Eng*. 2021;43:102587. doi: 10.1016/j.jobe.2021.102587.
21. Lyu K, de Dear R, Brambilla A, Globa A. Restorative benefits of semi-outdoor environments at the workplace: Does the thermal realm matter? *Build Environ*. 2022;222:109355. doi: 10.1016/j.buildenv.2022.109355.
22. Kciuk M, Bijok T, Lo Sciuto G. Design and modeling of intelligent building office and thermal comfort based on probabilistic neural network. *SN Comput Sci*. 2022;3(6):485. doi: 10.1007/s42979-022-01411-7.
23. Kinder K. Making healthy places: designing and building for well-being, equity, and sustainability. *Cities Health*. 2022. doi: 10.1080/23748834.2022.2123604.
24. Sorooshnia E, et al. A novel approach for optimized design of low-E windows and visual comfort for residential spaces. *Energy Built Environ*. 2025;6(1):27–42. doi: 10.1016/j.enbenv.2023.08.002.
25. Ko WH, et al. The impact of a view from a window on thermal comfort, emotion, and cognitive performance. *Build Environ*. 2020;175:106779. doi: 10.1016/j.buildenv.2020.106779.
26. Taylor L, Watkins SL, Marshall H, Dascombe BJ, Foster J. The impact of different environmental conditions on cognitive function: a focused review. *Front Physiol*. 2016;6:372. doi: 10.3389/fphys.2015.00372.
27. Mansi SA, et al. Measuring human physiological indices for thermal comfort assessment through wearable devices: a review. *Measurement*. 2021;183:109872. doi: 10.1016/j.measurement.2021.109872.
28. Kjellstrom T, Briggs D, Freyberg C, Lemke B, Otto M, Hyatt O. Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. *Annu Rev Public Health*. 2016;47:207–218. doi: 10.2486/indhealth.47.207.
29. Pilcher JJ, Nadler E, Busch C. Effects of hot and cold temperature exposure on performance: a meta-analytic review. *Ergonomics*. 2002;45(10):682–698. doi: 10.1080/00140130210158419.
30. Gauer R, Meyers BK. Heat-related illnesses. *Am Fam Physician*. 2019;99(8):482–489. doi: 10.29309/tpmj/2015.22.05.1264.
31. Mäkinen TM, Hassi J. Health problems in cold work. *Ind Health*. 2009;47:207–220. doi: 10.2486/indhealth.47.207.
32. Valinejadshoubi M, Moselhi O, Bagchi A, Salem A. Development of an IoT and BIM-based automated alert system for thermal comfort monitoring in buildings. *Sustain Cities Soc*. 2021;66:102602. doi: 10.1016/j.scs.2020.102602.
33. Chen CF, et al. The impacts of building characteristics, social, psychological, and cultural factors on indoor environment quality productivity belief. *Build Environ*. 2020;185:107189. doi: 10.1016/j.buildenv.2020.107189.
34. Elnaklah R, Walker I, Natarajan S. Moving to a green building: indoor environment quality, thermal comfort, and health.

Build Environ. 2021;191:107592. doi: 10.1016/j.buildenv.2021.107592.

35. Kakoulli C, Kyriacou A, Michaelides MP. A review of field measurement studies on thermal comfort, indoor air quality, and virus risk. *Atmos*. 2022;13(2):191. doi: 10.3390/atmos13020191.
36. Liu R, et al. Materials in radiative cooling technologies. John Wiley and Sons Inc. 2024. doi: 10.1002/adma.202401577.
37. Santamaria BM, Gonzalo FdA, Aguirregabiria BL, Ramos JAH. Evaluation of thermal comfort and energy consumption of water flow glazing as a radiant heating and cooling system: a case study of an office space. *Sustainability (Switzerland)*. 2020;12(18):7596. doi: 10.3390/su12187596.
38. Meng W, et al. Scalable photochromic film for solar heat and daylight management. *Adv Mater*. 2024;36(5):2304910. doi: 10.1002/adma.202304910.
39. Dumont M, Beaulieu C. Light exposure in the natural environment: relevance to mood and sleep disorders. *Sleep Med*. 2007;8(6):557–565. doi: 10.1016/j.sleep.2006.11.008.
40. Wan Shamsuddin WNS, Zuber K, Murphy PJ, Jane ML. Environmental durability of soft low-e coatings: a review. *Solmat*. 2024;266:112673. doi: 10.1016/j.solmat.2023.112673.
41. Abed RN, Abdallh M, Rashad AA, Al-Mohammedawi HC, Yousif E. Spectrally selective coating of nanoparticles (Co3O4) incorporated in carbon to captivate solar energy. *Heat Transfer*. 2020;49(3):1386–1401. doi: 10.1002/htj.21668.
42. Ahmed A, et al. Modification of poly(vinyl chloride) thin films with organic compound and nanoparticles for solar energy applications. *J Polym Res*. 2023;30(7):274. doi: 10.1007/s10965-023-03654-1.
43. Bosu I, Mahmoud H, Ookawara S, Hassan H. Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: a comprehensive review. *Sol Energy*. 2023;259:188–228.
44. Cannavale A, Ayr U, Fiorito F, Martellotta F. Smart electrochromic windows to enhance building energy efficiency and visual comfort. *Energies (Basel)*. 2020;13(6):1449. doi: 10.3390/en13061449.
45. Al-Yasiri Q, Szabó M. Incorporation of phase change materials into building envelope for thermal comfort and energy saving: a comprehensive analysis. *J Build Eng*. 2021;33:101554. doi: 10.1016/j.jobe.2020.101554.
46. Zhang F, de Dear R, Hancock P. Effects of moderate thermal environments on cognitive performance: a multidisciplinary review. *Appl Energy*. 2019;236:760–777. doi: 10.1016/j.apenergy.2018.12.005.
47. Huang L, Kang J. Thermal comfort in winter incorporating solar radiation effects at high altitudes and performance of improved passive solar design: case of Lhasa. *Build Simul*. 2021;14(6):1633–1650. doi: 10.1007/s12273-020-0743-x.
48. Passos LA, van den Engel P, Baldi S, De Schutter B. Dynamic optimization for minimal HVAC demand with latent heat storage, heat recovery, natural ventilation, and solar shadings. *Energy Convers Manag*. 2023;276:116573. doi: 10.1016/j.enconman.2022.116573.
49. Rizi RA, Eltaweel A. A user detective adaptive facade towards improving visual and thermal comfort. *J Build Eng*. 2021;33:101554. doi: 10.1016/j.jobe.2020.101554.
50. Abed RN, et al. Optical and morphological properties of poly(vinyl chloride)-nano-chitosan composites doped with TiO2 and Cr2O3 nanoparticles and their potential for solar energy applications. *Chem Pap*. 2023;77(2):757–769. doi: 10.1007/s11696-022-02512-6.
51. Osman AI, et al. Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ Chem Lett*. 2022;21(2):741–764. doi: 10.1007/s10311-022-01532-8.
52. Razmjoo A, Kaigutha LG, Rad MAV, Marzband M, Davarpanah A, Denai M. A technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO2 emissions in a high potential area. *Renew Energy*. 2021;164:46–57. doi: 10.1016/j.renene.2020.09.042.
53. Hoang AT, Pham VV, Nguyen XP. Integrating renewable sources into energy systems for smart cities as a sagacious strategy towards clean and sustainable processes. *J Clean Prod*. 2021;305:127161. doi: 10.1016/j.jclepro.2021.127161.
54. Irfan M, Elavarasan RM, Hao Y, Feng M, Sailan D. An assessment of consumers' willingness to utilize solar energy in China: end-users' perspective. *J Clean Prod*. 2021;292:126008. doi: 10.1016/j.jclepro.2021.126008.
55. Lee J, Shepley MMC. Benefits of solar photovoltaic systems for low-income families in social housing of Korea: renewable energy applications as solutions to energy poverty. *J Build Eng*. 2020;28:101016. doi: 10.1016/j.jobe.2019.101016.
56. Rabbi MF, Popp J, Máté D, Kovács S. Energy security and energy transition to achieve carbon neutrality. *Energies*. 2022;15(21):8126. doi: 10.3390/en15218126.
57. Hashim WM, Shomran AT, Jurmut HA, Gaaz TS, Kadhum AAH, Al-Amiery AAA. Case study on solar water heating for flat plate collector. *Case Stud Therm Eng*. 2018;12:666–671.
58. Mutezo G, Mulopo J. A review of Africa's transition from fossil fuels to renewable energy using circular economy principles. *Renew Sustain Energy Rev*. 2021;137:110609. doi: 10.1016/j.rser.2020.110609.
59. Chang KC, et al. Standalone and minigrid-connected solar energy systems for rural application in Rwanda: an in situ study. *Int J Photoenergy*. 2021;19(3):1–22. doi: 10.1155/2021/1211953.
60. Wacker M, Holick MF. Sunlight and Vitamin D: a global perspective for health. *Dermatoendocrinol*. 2013;5(1):51–108. doi: 10.4161/derm.24494.
61. Grant WB, Bhattoa HP, Pludowski P. Determinants of Vitamin D deficiency from sun exposure: a global perspective. In: Vitamin D: Health, Disease and Therapeutics. 4th ed. Vol 2. Elsevier; 2017:79–90. doi: 10.1016/B978-0-12-809963-6.00061-4.
62. Olds W. Elucidating the links between UV radiation and vitamin D synthesis: Using an in vitro model. In Vitro. 2009.
63. Moghaddam SA, Mattsson M, Ameen A, Akander J, Gameiro Da Silva M, Simões N. Low-emissivity window films as an energy retrofit option for a historical stone building in cold climates. *Energies (Basel)*. 2021;14(22):7584. doi: 10.3390/en14227584.
64. Pierucci A, Cannavale A, Martellotta F, Fiorito F. Smart windows for carbon neutral buildings: a life cycle approach. *Energy Build*. 2018;165:160–171. doi: 10.1016/j.enbuild.2018.01.021.
65. Jia LR, Li QY, Yang J, Han J, Lee CC, Chen JH. Investigation of the energy-saving potential of buildings with radiative roofs and low-E windows in China. *Sustainability (Switzerland)*. 2024;16(1):148. doi: 10.3390/su16010148.
66. deRichter R, Caillol S. Fighting global warming: The potential of photocatalysis against CO2, CH4, N2O, CFCs, tropospheric O3, BC, and other major contributors to climate change. *J Photochem Photobiol C Photochem Rev*. 2011;12:1–19. doi: 10.1016/j.jphotochemrev.2011.05.002.
67. Patz JA, Frumkin H, Holloway T, Vimont DJ, Haines A. Climate change: challenges and opportunities for global health. *JAMA*. 2014;312(15):1565–1580. doi: 10.1001/jama.2014.13186.

68. Fayad MA, Chaichan MT, Dhahad HA, Al-Amiery AAA, Isahak WNRW. Reducing the effect of high sulfur content in diesel fuel on NOx emissions and PM characteristics using a PPCI mode engine and gasoline-diesel blends. *ACS Omega*. 2022;7(42):37328–37339. doi: 10.1021/acsomega.2c03878.
69. Somasundaram S, Thangavelu SR, Chong A. Improving building efficiency using low-e coating-based retrofit double glazing with solar films. *Appl Therm Eng*. 2020;171:115064. doi: 10.1016/j.applthermaleng.2020.115064.
70. Rony MKK, Alamgir HM. High temperatures on mental health: Recognizing the association and the need for proactive strategies—A perspective. *Health Sci Rep*. 2023;6(12):1729. doi: 10.1002/hsr2.1729.
71. Corvalan C, et al. Towards climate-resilient and environmentally sustainable health care facilities. *Int J Environ Res Public Health*. 2020;17(23):8849. doi: 10.3390/ijerph17238849.
72. Razzaq I, et al. Reduction in energy consumption and CO2 emissions by retrofitting an existing building to a net-zero energy building for the implementation of SDGs 7 and 13. *Front Environ Sci*. 2023;10:1028793. doi: 10.3389/fenvs.2022.1028793.
73. Fei L, He Z, LaCoste JD, Nguyen TH, Sun Y. A mini review on superhydrophobic and transparent surfaces. *Adv Mater Interfaces*. 2020;7(20):2075. doi: 10.1002/tcr.202000075.
74. Garlisi C, et al. Multilayer thin film structures for multifunctional glass: self-cleaning, antireflective, and energy-saving properties. *Appl Energy*. 2020;114697. doi: 10.1016/j.apenergy.2020.114697.
75. Li DJ, Gu ZG, Zhang J. Auto-controlled fabrication of a metal-porphyrin framework thin film with tunable optical limiting effects. *Chem Sci*. 2020;11(7):1935–1942. doi: 10.1039/c9sc05881h.
76. Wang J, Shi D. Spectral selective and photothermal nanostructured thin films for energy-efficient windows. *Appl Energy*. 2017;209:466–474. doi: 10.1016/j.apenergy.2017.10.066.
77. An Introduction to Solar Radiation. Elsevier; 1983. doi: 10.1016/b978-0-12-373750-2.x5001-0.
78. Stewart SM, Johnson RB. Blackbody Radiation: A History of Thermal Radiation, Computational Aids, and Numerical Methods. CRC Press; 2016. doi: 10.1201/9781315372082.
79. Almutawa F, Vandal R, Wang SQ, Lim HW. Current status of photoprotection by window glass, automobile glass, window films, and sunglasses. *Photodermatol Photoimmunol Photomed*. 2013;29(2):65–72. doi: 10.1111/phpp.12022.
80. Gorgolis G, Karamanis D. Solar energy materials for glazing technologies. *Sol Energy Mater Sol Cells*. 2016;157:134–147. doi: 10.1016/j.solmat.2015.09.040.
81. Alghamdi S, Tang W, Kanjanabootra S, Alterman D. Effect of architectural building design parameters on thermal comfort and energy consumption in higher education buildings. *Buildings*. 2022;12(3):329. doi: 10.3390/buildings12030329.
82. Hutchins MG. Spectrally selective materials for efficient visible, solar, and thermal radiation control. In: Solar Thermal Technologies for Buildings: The State of the Art. CRC Press; 2014:37–64. doi: 10.4324/9781315074467.
83. Kamalisarvestani M, Saidur R, Mekhilef S, Javadi FS. Performance, materials, and coating technologies of thermochromic thin films on smart windows. *Renew Sustain Energy Rev*. 2013;26:353–364. doi: 10.1016/j.rser.2013.05.038.
84. Mohelnikova J. Materials for reflective coatings of window glass applications. *Constr Build Mater*. 2009;23(5):1993–1998. doi: 10.1016/j.conbuildmat.2008.08.033.
85. MacLeod BP, et al. Self-driving laboratory for accelerated discovery of thin-film materials. *Sci Adv*. 2020;6(20):1–8. doi: 10.1126/sciadv.aaz8867.
86. Kapsis K, Athienitis A, Harrison S. Determination of solar heat gain coefficients for semitransparent photovoltaic windows: an experimental study. *ASHRAE Trans*. 2017;123: 82–94.
87. Park K, Jin S, Kim G. Transparent window film with embedded nano-shades for thermoregulation. *Constr Build Mater*. 2021;269:121280. doi: 10.1016/j.conbuildmat.2020.121280.
88. Liu J, Wöll C. Surface-supported metal-organic framework thin films: fabrication methods, applications, and challenges. *Chem Soc Rev*. 2017;46(11):5730–5770. doi: 10.1039/c7cs00315c.
89. Kanu SS, Binions R. Thin films for solar control applications. *Proc R Soc A Math Phys Eng Sci*. 2010;466(2120):19–44. doi: 10.1098/rspa.2009.0259.
90. Hui SCM, Kwok MK. Study of thin films to enhance window performance in buildings. In: Proceedings of the Sichuan-Hong Kong Joint Symposium; 2006:158–167.
91. Santos AJ, Martin N, Outón J, Blanco E, García R, Morales FM. A simple two-step approach to the fabrication of VO2-based coatings with unique thermochromic features for energy-efficient smart glazing. *Energy Build*. 2023;285:112892. doi: 10.1016/j.enbuild.2023.112892.
92. Sampers J. Importance of weathering factors other than UV radiation and temperature in outdoor exposure. *Polym Degrad Stab*. 2002;76(3):455–465. doi: 10.1016/S0141-3910(02)00049-6.
93. Boye C, Preusser F, Schaeffer T. UV-blocking window films for use in museums–revisited. *WAAC Newsletter*. 2010;32(1):13–18.
94. Amirkhani S, Bahadori-Jahromi A, Mylona A, Godfrey P, Cook D. Impact of Low-E window films on energy consumption and CO2 emissions of an existing UK hotel building. *Sustainability (Switzerland)*. 2019;11(16):4265. doi: 10.3390/su11164265.
95. Teixeira H, Gomes MG, Rodrigues AM, Pereira J. Thermal and visual comfort, energy use, and environmental performance of glazing systems with solar control films. *Build Environ*. 2020;168:106474. doi: 10.1016/j.buildenv.2019.106474.
96. Sedaghat A, et al. Effects of window films on thermo-solar properties of office buildings in hot-arid climates. *Front Energy Res*. 2021;9:665978. doi: 10.3389/fenrg.2021.665978.