# Adaptive Greenhouse with Thermochromic Material: Performance Evaluation in Cold Regions

Jianying Hu[1] and Xiong Yu, M.ASCE[2]

**Abstract:** The intensive energy requirement is a major challenge for greenhouse producers, especially those located in cold regions. An adaptive greenhouse with thermochromic (TC) material has the potential to intelligently regulate solar radiation gain of the greenhouse in response to the outdoor environment, therefore abating energy demand of the greenhouse. This study evaluates the energy performance of an adaptive greenhouse with covering materials (TC glazing, TC film, TC film–TC glazing). The simulation results reveal that compared with normal glass, energy savings reaches up to 5%, 6%, and 13% with the application of TC glazing, TC film, and TC film–TC glazing to the greenhouse, respectively; the energy cost is correspondingly reduced by 7%, 17%, and 22% respectively; and the $CO_2$ emission is reduced by 6%, 14%, and 20%, respectively. In comparison with low-emissivity glass, the total energy saving of the greenhouse reaches up to 3%, 3%, and 11% by employing TC glazing, TC film, and TC film–TC glazing, respectively. Moreover, the increase in envelope thickness increases energy efficiency of the adaptive greenhouse to 17%. TC film–TC glazing is recommended for use in heating energy–dominated scenarios. This research framework allows designers to optimize overall energy performance of the proposed adaptive greenhouse for different climates.
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**Author keywords:** Adaptive greenhouse; Thermochromic material; Energy saving; Energy cost; $CO_2$ emission.

## Introduction

In 2003, Canada was the largest export market for US fresh vegetables, absorbing more than 80% of US exports in this product category (Cook and Calvin 2005). In recent years, the growth of the greenhouse industry in Canada has changed net trade flows of fresh vegetables between Canada and the United States. Canada produces and exports fresh vegetables, such as peppers, tomatoes, lettuce, and cucumbers, by operating sophisticated greenhouses. Currently, large, new greenhouses are operating in cold climate regions of the United States, such as Michigan and Ohio. Greenhouses provide a protected growing environment for plants in cold regions and have become a promising approach to increase food production. However, greenhouses consume large amounts of energy by creating a controlled environment where temperature, lighting, ventilation, and humidity are regulated so that plants can grow out of season. Of the total energy consumed, the heating energy demand represents 70%–80% of total greenhouse energy demand (Cuce et al. 2016), and even up to 85% for northern climates owing to the long winter season (Runkle and Both 2011). Heating energy is mostly provided by the combustion of fossil fuels and therefore contributes to global warming and environmental degradation. Thus, the green-house sector faces major challenges to reduce its energy consumption while maintaining product quality and quantity.

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Many efforts have been made to address energy-related challenges by tailoring thermo-optical properties of greenhouse covering materials or introducing new, innovative materials and designs. These efforts are categorized into three themes: (1) modulating thermal behaviors of covering materials, e.g., by using polycarbonate with advanced thermal insulation characteristics (Fabrizio 2012) and heat insulation solar glass (Cuce et al. 2015); (2) controlling optical properties of covering materials, e.g., with antireflective coating for transmission (Rosencrantz et al. 2005), low-emissivity coatings (Halleux et al. 1985), near-infrared (NIR) reflecting films with inorganic particles (e.g., $TiO_2$, $SiO_2$) (Liu et al. 2018; Emekli et al. 2016; Kavga et al. 2018; Kempkes and Hemming 2012), photoselective films (Kittas et al. 1999; Li et al. 2000; Oyaert et al. 1999; Cerny et al. 2003), or ultraviolet (UV)-blocking films (Kittas et al. 2006; Tsormpatsidis et al. 2008); and (3) integrating with alternative energy sources to improve energy efficiency of the greenhouse (Hassanien et al. 2018; Yildirim and Bilir 2017; Sonneveld et al. 2010). Despite their promise, alternative energy sources are not infallible and there are some obstacles preventing the full implementation of alternative energy sources, especially related to policy (Paço and Varejão 2010). Other greenhouses with improved thermal and optical properties are based on static designs that cannot adapt or react to changes in their surroundings. Thus, development of an adaptive greenhouse with responsive thermo-optical properties is critical to lessen greenhouse energy demand.

The adaptive greenhouse represents a new concept to improve the performance of greenhouses. It is capable of varying its thermo-optical properties in response to external stimuli (Favoino et al. 2015). This technology can be achieved by employing a chromogenic, i.e., thermochromic (TC) material. TC material is a type of smart material that is capable of reversibly varying its colors and optical properties in response to temperature variation. The greenhouse integrated with TC material enables the modulation of solar heat gains according to the outdoor environment, i.e., the higher the incident solar radiation, the higher the temperature of TC, and thus the higher the solar reflectance of the adaptive greenhouse, and vice versa (Bamfield and Hutchings 2010). Karlessi et al. (2009) have developed 11 TC coatings by incorporating organic TC pigment into polymer matrix, achieving a maximum solar reflectance of 43% at the colorless phase. Experimental evaluation showed that TC coatings are 6°C–10°C cooler than the conventional colored coatings in summer. The authors proposed to apply TC coating into the roof system and found that energy saving of the building is up to 41% and $CO_2$ emission is reduced by up to 47% compared to traditional building (Hu and Yu 2019). An innovative window system, namely TC glazing, is designed by depositing TC thin film onto conventional glazing. Studies have revealed that TC glazing has the potential to reduce overall energy demand in buildings by allowing visible light for day lighting, reducing undesired solar gain during the cooling season, while allowing useful solar gain during the heating season (Hoffmann et al. 2014; Warwick et al. 2014; Saeli et al. 2010b; Liang et al. 2018). Ye et al. (2013) reported that the use of TC glazing in an office leads to a reduction in cooling load by 10%–20% compared with traditional clear glazing. TC glazing was also found to reduce building energy consumption in warmer climates more than in cooler regions (Saeli et al. 2010a, b). However, limited study has been devoted to energy performance of adaptive greenhouses with both thermochromic coating and thermochromic glazing in cold regions.

This study aims to investigate energy performance of adaptive greenhouses with TC film/TC glazing through building energy simulation, compared with with normal glass and low-emissivity (low-E) glass. A special focus of the analysis compares energy performance of greenhouses in Canada (Ottawa, Ontario) and in the United States (Cleveland, Ohio). TC film is first fabricated and characterized using an optical spectrophotometer at different temperatures. Based on the measured optical reflectance, energy analysis of the greenhouse is implemented in EnergyPlus, evaluating annual heating and cooling loads. Then, energy-associated cost and $CO_2$ emission of adaptive greenhouse have been analyzed. Finally, the influence of thickness of covering materials on energy performance of the adaptive greenhouse is also assessed. The analysis is expected to provide a reference for the feasibility and design of an adaptive greenhouse with thermochromic material.

## Methodology

### Fabrication of Thermochromic Film

TC film in this study is fabricated by incorporating TC pigment powder into PVC through hot-pressing technique. TC pigment exhibits dark blue color below the transition temperature of around 31°C, and light blue color above the transition temperature. The chemical and physical properties of blue thermochromic pigment are described in previous studies (Hu and Yu 2013; Hu et al. 2015). The typical process to formulate TC film is illustrated in Fig. 1(a). As shown in Fig. 1(a), PVC powder was first mixed with 5% thermochromic pigment powders thoroughly in a ball mill for approximate 5 min. Next, the uniform distributed powder mixture was placed between two substrates and sandwiched between two hot parallel plates. The plates were preheated to 200°C before loading the samples. Then, the stack was kept at 200°C for 10 min and subsequently pressed under 5 MPa for 5 min. Finally, the film was formed and slowly cooled to ambient temperature. Pure PVC film without functional additives was prepared as the control sample.

### Design of Adaptive Greenhouse

The adaptive greenhouse is built with TC film or TC glazing. With the prepared TC film shown in Fig. 1(b), the reflectance spectra in the wavelength of 300–1,800 nm are characterized by a Cary 6000i UV–Vis–IR spectrophotometer (Cary 6000i, Aiglent Technologies, Santa Clara, California) with a diffuse reflectance accessory (DRA) integrating sphere. Fig. 1(c) displays the reflectance spectra of TC film at different temperatures. It is observed that TC film presents high solar reflectance, especially in the infrared range of the spectrum. The reflectance spectrum is changed in the visible range, which is ascribed to the color change of the TC material. Based on the spectral reflectance data, solar reflectance of each sample is calculated using weighted-averaging method (ASTM 2000). It is found that as temperature rises, the total reflectance of TC film increases from 15% to 20% and the reflectance in the visible portion of the spectrum increases from 4% to 16%. The input data, solar absorptance, is calculated by one minus solar reflectance and the expression of solar absorptance as a function of temperature is obtained by linear fitting method, summarized in Table 1.

To further improve energy efficiency of the building, TC glazing is also implemented. The optical data of TC glazing is directly taken from EnergyPlus, as shown in Fig. 2. As shown in this figure, as temperature rises, solar reflectance of TC glazing gradually drops, while solar transmittance of TC glazing decreases drastically. Taking the temperatures at 25°C and 85°C, for example, solar reflectance and transmittance of TC glazing at 25°C is respectively 6.5%, and 63%; while at 85°C, the corresponding values are 5.5% and 37%, respectively. In contrast to the TC roof, TC glazing mainly regulates solar transmittance.

The use of both TC roof and TC glazing is proposed for the greenhouse, which is shown in Fig. 3. In theory, with the characteristics of thermochromic material, both TC roof and TC glazing intelligently regulate the solar energy when triggered by environmental temperature: during the winter season, TC film is less infrared-reflective, and simultaneously TC glazing transmits more solar radiation; during the summer season, TC film reflects more solar energy and TC glazing prevents transmission of sunlight. The ability to modulate solar radiation in response to the outdoor environment suggests the potential for TC film and TC glazing to have excellent energy performance.

### Building Energy Simulation

Energy simulations of greenhouses are performed using EnergyPlus 8.9, which is a capable and validated whole-building energy simulation program for modeling thermal and electrical loads of buildings. EnergyPlus models are defined by building geometry, envelope characteristics, mechanical system characteristics, lighting system, occupancy, and HVAC setpoint schedules. The program has been extensively validated with analytical, comparative, and empirical tests available on the US DOE website (ANSI/ASHRAE 2002).

A single slope greenhouse with dimensions of $40 \times 10 \times 6$ m ($400\text{-m}^2$ floor area) is designed, as shown in Fig. 4. For this analysis, five types of greenhouse covering materials have been considered: TC film, TC glazing, TC film–TC glazing, low-E glass, and normal glass, in which TC film–TC glazing consists of TC film as the roof and TC glazing as the wall. The thermal characteristics of used covering materials are given in Table 2. Table 3 illustrates optical properties of normal glass and low-E glass. The temperature-dependent optical data of TC film, as illustrated in Table 1, are input through Energy Management System (EMS) in EnergyPlus.

Internal loads and schedules are set up as follows. The lighting load in the building is taken to be $105\ \mathrm{W/m^2}$, which is scheduled for the whole day. The HVAC system consists of natural gas for heating and central electric air-conditioning unit for cooling. The suggested temperatures for controlling the heating mode and cooling mode are 18°C and 25°C, respectively, and the value for relative humidity is set to 80% (Both 2004). All cooling and heating

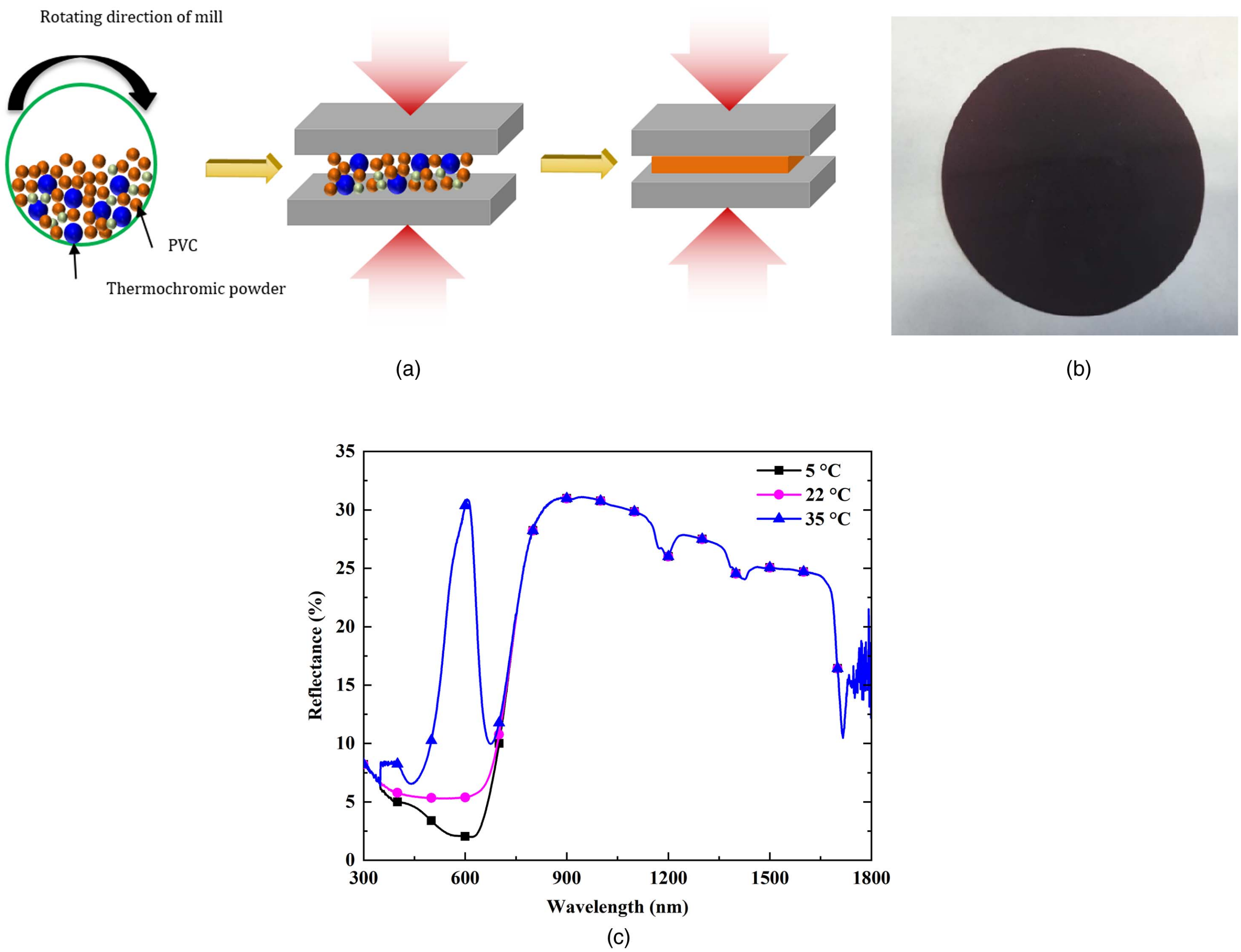


**Fig. 1.** TC film: (a) schematic illustration of hot-pressing technique; (b) photo of the sample; and (c) reflectance spectra at different temperatures.

**Table 1.** Optical properties of TC film in this study

| Façade material | Solar absorptance | Visible absorptance |
|---|---|---|
| TC film | $\begin{cases} 0.82, & T \leq 0°C; \\ 0.8449 - 0.00274T, & 0°C < T < 40°C \\ 0.74, & T \geq 40°C \end{cases}$ | $\begin{cases} 0.94, & T \leq 0°C; \\ 0.9927 - 0.0062T, & 0°C < T < 40°C \\ 0.75, & T \geq 40°C \end{cases}$ |

Note: T = temperature of TC film.

capacities are autosized to design day conditions corresponding with American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) climate zones. Time step of the simulation is set to 10 min. All simulations are run for 1 year.

### *Climate Conditions*

Energy simulation analysis is performed for two cities located in cold climate zones: Cleveland, Ohio and Ottawa, Ontario. The standard typical meteorological year (TMY) weather files of both cities taken from EnergyPlus weather data are used for the simulation. Fig. 5 shows the monthly statistics for the evolution of the dry bulb temperatures in Cleveland and Ottawa. It is obvious that in Cleveland, the warmest month on average is July, with an average temperature of 24.0°C and maximum temperature of 28.3°C, and the coldest month on average is February, with an average temperature of −3.5°C and the minimum temperature of −5.5°C. In Ottawa, the warmest month is July, with an average temperature of 20.3°C and maximum temperature of 24.3°C, and the coldest month on average is January, with an average temperature of −11.5°C and the minimum temperature of −13.4°C. Compared with Cleveland, Ottawa has lower temperature and longer winter season.

## Results and Discussion

### *Annual Heating and Cooling Energy Consumptions*

Fig. 6 illustrates the cumulative heating and cooling loads in 1 year with different covering materials of greenhouses. Fig. 6(a) summarizes the annual cooling loads for the greenhouse with five types of

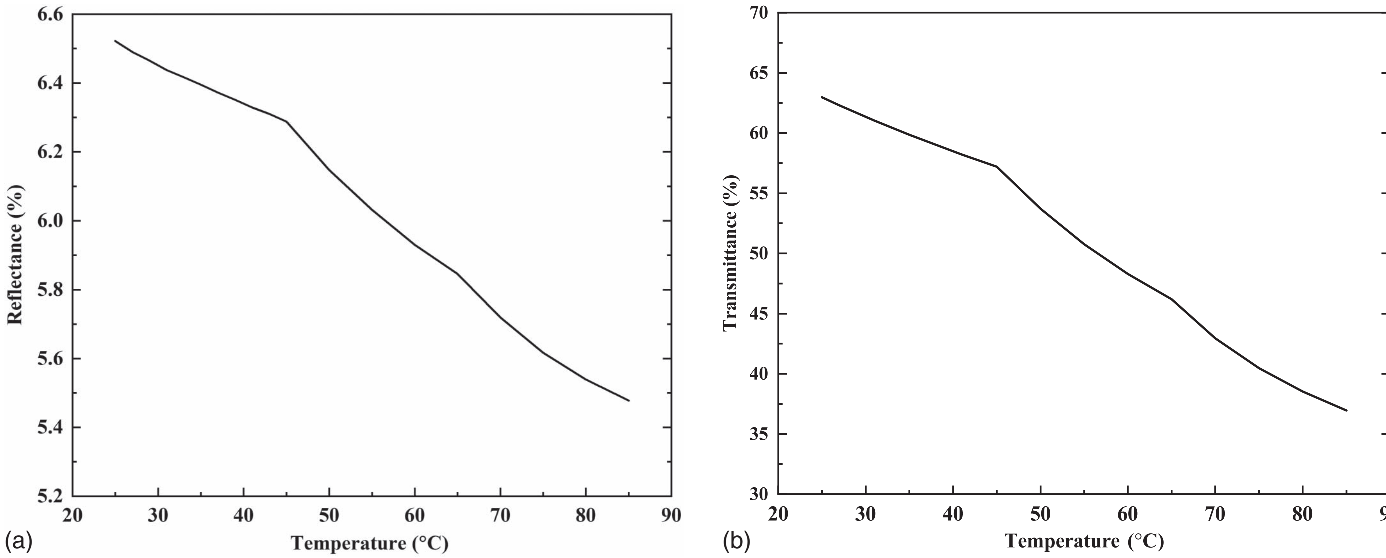


**Fig. 2.** Temperature-dependent optical data of TC glazing: (a) solar reflectance; and (b) solar transmittance.

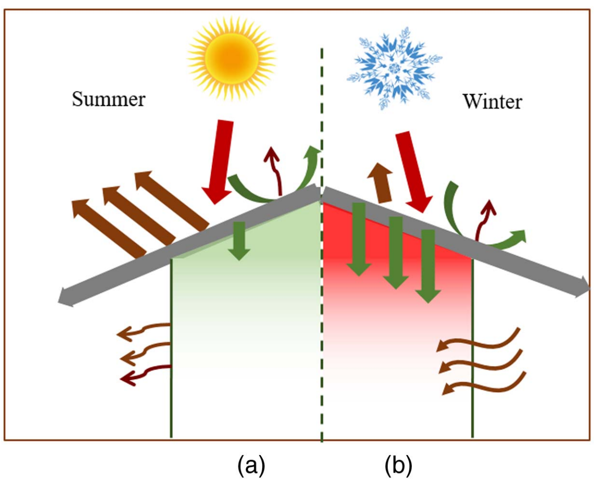


**Fig. 3.** Schematic principle of the greenhouse with TC film and TC glazing: (a) during summer or cooling season; and (b) during winter or heating season.

**Fig. 4.** Greenhouse configuration considered in the modeling.

**Table 2.** Properties of greenhouse covering materials used for energy simulation

| Covering material | Thickness (mm) | Conductivity (W/m · K) | Density (kg/m$^3$) | Specific heat (J/kg · K) | Emissivity |
|---|---|---|---|---|---|
| Normal glass | 3 or 10 | 0.90 | — | — | 0.84 |
| Low-E glass | 3 or 10 | 0.90 | — | — | 0.10 |
| TC glazing | 3 or 10 | 0.90 | — | — | 0.84 |
| TC film | 3 or 10 | 0.19 | 950 | 1,460 | 0.90 |

**Table 3.** Optical properties of investigated glazing

| Window property | Normal glass | Low-E glass |
|---|---|---|
| Solar transmittance at normal incidence | 0.85 | 0.63 |
| Front side solar reflectance at normal incidence | 0.08 | 0.19 |
| Back side solar reflectance at normal incidence | 0.04 | 0.22 |
| Visible transmittance at normal incidence | 0.88 | 0.85 |
| Front side visible reflectance at normal incidence | 0.085 | 0.056 |
| Back side visible reflectance at normal incidence | 0.045 | 0.079 |

covering materials in two sites. Compared with normal glass, low-E glass increases cooling energy demand by 3.9–4.4 kWh/m$^2$ with percentage of 4%–5%; TC glazing decreases cooling load by 6.6–7.7 kWh/m$^2$ (8%); TC film decreases cooling load by 31.5–32.4 kWh/m$^2$ (33%–37%); and TC film–TC glazing decreases cooling load by 28.8–31.9 kWh/m$^2$ with percentage of 32%–34%) for the greenhouse in two cities. Compared with low-E glass, the adoption of TC glazing, TC film, and TC film-TC glazing lowers the cooling load of the greenhouse by 11.0–11.6 kWh/m$^2$ (11%–12%), 35.9–36.3 kWh/m$^2$ (35%–41%), and 33.2–35.8 kWh/m$^2$ (35%–37%), respectively. The results reveal that TC film has the best performance in terms of cooling energy consumption, followed by TC film–TC glazing and TC glazing, while low-E glass has an adverse effect on cooling load of the greenhouse.

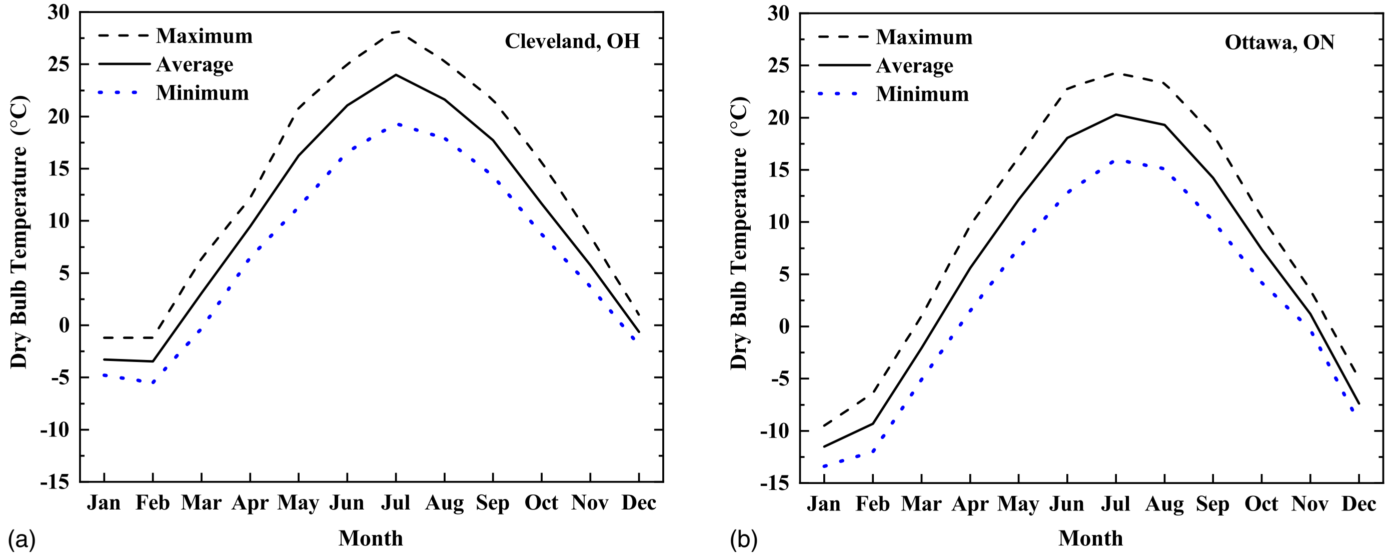


**Fig. 5.** Monthly statistics for the evolution of the dry bulb temperatures in: (a) Cleveland, Ohio; and (b) Ottawa, Ontario.

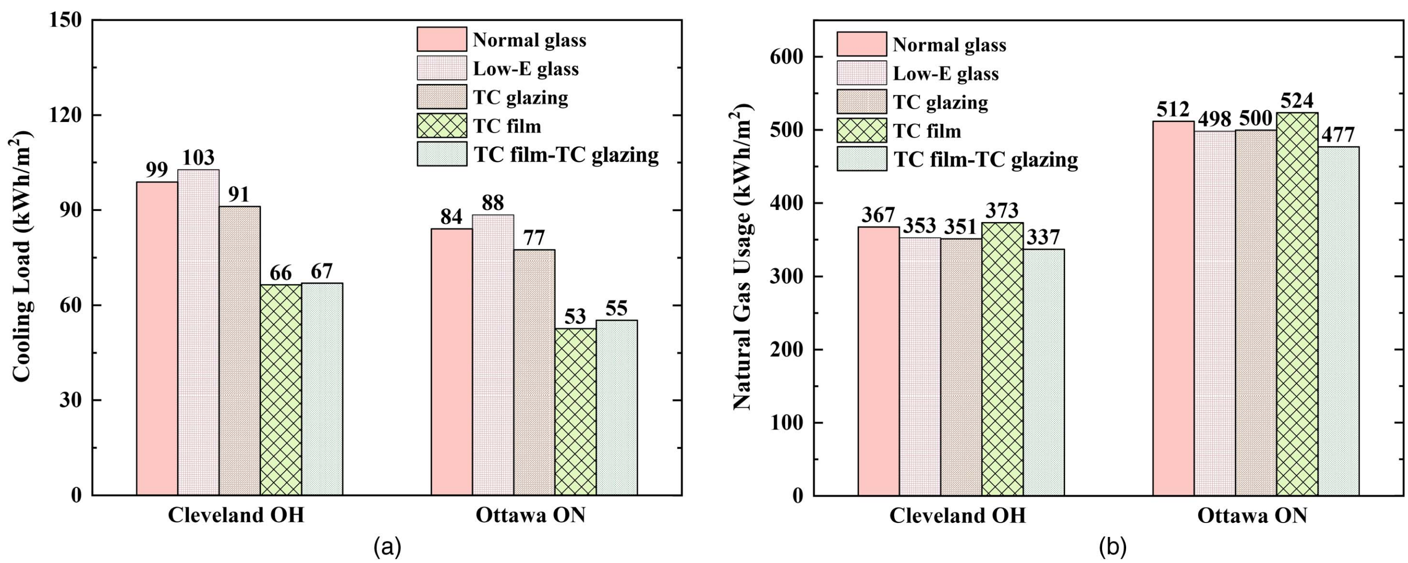


**Fig. 6.** Annual cooling load: (a) and heating load; and (b) for the greenhouse with various covering materials in two cities.

Fig. 6(b) displays the annual heating savings in $kWh/m^2$ for the greenhouse in Cleveland versus the greenhouse in Ottawa. It can be seen that compared with normal glass, the heating saving is 13.6–14.4 $kWh/m^2$ (3%–4%), 12.3–16.0 $kWh/m^2$ (2%–4%), and 30.4–35.2 $kWh/m^2$ (7%–8%) for the application of low-E glass, TC glazing, and TC film–TC glazing, respectively; while TC film causes slight heating energy penalty of 6.1–11.8 $kWh/m^2$ (2%). Compared with low-E glass, the use of TC glazing has negligible impact on heating load of the greenhouse, while the utilization of TC film increases heating load by 20.5–25.4 $kWh/m^2$ (5%–6%) and the application of TC film–TC glazing reduces heating load by 16.0–21.6 $kWh/m^2$ (4%–5%). Thus, in terms of heating energy consumption, TC film–TC glazing has the best performance, followed by TC glazing and low-E glass; while TC film causes insignificant heating load penalty. This might be ascribed to relatively low solar absorptance of TC film at low temperature and this is an area for further study.

Overall, low-E glass has a positive effect on heating energy load but a negative effect on cooling energy consumption of the greenhouse in cold regions. In contrast, TC film is effective in modulating cooling load but causes slight heating penalty. Both TC glazing and TC film–TC glazing show heating and cooling energy savings but TC film–TC glazing performs the best among various types of covering materials.

### *Monthly Energy Consumption*

Fig. 7 presents the monthly heating and cooling energy loads of the greenhouses with various covering materials in Cleveland. It is shown that the heating energy demand is mainly from October to April with a peak heating load in January while the cooling energy demand is typically from May to September, with a peak cooling load in July. Comparing Figs. 7(a and b), it is noticed that the use of low-E glass results in lower heating load by up to

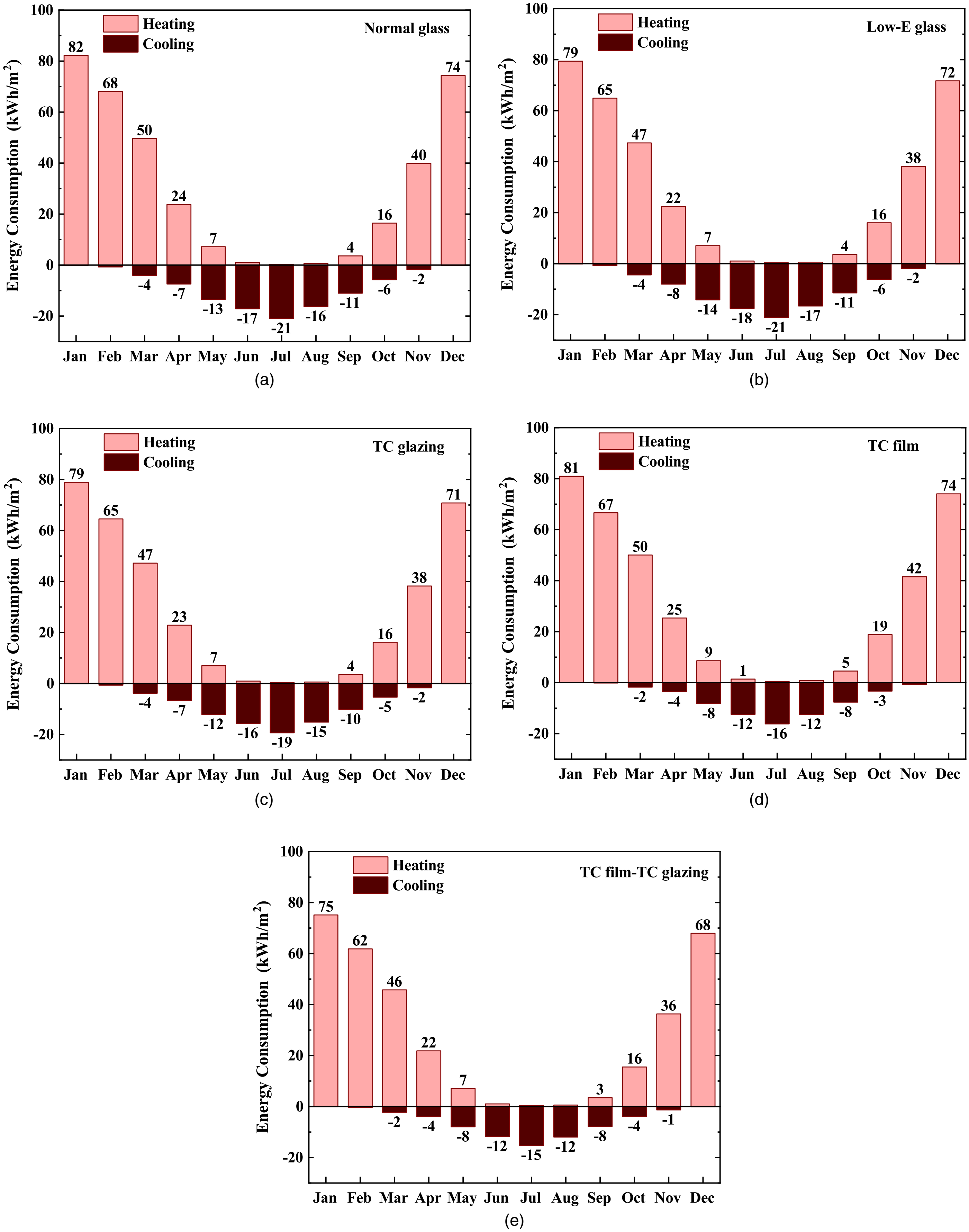


**Fig. 7.** Monthly heating and cooling requirements for greenhouses in Cleveland, Ohio: (a) normal glass; (b) low-E glass; (c) TC glazing; (d) TC film; and (e) TC film–TC glazing.

**Table 4.** Average electricity and natural gas prices in two cities

| City | Electricity ($/kWh) | Natural gas ($/m$^3$) |
|---|---|---|
| Cleveland, Ohio | 0.0996 | 0.2186 |
| Ottawa, Ontario | 0.0724 | 0.1082 |

3 kWh/m$^2$ during heating season. Fig. 7(c) demonstrates that TC glazing reduces both heating and cooling energy demands by up to 3 kWh/m$^2$ during extreme hot and cold period. As seen in Fig. 7(d), TC film exhibits considerable cooling energy savings of up to 5 kWh/m$^2$ during the cooling season. Fig. 7(e) shows that a monthly energy savings of up to 7 kWh/m$^2$ is achieved using the TC film–TC glazing system. The monthly energy consumption shows that the adaptive greenhouse with TC glazing and TC film–TC glazing exhibits a seasonal response in energy performance.

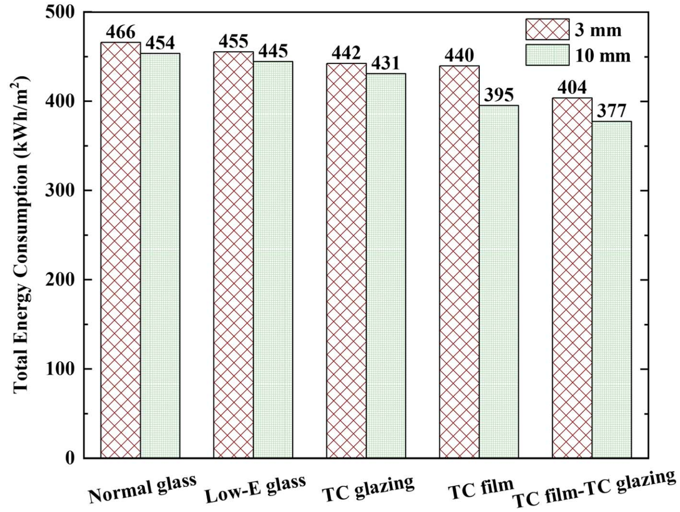


**Fig. 9.** Impact of envelope thickness on total energy loads of greenhouses with various covering materials in Cleveland, Ohio.

### Energy-Associated Cost and Equivalent Carbon Emission

The updated utility rates for electricity and natural gas were obtained from the US Energy Information Administration (EIA) and Ontario Energy Board for different locations, as summarized in Table 4. The energy-associated cost is the sum of electricity and natural gas expenditures. Energy-associated carbon dioxide emission is calculated by multiplying the $CO_2$ equivalent ($CO_{2eq}$) emission factors with electricity and natural gas loads. The taken $CO_2$ equivalent emission factors are 0.758 and 0.232 kg $CO_{2eq}$/kWh for electricity and natural gas, respectively (ANSI/ASHRAE/USGBC/IES 2010).

Fig. 8(a) presents the calculated energy costs per floor area of the greenhouse with all covering materials in two cities. It is apparent from the figure that similar to energy consumption, normal glass consumes maximum energy cost, followed by TC glazing, TC film, and TC film–TC glazing. Compared with normal glass, the energy-associated cost is negligibly affected by the use of low-E glass, while the energy cost is reduced by 0.9–1.1, 2.9–3.1, and 3.6–3.8 $/m$^2$ when employing low-E glass, TC glazing, TC film, and TC film–TC glazing in the greenhouse in two sites, respectively. Compared with low-E glass, the application of TC glazing, TC film, and TC film–TC glazing lowers the energy cost by approximately 1.2, 3.2, and 3.9 $/m$^2$, respectively. The results verify that the adaptive greenhouse requires lower energy cost than a conventional greenhouse. Furthermore, it is found that the greenhouse in Ottawa needs 1.6–1.8 $/m$^2$ greater energy cost.

Fig. 8(b) displays that carbon dioxide equivalent emission from the heating and cooling energy uses of greenhouses. Compared with normal glass, the $CO_2$ emission is reduced by 7–9, 21–23, and 30–31 kg/m$^2$ when using TC glazing, TC film, and TC film–TC glazing, respectively. Because both normal glass and low-E glass lead to similar carbon emission, the effect of the adaptive greenhouse on carbon emission stays the same compared with low-E glass. The $CO_2$ emission is highly related to energy demands, thus the lower energy use by TC film–TC glazing results in lower carbon emissions than other covering materials.

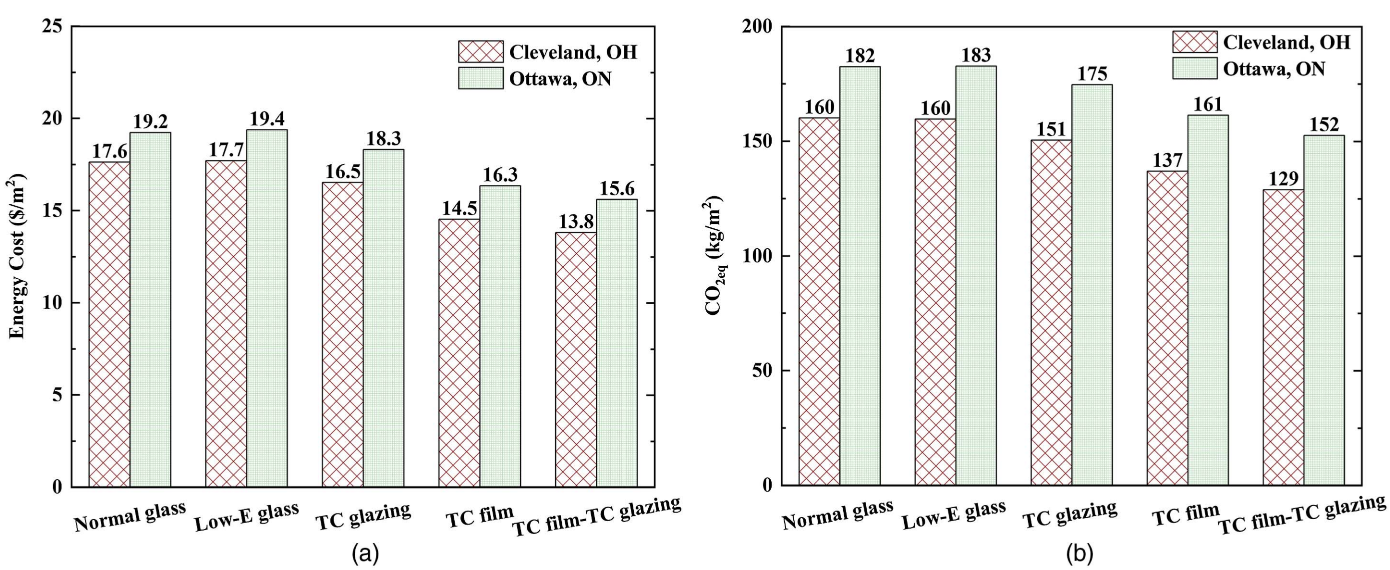


**Fig. 8.** Greenhouses with various covering materials in two cities: (a) energy-associated cost; and (b) equivalent carbon emission.

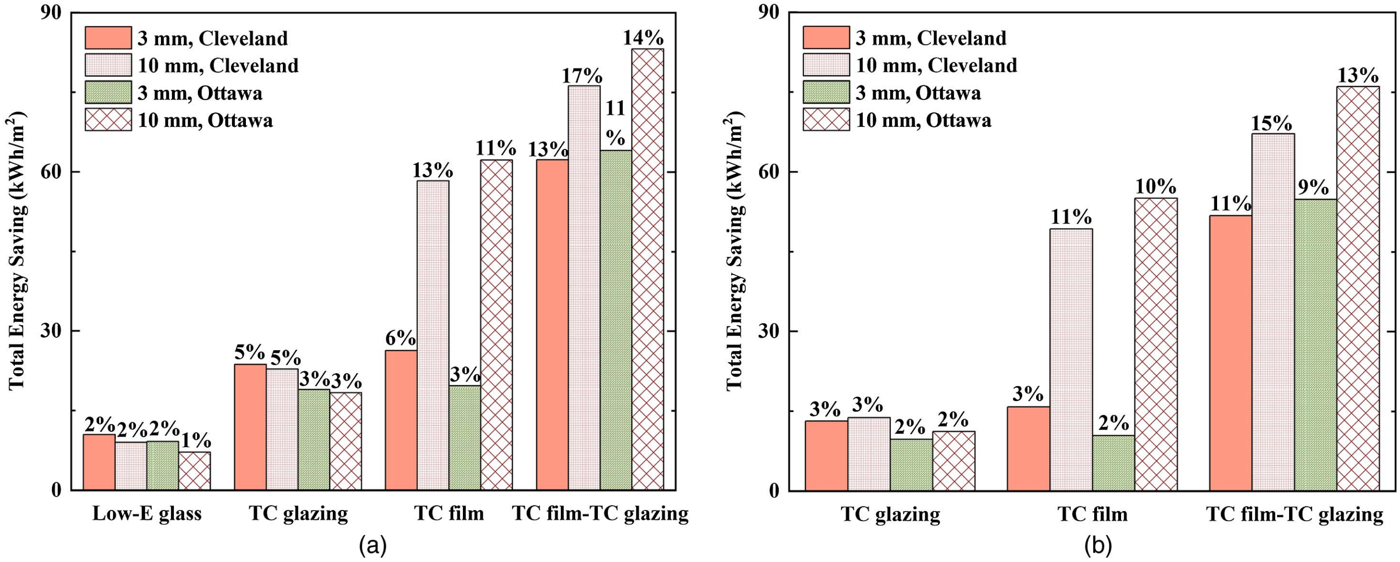


**Fig. 10.** Total energy savings with associated percentages: (a) compared with normal glass; and (b) compared with low-E glass.

### *Impact of Envelope Thickness*

In buildings, the envelope thickness has a negative correlation with the heat losses. Fig. 9 illustrates how thickness of covering materials affects total energy use of the greenhouse located in Cleveland. It can be seen that the increase of envelope thickness results in reduction of total energy consumption by 12 $kWh/m^2$ (3%), 10 $kWh/m^2$ (2%), 11 $kWh/m^2$ (3%), 45 $kWh/m^2$ (10%), and 37 $kWh/m^2$ (9%) for normal glass, low-E glass, TC glazing, TC film, and TC film–TC glazing, respectively. Therefore, the increase of envelope thickness has a positive influence on energy efficiency of the greenhouse, especially when using TC film.

### *Discussion*

A series of simulations was conducted to investigate energy performance of the greenhouse with various covering materials in cold regions. Fig. 10 summarizes the total energy savings of the adaptive greenhouse with various envelope thicknesses in two cities compared with normal glass and low-E glass. It is evident that all adaptive greenhouses show better energy efficiency in cold regions. As seen in Fig. 10(a), compared with normal glass, the total energy consumption of the greenhouse is reduced by 9.2–10.5 $kWh/m^2$ (2%), 19.0–23.4 $kWh/m^2$ (3%–5%), 19.7–26.3 $kWh/m^2$ (3%–6%), and 62.3–64.0 $kWh/m^2$ (11%–13%) when using 3-mm low-E glass, TC glazing, TC film, and TC film–TC glazing, respectively, in the two cities. The increase of envelope thickness is beneficial for TC film and TC film–TC glazing, which increases energy savings up to 58.3–62.2 $kWh/m^2$ (11%–13%) and 64.0–76.2 $kWh/m^2$ (14%–17%), respectively.

Fig. 10(b) shows the energy savings of adaptive greenhouses compared with low-E glass. It is evident that the total energy is decreased by 9.8–13.1 $kWh/m^2$ (2%–3%), 10.5–15.8 $kWh/m^2$ (2%–3%), and 54.8–51.8 $kWh/m^2$ (9%–11%) when using 3-mm TC glazing, TC film, and TC film–TC glazing, respectively, in the two cities. With the increasing envelope thickness, the energy savings of 11.2–13.8 $kWh/m^2$ (2%–3%), 49.3–55.0 $kWh/m^2$ (10%–11%), and 54.8–67.2 $kWh/m^2$ (13%–15%) is achieved by 10-mm TC glazing, TC film, and TC film–TC glazing, respectively. Overall, in terms of total energy use, TC film–TC glazing performs the best, which is more prominent in Ottawa than in Cleveland. Furthermore, the increase in thickness of greenhouse envelope leads to greater energy savings in the greenhouse.

Energy performance of the greenhouse depends on thermal and optical properties of covering materials as well as climate conditions. To enhance energy efficiency of the greenhouse with TC film, the following strategies might be further considered: (1) tailoring transition temperature and temperature-dependent optical properties of TC materials for various climate conditions, (2) improving thermal properties and thickness of TC film, and (3) integrating TC film with renewable energy technologies, such as thermal energy storage systems using phase change materials, ground-source heat pumps, and solar energy using photovoltaics.

## Conclusions

Greenhouses are large energy consumers. The present study analyzed the feasibility of adaptive greenhouse thermochromic material for energy efficiency improvement, particularly focusing on cold climates. The energy, environmental, and economic performance of the greenhouse with three types of covering materials (TC glazing, TC film, and TC film–TC glazing) is computationally investigated using EnergyPlus in cold regions and compared with that of normal glass and low-E glass. Moreover, the effect of envelope thickness on energy performance of greenhouses was also assessed. The main findings drawn from the analysis include:

1. For the greenhouse in cold regions, the application of TC glazing is effective in reducing cooling load by up to 8%, heating load by up to 4%, total energy consumption by up to 5%, energy-associated cost by up to 6% and $CO_2$ emission by up to 6% when compared with normal glass. When compared with low-E glass, the use of TC glazing results in cooling energy saving of 12%, total energy saving of 7% and reduction in $CO_2$ emission by 6%.
2. The application of TC film yields cooling energy saving of the greenhouse by 37%, heating energy penalty of 2%, total energy saving of 6%, cost saving of 17%, and reduction in $CO_2$ emission by 14% when compared with normal glass. In comparison with low-E glass, TC films yields a cooling energy saving of 40%, heating energy penalty of 5%, total energy saving of 3%, cost saving of 18%, and reduction in $CO_2$ emission by 12%.



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3. The adoption of TC film–TC glazing leads to 34% cooling energy savings, 8% heating energy savings, 13% total energy savings, 22% cost saving, and 20% less $CO_2$ emission when compared with normal glass. When compared with low-E glass, the application of TC film–TC glazing reduces cooling load by 37%, heating load by 4%, total energy use by 11%, cost by 22%, and $CO_2$ emission by 19%.
4. As envelope thickness increases from 10 to 30 mm, TC film and TC film–TC glazing increase energy efficiency of the greenhouse by up to 13% and 17%, respectively when compared with normal glass. With respect to low-E glass, the energy efficiency by 10-mm TC film and TC film–TC glazing is promoted to 11% and 15%, respectively.

In summary, the combined TC film–TC glazing shows the best performance compared with other greenhouse covering materials. It is verified that adaptive greenhouses with TC film–TC glazing has seasonal control over energy demands during both heating and cooling seasons, which is a distinct advantage over traditional greenhouses. Further work will focus on energy efficiency improvement of the adaptive greenhouse by tailoring transition temperature and temperature-dependent optical and thermal properties of thermochromic materials, as well as designing a hybrid system with an alternative energy source.

## Data Availability Statement

The data sets generated or analyzed in the current study are available from the corresponding author on reasonable request, including the model for energy analysis, the annual and monthly energy consumption, energy-associated cost, and equivalent carbon emission.


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