



MULTI-FUNCTIONAL RADIATIVE COOLING CURTAIN FABRIC WITH FLAME-RETARDANT AND SELF-CLEANING FUNCTIONS

Scientific paper
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ABSTRACT: Today, the development of functional curtain materials to promote building energy efficiency is highly demanded because of the effects of global warming and limits about natural sources. At this point, treating curtain materials with passive radiative cooling materials by different methods is valuable in thermal management of indoor environments. Besides thermal management performance, other functions such as self-cleaning and flame retardancy, which have been studied for longer periods, are crucial for building textile components. To address the mentioned requirements, a superhydrophobic passive cooling fabric was designed through a finishing treatment consisting of polyvinylidene fluoride (PVDF)-silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), and Al₂O₃@SiO₂ on a standard polyester curtain fabric. The required porous structure was enabled by solvent exchange phase separation method and a spray-dry procedure was used considering scalability and environmental concerns. Besides chemical and morphological analyses with FT-IR and SEM, passive cooling performance of the fabrics were determined indirectly by sphere-integrated FT-IR and UV-VIS spectrophotometers and directly by a designed hotplate system with a sun simulator. Results show that the nanocomposite treatments, especially the one including binary Al₂O₃@SiO₂ particles enabled a passive cooling performance up to 7.38°C compared to the raw fabric as a result of its enhanced solar reflectivity and infrared emissivity depending on the nanoparticles used and micro-nano multi-stage porous structure. Moreover, nanocomposite treated fabrics endow sufficient self-cleaning and flame-retardant performances as based on intrinsic characteristics of the nanocomposite materials. It can be concluded that, building textile components such as curtains can be functionalized as radiative passive coolers besides the garment systems to contribute economy and energy efficiency components of sustainability.

Keywords: Radiative cooling, curtain fabric, thermal management, energy efficiency.

VIŠENAMENSKA TKANINA ZA ZAVESE ZA RADIJACIJU SA FUNKCIJAMA OTPORNOSTI NA VATRA I SAMOČIŠĆENJA



APSTRAKT: Danas je razvoj funkcionalnih materijala za zavese radi promocije energetske efikasnosti zgrada veoma tražen zbog efekata globalnog zagrevanja i ograničenja prirodnih izvora. U ovom trenutku, tretiranje materijala za zavese pasivnim materijalima za zračenje različitim metodama je vredno u termičkom upravljanju unutrašnjim okruženjima. Pored performansi termičkog upravljanja, druge funkcije kao što su samočišćenje i otpornost na plamen, koje se proučavaju duže vreme, ključne su za tekstilne komponente zgrada. Da bi se zadovoljili pomenuti zahtevi, dizajnirana je superhidrofobna pasivna tkanina za hlađenje završnom obradom koja se sastoji od poliviniliden fluorida (PVDF)-silicijum dioksida (SiO_2), aluminijum oksida (Al_2O_3) i $\text{Al}_2\text{O}_3@\text{SiO}_2$ na standardnoj poliesterskoj tkanini za zavese. Potrebna porozna struktura je omogućena metodom fazne razdvojenosti izmenom rastvarača, a korišćen je postupak sušenja raspršivanjem uzimajući u obzir skalabilnost i ekološke probleme. Pored hemijskih i morfoloških analiza pomoću FT-IR i SEM, performanse pasivnog hlađenja tkanina su indirektno određene pomoću sferno integrisanih FT-IR i UV-VIS spektrofotometara i direktno pomoću dizajniranog sistema grejne ploče sa simulatorom sunca. Rezultati pokazuju da su nanokompozitni tretmani, posebno onaj koji uključuje binarne $\text{Al}_2\text{O}_3@\text{SiO}_2$ čestice, omogućili performanse pasivnog hlađenja do $7,38^\circ\text{C}$ u poređenju sa sirovim materijalom kao rezultat njegove poboljšane refleksivnosti sunčevog zračenja i infracrvene emisivnosti u zavisnosti od korišćenih nanočestica i mikro-nano višestepene porozne strukture. Štaviše, tkanine tretirane nanokompozitom imaju dovoljne performanse samočišćenja i usporavanja plamena na osnovu suštinskih karakteristika nanokompozitnih materijala. Može se zaključiti da se komponente građevinskog tekstila, kao što su zavese, mogu funkcionalizovati kao radijativni pasivni hladnjaci pored sistema odeće kako bi doprinele ekonomiji i energetske efikasnosti komponenti održivosti.

Ključne reči: Radijativno hlađenje, tkanina za zavese, upravljanje toplotom, energetska efikasnost.

1. INTRODUCTION

As heat stress triggered by global warming becomes a serious health issue threatening billions of people worldwide, the high energy consumption and greenhouse gas emissions of traditional air conditioning methods make the search for urgent solutions imperative for passive, energy-efficient thermal management solutions. According to annual reports, more than 30% of global final energy consumption used in buildings and also approximately 20% of global carbon emissions [1-4]. Therefore, passive thermal management systems that can reduce heat gain without external energy input have attracted considerable attention in recent years. Among these approaches, passive daytime radiative cooling (PDRC) has emerged as a promising strategy for building thermal management due to its ability to dissipate heat to outer space through the atmospheric transparency window (8-13 μm) while simultaneously minimizing solar heat absorption [5]. The main focus of PDRC materials for buildings is the fabrication of building envelope materials, exterior building coatings, wall, roof, greenhouse cover, and smart windows [6].



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Besides wearable applications, building textiles such as curtains, awnings, and shading systems have recently emerged as attractive candidates for passive cooling applications because they directly influence indoor solar heat gain and thermal comfort [7]. Curtain fabrics are particularly important due to their large surface area and direct exposure to solar radiation through windows. Curtain fabrics are particularly important due to their large surface area and direct exposure to solar radiation through windows. Functionalization of curtain textiles with radiative cooling materials can therefore contribute to building energy efficiency by reducing indoor heat accumulation. As interior elements that directly interact with incoming solar radiation, curtains can contribute significantly to reducing indoor thermal loads when designed with appropriate optical properties, namely high solar reflectance in the 0.3-2.5 μm range and high mid-infrared emissivity in the 8-13 μm atmospheric window. While recent studies have demonstrated the feasibility of passive radiative cooling in curtains [5], the application of such coatings specifically to curtain fabrics remains limited as compared with wearable cooling textiles, particularly when multifunctionality is considered. In one of the few studies about this subject, passive cooling curtain was developed by applying a porous SiO_2 /poly(vinylidene fluoride-hexafluoropropylene) composite coating onto the cotton by solvent exchange phase separation and sanding techniques. Although, an efficient outdoor cooling performance was obtained with an average of 10.3°C temperature drop as compared to the reference ones based on porous structure, low thermal conductivity, high solar reflectance and infrared emittance, flame-retardant capability has not been investigated [5]. On the other hand, additional functionalities such as flame retardancy and self-cleaning behavior are also essential for building textile applications in terms of safety, durability, and long-term performance preservation besides thermal management performance.

Among various radiative cooling materials, PVDF has attracted considerable attention owing to its intrinsic infrared emissivity, chemical stability, and processability for porous structure formation [8]. Furthermore, ceramic nanoparticles such as SiO_2 and Al_2O_3 are widely utilized to improve solar reflectance due to their strong light scattering capability and high refractive index contrast [9]. Especially, hierarchical porous structures combined with inorganic nanoparticles can enhance broadband Mie scattering across the solar spectrum while simultaneously increasing mid-infrared emission characteristics. Recent studies reported that binary or hybrid nanoparticle systems could generate synergistic optical effects, leading to improved passive cooling efficiency compared to single-particle systems [9].

In this study, multifunctional passive radiative cooling curtain fabrics were developed through porous PVDF-based nanocomposite coatings including SiO_2 , Al_2O_3 , and binary $\text{Al}_2\text{O}_3@/\text{SiO}_2$ nanoparticles using a solvent exchange phase separation and spray-coating method considering scalability and environmental concerns. In addition to passive cooling capability, flame-retardant and self-cleaning performances of the treated fabrics were also investigated to obtain multifunctional building textile materials suitable for practical applications.

2. MATERIALS and METHODS



2.1. Materials

A 100% polyester curtain fabric with a weight of 220 g/m² and a thickness of 0.4 mm, supplied by Berteks Tekstil (Bursa, Türkiye), was used as the substrate. For developing composite finishing treatment, PVDF (Kynar® 721, melting temperature: 168°C, glass transition temperature: -40°C) as matrix material, was kindly provided from Arkema, France. SiO₂ (12-23 nm) (Nanografi, Türkiye), Al₂O₃ (4 nm) (Nanografi, Türkiye) were used as nanofiller. To develop porous structure, binary solvents were N, N dimethyl acetamide (Sigma Aldrich, DMAc) and acetone (Acros Organics, ACE) and non-solvent component was deionized water used in solvent exchange phase separation method. Dispersion of nanoparticles in the polymer matrix was obtained with using non-ionic surfactant (sorbitan monostearate, Span60, Sigma Aldrich) during ultrasonic bath mixing.

2.2. Methods

2.2.1. Preparation of porous coated curtain fabrics

For developing heterogeneous porous nanocomposite structures on fabric surface by solvent exchange phase separation method, nanocomposite dispersions including SiO₂, Al₂O₃, and binary Al₂O₃@SiO₂ nanoparticles were sprayed on the fabric. Firstly, PVDF polymer chips at 10 wt. % were dissolved in a binary solvent system of DMAc and ACE (with a volume ratio of 1:1) at 50°C through mechanical stirring for 6 h. Subsequently, appropriate amounts of SiO₂, Al₂O₃, and binary Al₂O₃@SiO₂ (1:2 ratio) to get 2 wt. % particle content were sequentially added under continuous stirring, which was maintained for an additional 1 h. Also, non-ionic surfactant (Span60, with a particle/Span60 weight ratio of 1:2) was added into the dispersion to prevent particle agglomeration. To ensure homogeneous dispersion of the SiO₂, Al₂O₃, and binary Al₂O₃@SiO₂ nanoparticles within the PVDF polymer matrix, the solution underwent ultrasonication for 0.5 h. Subsequently, the prepared nanocomposite dispersions were applied onto the fabrics using a simple spraying system (Alfajet-W77S, Türkiye) at thickness of 200 µm. After 1 min, deionized water (50 mL) was sprayed on the coated surface and treated fabrics were dried at 20°C for 24 h. The obtained samples were coded as P_PVDF, P_SiO₂, P_Al₂O₃, and P_Al₂O₃@SiO₂, respectively.

2.2.2. Material characterization

The surface micro-morphology and porous structure of the raw and treated fabrics were characterized using scanning electron microscopy (SEM, ZEISS EVO LS10) at 250-1000 magnification. Chemical structures were determined using a Bruker VERTEX 70v Fourier transform infrared spectrometer (FT-IR) in ATR mode in the 400-4000 cm⁻¹ range, 2 cm⁻¹ resolution, and 16 scan at room temperature.

For determining spectral properties, reflectance ($\rho(\lambda)$) and transmittance ($\tau(\lambda)$) of the fabrics in the atmospheric window wavelength range (8-13 µm) were obtained using a FT-IR spectrometer (Bruker VERTEX 70v) having integrated sphere and the average emissivity values were calculated according to Equation (1) and Equation (2). According to Kirchhoff's Law, the spectral absorptivity is equal to emissivity when an object is in thermodynamic equilibrium.

$$\varepsilon(\lambda) = 1 - \rho(\lambda) - \tau(\lambda) \quad (1)$$

$$\bar{\varepsilon} = \frac{\int_{8\mu m}^{13\mu m} I_{BB}(\lambda, T) \varepsilon(\lambda) d\lambda}{\int_{8\mu m}^{13\mu m} I_{BB}(\lambda, T) d\lambda} \quad (2)$$

Also, the reflectance spectra of the fabrics in the sunlight band (0.3-2.5 μm) were recorded using a JASCO V-770 spectrophotometer equipped with an integrating sphere. The average solar reflectance was calculated according to Equations (3).

$$\rho_{solar} = \frac{\int_{0.3\mu m}^{2.5\mu m} I_{solar}(\lambda) \cdot \rho(\lambda) d\lambda}{\int_{0.3\mu m}^{2.5\mu m} I_{solar}(\lambda) d\lambda} \quad (3)$$

where ε : emissivity, ρ : reflection, τ : transmittance, and λ : wavelength, $I_{solar}(\lambda)$: global solar intensity spectrum according to ASTM G173, I_{BB} : spectral radiance of a blackbody defined by Planck's law at temperature T .

A custom-designed device including 8 K-type thermocouple sensor probes, a sun simulator halogen lamp, and a data acquisition system, was used to figure out passive radiative cooling performance under simulated indoor condition. After 1 min stabilizing period, temperature data was monitored with 10 s frequency and recorded precisely for 20 min lamp-on and lamp-off stages, respectively. The average temperature variation on the lower surface of the sample were determined by performing least three replications for each sample. All tests were carried out under 500 W/m² solar irradiance.

Flame retardant performance of the raw and treated fabric was determined using a BV AFC Auto flame-retardant test apparatus in accordance with standard AATCC 6941. During the test, the combustion phenomena during burning and post combustion morphology were recorded using a 12 s ignition duration by 40 mm flame height.

Self-cleaning performance of the coated fabrics were determined by solid contaminant removal test under ambient condition. Soil was uniformly distributed on the surfaces of the fabrics, which were fixed at a specific inclination for simulating contamination. Deionized water was then applied onto the contaminated area for rinsing surface. Also surface wettability of the samples were determined by depositing three liquids (methyl blue dye in water, water, and coffee) on the surface.

3. RESULTS

In this study, radiative cooling curtain fabrics with flame-retardant and self-cleaning functions, were designed to reduce indoor and outdoor heat exchange, thus achieving energy-saving in building thermal management from the perspective of curtains. These radiative cooling curtain fabrics with flame-retardant and self-cleaning functions were obtained with applying PVDF-SiO₂, Al₂O₃, and Al₂O₃@SiO₂ on a standard polyester curtain fabric by solvent exchange phase separation method and a spray-dry procedure. SEM images of the raw fabric samples (Figure 1 (a, b)) exhibited a flat and smooth surface

appearance. Through PVDF and PVDF- Al_2O_3 @ SiO_2 finishing process, a micro-nano-porous and rough coating layer was observed on the fabric surface Figure 1 (c-f) due to phase separation resulting from the displacement of ACE first, followed by DMAC and water, depending on the evaporation rates of the mixture reaching the fabric surface [5]. As compared to the coated fabrics with only PVDF, Al_2O_3 @ SiO_2 particles are also visible on the fabric surface (Figure 1 (e, f)) with a micro-nano-porous and rough coating layer. The enhanced microstructure of the raw fabric (standard PET curtain) by porous coatings is expected to increase passive cooling performance of those fabrics through the higher solar reflection and infrared emission.

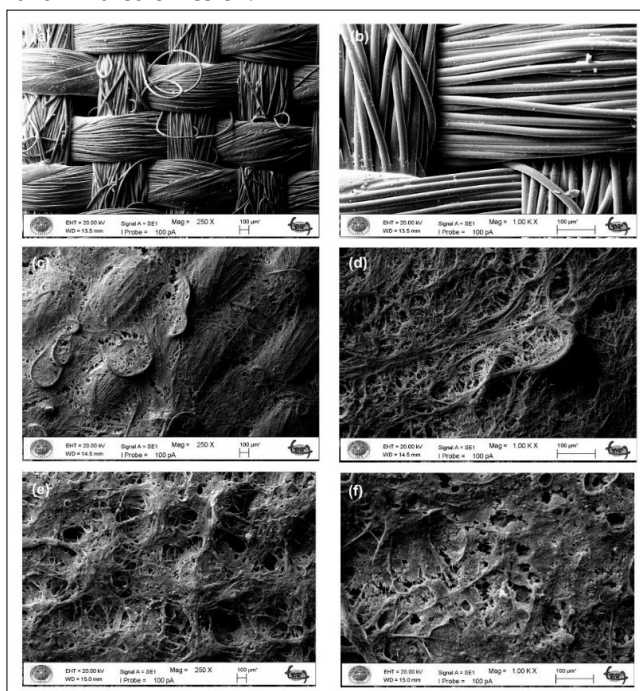


Figure 1: Surface SEM images of the raw (a, b), P_PVDF (c, d), and P_ Al_2O_3 @ SiO_2 (e, f) fabrics at 250x and 1000x magnification

To further understand the chemical composition of the raw and treated fabrics were characterized by FT-IR analysis and infrared spectra were given in Figure 2. The raw fabric sample show characteristic peaks of polyester; C=O stretching band at 1714 cm^{-1} , aromatic ring stretching at 1409 cm^{-1} , C(=O)-O stretching at 1242 cm^{-1} , and aromatic bending bands at 1016 and 725 cm^{-1} . In the FT-IR spectra of all composite-treated fabrics (P_ SiO_2 , P_ Al_2O_3 , and P_ Al_2O_3 @ SiO_2), characteristic C-F vibrations of the PVDF polymer [8] were detected at 1172 , 881 , and 838 cm^{-1} , respectively. In addition to these peaks, P_ SiO_2 and P_ Al_2O_3 samples exhibit intrinsic vibrational characteristic Al-O bond in $500\text{-}900\text{ cm}^{-1}$

range and Si-O stretching vibrations at around 462 cm^{-1} , symmetric Si-O-Si bendings at 721 cm^{-1} , Si-O-Si asymmetric bending at 1070 cm^{-1} , providing the existence of SiO_2 and Al_2O_3 particles in the structure. Also, the presence of mentioned characteristic peaks of Al-O and Si-O-Si asymmetric bending as well as C-F vibrations in $\text{P_Al}_2\text{O}_3@\text{SiO}_2$ ones indicates that binary $\text{Al}_2\text{O}_3@\text{SiO}_2$ nanoparticles within the PVDF polymer matrix has been successfully integrated into the fabric structure. According to FT-IR spectra coated fabrics especially $\text{P_Al}_2\text{O}_3@\text{SiO}_2$ ones could possess high infrared emission characteristics in the atmospheric transparent window due to the mentioned molecular vibration peaks overlapping the atmospheric transparency window ($8\text{--}13\text{ }\mu\text{m}$) corresponded exactly to the absorption at $1250\text{--}780\text{ cm}^{-1}$.

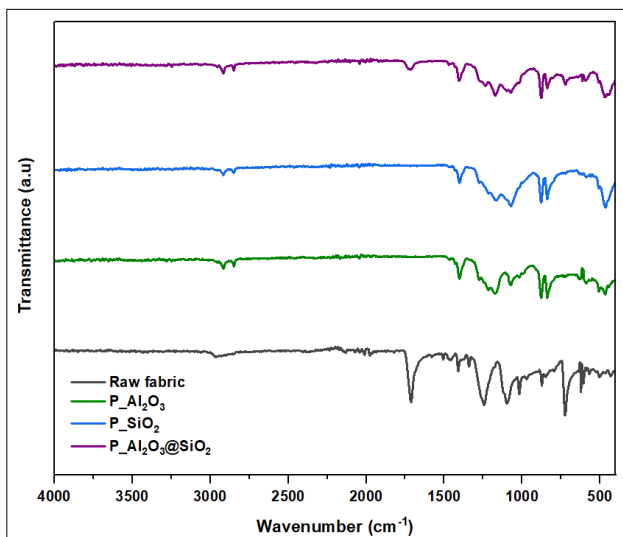


Figure 2: FT-IR spectra of the raw fabric, $\text{P_Al}_2\text{O}_3$, P_SiO_2 , $\text{P_Al}_2\text{O}_3@\text{SiO}_2$ samples

For developing passive radiative cooling curtain, solar reflectance and infrared emission in corresponding wavelength which are crucial parameters, were measured and corresponding spectra were given in Figure 3 and Figure 4, respectively. As compared to the raw samples, coated samples especially ones including binary $\text{Al}_2\text{O}_3@\text{SiO}_2$ particles exhibited higher solar reflectance function. Also, it is observed that P_SiO_2 sample exhibit higher solar reflectance than samples including Al_2O_3 when the effect of particle type is evaluated. This can be attributed to broad-band scattering properties of SiO_2 particles [9]. The raw fabric had 47.73% average solar reflectance while P_SiO_2 , $\text{P_Al}_2\text{O}_3$, and $\text{P_Al}_2\text{O}_3@\text{SiO}_2$ had average solar reflectance of 62.98, 67.16, and 77.64%, in turn. This was due to the micro-nano multi-stage porous structures of composite coatings on the fabric, which could have effectively enhanced the Mie scattering of sunlight and significantly reduced the sunlight energy absorption by the fabric. Also, the combination of Al_2O_3 and SiO_2 particles resulted in generation of multiple scattering effect spanning the entire solar spectrum.

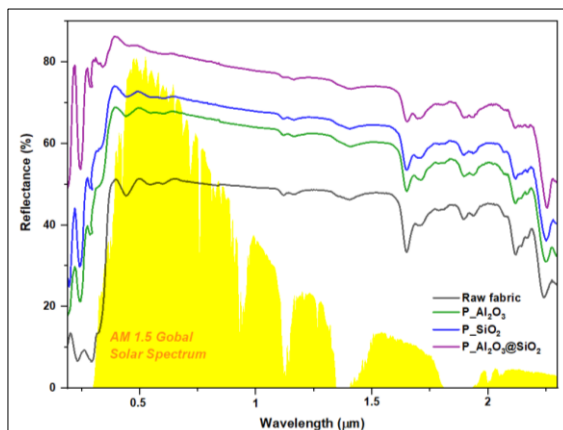


Figure 3: Solar reflectance spectra of the raw fabric, P_ Al_2O_3 , P_ SiO_2 , P_ $\text{Al}_2\text{O}_3@\text{SiO}_2$ samples

Similarly, the average infrared emissivity of the coated samples specially including binary $\text{Al}_2\text{O}_3@\text{SiO}_2$ particles from in the atmospheric transparent window increased from 86.83% to 88.16% compared to the raw fabric samples. The infrared emission of the material is mainly determined by its internal functional groups. The synergetic absorption molecular vibration peaks of PVDF polymer with Al_2O_3 and SiO_2 particles in mid infrared region overlapping the atmospheric transparency window (8-13 μm) corresponded exactly to the absorption at 1250-780 cm^{-1} , may resulted in higher infrared emissivity values. In summary, coated fabrics especially with PVDF- $\text{Al}_2\text{O}_3@\text{SiO}_2$ ones are characterized by high solar reflectance and high infrared emission, which represent promising candidates for energy-efficient thermal management in buildings.

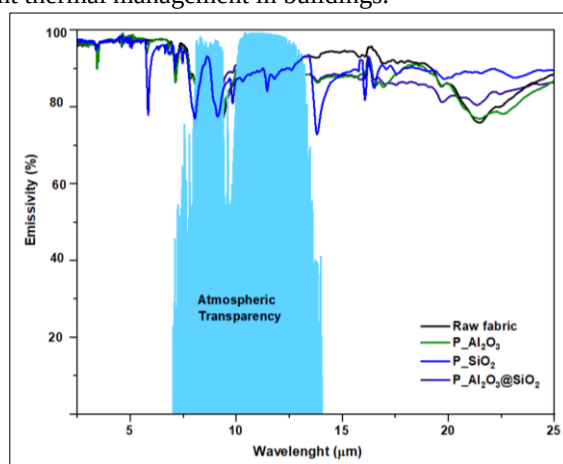


Figure 4: Infrared emission spectra of the raw fabric, P_ Al_2O_3 , P_ SiO_2 , P_ $\text{Al}_2\text{O}_3@\text{SiO}_2$ samples

To demonstrate the passive cooling capability of the samples were measured by recording the real-time temperature using a designed hotplate system under under 500 W/m^2 simulated sunlight. As seen in Figure 5, $\text{P_Al}_2\text{O}_3\text{@SiO}_2$ samples had a temperature of 44.12°C , which is lower than coated samples with composite coating including Al_2O_3 and SiO_2 (46.34 and 46.73 , respectively), PVDF ones (48.02°C) and the raw samples (51.5°C) under 500 W/m^2 solar irradiance. Furthermore, the maximum cooling performance was achieved in $\text{P_Al}_2\text{O}_3\text{@SiO}_2$ samples with 7.38°C temperature drop based higher solar reflectance and mid-infrared emittance as compared to raw ones.

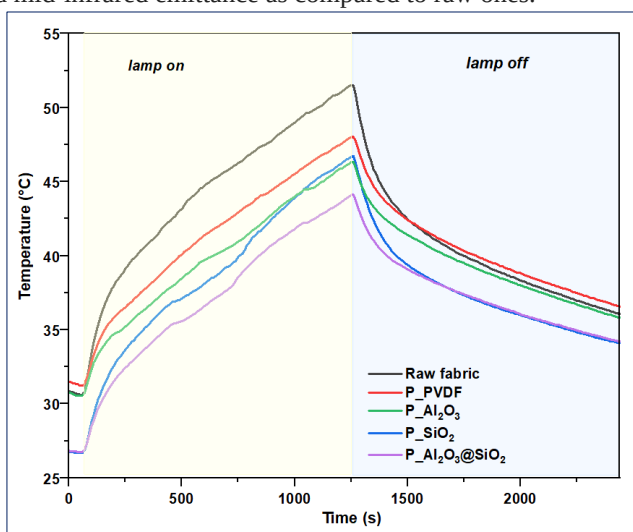


Figure 5: Real-time temperature curves of the raw fabric, P_PVDF, P_ Al_2O_3 , P_ SiO_2 , P_ $\text{Al}_2\text{O}_3\text{@SiO}_2$ samples

Flame retardant performance of the raw and treated fabric was determined in accordance with standard AATCC 6941 and corresponding results presented in Figure 6. As seen in Figure 6, the raw fabrics displayed a 4 cm char length with visible structural degradation upon flame exposure. The P_ Al_2O_3 one showed the highest char length with 12 cm among the all samples accompanied by extensive fabric damage and significant char formation, suggesting that the Al_2O_3 coating tends to decompose rather than play a flame-retardant role in the system, thus showing a flammable phenomenon under the applied test conditions. The P_ SiO_2 sample demonstrated a moderately improved flame resistance with a char length of 10.5 cm; however, considerable burning damage was still observed on the fabric surface. Upon the incorporation of the binary $\text{Al}_2\text{O}_3\text{@SiO}_2$ particles, the flame retardancy improved progressively, achieving the lowest char length of 1.8 cm with minimal fabric degradation. This may be resulted from $\text{Al}_2\text{O}_3\text{@SiO}_2$ binary structure rapidly form a cohesive inorganic protective barrier on the fabric surface, which effectively retards heat transfer to the underlying substrate and inhibits further flame propagation.

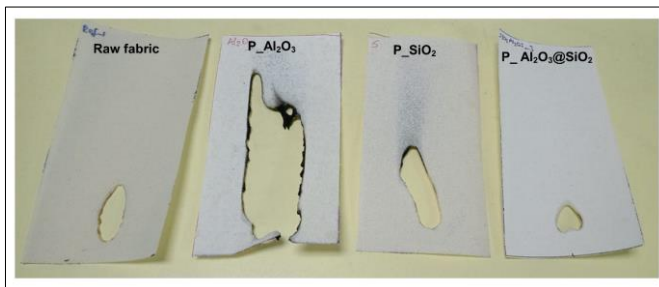


Figure 6: Photographs of the raw fabric, P_PVDF, P_ Al_2O_3 , P_ SiO_2 , P_ $\text{Al}_2\text{O}_3@\text{SiO}_2$ samples following flame test

Additionally, self-cleaning function is also necessary for practical applications to prevent dirt and various droplets from compromising the performance of the passive radiative cooling curtain. As shown in Figure 7 (a), when various solutions (methylene blue dye, water, and coffee) were dropped onto the P_ $\text{Al}_2\text{O}_3@\text{SiO}_2$ samples which have highest cooling performance the droplets maintained a quasi-spherical geometry, demonstrating the coating's excellent antipollution properties. Also, a controlled amount soil was deposited on to the sample surface followed by rinsing with water droplets from a rubber dropper to determine self-cleaning capability. As seen in Figure 7 (b), the contaminants were removed from the surface of P_ $\text{Al}_2\text{O}_3@\text{SiO}_2$ sample. These results verify that the micro-nano porous composite structure within the film provides self-cleaning ability, helping to preserve the material's optical and thermal performance in practical application.

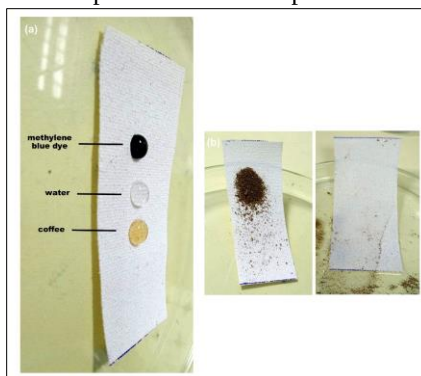


Figure 7: Droplets of different contaminants on the surface (a), self-cleaning capability of P_ $\text{Al}_2\text{O}_3@\text{SiO}_2$ (b)

4. CONCLUSION

In this study, multifunctional passive radiative cooling curtain fabrics were successfully developed with porous PVDF nanocomposite coatings including SiO_2 , Al_2O_3 , and binary $\text{Al}_2\text{O}_3@\text{SiO}_2$ nanoparticles by solvent exchange phase separation and spray coating process. Nanocomposite treated especially including binary $\text{Al}_2\text{O}_3@\text{SiO}_2$ particles exhibited the most effective passive cooling performance with 7.38°C temperature drop



under 500 W/m² solar irradiance based on higher solar reflectance (77.64%) and mid-infrared emittance (88.16%) due to the synergistic effect of the binary nanoparticle structure and hierarchical porous coating morphology. In addition to radiative cooling performance, binary Al₂O₃@SiO₂ particle also remarkably enhanced flame retardancy, yielding the lowest char length (1.8 cm) with minimal structural degradation after flame exposure. Also, this sample endows sufficient self-cleaning performance, which is essential for maintaining long-term optical and cooling performance in practical applications. Summing up, this developed curtain fabric presents a promising approach for sustainable building thermal management by simultaneously combining passive cooling, flame retardancy, and self-cleaning functionalities.

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REFERENCES

- [1] Mei, H., Xue, G., Gou, Q., Chen, Z., Wang, K., Zhang, S., Xiong, K., Xiao, J., Song, B., Li, M. (2025). Recent advances in bio-inspired radiative cooling film designs for sustainable building applications, *Journal of Materials Chemistry A*, 13(39), 33034-33056.
- [2] Pan, Q. H., Wang, M. H., Huang, Z. Y., Qiu, X. J., Wang, Y. T., Zhao, F. X., Zhu, M., Guo, X., Chen, C., Zhang, S., Wang, J., He, Z., Yu, S. H. (2025). Biomimetic pyramid structure film for enhancing building radiative cooling, *Advanced Science*, 12(14), 2413559.
- [3] Huang, W. W., Peng, H. K., Hu, X., Zhou, J., Wang, X., Li, T. T., Lin, J. H. (2026). Recent research progress in passive daytime radiative cooling technology in terms of material structure and practical application, *Journal of Applied Polymer Science*, 143(4), e58094.
- [4] Ma, Z., Feng, Y., Song, A. Y., Dinh, T., Hong, M., Bell, J., Hou, B., Song, P., Zheng, W. (2026). A scalable, durable, fire-safe all-day passive radiative cooling coating for sustainable buildings, *Advanced Functional Materials*, 36(10), e17278.
- [5] Ma, C. Q., Xue, C. H., Guo, X. J., Shi, W., Wang, H. D., Huang, M. C., Wan, L., Wu, Y., Cheng, J. (2024). Fabrication of passive cooling fabric as thermal management curtain for building energy-saving, *Chemical Engineering Journal*, 497, 154431.
- [6] Wang, Y., Chen, W., Zhang, F., Song, K., Meng, J., Wang, S. (2026). Bioinspired radiative cooling materials: from design principles to building energy savings, *ACS Nano*.
- [7] Mandal, J., Fu, Y., Overvig, A. C., Jia, M., Sun, K., Shi, N. N., Zhou, H., Xiao, X., Yu, N., Yang, Y. (2018). Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling, *Science*, 362(6412), 315-319.
- [8] Korkmaz Memiş, N., Kaplan, S., Kaya Kınaytürk, N. (2026). Structural optimization of radiative cooling nanocomposite films for clothing applications, *Polymers for Advanced Technologies*, 37(5), e70619.
- [9] Fu, Y., Wang, Y., Ding, Y., Kan, Z. (2026). Ultrathin and high-efficiency passive daytime radiative cooling coating via polymer-particle co-design, *Small*, e13462