

Nano-materiali per la protezione

Ada Ferri

Dipartimento di Scienza
Applicata e Tecnologia
Politecnico di Torino



**Politecnico
di Torino**

Prerequisiti di nuovi materiali per la protezione

Le soluzioni utilizzate nel campo della protezione devono soddisfare le linee guida pertinenti, tra cui:

- la resistenza alle alte temperature
- l'appropriata conducibilità termica e TPP (Thermal Protective Performance verso calore radiante e convettivo)
- la resistenza agli agenti chimici
- (nel caso di soluzioni wearable) la precisione di rilevamento, la velocità di trasmissione dei dati



Più complesso sviluppare nuove soluzioni per il settore protezione rispetto ad altri ambiti di applicazione (sport, medicale, ...)

Esempi di nanomateriali con potenziali applicazioni in ambito protettivo

Diversi livelli di
maturità delle
tecnologie

- **Aerogel di silice e aerogel avanzati**
- **Sistemi passivi per il raffreddamento - Passive cooling**
- **Generatori triboelettrici a base di nanofibre**
- **Additivi antifiamma nanostrutturati**

Aerogels

- Gli aerogel sono materiali con eccellente isolamento termico ($\lambda < 0.02 \text{ W/m}\cdot\text{K}$)
- Tuttavia, gli aerogel hanno scarsa resistenza meccanica e sono fragili
- Combinando aerogel con tessuti o tessuti-non-tessuti, si ottengono multistrati con ottime proprietà di isolamento termico

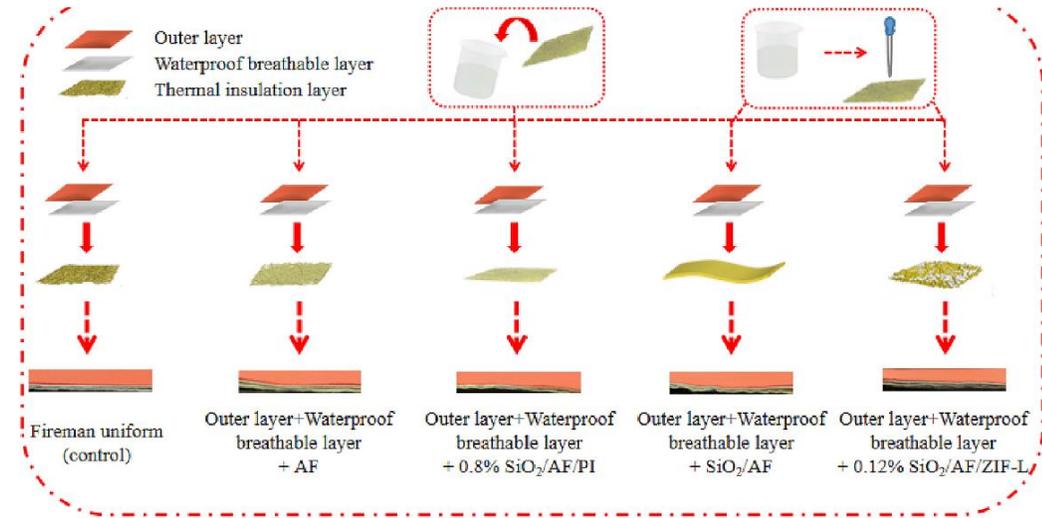


Fig. 1. Schematic of laminated fabrics preparation: outer layer (orange); waterproof breathable layer (white); thermal insulation layer (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Thermal conductivity of different laminated fabrics.

Laminated fabrics	Thermal conductivity (W/(m·K))
Fireman uniform (control)	0.052
Outer layer + Waterproof breathable layer + AF	0.050
Outer layer + Waterproof breathable layer + SiO ₂ /AF	0.040
Outer layer + Waterproof breathable layer+0.8 % SiO ₂ /AF/PI	0.043
Outer layer + Waterproof breathable layer+0.12 % SiO ₂ /AF/ZIF-L	0.038

Table 3
Second degree burn time of laminated fabrics.

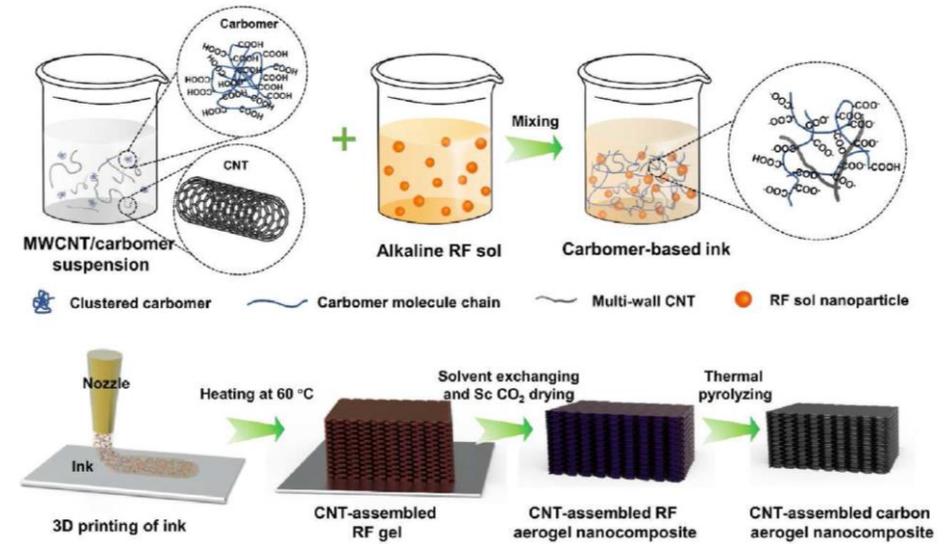
Laminated fabrics	Second degree burn time (s)
Fireman uniform (control)	72.10 ± 0.72
Outer layer + Waterproof breathable layer + AF	75.10 ± 1.21
Outer layer + Waterproof breathable layer + SiO ₂ /AF	78.20 ± 2.22
Outer layer + Waterproof breathable layer+0.8 % SiO ₂ /AF/PI	76.17 ± 1.53
Outer layer + Waterproof breathable layer+0.12 % SiO ₂ /AF/ZIF-L	91.73 ± 2.18

Rujing Xue, Fabrication and performance evaluation of aramid laminated fabrics incorporated with silica composite aerogel for protective clothing, *Ceramics International* 50 (2024) 10348–10354 <https://doi.org/10.1016/j.ceramint.2023.12.346>

Aerogel avanzati

3D-printed CNT aerogel nanocomposites

Stampato in 3D, un aerogel che contiene nanotubi di carbonio con proprietà meccaniche migliorate (CNT), tipica struttura porosa nanometrica (aerogel) e buona conducibilità elettrica

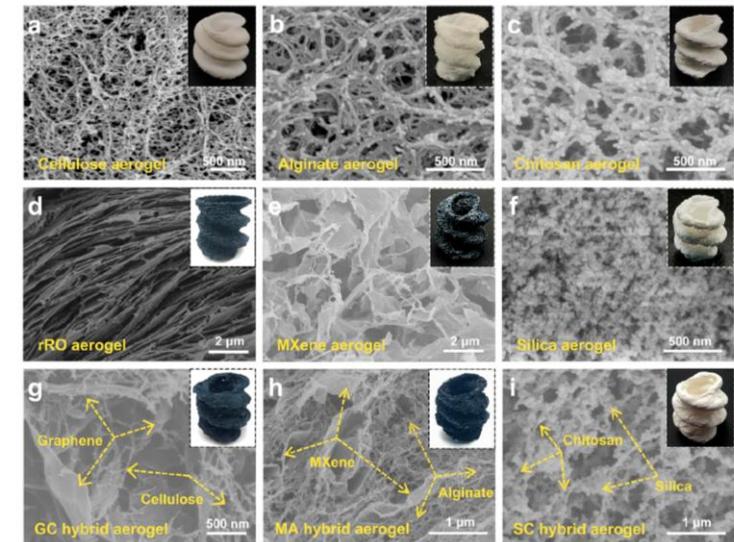


L. Wang et al., Extrusion 3D printing of carbon nanotube-assembled carbon aerogel nanocomposites with high electrical conductivity, Nano Materials Science 6 (2024) 312–319 <https://doi.org/10.1016/j.nanoms.2023.09.002>

Kevlar aerogel

Coniuga le proprietà meccaniche del polimero p-aramidico con la struttura nano-porosa dell'aerogel

Q. Cheng et al., General Suspended Printing Strategy toward Programmatically Spatial Kevlar Aerogels, ACS Nano 2022, 16, 4905–4916, <https://doi.org/10.1021/acsnano.2c00720>

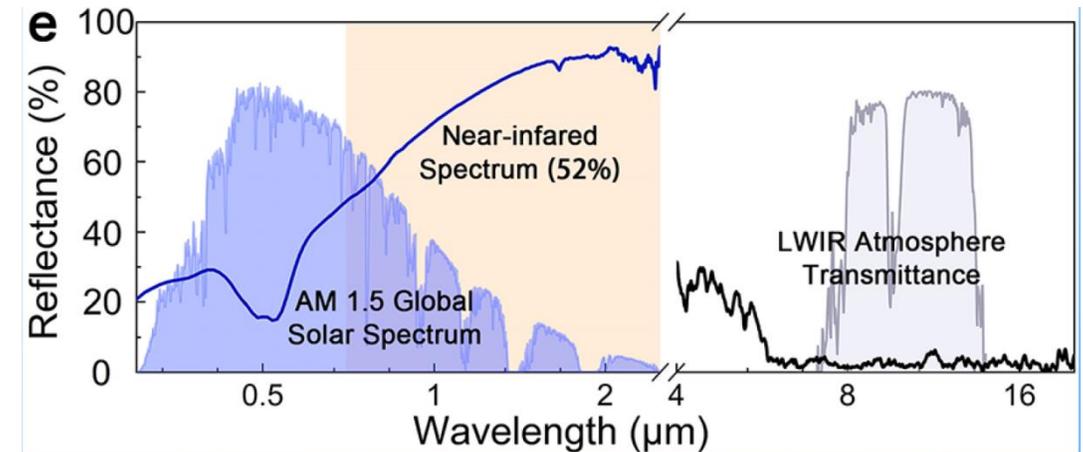
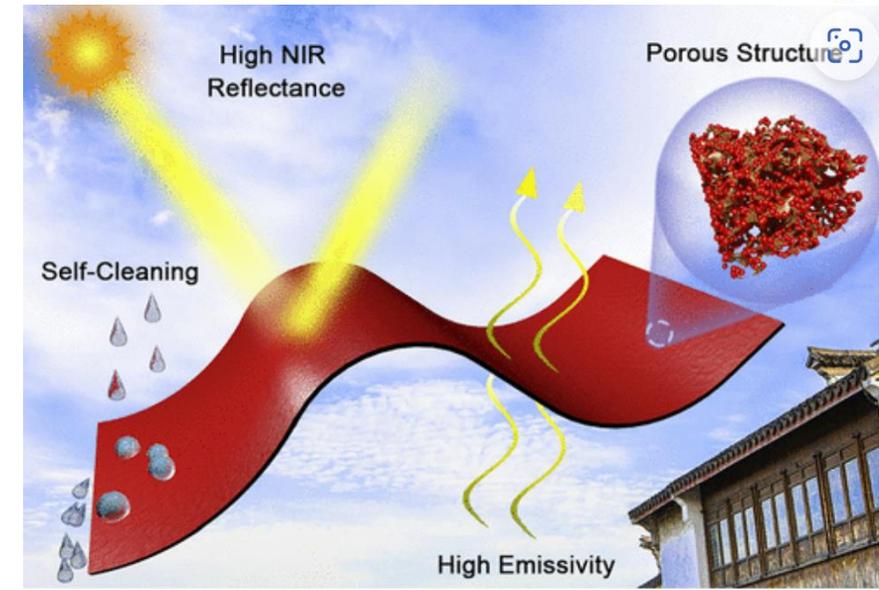


Passive cooling

La **riflettanza e l'emissività** dei materiali possono essere regolate controllando la forma, la dimensione e la disposizione della struttura micro-nanometrica della superficie di un materiale.

L'elevata riflettività può essere ottenuta grazie al mismatch degli indici di rifrazione di diversi materiali, come la matrice polimerica e le micro-sacche d'aria in un **materiale poroso**.

Shuo Yang et al. , Self-Cleaning Red-Toned Perylene Poly(aryl ether) Film with Superior NIR Reflectance for Passive Radiative Cooling, ACS Sustainable Chem. Eng. 2023, 11, 13668–13677 <https://doi.org/10.1021/acssuschemeng.3c03488>



Membrane nano-porose per il passive cooling

- Membrane per lo più a base di polimeri fluorurati.
- Esibiscono anche altre proprietà, come superidrofobicità e resistenza ai solventi.

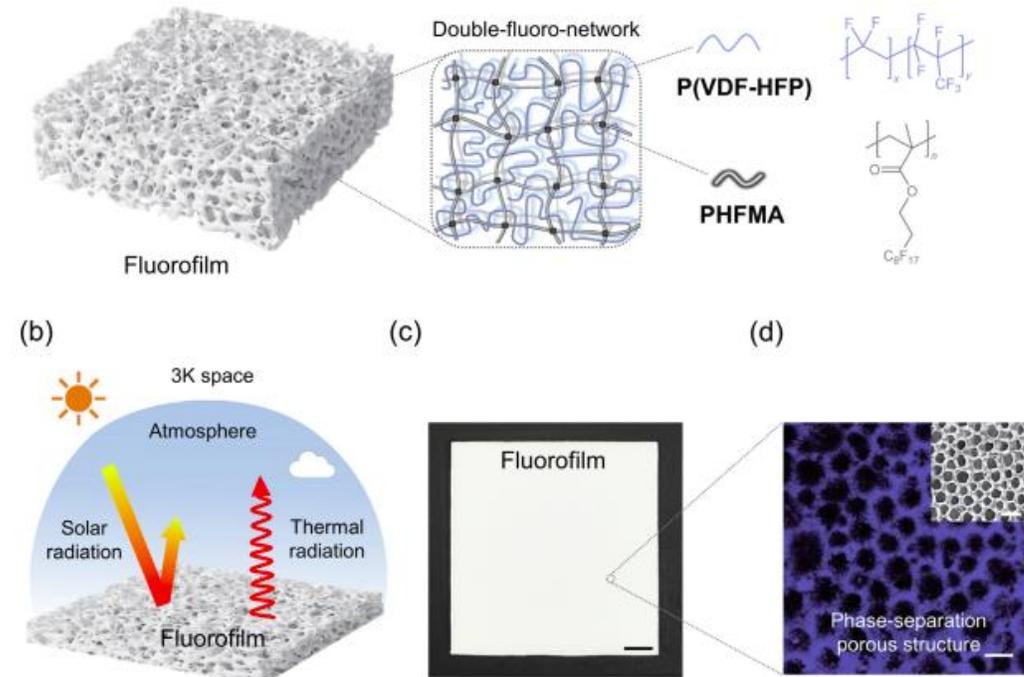
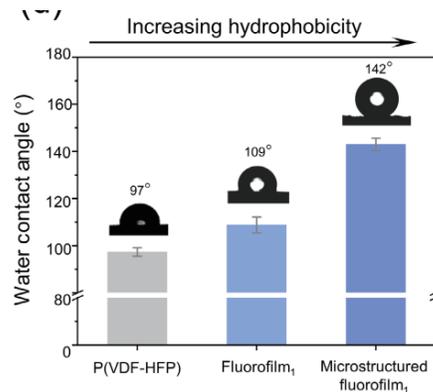
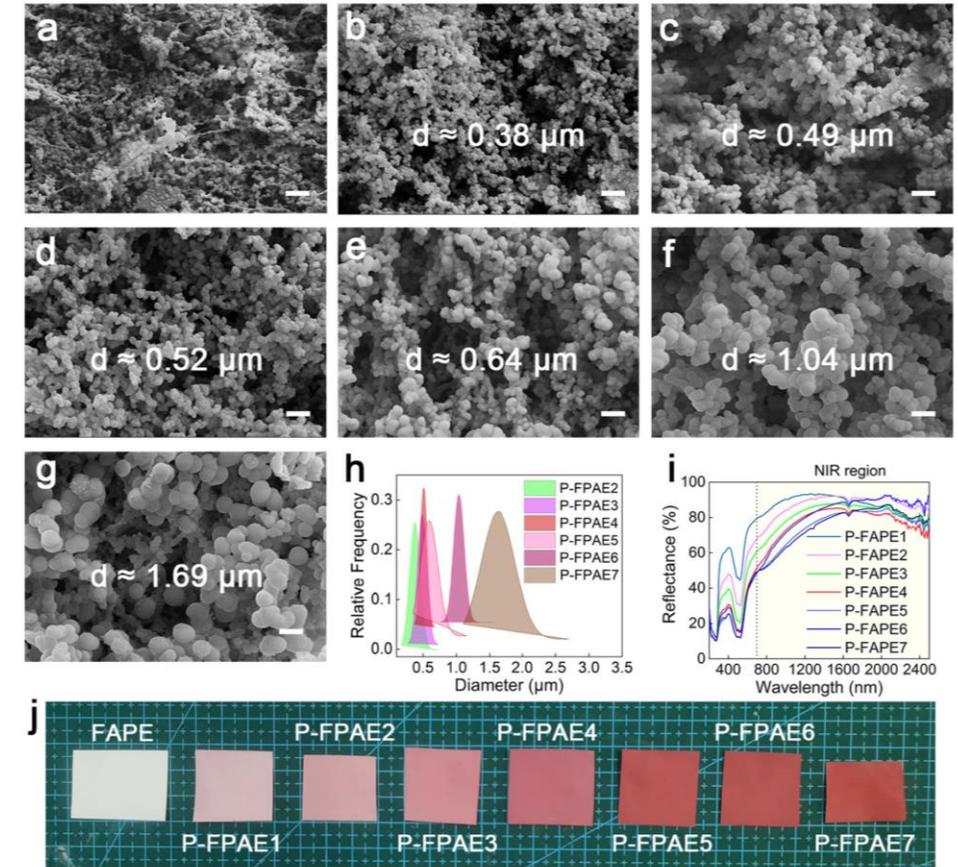
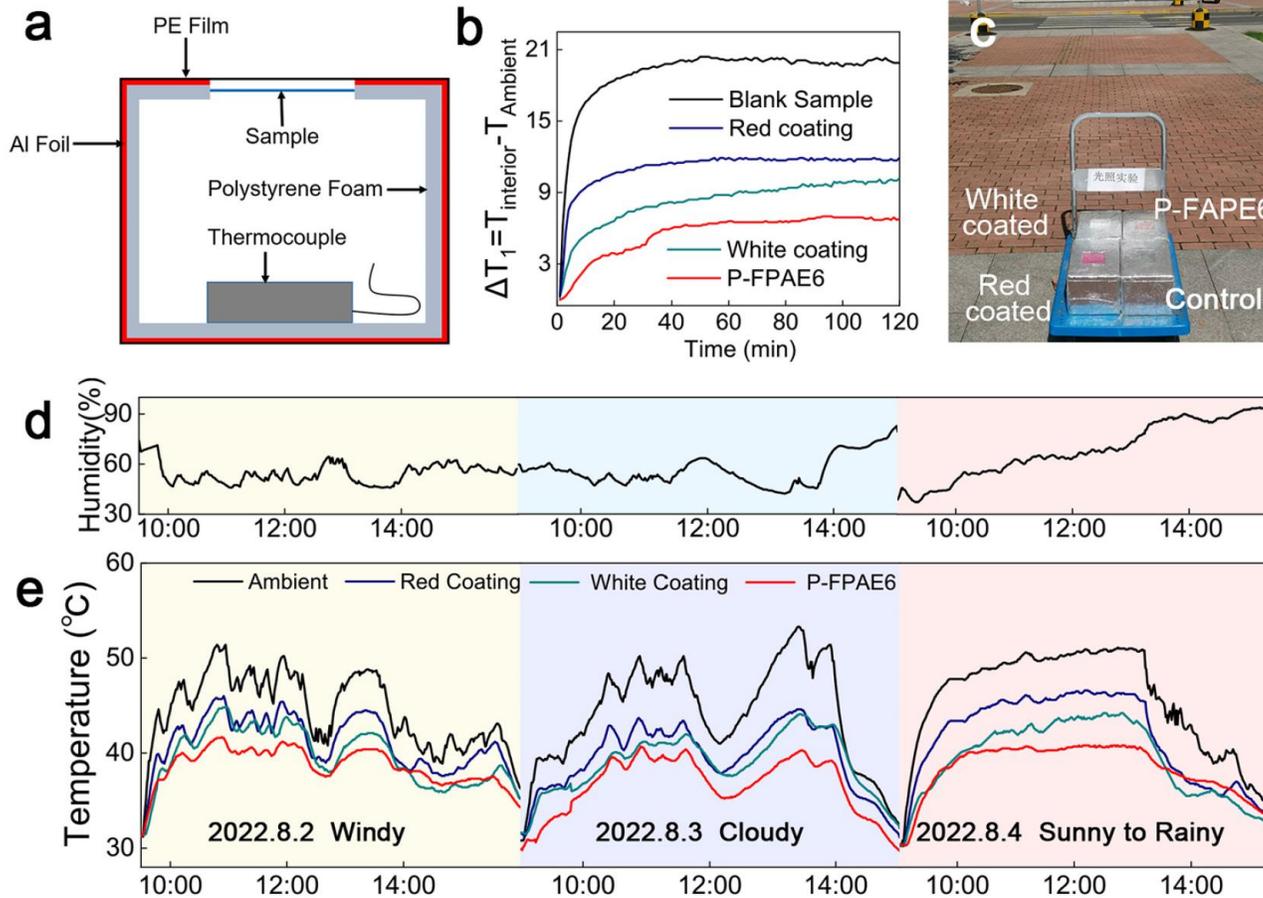


Figure 1 Structure design and function of the fluorofilm. (a) Schematic illustration of the structure design of the fluorofilm. (b) Schematic illustration of the passive radiation cooling function of the fluorofilm. (c) Photograph of the fluorofilm. Scale bar, 1 cm. (d) The phase-separation porous structural characterization. Scale bar, 5 μm.

W. Tang et al., Environment-adaptive phase-separation-porous-nanofilm for high performance passive radiation cooling, *Nano Res.* 2024, 17(6): 5636–5644 <https://doi.org/10.1007/s12274-024-6420-0>

Efficacia dei sistemi sviluppati



Shuo Yang et al. , Self-Cleaning Red-Toned Perylene Poly(aryl ether) Film with Superior NIR Reflectance for Passive Radiative Cooling, ACS Sustainable Chem. Eng. 2023, 11, 13668–13677
<https://doi.org/10.1021/acssuschemeng.3c03488>

Molte diverse strategie passive basate su nanomateriali

I sistemi di raffreddamento passivo sono basati su tre meccanismi:

- Accumulo di calore latente
- Raffrescamento radiativo
- Evaporazione del sudore

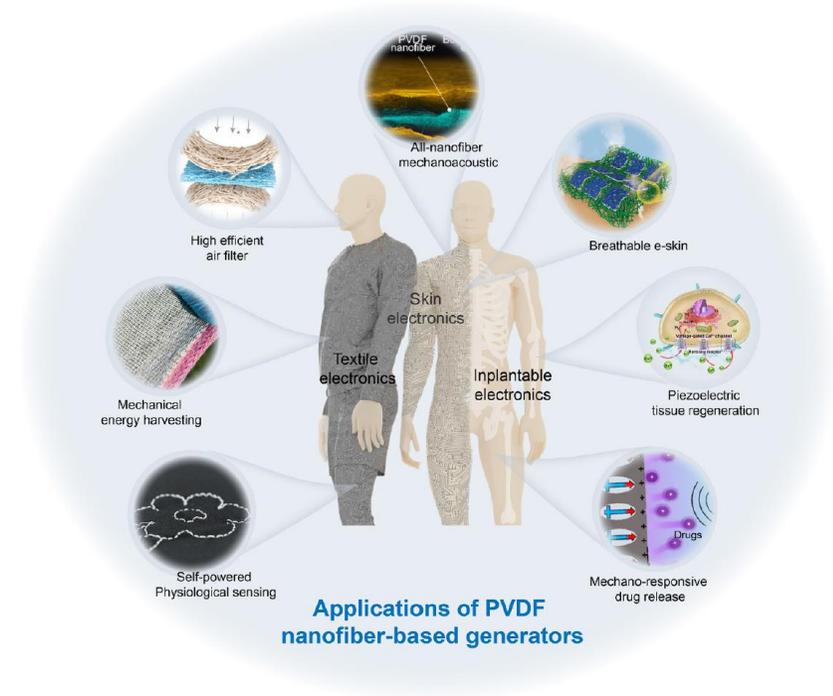
Table 2
Passive thermoregulation nanomaterial-based textiles.

Nanomaterials	Heat transfer mechanism	Cooling or heating	Performance	Energy consumption	Refs.
TiO ₂ -PVP nanofibers	Latent heat storage	Cooling & heating	PCMs up to 45 wt% octadecane, suitable for solids with melting points between 10 and 80 °C	No	[79]
Aerogel-directed smart fibers (ASFs)	Latent heat storage	Cooling & heating	A wide range of phase transition temperature and enthalpy (0-186 J g ⁻¹).	No	[81]
Graphene	Latent heat storage	Cooling & heating	Adjustable phase transition enthalpy and temperature in the region from about 5-60 °C, and highly mechanical flexibility.	No	[18]
Nanoporous polyethylene microfibers	Radiative cooling	Cooling	~2.3 °C lower than the commercial cotton fabric.	No	[87]
Nanobeads and nanofibers	Radiative cooling	Cooling	~4.8 °C lower than the commercial cotton fabric.	No	[22]
Boron nitride nanosheets (BNNs)	Radiative cooling	Cooling	Excellent dynamic personal cooling effect (2.2 °C).	No	[91]
Silver-coated polyamide textile	Radiative cooling	Cooling	Lower by 1.1 °C (indoor) and 0.9 °C (outdoor) than normal cloth.	No	
Silk with nanoparticles	Radiative cooling	Cooling	~3.5 °C below ambient (for an ambient temperature of ~35 °C.	No	[119]
Janus silk with opposite wettability	Sweat evaporation	Cooling	Less required liquid volume (5 µL) and a faster (2-3 min) response time.	No	[98]
Boron nitride (BN) particles	Sweat evaporation	Cooling	40 % higher thermal conductivity and over 50 % higher evaporation rate than conventional fabrics.	No	[101]
Polyester/nitrocellulose textile	Sweat evaporation	Cooling	An ultrahigh directional water transport capability of 1246 %.	No	[102]
Nickel titanium alloy	Thermal insulation	Cooling	An extra 40 s before the onset of second-degree skin burn.	No	[120]
Zirconium carbide (ZrC)	Photothermal effect	Heating	A higher photothermal conversion efficiency with an increase of 27.5 °C in 100 s.	No	[110]
Nylon nanofibers	Photothermal effect	Heating	~2.5-10.5 °C higher warmth than a commercial sweatshirt	No	[17]
Nanoporous polyethylene (nPE) textile	Photothermal effect	Heating	~3.8 °C higher warmth in indoor environment, and ~6.3 °C higher warmth under sunlight.	No	[115]
Natural melanin (NM) particles	Photothermal effect	Heating	~14.7 °C higher than pristine cotton.	No	[104]

R Zhang et al., Nanomaterial-based textiles for personal thermal management: Perspectives of the fabrications and properties, *Materials Today Communications* 40 (2024) 109818
<https://doi.org/10.1016/j.mtcomm.2024.109818>

Generatori triboelettrici

- Utilizzano la conversione di energia meccanica dal movimento umano in energia elettrica.
- I generatori triboelettrici possono essere incorporati nei capi di abbigliamento per effettuare energy harvesting, self-powered sensing e comunicazione interattiva.
- Si producono attraverso tecnologie come electrospinning, centrifugal spinning, or solution-blowing.
- L'elevata potenza di output è dovuta ad elevata rugosità superficiale delle nanofibre prodotte.



W. Gong et al., PVDF nanofibers for body-area triboelectric generators, Nano Energy 131 (2024) 110277
<https://doi.org/10.1016/j.nanoen.2024.110277>

Nanofibre di PVDF come materiale triboelettrico

- Le nanofibre di polyvinylidene fluoride (PVDF) si distinguono per la loro superiore elettroegatività.
- Inoltre sono flessibili, hanno proprietà piezoelettriche, che sono di interesse nella bioelettronica.

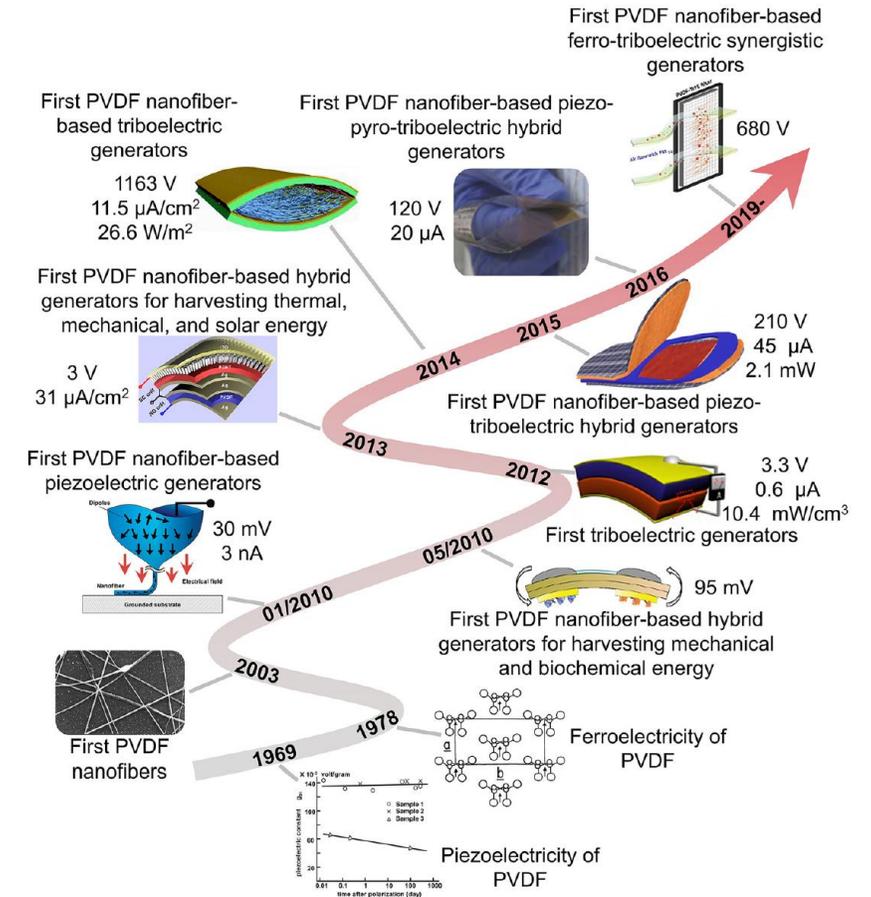
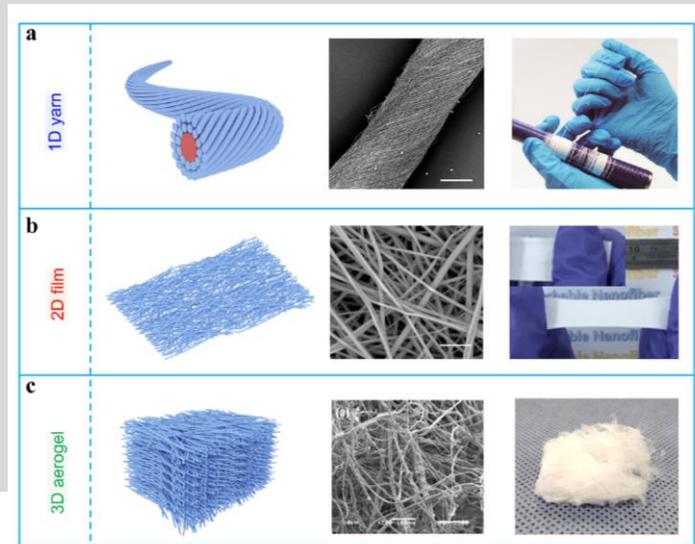


Fig. 1. An overview of PVDF nanofiber development for energy applications.

W. Gong et al., PVDF nanofibers for body-area triboelectric generators, *Nano Energy* 131 (2024) 110277
<https://doi.org/10.1016/j.nanoen.2024.110277>

Additivi antifiamma nano-strutturati

- Ampia varietà di ossidi metallici di scala nanometrica
- CNTs, grafene ed ossido di grafene (GO)
- Nanoargille (montmormollonite, ..)

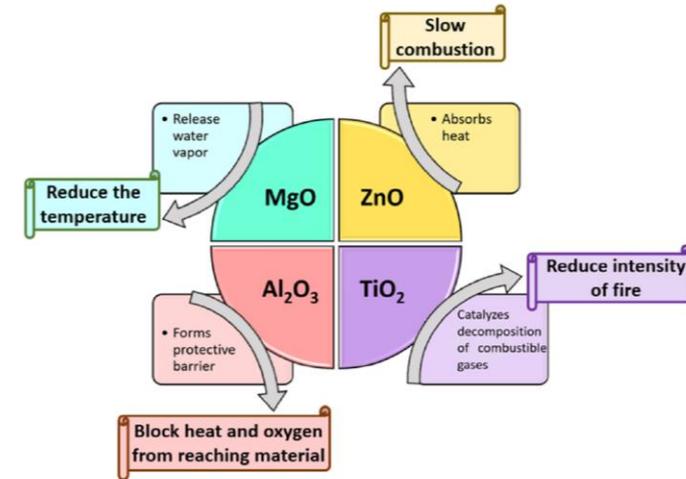


Fig. 1. Nanostructured metal oxides as flame retardant.

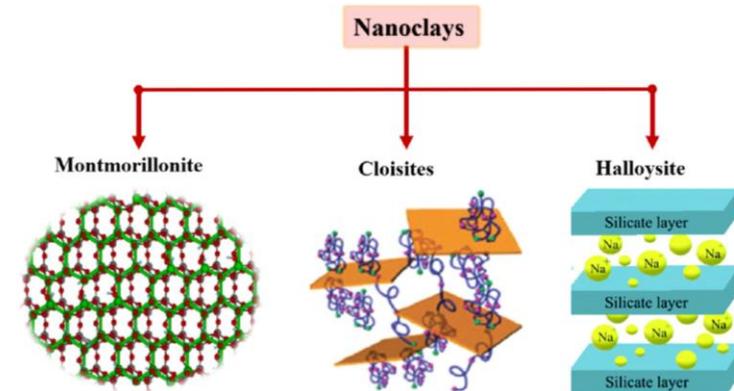


Fig. 3. Different types of nanoclays.

J. Rodrigues et al. Nanostructured flame retardants: An overview, Nano-Structures & Nano-Objects 39 (2024) 101253, <https://doi.org/10.1016/j.nanoso.2024.101253>

Nano-materiali come Megalon

I nano-materiali ricordano Megalon, il materiale misterioso del nuovo film di Coppola 'Megalopolis'.

Megolon può trasformarsi in qualsiasi cosa (edifici, passerelle, ecc.) ed è autosufficiente.

È una sostanza magica che apparentemente può fare qualsiasi cosa, evolvendosi contemporaneamente agli esseri umani.

