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Challenges to materials for local glacier conservation

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Glaciers, especially the small/local ones, are rapidly melting and disappearing due to their heightened sensitivity to climate change. A holistic understanding of the key criteria and fundamental challenges in developing materials for local glacier conservation is urgently needed, coupled with a call for interdisciplinary collaboration to effectively address the pressing issue of local glacier retreat.

Glaciers cover ~11% of the Earth's total land area and serve as a vital freshwater storage and distribution system, playing a crucial role in maintaining the global water cycle and ecological balance[1]. Yet, driven by severe climate change and uncontrolled anthropogenic greenhouse gas emissions, glaciers worldwide have been losing mass at an alarming rate of 267 ± 16 gigatonnes annually over the past 20 years[2]. Recognizing the urgency of this issue, the United Nations has designated 2025 the International Year of Glaciers' Preservation, calling for immediate global attention and action to address this challenging yet crucial task.

Glaciers of varying sizes respond differently to climate change. Model projections for a temperature increase of 1.5–4 °C from 2015 to 2100 indicate that smaller glaciers, particularly those under 1 km^2 (accounting for 79.2% of the total number of glaciers), are more susceptible, with projected losses reaching 60–90% under the above warming scenarios. In contrast, larger glaciers are estimated to experience losses of 10–50% (ref. 3). This projection underscores the critical need for focused conservation of smaller/local glaciers, as their disappearance will markedly impact local hydrology, glacier hazards, ecology, and economy.

Glaciers, like other objects on Earth's surface, should balance the thermal radiation between incoming solar energy and outgoing emissions to space, a process governed by the energy transfer equation, alongside conduction and convection at their surface. Indeed, analysis of the energy transfer processes within low-, middle-, and high-latitude glacier (ice) systems reveals that the solar irradiation is the primary energy input, while the mid- to far-infrared radiation serves as the principal channel for energy dissipation[4,5]. The above-mentioned energy balance, however, is typically disrupted by an excess of absorbed solar energy, particularly in small/local glaciers. This imbalance leads to a net energy input, predominantly directed toward the melting of glaciers once their surface temperature reaches 0 °C. Consequently, this surplus energy accelerates surface melting rates, thus driving the glaciers' mass loss on a substantial scale[5,6].

Current artificial intervention measures[1,5,7], like glacier cover, artificial snow, and water injection, have been implemented to mitigate the melt rates in small/local glaciers and glacier ski resorts. Among these methods, covering glaciers' surfaces with various materials can effectively slow down the melting rate of the glacier, showcasing a certain practical feasibility[5]. Notably, white geotextiles have been used to increase the glaciers' solar reflectance by up to 70–80%, thus reducing the net energy input[5,6]. More recently, the passive daytime radiative cooling (PDRC) technique and materials, featuring high solar reflectance (>90%) across the sunlight spectrum (0.3–2.5 μm) and strong thermal emittance (>0.9) within the long-wavelength infrared atmospheric transparency window (8–13 μm) (Fig. 1a), have been demonstrated to be effective for ice and snow conservation[4].

To establish a viable approach for small/local glacier conservation, it is essential to thoroughly understand the key criteria and stringent requirements from the materials design perspective.

Spectral characteristics

Glacier melting arises from the interplay of all positive and negative energy fluxes. To effectively mitigate glacier melting, it is essential to thoroughly analyze the energy balance process at its surface. The energy balance of the glacier surface is governed by the following equations[6]:

$$\mathrm{TEM} = \mathrm{NR} + \mathrm{SH} + \mathrm{LH} \tag{1}$$

$$\mathrm{NR} = \mathrm{NR}_{\mathrm{SW}} + \mathrm{NR}_{\mathrm{LW}} = (1 - R_{\mathrm{solar}})R_{\mathrm{SW,in}} + (R_{\mathrm{LW,in}} - \varepsilon_{\mathrm{LWIR}}\sigma T^4) \tag{2}$$

where TEM is the total energy available for melting, NR is the net radiation, that is, the difference between the incoming and outgoing radiation, SH is the sensible heat transfer (related to air temperature), while LH is the latent heat flux (related to evaporation or condensation). $\mathrm{NR}_{\mathrm{SW}}$ and $\mathrm{NR}_{\mathrm{LW}}$ are the net radiation in shortwave (SW = 0.3–2.5 μm) and longwave (LW = 8–13 μm), respectively. $R_{\mathrm{SW,in}}$ and $R_{\mathrm{LW,in}}$ are the incoming radiation in the SW and LW bands, respectively. R_{solar} is the reflectance of materials (snow, ice, and so on) in SW band, typically referred to as 'albedo' in glaciology. Specifically, a perfectly white body demonstrates an R_{solar} toward 100% or 1; on glaciers, this value typically ranges from 0.9 for fresh snow to 0.2 for dark ice and can further decrease to 0.1 for debris-covered surfaces[5,6]. $\varepsilon_{\mathrm{LWIR}}$ is the emittance of materials in the LW band. σ is the Stefan–Boltzmann constant (5.6697×10^{-8} W m^{-2} K^{-4}), while T is the surface temperature of materials (K). Indeed, the main control factors for SH and LH terms are the air temperature and air humidity, respectively, which are independent of the spectral characteristics of materials. Quantitatively, for most alpine glaciers, the primary source of surface energy is NR, which typically accounts for 75–80% of the total heat gain for melting, compared to SH

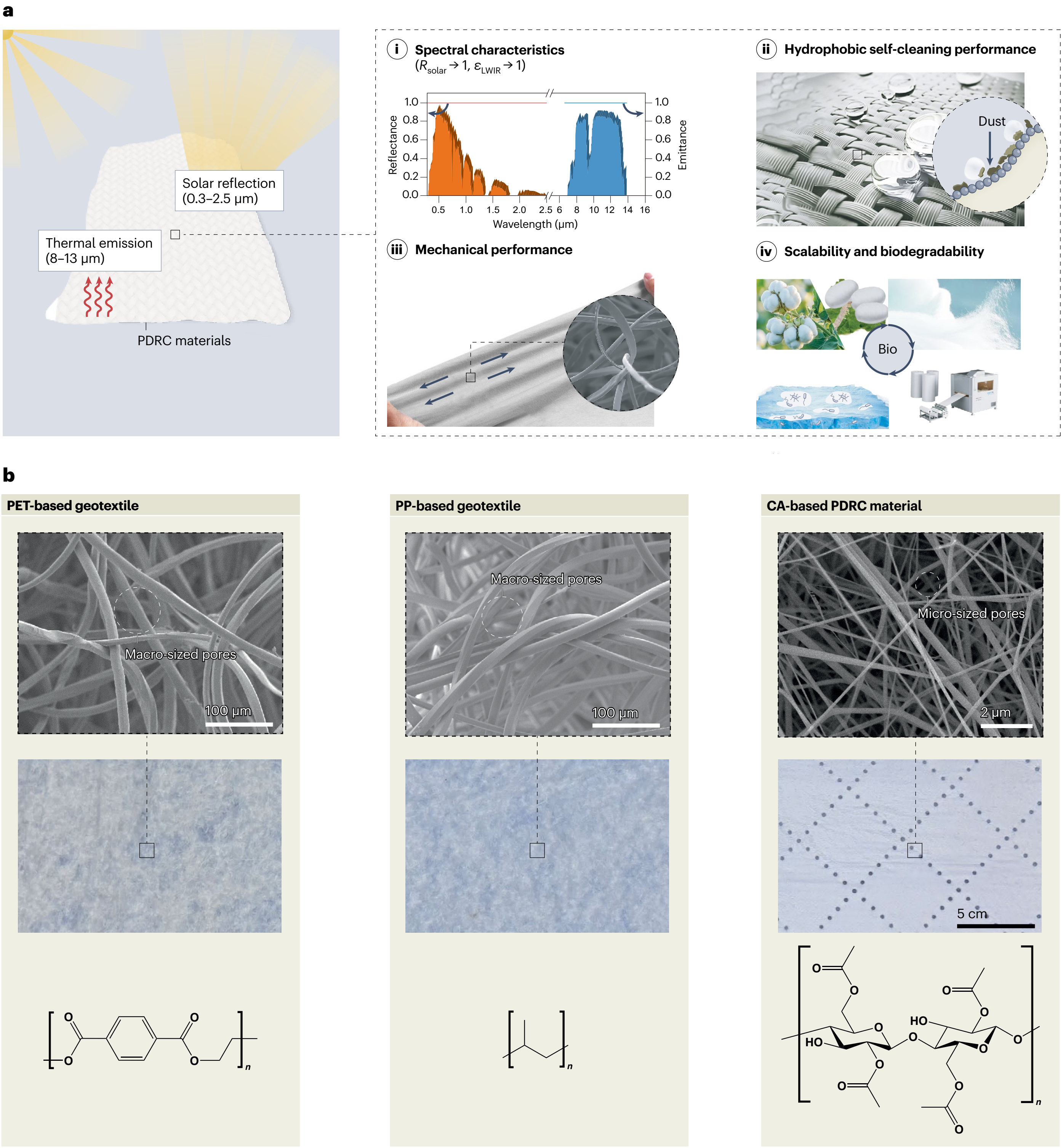

Fig. 1 | Materials for glacier conservation. **a**, Schematic showing the key criteria and stringent requirements of geotextiles deployed for local glacier conservation. **b**, Optical photos, scanning electron microscopy images, and molecular formulas of the traditional geotextiles and the newly CA-based PDRC material.

Table 1 | Spectral characteristics, water contact angle, mechanical strength, and biodegradability of the traditional geotextiles and the newly CA-based PDRC material

Material	Spectral characteristics	Water contact angle	Mechanical strength	Biodegradability
PET-based geotextile	R_{solar} = 72.80%, ε_{LWIR} = 0.910	114.6°	Strain = 66.47%, Stress = 0.096 MPa	>50 years (ref. 12)
PP-based geotextile	R_{solar} = 78.42%, ε_{LWIR} = 0.885	127.8°	Strain = 103.78%, Stress = 0.070 MPa	>30 years (ref. 13)
CA-based PDRC material	R_{solar} = 94.58%, ε_{LWIR} = 0.942	148.6°	Strain = 58.63%, Stress = 0.135 MPa	4–9 months (ref. 14)

The spectral characteristics, water contact angle, and mechanical strength of various materials were systematically evaluated via empirical testing. Biodegradability information was sourced from the relevant studies (refs. 12–14) on material breakdown in environmental conditions.

(15–20%) and LH (0–10%) (ref. 6). As such, integrating Eqs. (1) and (2) clearly indicates the interaction among the spectral characteristics of materials, NR, and glacier melting risk. The geotextile covering experiments on Urumqi Glacier No. 1 by Wang et al.[5] further demonstrated that NR is the primary energy driver of glacier melt. Notably, the geotextile with a high R_{solar} (78%), compared to the uncovered one (48%), greatly reduced $R_{SW,in}$ contributing to glacier melting by 45%. Additionally, the cooling effect of the geotextile, achieved through enhanced longwave radiation and negative LH, decreased the energy available for ablation by 20% (ref. 5). The above analysis reveals that high-efficiency alleviation of glacier melting, at the material design level, requires materials featuring high R_{solar} ($R_{solar} \rightarrow 1$) and strong ε_{LWIR} ($\varepsilon_{LWIR} \rightarrow 1$) (Fig. 1a,i), which would help reduce the NR component.

To achieve high R_{solar}, materials design based on Mie and Chandrasekhar radiative transfer theories indicates that regulating microscopic pore size is essential. When pore sizes are maintained within the 0.5–3 μm range, the material's reflective performance will be maximized, thus enhancing the R_{solar} values[4]. Additionally, achieving high ε_{LWIR} requires the materials' molecular structure to demonstrate rich and strong stretching or bending vibrations in the 769–1,250 cm^{-1} spectral range, which corresponds to the long-wavelength infrared atmospheric transparency window across 8–13 μm. Currently, the traditional geotextiles used for glacier conservation mainly include polyester (PET) and polypropylene (PP). For PET, absorption peaks in the 769–1,250 cm^{-1} range correspond primarily to its ester group vibrations, specifically the C–O and C=O stretching modes. PP, however, has characteristic absorption bands outside of this range, typically above 1,250 cm^{-1}, including around 1,375 cm^{-1} (CH_3 bending) and 1,455 cm^{-1} (CH_2 bending), leading to a lower ε_{LWIR} compared to PET. Additionally, traditional geotextiles are often produced by weaving, melt blowing, and hot pressing techniques, and their microporous structure is challenging to precisely control, thus yielding poor solar reflectance (<80%). Notably, the newly developed cellulose acetate (CA)-based passive daytime radiative cooling (PDRC) material can be fabricated via industrial electrospinning technology, allowing precise control over its microporous structure (Fig. 1b), which enhances its R_{solar}. Moreover, CA molecular structure demonstrates rich and strong absorption peaks within the 769–1,250 cm^{-1} range, contributing to high ε_{LWIR}. This dual enhancement – both in shortwave and longwave ranges – positions the CA-based PDRC material as a promising candidate for local glacier conservation[4]. Table 1 compares the spectral characteristics of the traditional PET-, and PP-based geotextiles, and CA-based PDRC material through experiments to substantiate the viewpoint above.

Pollutant-proof

Dust soiling on radiative cooling surfaces would elevate solar absorption within the 0.3–2.5 μm range, with an increase from 9.5% to 64% as coverage intensifies. Yet, its influence on emissivity in the atmospheric window (8–13 μm) remains limited. This disparity underscores the dust's selective impact – impeding solar reflectance while preserving thermal emission capacity – thus compromising overall cooling efficiency[8]. In glacial regions, airborne pollutants, like grey-black mineral dust, settle on geotextile surfaces via rainfall, snowfall, and other environmental processes, which can gradually diminish the geotextile's R_{solar}. Indeed, this reduction undermines the long-term service stability of the geotextiles, thus compromising their protective efficacy and potentially accelerating glacier melting. Recent advancements in bio-inspired superhydrophobic surfaces demonstrate these materials' effectiveness in repelling water and pollutants, helping maintain the spectral characteristics and protection function even under harsh environmental conditions[9]. Accordingly, to counteract the adverse effects of dust, it is crucial that the covering geotextiles possess a hydrophobic self-cleaning capability (Fig. 1a,ii) to ensure continued glacier conservation. This functionality necessitates a high apparent contact angle (~150°) for water droplets on the materials' surface, achievable through methods like microstructural design and hydrophobic treatments[9]. As shown in Table 1, the experimental results reveal that the CA-based PDRC material attains a contact angle of 148.6°, approaching superhydrophobicity and exceeding that of PET-based (114.6°) and PP-based (127.8°) counterparts.

Mechanical stability

In the transport, laying, and service phases, the geotextiles also need to maintain sufficient structural integrity to withstand various environmental stresses. Specifically, when deploying the protective geotextiles upon glaciers, careful consideration must be given to potential mechanical damage from sharp objects[6], like icicles, wood stems, and animal bones, which pose a greater risk to the material's integrity than environmental factors like wind pressure. While wind-driven forces are often cited in discussions of material failure, the threat from physical objects should not be underestimated. Sharp debris, such as icicles formed from melting ice, can easily puncture or tear through the protective geotextiles. Similarly, wood stems or animal bones, which may be deposited into glaciers through natural processes, can exert concentrated pressure on geotextiles, leading to their localized damage. These materials are typically designed to withstand environmental stresses like solar radiation and temperature fluctuations, but they may not be sufficiently resistant to puncturing or tearing by solid, sharp objects. This form of mechanical damage will compromise the geotextiles' protective function, weakening their ability to protect the glacier from accelerated melting. Even worse, such damage may complete material failure, undermining conservation efforts. Therefore, in glacier conservation applications, it is critical to select or design materials that are not only effective in spectral characteristics and superhydrophobic properties but also resilient to mechanical impacts (Fig. 1a,iii). Incorporating puncture-resistant layers, or utilizing materials that can absorb localized impacts, can enhance the long-term effectiveness and durability of the protective systems, thus ensuring that they maintain the protective role over time, even in harsh and debris-laden environments. As demonstrated in Table 1, the newly developed CA-based PDRC material exhibits comparable flexibility to traditional PET-based geotextiles, while its mechanical strength exceeds that of both the PET- or PP-based geotextiles, thus basically meeting the necessary mechanical criteria for glacier conservation applications.

Large-scale production and biodegradability

The extensive usage of geotextiles for glacier conservation, as exemplified by the Presena Glacier in northern Italy, where over 100,000 square metres of geotextiles are required annually, underscores the need for careful consideration of production capacity and associated costs[1,5,10]. Additionally, as these materials are applied on a large scale, their effectiveness should be balanced with environmental responsibility[11] (Fig. 1a,iv). Accordingly, cost-effective, biodegradable options, such as cotton or cellulose, present promising alternatives[4]. Take the CA-based PDRC material for example — its abundant raw material sources and scalable production via a roll-to-roll industrial electrospinning process provide both environmental benefits and production efficiency. Although the cost of CA-based PDRC material (US$5–15 per square metre) is currently five to ten times higher than that of commercial composite geotextiles, it is expected to be reduced effectively in the future via the usage of more affordable raw alternatives, just like the agricultural and forestry wastes, and optimizing the production process. Additionally, compared to the biodegradable CA-based material, commercial geotextiles are typically made from synthetic polymers such as PET and PP, which are challenging to degrade naturally[4,5,12–14] (Table 1), thereby limiting their environmental sustainability and friendliness. Furthermore, deploying natural materials can help mitigate the release of microplastics typically associated with synthetic materials. When exposed to extreme environmental conditions over prolonged periods, the synthetic materials can break down, releasing microplastics that persist in aquatic ecosystems, posing ecological risks to the aquatic organisms and water quality.

Beyond the intrinsic requirements for materials, some other considerations are also crucial. According to the Second Chinese Glacier Inventory (CGI-2), for example, there are more than 42,370 glaciers in China, but only a few dozen or so (only one-thousandth of the total) have received major attention, such as those located in the Qinghai–Tibet Plateau, Tanggula Mountains, and the Himalayas[15]. To scale up the glacier conservation efforts, it is essential to move beyond manual geotextile deployment due to challenges like harsh environmental conditions and personnel safety concerns. As such, alternative artificial solutions, including space-based solar radiation management, cloud seeding, snow production, water pumping, cirrus cloud thinning, tropospheric iron salt aerosol injection, black carbon reduction, and powder dispersion have been developed[7]. Among these, developing eco-friendly, bio-degradable, and surface-functionalized CA-based PDRC powders with strong ice/snow adhesion and enhanced overall performance, then spraying them onto glacier surfaces, may provide a cost-effective, low-carbon, and fast-acting solution for achieving local glacier conservation. Employing convenient and efficient automated techniques, particularly drones for powder application, presents a promising approach to spraying these powders on glacier surfaces. For example, it is calculated that the DJI T-40 drone, capable of carrying up to 50 kg and with a maximum coverage radius of 2 km, can spray CA-based PDRC powders (with a density of ~1.3 g cm^{-3}) across an area of ~192.5 m^2 at a thickness of ~200 μm — required for playing a protective function — in a single 30-minute operation. This efficiency far surpasses that of manual labour. Such an innovative approach holds great potential to extend the applicability of these 'green' materials to a broader range of glaciers.

While materials development for glacier conservation is critical, it's just one part of the comprehensive conservation system. Glacier conservation is inherently complex, requiring interdisciplinary collaboration of materials science, glaciology, climatology, geology, hydrology, and ecology[1]. By leveraging expertise and data across these fields, the causes and impacts of glacier retreat can be more comprehensively understood, and an efficient, multidisciplinary communication platform for glacier conservation can be created. Specifically, climatologists can build global climate prediction models using global and regional data on temperature, precipitation, and wind speed, while geologists can elucidate the movement mode and stability of glaciers through studies of bedrock and geological structures beneath glaciers. By integrating these models with real-time monitoring data, glaciologists can dynamically adapt glacier protection schemes, especially for small/local glaciers. Moreover, glaciologists can obtain dynamic data on glacier ablation by analysing flow patterns of glacier meltwater, providing hydrologists with vital data to develop sustainable water management strategies for agriculture and urban areas. Throughout the process of glacier conservation, ecologists play a key role by monitoring the impacts of laying protective materials on surrounding ecosystems, and implementing protective measures as necessary. The interdisciplinary data sharing described above can support materials scientists in optimizing the deployment methods, locations, and coverage areas of materials, thereby enhancing glacier conservation efforts and potentially promoting positive glacier mass balance. This interdisciplinary cooperation model is expected to address global climate change and protect glaciers.

Investing in materials for covering glaciers is encouraging as an adaptation to climate change. As global commitments to reducing greenhouse gas emissions continue to fall short, localized solutions like covering glaciers with PDRC materials offer immediate, practical benefits, especially for nearby communities dependent on glacier meltwater. Moreover, the continued development and refinement of these materials contribute to the broader efforts of climate change adaptation and mitigation. Indeed, they represent a proactive response, addressing the immediate challenges posed by a warming climate while buying time for longer-term solutions to be implemented. As such, the continued investment in glacier coverings is not just a stopgap measure but a critical component of a multi-faceted strategy to combat the adverse effects of climate change on both local and global scales.

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