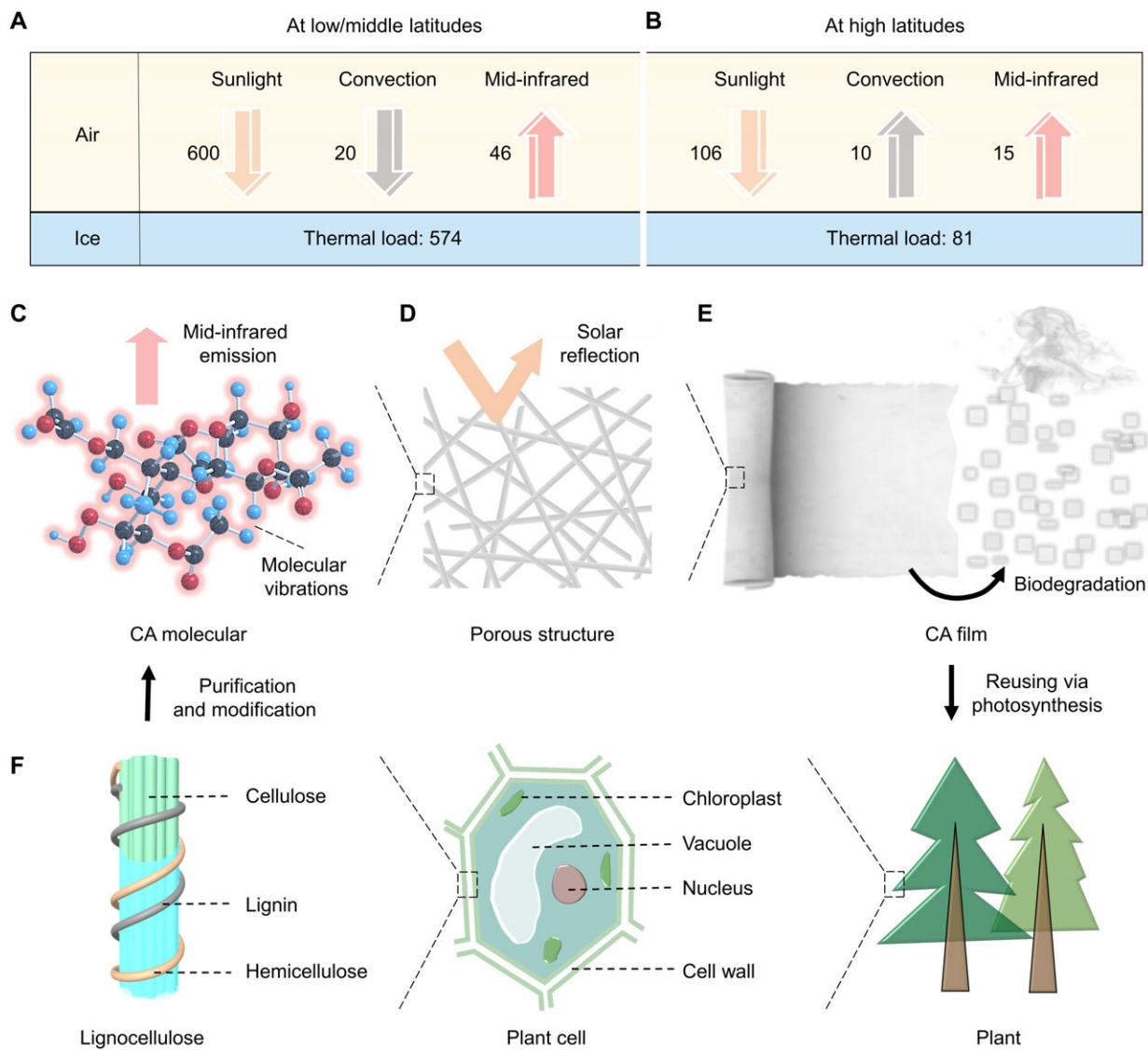


Radiative cooling: Protecting ice from melting under sunlight, from iced food to glaciers

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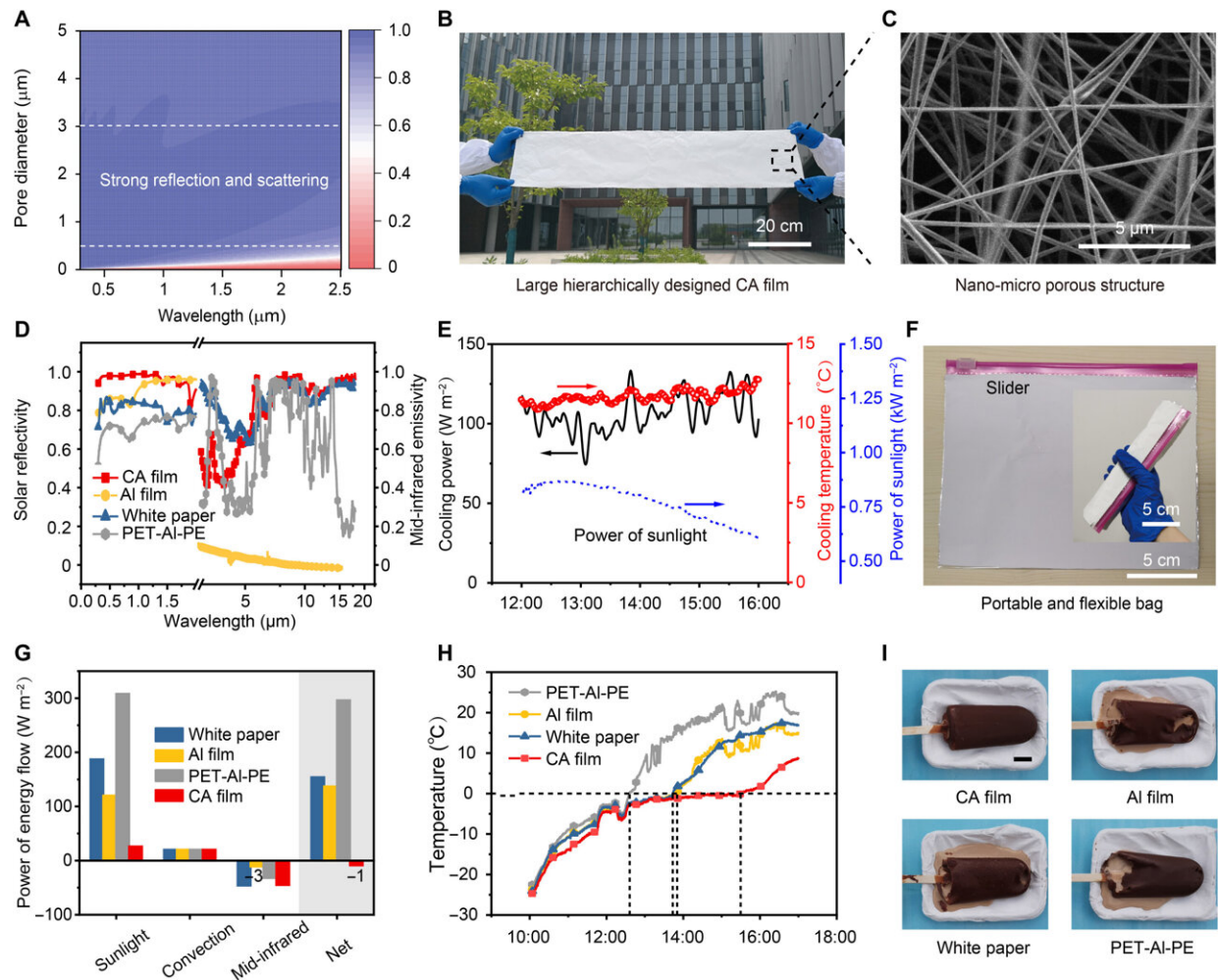


Hierarchically designed and eco-friendly CA film for passive protection of ice under sunlight via radiative cooling. Energy transfer process of ice systems at (A) low/middle and (B) high ($>70.5^{\circ}\text{N}$) latitudes, respectively, in a unit of watts per square meter. The solar irradiation and mid-infrared emission are the dominant energy input and output for both scenarios. The unbalanced energy flows lead to the melt of ice. (C to F) Hierarchical designs and life cycle of the porous CA film for realizing passive ice protection via radiative cooling. (C) The intrinsic molecular vibrations and (D) porous structure endow the CA film with high mid-infrared emissivity and solar reflectivity, respectively. Therefore, the thermal loads on the ice systems are substantially reduced with the hierarchically designed film. (E) At the end of the life cycle, the hierarchically designed CA film can be decomposed by the natural microorganism to reproduce CA (right). (F) The abundant raw materials of the hierarchically designed CA film can be derived from the cytoderm of natural plants. Credit: *Science Advances*, DOI: 10.1126/sciadv.abj9756

Ice plays a significant role in many aspects of life, ranging from food preservation to ice sports and ecosystems, thereby providing incentive to protect ice from melting under sunlight. Fundamentally, ice melts under sunlight due to the imbalance of energy flow of incoming sunlight and outgoing thermal radiation. Radiative cooling can therefore balance the energy flows without energy consumption to sustainably protect ice. In a new report now published in *Science Advances*, Jinlei Li and a team of scientists in advanced microstructures, engineering, atmospheric sciences, and fine mechanics and physics, in China and the U.S., developed a hierarchically designed radiative cooling film using abundant and eco-friendly cellulose acetate molecules. The versatility of the materials provided effective and passive protection to ice in various forms and scales, under sunlight. The outcomes can effectively provide a scalable and tunable route to preserve ice and other critical elements of ecosystems.

Preserving ice

The process of ice preservation can impact daily ice or iced food, iced sports and iceberg levels at [high altitudes or latitudes](#). Research shows how [cold chain logistics](#) alone consume 11 percent of global electricity, and approximately 2.5 percent of the world's greenhouse gas emission to preserve 40 percent of the world's food. Resource limitations have clearly arisen due to imbalanced energy flow due to ice melt under sunlight, and it is of great practical significance to balance this and create a sustainable path for passive preservation of ice systems under sunlight. The bioengineering development in daytime [radiative cooling](#) offers a promising strategy to [balance the energy flows](#). Materials scientists have used a range of materials and structures in these promising works, including multilayer or [patterned photonic structures](#), porous poly film based on nanoparticles, cooling wood and [super-white paints](#) with solar reflectivity greater than 0.95. To preserve ice under sunlight, several stringent requirements must be in place. For example, a calculated increase of net radiation power from 70 to 110 Wm^{-2} can prevent ice or ice food from melting without additional refrigeration. In this work, Li et al. designed a hierarchical film based on abundant and eco-friendly cellulose acetate (CA) to achieve high cooling performance.

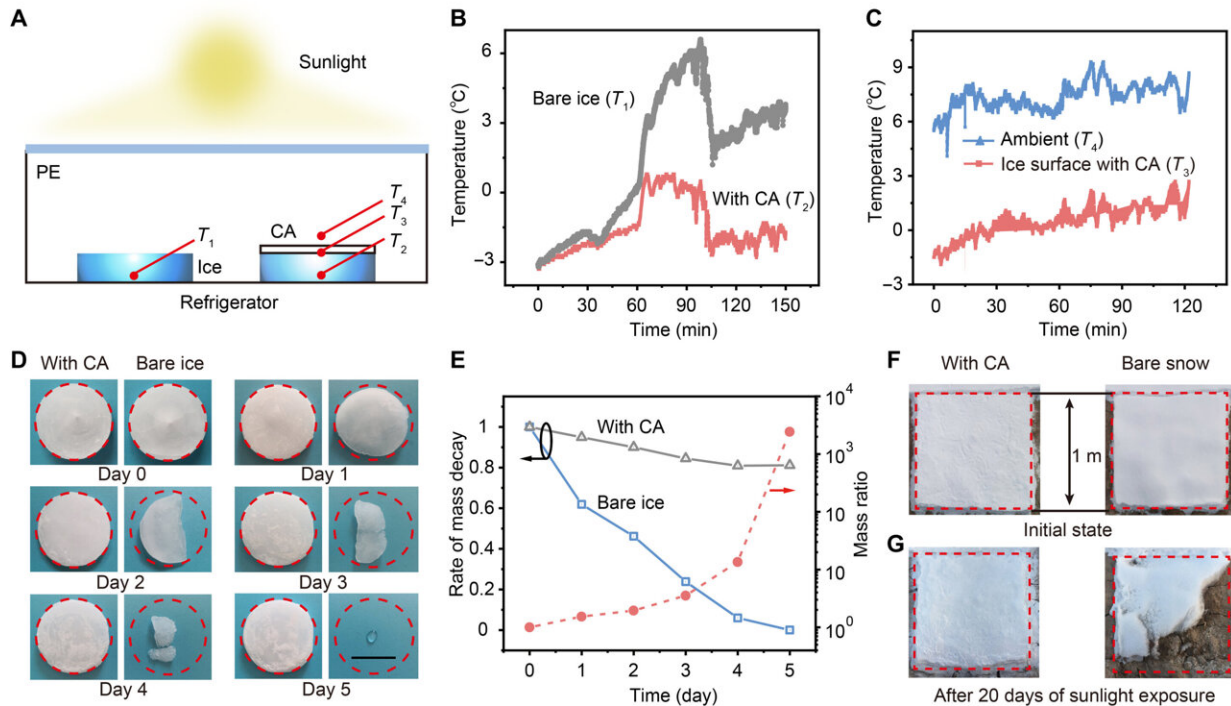


Outdoor ice/iced-food preservation at low/middle latitudes. (A) Theoretical analysis of the pore's scattering effect on the incident sunlight. The color bar represents reflectivity. (B) A photograph of the hierarchically designed CA film. (C) An SEM image of the hierarchically designed CA film. (D) Solar reflectivity (left axis, before the break) and mid-infrared emissivity (right axis, after the break) spectra of the hierarchically designed CA film. The spectra of white paper, Al film, and PET-Al-PE film are shown for comparison. (E) Cooling performance under sunlight referring to the ambient of the hierarchically designed CA film. (F) A photograph shows that the hierarchically designed CA film is tailored into a homemade portable and flexible bag specifically for outdoor ice/iced-food preservation. The pink bar is a slider. (G) Energy flows of ice/iced food wrapped by different packing materials. (H) The temperature evolutions (left axis) of the iced food with different packing ways under sunlight.

(I) Photographs of the ice creams after ~80 min of sunlight exposure (~540 W m⁻²). Scale bar, 2 cm. The hierarchically designed CA film provides the best preservation. Photo credit of (B), (F), and (I): Jinlei Li and Ning Xu, Nanjing University. *Science Advances*, DOI: 10.1126/sciadv.abj9756

Biodegradable cellulose acetate (CA) materials for enhanced cooling performance

The material showed favorable traits for high-performance, large-scale cooling applications due to broadband and high mid-infrared emissivity. The tailored pores functioned as effective scattering centers for incoming solar radiation to minimize thermal load on ice under sunlight to realize passive protection for ice systems. Li et al. chose CA to construct the film due to its eco-friendly abundance as a biodegradable film that can undergo degradation in nature. The team derived [raw cellulose acetate](#) (CA) from natural cellulose, which exists in the plant cytoderm. To design, develop and characterize the cellulose acetate film, the team showed how the impact of broadband and the effective reflection of sunlight allowed the realization of radioactive cooling under sunlight. Based on the theoretical model, Li et al. showed a cellulose acetate based film with a porous structure, with multiple pores sizes to support strong scattering and reflection of sunlight. To accomplish this, they developed a CA molecule-based scalable film using [roll-to-roll electrospinning](#). They presented the microscopic appearance of the product with nanofibers connected to form multiple pores with varying sizes, to ideally scatter sunlight.



Ice and snow protection via the hierarchically designed CA film. (A) A schematic of the custom-made device for verifying the cooling effects of the hierarchically designed CA film for ice. A refrigerator is used to simulate the atmosphere temperature at high latitudes under sunlight. (B) Comparison of the temperature of ice between with and without the hierarchically designed CA film. (C) Subambient cooling enabled by the hierarchically designed film under intense illumination of sunlight of $\sim 700 \text{ W m}^{-2}$ (higher than the case at high latitudes of below 350 W m^{-2}). (D) Photographs show the mass evolution of ice with (left) and without (right) the hierarchically designed CA film. Scale bar (in black), 2 cm. (E) Mass decay of the ice with and without the hierarchically designed film (left axis). The mass ratio of the unmelted ice is also shown (right axis). (F and G) Protection for snow. Photographs show snow (F) at the initial state and (G) after 20 days of outdoor sunlight exposure. Snow melt is slowed thanks to the protection of the hierarchically designed CA materials. Photo credit of (D), (F), and (G): Jinlei Li and Ning Xu, Nanjing University. *Science Advances*, DOI: 10.1126/sciadv.abj9756

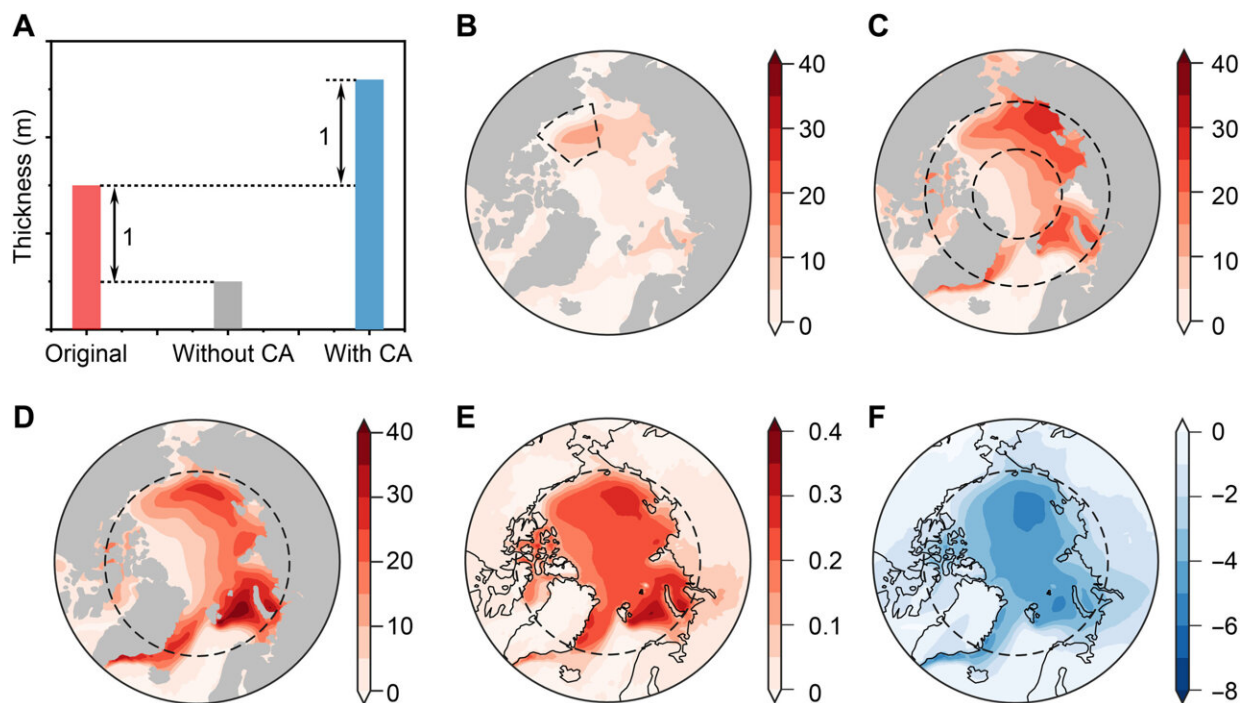
The design and development of cellulose acetate (CA) for ice and iced food preservation

During its mechanism of function, the emissivity of high mid-infrared was critical to conduct heat flow to the [cold universe](#) (3 K) to realize radiative cooling. The hierarchically designed CA film showed a broadband [mid-infrared emissivity](#), with an emissive peak to cool large-scale ice at high latitudes as described using modeling experiments. After achieving the desired optical properties for CA films, Li et al. measured the cooling temperature and power of the films to understand their radiative cooling performance. The experimental setup achieved a cooling power of up to 110 Wm^{-2} and a cooling temperature approximating 12 degrees Celsius under direct sunlight irradiation. The resulting CA film with excellent radiative cooling performance were suited for flexible and portable outdoor ice and iced food preservation. Compared to the newly designed CA film, the team used white paper aluminum (Al) film, and [polyethylene terephthalate \(PET\)-Al-polyethylene films](#) (PET-Al-PE) as controls to show lower solar reflectivity. They next monitored the temperature evolution of iced food wrapped in different materials under natural outdoor sunlight to show longer preservation of iced food covered with the CA film below 0 degrees Celsius for 5.5 hours owing to optical properties of the packing materials. The material provided a very effective mode of passive preservation with 98 percent integrity after 80 minutes of sunlight.

Protecting ice and snow and modeling the cooling effects for ice at high latitudes.

Since the solar input and mid-infrared output can be balanced for outdoor ice and iced [food preservation](#), Li et al. considered this a dominant factor to maintain the ecosystem at high altitudes. While ice and snow are two representative geomorphologies, they maintain

different solar reflectivity, although with similar mid infrared emissivity. The team showed passive cooling effects of the film for ice and snow to confirm protective effects for ice under sunlight. The material also showed excellent protection for snow surfaces at [high altitudes](#) during field testing, to provide direct proof of radiative cooling effects, to slow the melt of local glaciers. The researchers then modeled the cooling effects for ice at high latitudes with global climate impact on the long-term. They accomplished this by studying an iceberg by using a thermodynamic model to show how icebergs melted by approximately 1-m in the summer. In contrast, the CA film facilitated preservation and 1-m thickening of the iceberg. Using climate model experiments, the scientists showed how the approach effectively protected ice systems at high latitudes and credited the design of CA [films](#) and their excellent radiative cooling capacity, to solar reflectivity and other properties of the material, which decreased the surface temperature at high latitudes, by 4 degrees Celsius. The [biodegradability](#) of the material also contributed to the diversity, while soil exposure tests verified the potential to offer environmental-friendly protection for ice and snow at different latitudes.



Ice protection at high latitudes. (A) Thickness change of an iceberg (with a size of dozens of square kilometers). The hierarchically designed CA film can effectively protect an iceberg from melting during the summer season. (B to D) Maps show the differences of sea ice concentration (in the unit of %) between with and without the hierarchically designed CA film. The CA film is applied over the sea ice within (B) the Beaufort Gyre region, (C) the annulus between 70.5°N and 80.5°N , and (D) the north of 70.5°N , respectively. These applied areas are labeled by dark dashed lines. The hierarchically designed CA film is capable of effectively regional/targeted protection for the ice at high latitudes. (E and F) Maps of the differences in surface (E) solar reflectivity and (F) temperature (unit in kelvin) between with and without the hierarchically designed CA film, respectively. The great protective potential for ice at high latitudes of the hierarchically designed CA film is attributed to its excellent sunlight reflection and consequential cooling. Credit: *Science Advances*, DOI: 10.1126/sciadv.abj9756

Outlook

In this way, Jinlei Li and colleagues showed how a hierarchically designed CA film effectively provided eco-friendly and scalable radiative [cooling](#) under [sunlight](#). The team highlighted the mechanism of function and the biodegradability of the material, and its implications to protect ice in daily life and ecosystems. The work calls for more consistent and collective global efforts to maintain a sustainable pathway to protect ice melting with potential climate impact.

More information: Jinlei Li et al, Protecting ice from melting under sunlight via radiative cooling, *Science Advances* (2022). [DOI: 10.1126/sciadv.abj9756](https://doi.org/10.1126/sciadv.abj9756)

XiaoZhi Lim, The super-cool materials that send heat to space, *Nature* (2019). [DOI: 10.1038/d41586-019-03911-8](https://doi.org/10.1038/d41586-019-03911-8)

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