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Perspective

Exploring real-world applications of passive radiative cooling for sustainability

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SUMMARY

Global energy consumption is significantly impacted by the thermal regulation demands in the industrial and building sectors, creating an urgent need for sustainable thermal energy solutions. Passive radiative cooling (PRC) has emerged as a promising strategy, capitalizing on the natural thermal exchange between Earth and outer space to achieve cooling without electricity input. Recent advancements in PRC materials and systems have prompted researchers to explore wider applicability and enhanced functionality. PRC study now extends beyond cooling-optimized spectral designs focused on high solar reflectance and thermal emittance. The current primary research gap centers on leveraging PRC technology to address thermal management needs beyond mere cooling while incorporating specific functionalities for various practical applications. In this perspective, we analyze the current challenges in PRC implementation and identify potential research opportunities for future exploration. Additionally, this perspective seeks to stimulate innovative approaches to PRC design that address real-world applications, bridging the gap toward diverse practical thermal management solutions.

INTRODUCTION

The escalating energy consumption of space cooling and heating systems poses a critical challenge in the face of global warming and greenhouse gas emissions. Radiative heat transfer stands out as a pivotal mechanism that significantly influences thermal management across diverse applications. In response to the mounting need for energy-efficient space cooling solutions, passive radiative cooling (PRC) has emerged as a renewable cooling alternative, which leverages spectral designs to enhance thermal performance in high-cooling-demand environments.

Typical PRC designs feature high solar reflectivity within the 0.3–2.5 μm wavelength range to minimize solar heating, along with high thermal emissivity within atmospheric windows, i.e., 8–13 and 16–24 μm, to radiate heat to the cold universe (~3 K).[1] These optical design modifications deviate PRC materials from ordinary thermal equilibrium, resulting in temperatures dropping below those of the surrounding air. In contrast to traditional air-conditioning systems that expel waste heat and pollutants into the external environment, PRC efficiently dissipates excess heat into outer space without any electricity input. Recent investigations into disordered random photonic structures in coating,[2] film,[3] and ceramic[4] formats have significantly reduced the complexity and cost associated with conventional patterned photonic structures,[5] leading to novel concepts for large-scale implementation. These advancements have attracted attention from industries with high thermal management demands, such as the building sector.

In this perspective, we delve into the fundamental limitations inherent in traditional PRC designs and evaluate recent research progress addressing these challenges. Specifically, the three most primary constraints will be focused on (1) the inherent tension between aesthetic color requirements and cooling efficiency, (2) overcooling due to static optical properties, and (3) weather-dependent energy harvesting. Furthermore, we will examine the unique challenges for diverse application scenarios, including buildings, personal thermal management, agriculture, water harvesting, and military technologies. Lastly, the discussion will extend to emerging opportunities in the context of large-scale PRC technology deployment, such as mitigating urban heat island effects and advancing sustainable design practices.

ADVANCING PRC BEYOND TRADITIONAL LIMITATIONS

PRC research, optimized for cooling performance, has made significant achievements in both spectral design and applicability. However, the limitation inherent to PRC's fixed spectral properties and monofunctional nature have become increasingly apparent.

The color-cooling conundrum

Beyond energy-wise enhancement, there is a growing demand for aesthetic appeal in PRC design, considering PRC requires that surfaces be externally exposed. Due to high reflectivity across the whole solar spectrum, high-performance PRC

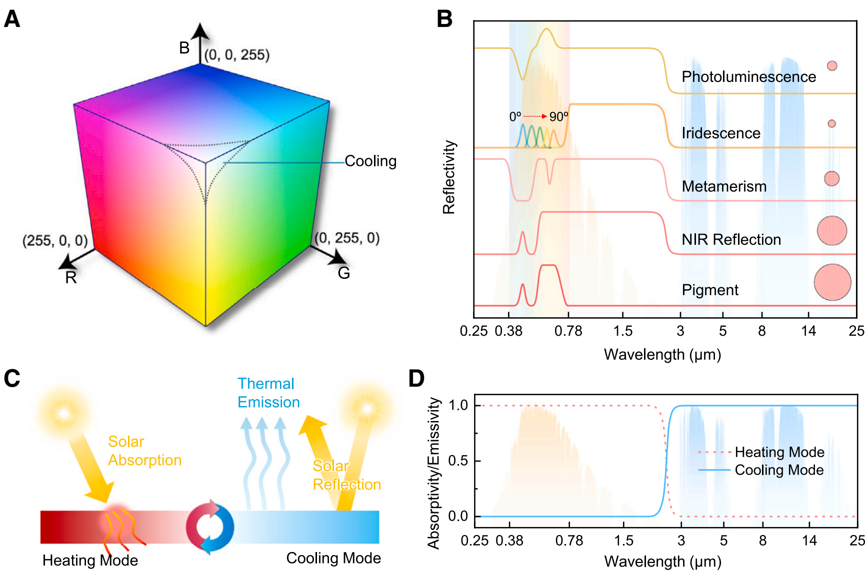

Figure 1. Approaches to overcome inherent limitations in conventional PRC designs

(A) Color with radiative cooling capacity in the RGB color coordinates.

(B) Spectral reflectivity of typical coloration strategies for CPRC materials. The pink circles denote the corresponding thermal loads.

(C) Schematic of APRC materials.

(D) Spectral absorptivity of an ideal APRC material design.

designs feature a stark white appearance that presents both aesthetic and visual pollution challenges, potentially causing physical discomfort and psychological strain for individuals.[6,7] The incorporation of colors, while essential for identification, protection, and aesthetic enhancement, fundamentally conflicts with high-performance cooling, as color creation inherently involves certain visible (VIS) light absorption and additional thermal load generation.[8,9] VIS light counts for almost half of incident solar energy. As a result, most mid-tone shades and all dark hues with VIS absorption exceeding 30% can potentially nullify the cooling power generated by PRC systems (i.e., the maximum cooling power for high-performance PRC is around 130 W/m^2). Thus, a critical compatibility challenge lies in the introduction of coloration, initiating a delicate equilibrium between aesthetic appeal and cooling power (Figure 1A).[10]

To tackle thermal loads in the VIS spectrum, techniques such as structural colors and photoluminescence (PL) can be utilized, leveraging light redistribution or conversion mechanisms (Figure 1B). Structural colors provide a method to manipulate VIS light reflections either spectrally or spatially using photonic structures. Spectral modulation can be achieved by narrowing the reflectivity dips while preserving the color. This phenomenon, known as metamerism, requires precise optimization of the spectral reflectance.[10–12] Spatial engineering can reflect and disperse the VIS light in various directions to create iridescent colors.[13,14] Ideally, this process should involve no VIS light absorption, thereby eliminating any parasitic thermal load for coloration.

Apart from spectral and spatial light manipulation, a simple yet effective method entails converting absorbed VIS light into re-emitted photons by utilizing PL materials, thus reducing light-to-heat conversion and restoring cooling power.[15] Furthermore, the re-emitted light can be tailored to fall within the VIS spectrum, enriching the color diversity of PL-based colored PRC (CPRC) materials and effectively altering the perceived colors.

Noteworthy, numerous challenges in CPRCs need to be addressed to effectively counteract the thermal load resulting from coloration. In the domain of structural colors, the challenge of attaining angle-insensitive and intensely saturated colors with substantial cooling capacities persists. A potential avenue involves a dual strategy that merges spatial and spectral redistribution.[16] Besides, research opportunities lie in developing substrate-independent structural CPRC systems that can achieve high solar reflection without relying on reflective substrates, which would enable broader implementation across diverse surface materials. Moreover, the integration of artificial intelligence models for optimizing spectral and spatial redistribution shows promise in the quest for cool colors without sacrificing cooling power.[17] Concerning PL-based CPRC materials, several critical considerations should be addressed: firstly, the exact spectral properties, energy conversion efficiency, and cooling power recovery should be well evaluated. Secondly, the perceived color in PL-based CPRC materials, including both the reflected VIS light and the re-emitted VIS light, should be clearly defined and distinguished from luminous and reflective colors. Thirdly, the upper limits of cooling potential or the attainable color range with cooling capacities should be determined. A comprehensive methodology that can separate light reflection from re-emission may be explored.[18,19]

Smart thermoregulation

Another limitation of traditional PRC designs lies in the very nature of static and cooling-optimized optical properties. Even though there are significant advantages in hot climates with continuous cooling needs, these designs lead to overcooling during colder periods, such as nights and winter months, resulting in a cooling penalty. In other words, once PRC materials are integrated, cooling occurs spontaneously and uncontrollably.

Adaptive PRC (APRC) designs utilizing optical switching are emerging as a novel research direction to avoid the cooling penalty and fulfill dynamic thermal demands (Figure 1C). An ideal APRC design should exhibit high solar reflectivity as well as high thermal emissivity for cooling in hot periods while demonstrating high solar absorptivity and low thermal emissivity for heating during cold periods (Figure 1D). Active APRC designs, which rely on stimuli, such as electrical[20] or mechanical actuation,[21] offer rapid responses and user-controlled adjustments but come with additional energy requirements. In contrast, passive APRC designs respond to changes in operating conditions, such as temperature,[22] photon interaction,[23] and humidity.[24] The energy-free nature of passive APRC makes it appealing for sustainable applications. The most promising solution lies in thermochromic designs that exhibit tunable optical properties induced by changes in ambient temperature. The thermal regulation capability depends on the spectral tunability range and the modulation of spectral amplitudes between heating and cooling modes. A suitable phase transition temperature is also critical, as it determines the point at which the material transitions between cooling and heating modes. While various materials, like vanadium dioxide (VO_2),[22] hydrogels,[25] thermochromic microcapsules,[26] germanium-antimony-tellurides,[27] and perovskites,[28] have been investigated for reversible optical regulation, a research gap persists in developing passive APRC materials that combine high-contrast, broadband optical switching with suitable transition temperatures and long-term stability. These materials face several challenges that impede their widespread implementation in real-world scenarios. Such limitations include phase transition temperatures that exceed practical ranges, the necessity for complex containment systems, and a tendency to deteriorate when subjected to extended periods of outdoor environmental conditions. Addressing this challenge is crucial for creating effective thermal regulation solutions. Recent studies have shown promise in integrating double-sided static optical designs with thermo-responsive moving components.[29] This innovative approach leverages the benefits of a cooling-optimized surface and a heating-optimized surface, providing high optical contrast that enhances performance and temperature-triggered passive control. However, the feasibility and durability of incorporating movable components into real applications still require further investigation.

All-weather energy harvesting

The cooling performance of PRC materials is not solely dependent on the intrinsic spectral properties of the materials but is also heavily influenced by local weather conditions. While effective in blocking sunlight and reducing solar heating, an opaque atmosphere completely hinders the dissipation of mid-infrared (MIR) radiation from the Earth's thermal emissions to outer space, leading to a significant suppression of the PRC effect as well as the thermal regulation capability of APRC systems. By selectively designing in the MIR wavelength range, the cooling performance can be enhanced under high humidity conditions. Selective cooling materials are engineered with high reflectivity in wavelength bands outside the atmospheric window, reducing the absorption of atmospheric thermal radiation[30] and enabling these materials to achieve a better cooling performance compared to broadband IR-emissive materials in low-transmittance atmospheric conditions.

However, in extreme conditions, such as rainy days, selective optical designs may still fail to provide effective radiative cooling. Globally, on average, one-third of the year is characterized by rainy conditions. During these periods, dense cloud cover obscures the atmosphere and makes PRC systems completely ineffective. Rainy conditions, while hindering radiative heat transfer, present an opportunity to harness energy.[31] Droplet-based electricity generation could be the solution to increasing energy utilization and productivity per unit area. A triboelectric nanogenerator leverages surface electron transfer and electrochemical reactions that occur when droplets contact specific materials and electrodes. This energy harvesting method has the potential to power low-power devices or supplement building electrical needs. Integrating PRC or APRC materials with tailored droplet electricity generation surfaces creates a synergistic system for year-round energy harvesting, further enhancing the energy efficiency of buildings.

APPLICATIONS

PRC technology can provide valuable insights and/or potential solutions for scenarios involving thermal management. Researchers have extensively studied its applicability across various fields. In this perspective, the focus is on exploring five distinct application scenarios for PRC technology: buildings, personal thermal management, agriculture, water harvesting, and military applications, each of which presents unique challenges and opportunities, requiring careful consideration of optical properties to specific needs and addressing diverse thermal management targets.

Buildings

Given buildings' significant impact on global energy,[32] implementing PRC technologies in buildings offers a promising approach to enhance energy efficiency and thermal performance (Figure 2A). Integrating PRC with buildings can be broadly categorized into two types: incorporation into building envelopes as enhanced cooling measures and integration with building services systems as an additional cooling source to improve systematic cooling efficiency. Furthermore, in alignment with standard-compliant practice, integrating PRC technology into local building energy codes can serve as a viable measure for innovating building energy regulations.

For building envelopes, PRC can be applied in the form of paint or coatings on roofs or walls as a passive cooling strategy. This has led to the widespread adoption of cool roof schemes.[32] However, traditional cool roof coatings on the market typically have a solar reflectance below 0.86,[33] which significantly curtails the daytime sub-ambient cooling performance under direct sunlight. In order to address this limitation, super-cool roof strategies based on PRC technology have been proposed, which involve integrating state-of-the-art PRC coatings into building roofs.[34] To fulfill the city landscaping aesthetic requirements and to avoid the white glare effects of PRC caused by broadband solar reflection, CPRC coating is highly desired for building applications.[35,36] To further enhance the performance of PRC-integrated wall structures and mitigate challenges arising from environmental temperature disparities, directional thermal emitters have been developed to leverage the directional characteristic of thermal emission.[37,38]

In addition to direct implementation on building envelopes, PRC technology can be effectively integrated with various building service systems for systematic performance improvement. Common applications include combining PRC with direct/indirect evaporative cooling systems, thermoelectric cooling

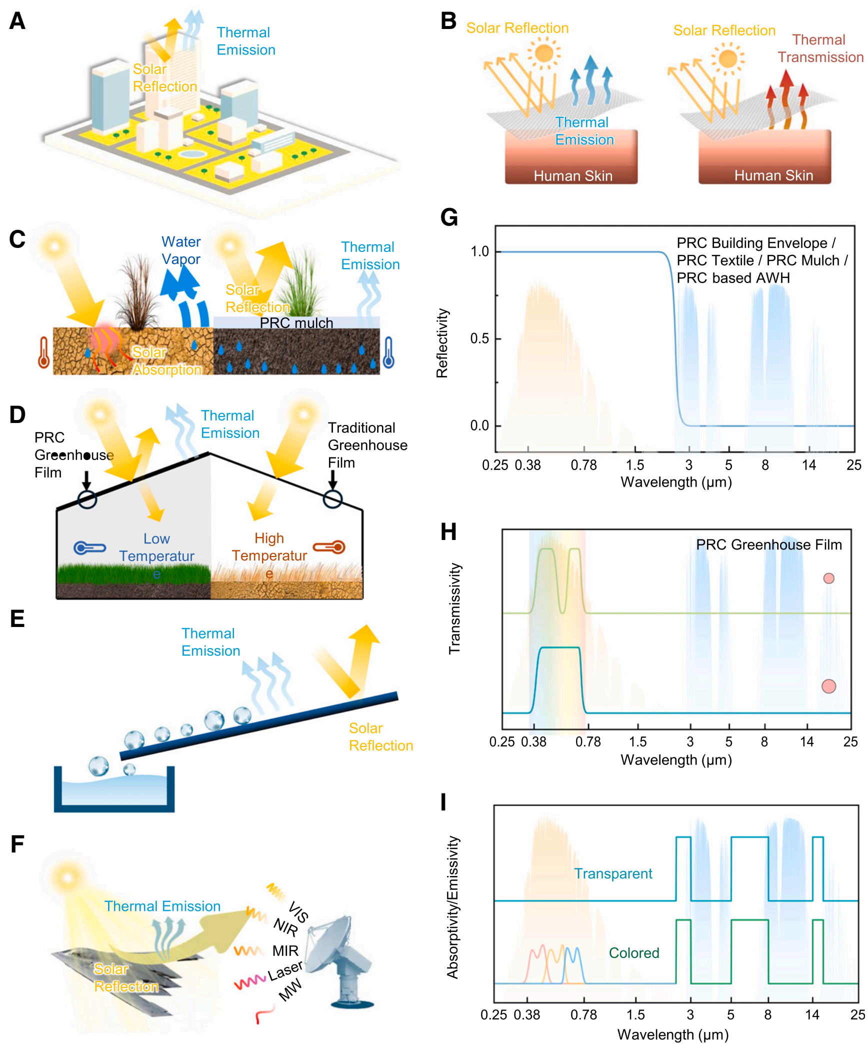

Figure 2. Applications and optical designs of PRC

(A) PRC in building envelope applications.
(B) Personal thermal management enhancement via PRC textile.
(C) Water conservation and crop temperature regulation in agriculture applications via PRC mulch.
(D) Indoor temperature management via greenhouse PRC film.
(E) Water harvesting and collection via PRC technology.
(F) Camouflage and PRC in military applications.
(G) Optical design for PRC building envelopes, PRC textile, PRC mulch, and PRC-based atmospheric water harvesting.
(H) Optical design for greenhouse PRC film. The pink circles denote the corresponding thermal loads.
(I) Optical design for military applications.

systems, ground-source heat pump systems, and vapor-compression air-conditioning systems.[32] For building applications, an important research question is how to merge this PRC technology into local building codes to innovate building energy regulations. This integration relates to building energy savings evaluation on a regional scale. For instance, incorporating PRC-based super-cool roof strategies into the revision of the overall thermal transfer value codes of practice represents a notable application to facilitate substantial energy efficiency improvements.[39]

Personal thermal management

PRC technology also presents a promising and sustainable solution for personal thermal management.[40] Advanced material engineering, including nanomaterial fabrication,[41,42] metamaterial architectures,[43–45] and multilayer structural designs,[45] has enabled the development of PRC textiles with enhanced MIR emissivity/transmittance and solar reflection compared to conventional textiles (Figures 2B and 2G). These improvements effectively regulate personal microclimates, thereby mitigating heat stress and health risks in outdoor environments.

PRC textiles with MIR-emissive designs[43,46] receive heat transferred from the human body and efficiently dissipate it through outgoing thermal radiation from the textile's outer surfaces. MIR-transparent textiles enable cooling effects as well. The human body, with an IR emissivity of up to 98%,[47,48] acts as an excellent thermal radiator. MIR-transparent materials such as polyethylene (PE)[41,42,49] and polyamide[50] enable human radiation to transmit through them with low heat loss and directly dissipate the heat into the universe. The structural versatility and material diversity of these PRC textiles enable applications beyond personal cooling, including integration with flexible electronics[51] and wearable energy-harvesting devices.[52–54]

Despite promising outcomes from laboratory and small-scale tests, PRC textiles face significant challenges in achieving large-scale production and commercialization. A critical hurdle is balancing optical performance, such as solar reflectance, with visual appearance, including color and design, which is essential for the widespread adoption of this technology. Recent studies have proposed methods to improve the aesthetics of PRC textiles, such as doping with PL quantum dots[55] or incorporating colored inorganic nanoparticles[56] to achieve vibrant coloration. However, ensuring the long-term stability and durability of these materials while simultaneously meeting consumer demands for comfort and aesthetics remains a key challenge.[57,58] Moreover, addressing the environmental impact of production processes and material sustainability is crucial for the future of PRC textiles.

Current manufacturing practices often involve synthetic polymers, which can produce non-biodegradable "white waste" and pose long-term environmental risks. In order to improve sustainability, research is shifting toward using natural materials.[59,60] These efforts aim to develop more durable materials and products while advancing recycling and reuse technologies. Such approaches can help reduce waste and reliance on virgin resources, supporting a more circular and eco-friendly production model.

Agriculture

In contrast to improving human thermal comfort and reducing energy consumption in buildings, thermal management in agriculture is primarily focused on optimizing plant growth conditions. Global warming has intensified heatwaves and droughts in many regions, presenting significant challenges to agriculture. PRC technology offers two key applications to optimize the photothermal environment for plant growth: films to cover greenhouses and mulches (Figures 2C and 2D). Polymer films, such as PE, are commonly used as greenhouse coverings, shielding crops from external environmental factors while facilitating sunlight exposure.[61] However, in hot climates, those conventional greenhouse films often lead to excessive solar heating and heightened indoor temperatures due to their high solar transmittance.[62] This can adversely affect crop yields. Therefore, managing the spectrum of greenhouse films is vital for agricultural productivity. One strategy is to enhance the effectiveness of radiative heat dissipation by covering greenhouses with films that have high thermal emittance or transmittance, similar to the design principles of PRC textiles. For instance, traditional greenhouse films can be modified by incorporating transparent particles with high MIR emission. This modification can increase thermal emittance without impeding sunlight transmittance, thereby reducing the thermal load inside the greenhouse. Another approach to mitigating indoor heat accumulation is to block unnecessary solar radiation on greenhouse films. Plant photosynthesis relies on photosynthetically active radiation (PAR) within the 400–700 nm wavelength range.[63] Specifically, the process utilizes blue-violet (400–480 nm) and red-orange light (600–700 nm).[64] Ideally, PRC greenhouse films should transmit PAR only, reflect the surplus sunlight, and emit thermal radiation within atmospheric windows (Figure 2H). Achieving this requires the fabrication of highly selective broadband optical management films, a feat realized through the creation of multilayer photonic crystal superlattices using sputtering technology.[65] While effective, this manufacturing process is intricate and economically challenging. Future practical applications demand simpler and more cost-effective fabrication methods. Cost-effective PL materials present a promising solution, as they absorb radiation that is not needed by plants, like ultraviolet or green light, and emit useful PAR, curbing thermal buildup from ultraviolet exposure and benefiting plant photosynthesis.[66–68] Notably, PL particles can be seamlessly integrated into PRC films, existing as micro-particles dispersed within transparent, high-emissivity polymer films to facilitate light conversion.[69] In practical outdoor applications, PL materials face stability challenges under prolonged solar exposure. Degradations such as PL quenching, thermal-induced PL quantum yield decreases, and efficiency losses could impact long-term performance efficiency and should not be overlooked.[70] Moreover, greenhouse-covering films are prone to accumulate electrostatic dust on their external surfaces from soil and air contact. This dust accumulation can lead to shading effects, diminishing light transmittance,[71] compromising crop quality and yield, and increasing the financial burden on agricultural producers. Consequently, incorporating self-cleaning and dust-proof features is vital for these films.

High solar absorption by the soil raises temperatures,[72] inhibiting root growth[73] and accelerating soil water evaporation, which reduces water absorption by the roots and ultimately leads to decreased yields. Mulches serve as an additional protective barrier, isolating the underground part of plants while retaining soil temperature and moisture for crop cultivation.[74–76] However, typical mulches are often gray or dark in color, causing high solar absorption and primarily serving purposes of insulation, warming, or weed and pest control rather than specifically addressing heat stress.[77–79] This creates an opportunity for PRC technology. By leveraging PRC mechanisms, polymer blends[74] or biomaterial cellulose[75] can be used to develop opaque mulch, helping to maintain cooler soil temperatures under direct sunlight and thereby alleviating soil thermal stress. Future research on PRC mulches should include a broader range of crop varieties and soil types to validate the field performance of PRC mulches in terms of cooling capacity, breathability, biodegradability, etc. The removal process of these mulches after use also warrants attention, as minimizing soil pollution is crucial. Utilizing biomass for mulches presents a potential solution, but the extraction and production costs of raw materials, along with the lifespan of these coverings, must be assessed. Ideally, the lifespan of biomass-based PRC coverings should coincide with the crop growth cycle, allowing the coverings to naturally degrade into the soil after harvest, thereby providing nutrients for future crop growth.

Water harvesting

PRC can be used for direct water vapor condensation by lowering the temperature to the dew point and collecting liquid water, known as passive radiative condensers (Figure 2E). Ideally, they can produce water without energy input, representing one of the passive atmospheric water harvesting (AWH) methods. Radiative condensers can be categorized into nighttime radiative condensers and all-day radiative condensers based on their functionality derived from optical properties. Materials with high MIR emissivity can be used in nighttime radiative condensation, yet all-day radiative condensers need designed materials with high reflectance in solar radiation (Figure 2G), including metamaterials and advanced photonic structures (porous polymers, multilayer structures, and randomly distributed structures).[80,81] Other than optical properties, the water harvesting performance of radiative condensers is dependent on their wetting properties, aiming for the effective collection of condensed water based on the water removal mechanism. In addition, ambient factors, such as temperature, relative humidity (RH), wind speed, and cloud coverage fraction, greatly influence the water harvesting performance.[82] It was calculated that the theoretical upper limit of radiative condensers could reach a dew harvesting mass flux of 13 g/m^2/h at an ambient temperature of 20°C and an RH of 40%.[83]

Considering synergetic effects, there are several applications of PRC in AWH. For example, radiative condensers can be combined with other passive or active AWH methods, such as sorption-based AWH.[84,85] Also, PRC can be used to lower the sorption temperature in sorption-based AWH systems to increase the water uptake of sorbents and further boost the water harvesting performance.[86]

The current challenges of radiative condensers include low water productivity, dependence on weather conditions, and complicated fabrication of elaborately designed materials, which impede large-scale and wide-spread applications. In the future development, suitable condenser materials and effective condenser designs should be employed to boost water productivity and condensation efficiency, such as manipulated desired optical properties,[87] wettability-engineered surfaces,[88] tilted condensation surfaces with an inclined angle,[89] lowered condenser temperatures via auxiliary shielding,[90] etc. From a long-term global perspective, the environmental impact caused by large-scale and wide-spread applications of radiative condensers needs attention from researchers, such as the redistribution of water vapor, greenhouse effect, and radiation balance of the Earth.[91]

Military

Military applications of PRC technology present the most stringent and complex requirements for optical design, driven by the critical need for both thermal management and stealth in diverse operational environments. The integration of PRC has become increasingly prevalent in the design of personal gear and military installations, such as camouflage clothing and combat aircraft. This incorporation aims to boost user comfort and ensure the thermal stability of facilities (Figure 2F). The extensive use of IR detection for identifying heat-emitting entities is attributed to the passive and universal nature of thermal radiation, accounting for up to 30% of all military detection methods.[92] Notably, achieving IR stealth necessitates reducing MIR emissivity to blend with the environment and evade detection. This objective contrasts with PRC technology's requirement for high MIR emissivity, posing a unique challenge in maintaining stealth capabilities while leveraging PRC for thermal management purposes.

Numerous strategies have been suggested to tackle the challenges mentioned above, with mainstream design approaches categorized into active and passive methods. Active IR modulators dynamically control the IR characteristics of objects like human bodies or military equipment, enabling the seamless transition between IR camouflage and PRC states. Techniques involving phase-change materials,[93] graphene,[94] and nanometal particles based on hybridized localized surface plasmon resonance[95] have shown promise in achieving this adaptability.[96] Furthermore, through the precise design of conductive oxide materials via doping or nanostructuring, optical transparency can be delivered, presenting opportunities for VIS light stealth.[97] This property enables the material itself to achieve VIS light stealth by blending into its surroundings, as it does not obstruct or alter the transmission of VIS light. Changes in the MIR emissivity of the active IR modulator will affect the basic electrical characteristics of the device. How to stabilize these properties and ensure compatibility with stealth performance in different wavelength ranges will be a key research direction in the future.

Moreover, by capitalizing on the spectral differentiation mechanism of IR detectors, passive spectral selective emission technology can reconcile IR camouflage with PRC. Utilizing metamaterial structure designs based on surface plasmons[98] and slow-wave effects,[99] the spectral properties of materials can be precisely adjusted by varying the size parameters of metamaterial unit cells. This method can fulfill the requirements of low emissivity at the atmospheric window range while upholding high emissivity elsewhere, thereby evading IR detectors and achieving PRC.[100] Additionally, by optimizing the material systems and leveraging metamaterial structural designs, the spectrum of selective emitters can be more finely controlled. Based on the original MIR selective emission, combined with the low NIR emissivity and the high reflectivity or structural color effect in the VIS range, NIR camouflage and VIS light stealth can be achieved (Figure 2I).[96] This capability can be extended to include laser and microwave stealth, ensuring compatibility between PRC and multispectral stealth.[101] This strategy is more suitable for high-temperature targets but has limitations when applied to low-temperature targets, such as human-related applications like camouflage clothing. At a body temperature of ~300 K, radiative power is relatively low, and radiative cooling accounts for only a small portion of the total heat dissipation, with convection and evaporation being the dominant mechanisms. Future research should focus on developing hybrid solutions that combine radiative cooling with other cooling mechanisms to enhance adaptability in low-temperature environments. Moreover, most metamaterial-based selective emitters feature complex structures and manufacturing processes. It is crucial to simplify the process and avoid the risk of structural degradation in application scenarios. There is an urgent need for new theoretical approaches or the development of novel material systems or structures to overcome these challenges.

SCALABILITY AND AFTER

As the benefits of technology are most impactful when applied over large areas, such as building envelopes and urban infrastructure, the development of scalable solutions for PRC becomes crucial (Figure 3A). Research aiming to find the ideal spectra for PRC has traditionally involved high-precision processes, such as electron beam evaporation and etching, to fabricate nano- or micro-scale structures in photonic PRC materials. While these methods offer efficient cooling performance, their practical application is limited due to the high costs associated with their fabrication, installation, and maintenance. This limitation has driven efforts to develop more scalable and cost-effective approaches to PRC material designs.

Early scalable PRC designs utilized metal film substrates with solar-transparent polymer coatings, providing flexibility but facing challenges in durability and installation. Scattering systems have emerged as promising alternatives, particularly porous/fibrous structures and particle-dispersed polymers. Porous structures leverage refractive index mismatches from air

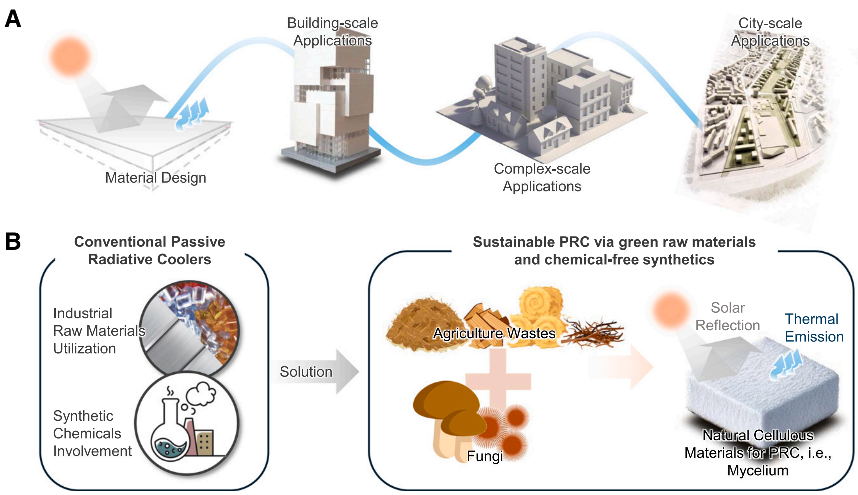

Figure 3. Scalability and sustainability

(A) Scalability process of PRC from material design to city-wide implementation.

(B) Transitioning to sustainable PRC materials.

pockets and can be created using cost-effective techniques, such as phase inversion and melt spinning, allowing customized PRC performance through structural adjustments. Particle-dispersed polymers employing a high refractive index and high band-gap particles as an effective scattering medium enable easy application of PRC onto various surface conditions. The paint-like characteristics of particle-dispersed polymers demonstrate significant potential for widespread acceptance due to their compatibility with familiar application methods and existing manufacturing and distribution networks.

Given the increasing use of PRC in building applications, it is considered a possible approach for mitigating urban heat islands, especially in the face of rapid urbanization. Previous research has not yet fully encompassed the intricate interactions on an urban scale. The geometry of a city has a significant influence on the large-scale thermal performance, which is generally overlooked. Tall buildings cast shadows that alter the solar exposure of surrounding surfaces, while street canyons impact airflow and radiation exchange. Multiple reflections between buildings can increase overall solar radiation absorption, potentially offsetting the benefits of PRC on individual surfaces. Additionally, the effectiveness of PRC is directly influenced by factors such as the sky view factor, variations in sun angles, and resulting shadow patterns, underscoring the importance of strategically placing PRC materials based on specific urban morphology. Current research methodologies encompass both experimental and modeling approaches, including computational fluid dynamics, energy simulation tools, and meteorological modeling. However, existing analyses predominantly focus on building rooftops, with limited studies on walls and streets. Future research directions could expand to capture the broader climatic impacts of large-scale PRC deployment by integrating urban canopy models with meso-scale atmospheric models. Long-term simulations spanning different seasons and weather conditions would provide valuable insights into assessing year-round performance across various climate zones. It is crucial to incorporate climate change scenarios to ensure the long-term viability of PRC strategies. Comprehensive simulation studies will play a pivotal role in guiding the development and implementation of PRC technologies, ultimately contributing to the establishment of more sustainable and climate-resilient urban environments.

Finally, the construction industry plays a significant role in global energy consumption and greenhouse gas emissions, making it a primary focus for sustainable development initiatives. PRCs present a promising avenue for reducing energy usage in buildings, but their environmental impact throughout their life cycle must be carefully evaluated to align with Sustainable Development Goal (SDG) principles. Eco-friendly and sustainable PRC materials should ideally embody several essential characteristics, including the use of renewable or recycled raw materials, energy-efficient manufacturing processes, non-toxic compositions, long-term durability, and the potential for recycling or biodegradability at the end of their lifespan. Research in this field remains limited, with most PRC studies focusing on cooling performance and scalability rather than considering the environmental footprint of the materials and processes involved. Current PRC designs often rely on highly processed materials, such as high-purity polymers and dimension-controlled particles, with material synthesis frequently involving organic solvents, which are not environmentally friendly (Figure 3B). Some promising developments have emerged in utilizing natural and sustainable materials, such as cellulose,[75] wood,[102] and mycelium for PRC material fabrication, offering potential pathways to more environmentally friendly PRC solutions (Figure 3B). Achieving high cooling performance with environmentally friendly materials may necessitate innovative design strategies and material combinations. Scaling up the production of sustainable PRCs while maintaining cost effectiveness poses another obstacle. Additionally, ensuring the long-term resilience and weather resistance of eco-friendly PRCs in various climatic conditions remains a significant challenge.

CONCLUSION

The evolution of PRC from a theoretical concept to a potentially transformative technology showcases the power of interdisciplinary research in tackling global energy challenges. As PRC progresses, it transcends being just a cooling solution to become a pivotal shift in thermal management that intertwines materials science, photonics, and sustainable engineering. The array of challenges encountered during its development—from aesthetic integration to adaptive control and scalability—mirrors broader hurdles in adopting sustainable technologies. These challenges underscore the necessity for solutions that seamlessly harmonize innovation with practicality, a pivotal equilibrium for translating scientific progress into tangible impacts across diverse sectors. The versatility of PRC applications, spanning urban infrastructure, agriculture, and military equipment, positions it as a unifying platform for sustainable development, potentially fostering unparalleled collaborations across industries and research domains.

Looking ahead, the true potential of PRC lies in its role within a wider ecosystem of sustainable technologies. Its fusion with renewable energy systems, smart materials, and Internet of Things (IoT) technologies could pave the way for comprehensive approaches to energy management and climate adaptation. The journey of PRC from the laboratory to large-scale implementation provides invaluable insights for the advancement and commercialization of other emerging sustainable technologies, stressing the significance of considering scalability, environmental impact, and economic viability from the outset. As we refine and expand PRC technology, we are not simply cooling surfaces—we are establishing the foundation for a more resilient and sustainable future. This progress prompts us to look at past conventional boundaries, advocating for a holistic perspective on sustainability that encompasses energy efficiency, resource management, and human comfort.

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AUTHOR CONTRIBUTIONS

Conceptualization, C.Y.T.; writing – original draft, K.L., Y.F., H.L., X.L., J.C., S.C., and S.B.; writing – review & editing, C.Y.T., K.L., Y.F., H.L., X.L., J.C., S.C., S.B., and A.P.; visualization, K.L., Y.F., H.L., X.L., J.C., and S.C.; supervision, C.Y.T.; project administration, C.Y.T.; funding acquisition, C.Y.T.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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