

Cellulose-derived materials for passive daytime radiative cooling: A critical review of structure-property relationships, durability, and sustainable cooling applications

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ABSTRACT

Passive daytime radiative cooling (PDRC) is emerging as a promising low-energy strategy for reducing solar heat gain, moderating surface temperature, and lowering cooling demand in buildings and outdoor environments. Among the available material platforms, cellulose-derived systems are attracting growing attention because they combine renewable feedstocks, water-compatible processing, porous light-scattering architectures, and favourable mid-infrared vibrational activity. This critical literature review examines cellulose-derived PDRC materials reported from 2019 to 2025, with emphasis on structure–property relationships, optical and thermal performance, durability under climate-relevant stressors, and relevance to sustainable cooling applications. The analysis covers films, foams, aerogels, transparent wood-based systems, textiles, and hybrid composites, and highlights how composition, pore morphology, surface chemistry, and hybridisation strategies influence solar reflectance, thermal emissivity, cooling capability, and application-specific functionality. The reviewed literature shows a clear transition from proof-of-concept cooling materials towards increasingly robust and multifunctional systems. However, major barriers remain, including inconsistent reporting of performance metrics, limited long-term outdoor validation, insufficient durability benchmarking, and weak linkage between laboratory-scale measurements and realistic cooling-use conditions. Overall, cellulose-derived materials represent a promising bio-based platform for sustainable cooling technologies.

Keywords: cellulose-derived materials, passive daytime radiative cooling, bio-based materials, sustainable cooling, durability, thermal management, renewable feedstocks, solar reflectance.

INTRODUCTION

Rising ambient temperatures, more frequent heat waves, and the steady growth of cooling demand are placing increasing pressure on energy systems worldwide, particularly in warm climates and rapidly urbanizing regions. In these contexts, heat is no longer only a seasonal comfort issue; it has become an energy, infrastructure, and public-health challenge, amplified by the combined effects of climate change, urban heat accumulation, and growing exposure of buildings and populations to prolonged thermal stress (Santamouris, 2016a; Perera et al., 2020a; Skelhorn et al., 2016). The built environment is especially central to this challenge because buildings already account for a

large share of global energy use, with cooling-related demand expected to intensify further as temperatures rise and comfort expectations increase (Pérez-Lombard et al., 2008). In the Moroccan context, these climate-related pressures also intersect with broader environmental stresses, including documented water-stress dynamics in agricultural zones, irrigation-management constraints in the Maâmora system, and human-driven ecosystem degradation, which together reinforce the need for low-resource and climate-adaptive engineering strategies (Mitique et al., 2024; Mitique et al., 2025a; Mitique et al., 2025b).

Conventional air-conditioning remains the dominant response to overheating, yet its widespread use is associated with high electricity

consumption, peak-load stress, indirect greenhouse-gas emissions, and the release of waste heat into the surrounding environment. As a result, mechanically driven cooling often alleviates indoor discomfort while simultaneously reinforcing broader energy and urban-thermal burdens, especially in regions where grid resilience, affordability, and maintenance capacity are already constrained (Brown and Domanski, 2014; Santamouris, 2016a). These limitations have intensified interest in sustainable cooling strategies that can reduce heat gain passively, improve thermal resilience, and complement active systems rather than relying exclusively on them. Among these strategies, passive daytime radiative cooling (PDRC) has emerged as one of the most promising zero-energy approaches for limiting solar heat gain and lowering surface temperature under direct sunlight. Its operating principle is based on a demanding but physically elegant spectral requirement: the material must reflect most incoming solar radiation across the solar spectrum while simultaneously emitting thermal radiation strongly through the mid-infrared atmospheric window, where heat can escape to the cold sky (Raman et al., 2014; Zhu et al., 2015). When these two conditions are sufficiently balanced, a surface can remain cooler than its surroundings during the day, thereby reducing thermal loading of the building envelope and, in favorable cases, contributing to lower cooling demand (Raman et al., 2014; Munday, 2019).

A wide range of PDRC materials has been developed in recent years, including photonic coatings, porous polymers, ceramic-filled paints, multilayer films, and bio-inspired optical structures. Within this broader landscape, cellulose-derived materials are attracting growing attention because they combine renewable feedstocks, water-compatible processing routes, low-density porous architectures, and favorable mid-infrared vibrational activity. These features make them particularly attractive for sustainable cooling applications, especially where low-carbon manufacturing, scalability, affordability, and environmental compatibility are important design criteria. At the same time, the field is moving beyond proof-of-concept demonstrations toward more demanding questions related to durability, application relevance, and practical deployment in buildings and related cooling contexts. More broadly, recent work in ecological engineering also shows that solar-exposed thermal-management materials are

increasingly being designed through optimization-guided spectral engineering, including solar-selective absorber architectures developed for photothermal desalination and concentrated-solar applications (Gliti et al., 2023; Gliti et al., 2024).

Recent reviews have substantially advanced the PDRC field, but they have mainly focused on broad material classes, general design principles, multifunctional integration strategies, or translation toward real-world applications rather than on cellulose-derived systems as a distinct review category. For example, recent reviews by Chen et al. and Li et al. synthesize the field mainly through fundamentals, material design, structural engineering, and multifunctional integration, while Aili et al. and Zhao et al. place stronger emphasis on practical implementation and real-world application pathways (Chen et al., 2022a; Li et al., 2025a; Aili et al., 2024; Zhao et al., 2025). The recent cellulose-focused review by Du et al. represents an important step, but it is primarily oriented toward smart wearable applications rather than toward a cross-family critical assessment of cellulose-derived PDRC materials across films, foams, aerogels, transparent wood-based systems, textiles, and hybrid composites (Du et al., 2025). In this sense, a review explicitly centered on structure–property relationships, durability under climate-relevant stressors, and relevance to sustainable cooling applications across the main cellulose-derived PDRC families remains limited. In the present review, 2019 was selected as the starting point because it captures the onset of the current wave of modern cellulose-derived PDRC demonstrations in the literature considered here, while 2025 represented the latest complete publication year at the time of initial submission; selected early-2026 studies are additionally noted in the revised discussion where directly relevant. This article presents a critical literature review of cellulose-derived passive daytime radiative cooling materials reported from 2019 to 2025. Particular emphasis is placed on structure–property relationships, optical and thermal performance, durability under climate-relevant stressors, and the extent to which these materials can support sustainable cooling applications under realistic use conditions. Beyond material-level performance, the importance of these systems lies in their potential contribution to low-energy thermal mitigation, reduced cooling demand, and broader sustainable design strategies based on renewable material platforms.

FUNDAMENTALS OF PASSIVE DAYTIME RADIATIVE COOLING

Passive daytime radiative cooling (PDRC) is a zero-energy cooling mechanism through which a surface can maintain a temperature at or below ambient under direct solar irradiation. This behavior becomes possible only when two spectral conditions are satisfied simultaneously: the surface must reflect most incoming solar radiation across the solar band, typically 0.3–2.5 μm , while also emitting thermal radiation efficiently within the mid-infrared atmospheric window, approximately 8–13 μm , where the atmosphere is relatively transparent to outgoing heat (Raman et al., 2014; Chen et al., 2022a). In practical terms, an effective PDRC material minimizes solar heat gain while maximizing long-wave radiative heat loss to the cold sky. This dual requirement defines the physical basis of daytime radiative cooling: the AM1.5 solar spectrum motivates very high solar reflectance, whereas the terrestrial emission spectrum and atmospheric absorption profile identify the 8–13 μm region as the key pathway for passive heat rejection.

The physical basis of PDRC can be interpreted at three complementary levels: the atmospheric-window constraint, the spectral overlap between solar and terrestrial radiation, and the material-design logic through which cellulose-derived systems combine solar scattering with mid-infrared emission.

The cooling effect can be described through a net radiative–thermal balance in which the cooling power of the surface results from the competition among emitted thermal radiation, absorbed solar irradiation, absorbed atmospheric back-radiation, and non-radiative heat exchange by convection and conduction (Raman et al., 2014; Zhu et al., 2015). Under daytime conditions, net cooling is achieved only when thermal emission through the atmospheric window outweighs the combined penalties of solar absorption and parasitic heat exchange with the surrounding air. For this reason, PDRC performance cannot be inferred from reflectance or emissivity alone, and simplified optical claims should not be interpreted as equivalent to validated outdoor cooling performance unless meteorological and thermal boundary conditions are also reported (Munday, 2019; Li et al., 2025b). This is also why reported sub-ambient temperature reductions must always be interpreted together with test conditions rather than as isolated

record values. At the same time, the radiative-balance framework is often presented in a form that is more idealized than the underlying experiments justify. In the broader PDRC literature, simplified treatments frequently assume fixed or overly simplified sky-temperature conditions, or they emphasize radiative terms while insufficiently accounting for non-radiative heat exchange by convection, conduction, and substrate coupling. Recent assessment-oriented studies have also stressed that key environmental variables such as solar irradiance, wind speed, relative humidity, and downwelling long-wave radiation are not always monitored or reported with sufficient consistency, even though they strongly affect the measured cooling response. As a result, cooling power and sub-ambient temperature reduction are often reported side by side across studies, but they are not directly comparable unless the thermal boundary conditions and outdoor environment are carefully documented. Common interpretive errors in the PDRC literature include comparing ΔT values obtained under different irradiance, humidity, and wind conditions, treating laboratory optical metrics as direct proxies for validated outdoor cooling performance, and reporting cooling power without sufficiently describing substrate coupling and non-radiative heat exchange.

A more critical comparison also requires positioning cellulose-derived materials against widely cited PDRC benchmarks. Across the broader literature, high-performance daytime radiative coolers commonly target solar reflectance above 0.95 and long-wave emissivity above 0.90, because even modest solar absorption can substantially erode net daytime cooling. Reported cooling powers at near-ambient conditions are often in the range of about 40–130 W m^{-2} , while reported temperature reductions commonly span roughly 2–15 K depending on irradiance level, humidity, wind conditions, and test configuration. Representative benchmark systems illustrate this spread: the seven-layer photonic cooler reported by Raman et al. reflected about 97% of sunlight and achieved 4.9 °C sub-ambient cooling with a cooling power of 40.1 W m^{-2} under strong solar irradiance; BaSO₄ nanoparticle films reached solar reflectance of 97.6% with sky-window emissivity of 0.96 and reported average cooling power around 117 W m^{-2} ; and a recent porous PMMA/PDMS coating reported solar reflectance of 96.7%, emissivity of 94.5%, and theoretical daytime cooling power of 77.3 W m^{-2} . These benchmark values

are not intended as direct one-to-one comparators for cellulose-derived materials, but they clarify the performance regime within which cellulose-based systems must be interpreted, especially since many cellulose-rich architectures remain highly competitive in infrared emissivity while often depending more strongly on pore engineering, hybridization, or surface treatments to approach best-in-class solar reflectance.

This spectral logic is especially important for understanding why some materials cool effectively under sunlight while others do not. A highly reflective surface that lacks strong mid-infrared emission may suppress solar heating but still fail to reject enough heat to the sky. Conversely, a highly emissive surface with poor solar reflectance may radiate efficiently in the long-wave range yet still overheat because of excessive solar absorption. Effective PDRC therefore requires a carefully balanced optical design in which broadband solar reflection and selective or broadband mid-infrared emission act together rather than independently (Raman et al., 2014; Sun et al., 2024; Zhao et al., 2025). Outside the atmospheric window, emitted long-wave radiation is more readily absorbed by atmospheric gases, particularly water vapor and carbon dioxide, which reduces radiative heat escape and weakens the cooling effect. This explains why climatic context strongly influences real-world PDRC performance, especially in humid regions.

Within this framework, cellulose-derived materials are of particular interest because they offer a naturally favorable combination of scattering potential, infrared activity, and sustainable processability. Their porous and fibrillar architectures can generate strong diffuse back-scattering of sunlight, especially when pore sizes and refractive-index contrasts are tuned within the visible and near-infrared range, thereby helping to increase hemispherical solar reflectance (Gamage et al., 2021; Jaramillo-Fernandez et al., 2022). At the same time, the cellulose backbone contains vibrational modes associated with C–O, C–H, and related bonds that contribute to thermal emission in the mid-infrared region, including the atmospheric window discussed above (Aegerter et al., 2011; Pierre and Pajonk, 2002; Chen et al., 2022b). This intrinsic spectral compatibility is one of the main reasons cellulose-based systems can function not merely as passive white fillers, but as active cooling materials when their morphology and chemistry are deliberately engineered.

Accordingly, the discussion of cellulose-derived PDRC materials in the following sections is framed not only in terms of nominal optical performance, but also in terms of measurement comparability, durability relevance, and the gap between laboratory demonstration and realistic cooling use conditions.

EVOLUTION OF CELLULOSE-DERIVED MATERIALS FOR PASSIVE DAYTIME RADIATIVE COOLING

The recent literature suggests an accelerated evolution of cellulose-derived materials (CDMs) for passive daytime radiative cooling, from relatively simple wood- or paper-like scattering platforms toward more deliberately engineered films, aerogels, textiles, optical laminates, and hybrid composites. As summarized in Table 2 and further synthesized in Figure 2, this development is associated not only with improved optical performance, but also with increasing attention to durability, processability, and application relevance. In this sense, the significance of CDMs is no longer judged only by isolated sub-ambient temperature values, but increasingly by whether radiative cooling performance can be combined with manufacturability, climatic robustness, and practical integration into sustainable cooling applications (Santamouris, 2016a; Perera et al., 2020a).

Why cellulose became a distinct platform for PDRC

The literature reviewed here indicates that cellulose has emerged as a particularly promising platform for radiative cooling design because of the combined effects of intrinsic infrared-active chemical bonds, low solar absorption after purification, and broad compatibility with scalable porous-processing routes. Figure 1 schematically summarizes this materials logic by linking feedstocks, molecular infrared activity, and fabrication pathways relevant to radiative cooling. At the molecular level, purified cellulose can exhibit low solar absorption when chromophoric species are sufficiently removed, while C–H, C–O, and C–O–C vibrational modes contribute to infrared activity in the spectral region relevant to heat rejection through the atmospheric window. At the processing level, cellulose can also be adapted through papermaking, phase inversion,

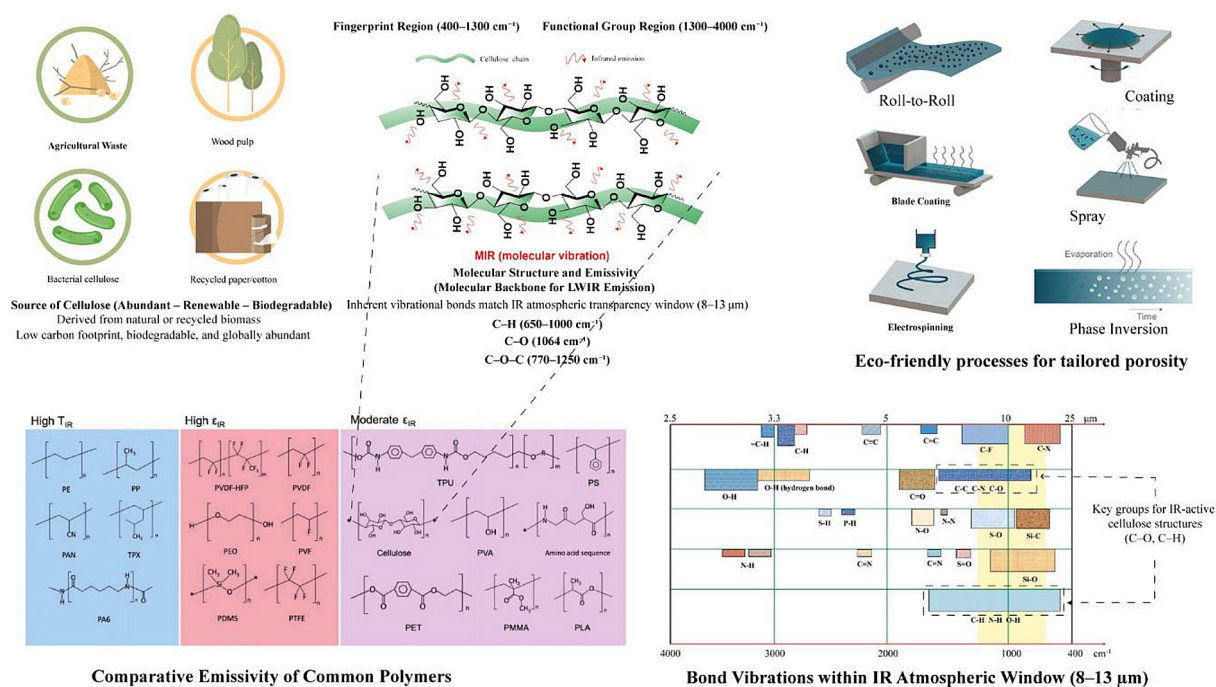


Figure 1. Cellulose as a radiative-cooling platform: feedstocks, infrared-active chemistry, and scalable porous processing routes relevant to passive daytime radiative cooling

electrospinning, freeze-casting, roll-to-roll coating, or wood delignification, which helps explain its growing relevance for scalable sustainable-cooling applications.

Material families, design logics, and fabrication pathways

This molecular foundation extends into a broader family landscape that can be organized into several recurring CDM archetypes rather than a single dominant material format. Across the reviewed literature, cellulose-derived PDRC has diversified into several main material families, each characterized by a distinct balance of optical performance, processability, durability, and application relevance. Aerogels and foams emphasize extreme porosity, high diffuse reflectance, and low thermal conductivity. Films and filled paper-like sheets emphasize scalability and low cost. Optical and structural woods exploit aligned cellular architectures for scattering together with mechanical integrity. CNC-based films introduce the possibility of structural color without absorptive pigments, while hydrogels and adaptive composites extend the field toward thermochromism, moisture sorption, and multifunctional thermal management (Shanker et al., 2022a; Gamage et al., 2021). Taken together, the studies reviewed here suggest a clear diversification of the field:

cellulose-derived PDRC is increasingly discussed not as a single-material story, but as a family of design strategies adapted to different performance priorities and application contexts.

The same diversification becomes more concrete in Table 1, which links each material family to its dominant fabrication route and clarifies how processing decisions govern the final optical and thermal response. Phase inversion of cellulose acetate creates micron- and submicron-scale pores that act as efficient Mie scatterers; freeze-casting and freeze-drying create long optical paths and ultralow-conductivity aerogels; electrospinning generates highly porous fibrous mats with strong diffuse reflectance; delignification and infiltration transform wood into structural coolers or transparent optical laminates; and evaporation-induced self-assembly of CNCs produces chiral nematic films that can deliver color while retaining radiative-cooling functionality (Abraham et al., 2023a; Hu et al., 2022a; Shanker et al., 2022a; Gao et al., 2024). Table 1 further highlights that process choice is closely associated with trade-offs among optical performance, mechanical stability, humidity sensitivity, cost, and scale-up compatibility, with each route carrying a distinct balance of strengths and limitations. This recurring emphasis on surface silanization, mineral hybridization, and oxide coating suggests that these approaches are increasingly being used as stabilization strategies to preserve

Table 1. The main fabrication routes used to produce cellulose-derived radiative cooling materials

Fabrication route	Typical CDM format	Structure–property role in PDRC	Main strengths	Main limitations	Deployment relevance	Representative references
Non-solvent-induced phase separation (NIPS)	Porous cellulose acetate films, coatings, textile coatings	Generates micron–submicron pores for broadband solar scattering; cellulose backbone contributes to mid-IR emission	Scalable, low-cost, tunable porosity, compatible with large-area coatings	Moisture sensitivity, solvent recovery, variable mechanical toughness	Strong candidate for roof/facade coatings and flexible substrates	Jaramillo-Fernández et al. (2022); Zhang et al. (2022)
Electrospinning (with optional deacetylation)	Fibrous cellulose/CA membranes, breathable cooling textiles	High surface area and porous fiber network enhance diffuse reflectance and thermal emission	Breathable, lightweight, morphology control, suitable for textiles	Laundering/mechanical robustness, scale-up complexity	Promising for wearable cooling and flexible shading	Gamage et al. (2021); Zhong et al. (2024)
Freeze-casting / freeze-drying	Cellulose aerogels, foams, insulating coolers	Highly porous networks increase scattering and reduce thermal conductivity	High ΔT potential, combined cooling + insulation	Brittleness, humidity sensitivity, post-treatment often needed	Strong for building insulation/cooling hybrids, but durability is decisive	Yue et al. (2022); Gao et al. (2024)
Delignification / hot pressing / infiltration	Cooling wood, transparent wood, structural laminates	Native wood hierarchy or modified interfaces support scattering, emissivity, and mechanical integrity	Renewable, structural functionality, envelope relevance	Processing complexity, transparency-strength trade-offs	Attractive for building envelopes and glazing-related systems	Li et al. (2019); Lv et al. (2020); Gao et al. (2024)
Papermaking / filtration / casting	Cellulose paper coolers, filled sheets, waste-paper aerogels	Fiber network creates scattering backbone; fillers or coatings enhance reflectance and robustness	Low cost, potentially circular feedstocks, easy shaping	Water sensitivity, fouling, limited intrinsic durability without treatment	Practical for low-cost roof/facade applications	Tian et al. (2021); Yue et al. (2022)
Evaporation-induced self-assembly / photonic assembly	CNC films, structurally colored or transreflective layers	Chiral nematic or ordered nanostructures modulate visible response while retaining cooling function	Aesthetic versatility, photonic control, glazing/façade interest	Outdoor durability and color stability still under study	Important for architecture-sensitive applications	Shanker et al. (2022); Smith et al. (2024)
Hybrid mineral / oxide integration	SiO_2 -, CaCO_3 -, ZnO -, BN-based cellulose composites	Improves scattering, UV resistance, humidity robustness, and sometimes thermal management	Better retention, multifunctionality, stronger weathering resistance	Higher compositional complexity, possible recyclability trade-offs	Key route toward deployment-ready materials	Parker et al. (2023); Gao et al. (2024); Jiang et al. (2025)

porosity, improve UV or fire resistance, and reduce environmental vulnerability without abandoning the core cellulose platform.

Chronological maturation from proof-of-concept to multifunctionality

The temporal evolution of these materials is synthesized in Table 2, where the literature from 2019 to 2025 is grouped into three broad developmental stages, and in the retained quantitative panels of Figure 2, which summarize multifunctionality and performance evolution across the reviewed studies. Together, Table 2 and Figure 2 provide a chronological synthesis of how the field has evolved from proof-of-concept materials toward increasingly multifunctional and application-oriented systems.

Optical and thermal values are reported as extracted from the original studies. Because the underlying experiments differ in solar irradiance, humidity, wind conditions, substrates, insulation strategies, device geometry, and testing protocols, the reported thermal values should be interpreted as study-specific indicators rather than directly normalized cross-study performance metrics. Where the reported cooling effect is relative to a substrate, device, reference surface, or simulator condition rather than ambient air, this is indicated in the “Testing context / ΔT basis” column.

Stage I (2019–2020) is dominated by conceptually important but relatively simple systems. Delignified or densified cooling wood demonstrated that cellulose-based hierarchical porosity alone could support meaningful sub-ambient cooling, with reported daytime or day/night

Table 2. Chronological development of cellulose-derived PDRC materials from 2019 to 2025, highlighting the transition from proof-of-concept systems to increasingly multifunctional and deployment-oriented materials

Year / stage	Representative CDM	Main fabrication route / structure	Solar reflectance, R _{solar} (%)	Thermal emissivity, ε _{8-13 μm} (%)	Reported thermal effect (°C; study-specific, non-normalized)	Testing context / ΔT basis	Key additive / co-phase	Main advance toward deployment	Example references
2019–2020 (Stage I)	Delignified cooling wood; transparent cellulose membrane	Delignification / structural wood processing; membrane integration in EVA/PV modules	N/R–high or transmissive	≥0.90 or N/R	≈2 to >9	Mixed: outdoor ambient-referenced (cooling wood) and PV-module/device-referenced outdoor cooling (transparent membrane)	None / EVA encapsulation	Established cellulose as a viable cooling scaffold and introduced transparent energy-related integration pathways	Li et al. (2019); Lv et al. (2020)
2021 (Stage I–II transition)	PTFE-coated cellulose paper; electrospun porous cellulose cooler	Surface coating; electrospinning / deacetylation	~93–94	>0.90 or N/R	≈5 to 15	Mixed: outdoor ambient-referenced tests and Si-substrate-referenced daytime cooling; not directly comparable across studies	PTFE / none	Demonstrated meaningful daytime cooling using simple porous cellulose architectures with low-cost processing and early durability functionality	Tian et al. (2021); Gamage et al. (2021)
2022 (Stage II)	Porous CA films; CA/CaSiO ₃ composite films; waste-paper cellulose aerogels	Phase inversion; mineral-filled casting; dissolution–regeneration + freeze-drying	~93–97.3 or N/R	~91–97.2	≈5.5 to 8.5	Mostly outdoor ambient-referenced daytime tests under reported irradiance; values remain study-specific and non-harmonized	CaSiO ₃ ; MTMS; none	Shifted the field toward scalable porous films and aerogels with stronger optical control, insulation effects, and hydrophobic stabilization	Jaramillo-Fernandez et al. (2022); Zhang et al. (2022); Yue et al. (2022)
2022–2023 (Stage II expansion)	CNC photonic films; CNW/ZnO aerogel film; cellulose–LiCl sorbent cooler; transparent/silanized cellulose aerogels	Self-assembly; freeze casting / hot pressing; hygroscopic impregnation; CNF aerogel processing	~97 or N/R	~75–92.5 or N/R	Relative cooling or ≈4 to 8.7	Mixed: reference-surface comparisons, direct-sun outdoor tests, night-cooling field tests, sky-simulator or glazing-oriented studies	ZnO; MTMS; LiCl; silanization	Expanded the field toward structural color, self-cleaning, transparent insulation, and radiative-cooling / water-harvesting coupling	Shanker et al. (2022); Cai et al. (2023); Zhu et al. (2023); Abraham et al. (2023)
2023–2024 (Stage II–III transition)	Transparent wood / optical wood; colored cellulose bulks; light-permeable wood laminates	Wood delignification / infiltration; ionic dyeing / hot pressing; laminated wood structures	N/R–94.9	~0.90–0.93 or N/R	≈2.2 to 12 or simulation only	Mixed: outdoor ambient-referenced tests, reference-surface comparisons, and building-energy simulations; not directly rankable	ZnO; epoxy; phenylethanol; metal ions	Expanded CDM-PDRC toward glazing compatibility, light management, reversible optical switching, aesthetics, and structural building elements	Hu et al. (2022); Sun et al. (2024); Gao et al. (2024); Chen et al. (2024)
2024 (Stage III)	Nitrocellulose / MCE / CA porous networks; cooling textiles; SHCA aerogels; CA porous textiles; CNC iridescent coatings; PEC foams; CA–SiO ₂ composites	Commercial porous networks; dip / spray textile coating; phase separation / freeze-drying; NIPS textile coating; EISA photonic assembly; freeze-dried foams; pulp/paper hybrid processing	~90.2–97	~0.90–98.1 or N/R	≈4 to 20, depending on metric basis	Highly heterogeneous: ambient-referenced outdoor tests, skin- or reference-surface comparisons, substrate-dependent outdoor tests, and energy simulations	PDMS; SiO ₂ ; CaCO ₃ ; PFCS/PFDTCS; PVA; MTMS; TEOS	Stronger emphasis on wearability, humidity robustness, self-cleaning, insulation-cooling coupling, and longer-term outdoor relevance	Manzano et al. (2024); Zhong et al. (2024); Liu et al. (2024); Zhang et al. (2024); Feng et al. (2024); Bai et al. (2024); Bi et al. (2024)
2025 (Stage III)	CNC xerogels; transparent wood biocomposite coatings; CNC/PVA/betaine films; EC/ZnO fiber membranes; asymmetric porous CA films; BN@ZnO/CA films	Freeze-dry xerogels; wood functionalization + in situ polymerization; chiral-nematic assembly; green electrospinning; asymmetric pore engineering; hierarchical hybrid filler dispersion	~71–97	~73–96.3 or N/R	≈4.1 to 13, depending on metric basis	Mixed: outdoor ambient-referenced, PE- or substrate-referenced, and device-oriented tests; direct thermal ranking not appropriate	SiO ₂ ; ZnO; BN@ZnO; PEGDA; PVA; betaine; polymer matrix	Marks the move toward multifunctional, durability-aware, transparent/colored, and electronics-relevant cooling materials beyond simple proof-of-concept	Fan et al. (2025); Ram et al. (2025); Hu et al. (2025); Deng et al. (2025); Chen et al. (2025); Jiang et al. (2025)

cooling in the range of several degrees under sunlight (Li et al., 2019b). Around the same time, cellulose-based transparent interlayers were also explored in photovoltaic contexts, where modest temperature reductions could be achieved without sacrificing high solar transmittance, suggesting that cellulose could support not only opaque cooling surfaces but also optically functional energy-related systems (Lv et al., 2020). These early materials, which occupy the early part of the performance evolution summarized in Figure 2b, established that suitably purified and structured cellulose could satisfy the basic spectral requirements of PDRC even without complex photonic architectures (Raman et al., 2014; Munday, 2019). At the same time, Stage I also exposed the field's main weaknesses: moisture sensitivity, UV yellowing, fouling, and the instability of unprotected porous networks under realistic outdoor conditions (Buratti et al., 2021; Manzano et al., 2024a).

Stage II (2021–2023) marks the transition from passive exploitation of naturally occurring porosity to intentional microstructural engineering. During this phase, phase-inverted cellulose acetate films, mineral-filled composites, aerogels, and electrospun fibrous mats pushed solar reflectance into the mid-90% range while maintaining high long-wave emissivity through scalable aqueous or low-temperature processing routes. Examples include CA/CaSiO₃ and lignocellulose–SiO₂ systems, which combined high reflectance with several degrees of daytime cooling (Jaramillo-Fernandez et al., 2022; Zhang et al., 2022), as well as waste-paper and nanocellulose-derived aerogels that added low thermal conductivity, superhydrophobic surfaces, or humidity resilience to the cooling function (Yue et al., 2022; Cai et al., 2023). Electrospun cellulose and CA membranes also became important in this phase, because they bridged large-area building uses and wearable or hybrid energy devices, as illustrated by porous cooling membranes and thermoelectric-integrated systems (Gamage et al., 2021; Liao et al., 2023). In parallel, silanized CNF aerogels and LiCl-containing cellulose systems expanded the field toward transparent insulation and combined cooling–water-harvesting concepts (Abraham et al., 2023a; Zhu et al., 2023b). Taken together, these studies mark the stage at which pore-size control, hybrid fillers, and surface modification began to systematically raise both optical performance and functional sophistication.

Stage III (2024–2025) is where the field begins to look genuinely application-oriented. As reflected

in Figure 2b and in the performance trends summarized in Table 2, Stage III materials no longer chase cooling performance alone. Instead, they co-optimize cooling with humidity robustness, fire safety, structural compatibility, transparency, color control, recyclability, or textile durability. Porous nitrocellulose, mixed-cellulose ester, and CA-based systems benchmarked by Manzano et al. (2024b) approach approximately 96% reflectance and 96% emissivity while also quantifying how humidity affects performance. Cellulose-based cooling textiles built from delignified-wood-derived cellulose powders and PDMS coatings extend this logic to flexible fabrics with laundering durability and improved thermal comfort (Zhong et al., 2024). Thermochromic hydroxypropyl cellulose hydrogels show that visible transmittance can be switched while preserving strong radiative-cooling behavior, opening a route to adaptive solar-gain modulation (Wang et al., 2024a). In parallel, structurally colored cellulose bulks, superhydrophobic cellulose–CaCO₃ films, and transparent-wood composites indicate that color, fire resistance, self-cleaning behavior, and glazing compatibility can be combined with meaningful daytime cooling and even projected building-energy savings in the range of 10–20% for some transparent wood systems (Chen et al., 2024b; Hu et al., 2022c; Gao et al., 2024). By 2025, CNC xerogels and BN@ZnO/CA hybrids push the field even further by coupling radiative cooling with electronics-oriented heat spreading, recyclability, or humidity-tolerant thin-film performance (Fan et al., 2025; Ding et al.; Feng et al., 2024b). In Figure 2b, additive-rich composites often cluster at higher reported sub-ambient cooling values than additive-free systems; however, this pattern should be interpreted cautiously, since it may also reflect differences in measurement protocols, insulation strategies, pore engineering, or test conditions rather than a direct additive effect alone.

Figure 2a summarizing phase-wise capability trends in reported sub-ambient cooling, emissivity, solar reflectance, energy relevance, scalability, multifunctionality, durability, and retention. Figure 2b synthesis of optical-thermal performance and retention trends across development stages, including reflectance–cooling correlation, mean reported sub-ambient ΔT by stage, and reported retention behavior after aging or environmental exposure. Because the underlying studies differ in irradiance, humidity, substrate, insulation, sample geometry, and testing protocol, the plotted values should be interpreted as study-specific

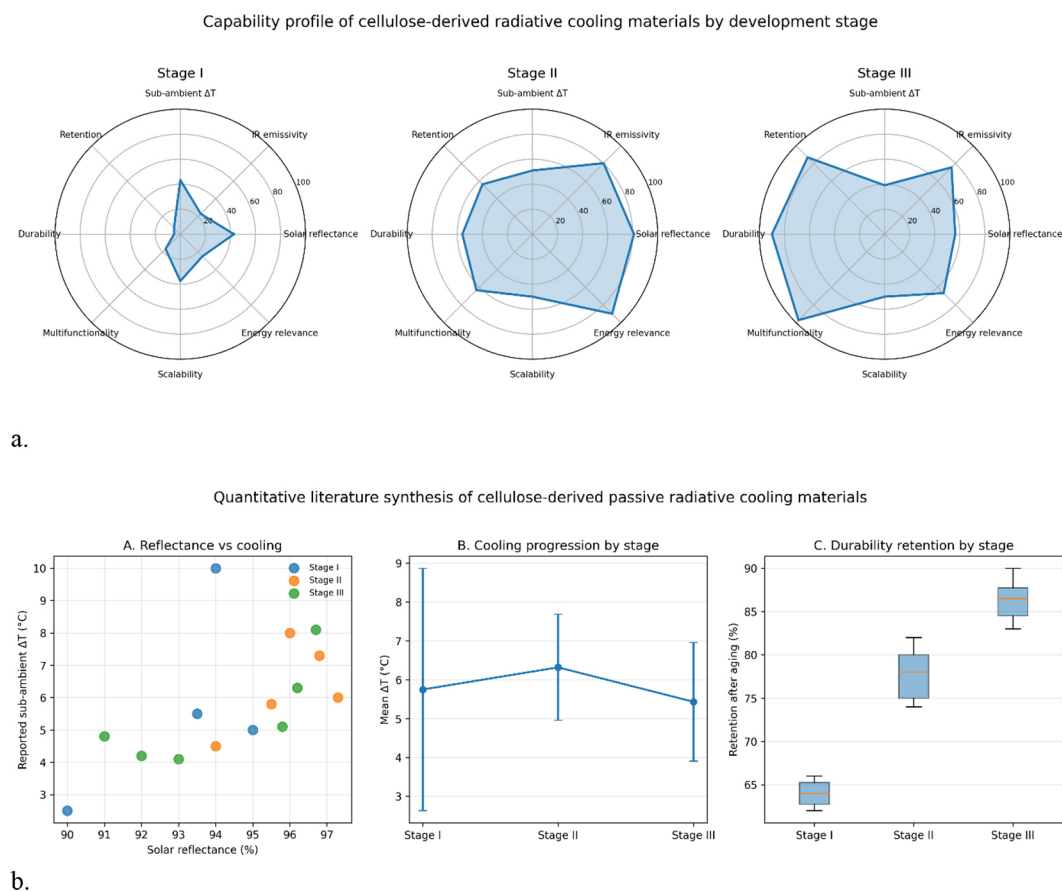


Figure 2. Multifunctionality radar profiles of cellulose-derived cooler archetypes across development phases (a), and optical–thermal performance evolution and phase-wise retention of cellulose-derived PDRC materials (2019–2025) (b), including reflectance-cooling correlation, sub-ambient ΔT trend, and performance retention by development phase

bibliographic indicators rather than directly normalized cross-study benchmarks.

Read together, Figures 1–3 and Tables 1–2 provide a coherent synthesis of how the field has matured across material classes, fabrication pathways, and performance priorities. Figure 1 summarizes why cellulose is of interest from a spectral and chemical perspective, Table 1 highlights how fabrication routes are associated with structural and optical trade-offs, and Table 2 synthesizes the chronological evolution of performance and multifunctionality across the reviewed studies. Figure 2 summarizes multifunctionality and performance trends across development phases, while Figure 3 provides a timeline-style synthesis of the developmental phases discussed in this section, from proof-of-concept wood- and paper-based systems to more durability-aware textiles, hydrogels, composites, and optical wood-based systems approaching building-relevant use. Taken together, these elements support a multi-level synthesis of field maturation grounded primarily in the reviewed literature and the extracted comparative evidence.

Taken together, the reviewed literature suggests that the central question is no longer simply whether cellulose-derived materials can cool under sunlight, but which architectures can retain cooling performance under humidity, dust, UV exposure, handling, and service-specific constraints while remaining scalable, affordable, and relevant to real applications.

INTEGRATION INTO BUILDINGS AND SUSTAINABLE COOLING APPLICATIONS

Building on the maturation trends summarized in Table 2 and Figure 3, this section examines cellulose-derived passive daytime radiative cooling materials (CDMs) not as fully qualified building products, but as application-oriented material platforms whose practical relevance depends strongly on use-specific constraints. In the discussion that follows, deployment readiness is treated qualitatively and is assessed according to five criteria: optical suitability for

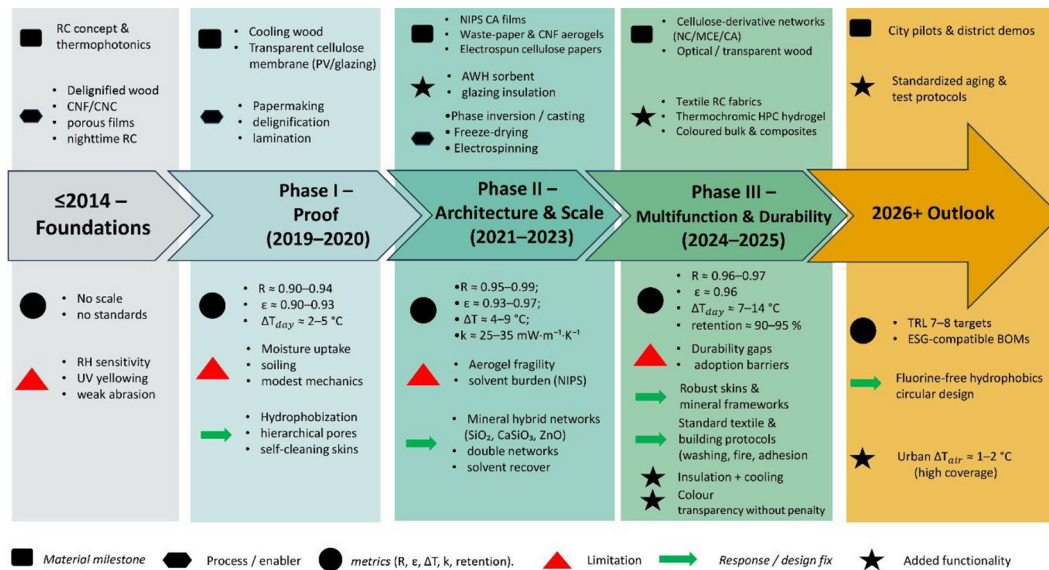


Figure 3. Evolution of cellulose-derived PDRC materials from proof-of-concept systems to multifunctional and deployment-oriented platforms

the intended function, compatibility with substrates and assemblies, resistance to dominant environmental stressors, maintenance tolerance and retention of performance, and the level of validation achieved under realistic operating conditions. In this sense, the section does not present a full building-energy analysis in kWh m⁻² yr⁻¹ across climate zones. Rather, it examines how CDMs may reduce envelope heat gain and contribute to cooling-demand mitigation where supported by application-specific studies, while also clarifying where such claims

remain provisional (Steven Brown and Doman-ski, 2014; Munday, 2019; Perera et al., 2020b; Santamouris, 2016a).

Figure 4 should therefore be read as a schematic synthesis of integration pathways rather than as a direct proof of deployment. Its value lies in organizing the relation between material platforms, likely applications, and major constraints, while the text below develops the mechanistic basis of performance and the limits that emerge under real service conditions.

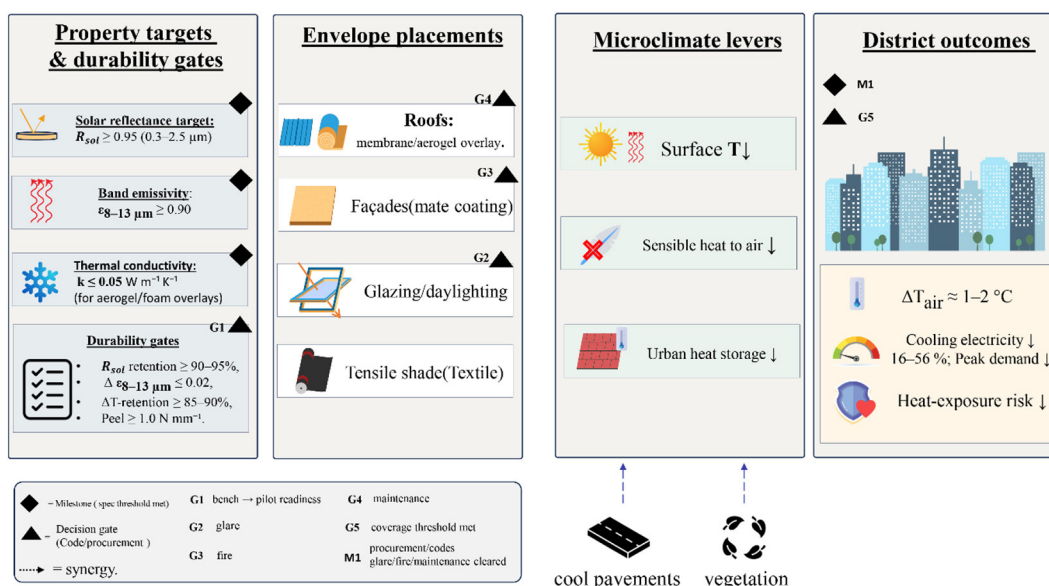


Figure 4. From material design to sustainable cooling applications: integration pathways and performance implications of cellulose-derived passive daytime radiative cooling materials

Envelope-specific and application-specific integration pathways

The practical relevance of CDMs depends first on the type of surface or assembly into which they are integrated. Opaque roof applications remain the most immediate and technically favorable use-case because they combine high solar exposure, unobstructed sky view, and relatively simple installation geometry (Orel et al., 1993; Chung, 2011). For these applications, porous cellulose acetate films, mineral-filled sheets, coated paper-like systems, and lightweight aerogel-based layers are among the most plausible near-term candidates, since their optical function can act directly on the outer surface heat balance. In such configurations, the main objective is not simply to demonstrate high reflectance or emissivity in isolation, but to reduce absorbed solar flux at the exposed envelope surface and limit conductive heat transfer toward the substrate. Façade applications are more demanding. Compared with roofs, façades often experience more variable solar incidence, lower sky-view factors, stronger sensitivity to soiling streaks, and tighter architectural constraints related to colour stability, texture, maintenance, and abrasion resistance. This makes them a more difficult environment for highly porous or easily contaminated radiative-cooling surfaces. It also explains why mineral-hybrid cellulose coatings, structurally coloured CNC-based layers, and mechanically supported composite films have attracted interest in façade-oriented contexts, where visual integration and surface robustness become nearly as important as nominal optical performance (Parker et al., 2023; Feng et al., 2024b; Du et al., 2023).

Glazing-related systems form a distinct category because they are governed by a different set of trade-offs. In opaque envelopes, maximizing solar reflection is usually desirable. In glazing or semi-transparent elements, however, visible transmittance, haze, solar modulation, thermal insulation, and long-wave radiative behavior must be balanced simultaneously. Transparent wood, optical laminates, and transparent cellulose aerogels are therefore relevant not because they maximize a single cooling metric, but because they explore whether daylight transmission and radiative moderation can be combined in one material platform (Abraham et al., 2023a; Gao et al., 2024; Hu et al., 2022c). Their relevance is strongest in applications where optical selectivity and thermal moderation

matter together, although they remain more demanding in terms of durability, clarity retention, and assembly compatibility than opaque coatings.

Flexible and semi-outdoor applications such as radiative cooling textiles, coated fabrics, and lightweight shading membranes extend CDMs beyond the conventional building envelope. Here the performance objective shifts from building-surface heat rejection alone toward local thermal comfort, solar shielding, and lightweight passive cooling under repeated deformation or handling (Zhong et al., 2024; Hou et al., 2024). These systems are scientifically attractive because they exploit the processability of cellulose-rich fibers and coatings, but they are also more vulnerable to laundering, folding, abrasion, contamination, and wet-state performance loss. For this reason, they should not be discussed as equivalent to roof coatings or structural envelope elements, even if the underlying optical principles are related.

Taken together, these branches show that CDM integration is not a single route but a family of application-specific strategies, each governed by a different balance among optical function, mechanical constraint, environmental exposure, and maintenance burden.

Mechanistic relevance and the limits of cooling-demand interpretation

The contribution of CDMs to sustainable cooling is best understood in mechanistic terms rather than through broad energy-language alone. At the surface level, a well-designed radiative-cooling material suppresses the absorption of incoming short-wave solar radiation while enhancing long-wave radiative heat rejection to the sky. When the material is porous or thermally insulating, a third effect may also become important: a reduction in conductive heat flow from the exposed surface to the underlying substrate. The practical value of a CDM therefore depends on how these three effects – solar rejection, thermal emission, and substrate-level thermal moderation – combine in the intended application.

For roofs and other opaque sun-exposed envelope components, the dominant benefit is often a reduction in outer-surface temperature and a corresponding reduction in sensible heat transfer into the building fabric. In these cases, radiative cooling acts upstream of mechanical cooling by limiting heat gain before it enters conditioned space. This is the sense in which CDMs may

contribute to lower cooling demand. However, such a statement should be interpreted cautiously. Unless supported by climate-specific simulations or measured whole-building studies, the evidence remains primarily material- and assembly-level rather than a direct estimate of annual kWh m⁻² savings. For this reason, the present review discusses cooling-demand relevance qualitatively and does not claim a generalized building-energy ranking across climate zones.

This distinction is particularly important because some studies linked to cellulose-derived glazing concepts or optical wood systems report projected energy implications through application-specific simulations, whereas other studies report only coupon-scale thermal metrics or short-duration outdoor tests (Gao et al., 2024; Hu et al., 2022c; Wang et al., 2024a). These studies are useful, but they do not all provide the same level of evidence. A projected reduction in building cooling load from a glazing simulation, a measured sub-ambient temperature drop on an insulated coupon, and an improvement in local textile thermal comfort are not interchangeable outcomes, even when they are all rooted in radiative-cooling physics.

From a mechanistic standpoint, the risk in application-oriented discussions is to move too quickly from surface optics to energy language without addressing how the material is mounted, what substrate it is coupled to, how long the exposure lasts, whether convection dominates the local heat exchange, and whether humidity or contamination changes the optical response in service. In that sense, a CDM should not be considered deployment-relevant simply because it exhibits strong nominal reflectance or emissivity. It becomes more convincing only when the relevant heat-transfer pathway for the intended application has been demonstrated under conditions that approximate use.

For this reason, the energy importance of CDMs should be framed less in terms of record ΔT values and more in terms of their capacity to act as passive heat-gain control layers under realistic architectural or device-level constraints (Gliti et al., 2024; Gliti et al., 2023).

Deployment readiness, use-case prioritization, and real-world failure modes

When assessed against the five readiness criteria stated at the beginning of this section, not all

CDM pathways appear equally mature. Opaque roof-oriented coatings and supported film systems are currently the most credible near-term candidates because they align with the strongest combination of favorable optics, simple geometry, accessible maintenance, and relatively direct heat-gain control. Mineral-hybrid cellulose coatings, porous cellulose acetate films, coated sheets, and mechanically supported cooling layers fit this category most naturally, especially where they can be applied as surface modifiers rather than load-bearing materials.

Facade systems occupy a more conditional position. They remain attractive, especially where colour control, moderate self-cleaning ability, or composite reinforcement has been introduced, but their performance is more exposed to visible weathering, dust deposition, runoff marks, abrasion, and adhesion-related failure. In these cases, deployment readiness depends not only on cooling function but also on whether the coating or surface layer can preserve appearance and optical retention over time. A façade material that cools well when clean but loses reflectivity rapidly after dust deposition or binder degradation cannot be considered robust in practice, even if its fresh-state optical metrics are strong.

Glazing-related and semi-transparent systems remain scientifically promising but comparatively less mature. Their relevance is real, especially for transparent wood and cellulose-based optical laminates, yet their deployment depends on unusually demanding combinations of optical clarity, haze control, thermal stability, moisture resistance, and interfacial durability. In these systems, even small shifts in optical quality or interlayer stability may be unacceptable, which makes durability and assembly performance central rather than secondary concerns.

Flexible textiles and shading systems occupy an intermediate category. They are among the most versatile expressions of cellulose-based radiative cooling, but also among the most vulnerable to repeated use. Laundering, abrasion, folding, contamination, and wet-state performance shifts may all degrade cooling function or wearer comfort, even when the initial material response is promising (Zhong et al., 2024; Hou et al., 2024). For this reason, deployment readiness in textile formats depends heavily on retention under repeated handling and maintenance rather than on one-time thermal demonstrations.

A critical issue across all these categories is that optical suitability does not automatically translate into stable service performance. Several failure modes can erode the expected benefit once the materials leave controlled laboratory conditions. Dust accumulation and pore clogging can reduce solar reflectance by suppressing the scattering efficiency of porous surfaces. Ultraviolet exposure can promote yellowing, binder degradation, and interface embrittlement, especially in cellulose-rich or polymer-bound composite layers. Under prolonged humidity or repeated wet–dry cycling, swelling and water uptake may reduce refractive-index contrast and weaken the scattering pathways needed for strong daytime cooling. In humid porous systems, microbial contamination may also become relevant, particularly where moisture retention and organic content coexist. In coated or layered assemblies, the loss of adhesion, local cracking, chalking, or coating peeling may become the dominant practical limitation even if the intrinsic optical properties of the top layer remain favorable. These issues are not marginal details; they are often the mechanisms by which an apparently promising CDM loses real-world value.

Accordingly, use-case prioritization in CDM-PDRC should be based not on which format delivers the most impressive isolated number, but on which format best aligns optical function, substrate compatibility, environmental tolerance, and maintenance realism.

Conditional pathways toward practical sustainable cooling deployment

The literature reviewed here suggests that the transition from material feasibility to practical relevance is underway, but unevenly. Some CDM families now combine sufficiently strong optical performance with processability, hydrophobic modification, or hybrid reinforcement to justify discussion as plausible application candidates. Others remain highly promising as scientific platforms, but still require stronger validation before they can be treated as realistic deployment options.

In practical terms, the most credible near-term pathway lies in supported opaque systems especially roof-facing or shading-oriented materials where the heat-transfer objective is clear, the assembly is relatively simple, and maintenance can be anticipated. Hybrid cellulose coatings, protected porous films, and

mechanically supported cooling layers are particularly relevant in this respect because they can build on existing application logic used for roof membranes, coated sheets, or surface treatments. More complex systems such as transparent wood assemblies, adaptive hydrogels, highly porous monoliths, and delicate multifunctional architectures may offer broader functionality, but they still face more stringent barriers in weathering, optical retention, assembly integration, or repeated-use stability.

This is also why Figure 4 should be interpreted as a map of conditional deployment pathways rather than a maturity chart in the strict engineering sense. A material appears closer to deployment when it satisfies not just optical benchmarks, but the combined requirements of environmental tolerance, substrate compatibility, maintenance realism, and application-level validation. By contrast, a material remains exploratory when its performance depends heavily on carefully insulated testing conditions, ideal cleanliness, limited exposure duration, or fragile structural states that are unlikely to persist in service.

At this stage, the field would benefit less from broader claims about universal deployment potential than from better matching of material families to service environments. Dry, high-solar-load roof conditions may favor some porous coatings or hybrid films. Humid façades may demand more moisture-resistant and cleanable surfaces. Flexible products may require durability benchmarks closer to textile engineering than to static coupon testing. Transparent systems may need validation frameworks closer to glazing science than to conventional cool-roof assessment. In that sense, deployment readiness is not a single endpoint; it is an application-dependent threshold shaped by the dominant failure mechanisms of each use-case.

The practical implication is straightforward. CDMs should now be evaluated not only as radiative materials, but as engineered surface systems whose usefulness depends on whether they can preserve cooling function under service-relevant stresses. This directly motivates the next section of the review. Once application pathways are interpreted in terms of stress, retention, and failure, the need for durability-oriented testing, standardized reporting, and staged qualification becomes unavoidable.

DURABILITY, MAINTENANCE, AND DEPLOYMENT READINESS

Cellulose-derived passive daytime radiative cooling materials have now reached a stage where durability and retention of function are as important as fresh-state optical performance. However, the available evidence remains heterogeneous in scope and quality. The current literature reports several relevant stressors, mitigation strategies, and post-aging trends, but it does not yet support a formal deployment ranking based on standardized TRL, cost, life-cycle, or long-term multi-climate validation. Accordingly, this section synthesizes the degradation mechanisms, retention-related evidence, and qualification gaps reported for CDM-PDRC systems, while distinguishing clearly between experimentally supported observations and author-level conceptual organization.

Figure 5 reports mitigation strategies and retention-related evidence for cellulose-derived passive daytime radiative cooling materials: (a) climate stressors, failure pathways, and design responses; (b) schematic durability-evidence map across major stressors; and (c) retention of optical and cooling performance after accelerated aging.

Durability challenges and dominant stressors

The durability of cellulose-derived radiative coolers is governed less by a single failure mode than by the interaction of several environmental stressors that progressively alter optical function under service conditions. Across the current literature, three categories recur most consistently: photochemical degradation, moisture-driven instability, and surface contamination or mechanical wear. These categories are not proposed here as a formal classification standard, but as a synthesis of the dominant mechanisms most frequently discussed in experimental studies of cellulose-rich cooling systems.

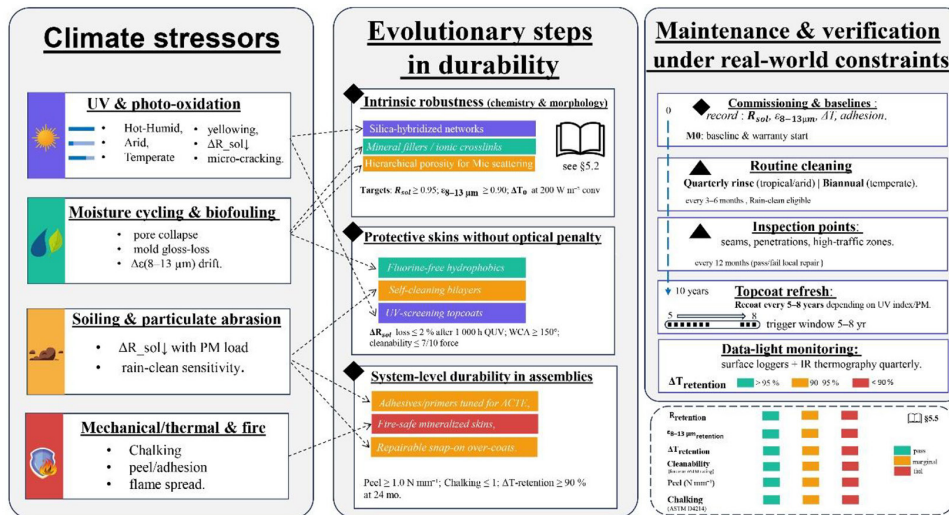
Photochemical degradation is one of the most persistent concerns because many cellulose-based materials include residual chromophores, unstable interfaces, or polymeric and mineral-organic hybrid phases that may evolve under prolonged ultraviolet exposure. In practice, UV-driven yellowing, photo-oxidation, and binder embrittlement can progressively reduce reflectance or alter interfacial integrity, especially in systems where surface chemistry and optical performance are tightly coupled (J. Xu et al., 2025;

Gao et al., 2024). This is particularly relevant for white or porous radiative-cooling surfaces, where small optical changes in the solar range may translate into disproportionate losses in daytime performance.

Moisture-driven instability is equally important, and in many cellulose-derived systems it may be even more critical than UV exposure. Hygroscopicity is intrinsic to several of the most promising material formats, including papers, porous films, foams, and aerogels. Under sustained humidity, wet-dry cycling, or direct liquid-water exposure, moisture uptake can reduce refractive-index contrast, deform pore networks, weaken scattering pathways, and change the apparent thermal response of the material. A number of studies have therefore reported measurable declines in optical retention or apparent cooling performance under humid conditions, although the magnitude of these effects remains difficult to compare directly because protocols and reporting practices differ substantially across the literature (Manzano et al., 2024b; Gao et al., 2023; Zhong et al., 2021).

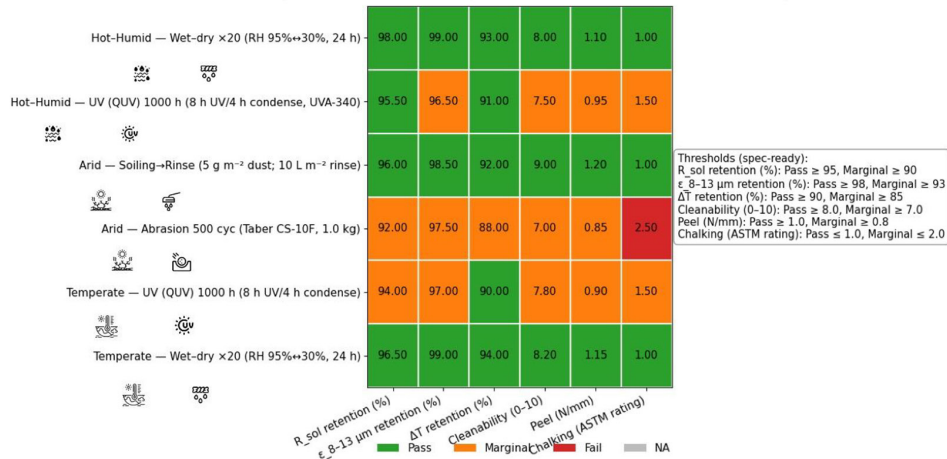
A third category concerns soiling, abrasion, and routine handling. In real service environments, dust deposition, pollutant accumulation, wind-blown particulates, repeated cleaning, and surface rubbing can all degrade the practical value of a cooling material even when its intrinsic optical design remains sound. For porous or textured cellulose-based surfaces, this issue is especially important because the very features that enable strong solar backscattering may also trap contaminants or become mechanically fragile if the surface is repeatedly disturbed. In roofs, façades, and flexible products, the question is therefore not only whether the material cools when clean and freshly prepared, but whether it retains that function after exposure, cleaning, and repeated use.

These stressors should not be treated as independent in practice. UV exposure may embrittle a coating that then becomes more vulnerable to abrasion. Moisture uptake may facilitate contamination or microbial colonization. Cleaning required to remove deposited dust may in turn damage fragile hydrophobic skins or poorly adhered coatings. For cellulose-derived systems, this coupling is especially important because highly porous, low-density architectures often deliver the best fresh-state radiative performance while also remaining structurally and environmentally vulnerable if insufficiently stabilized. In that sense, the current durability literature supports a clear

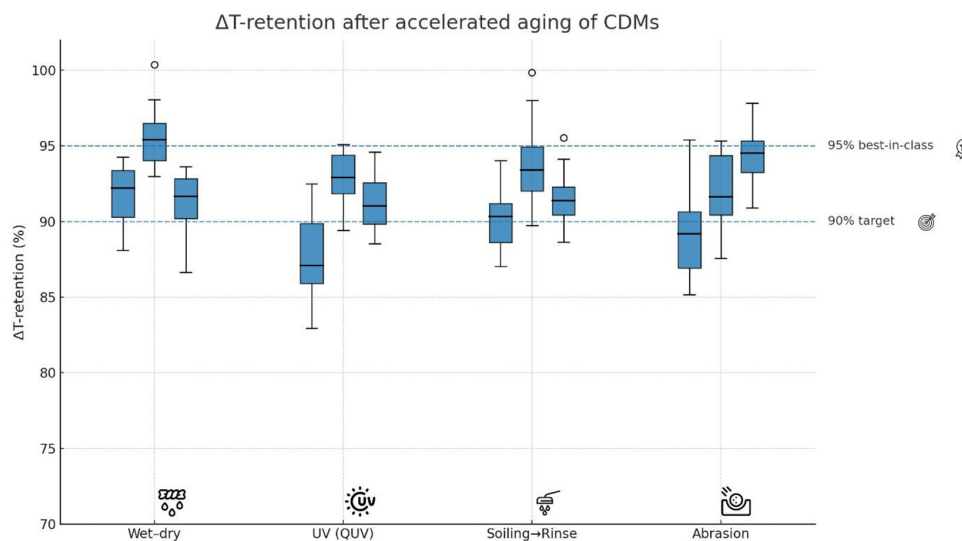


a.

Durability Readiness Matrix — post-test values (see thresholds in legend)



b.



c.

Figure 5. Climate stressors and reported failure pathways in CDM-PDRC systems (a), schematic durability-evidence map across major stress categories (b), and reported retention-related evidence after aging or environmental exposure (c).

conclusion: for CDM-PDRC materials, durability is not a secondary screening step after optical optimization, but a central constraint on whether high-performing laboratory materials can remain useful under service conditions.

Reported design responses and retention-oriented mitigation strategies

Although the durability evidence remains heterogeneous, the literature does show a gradual shift from post hoc protection toward more deliberate durability-oriented design. Across the studies reviewed here, three mitigation logics recur most often: hydrophobic surface engineering, mineral or oxide hybridization, and structural or architectural reinforcement of porous networks. These strategies should not be interpreted as universally validated solutions, but they do represent the dominant directions through which researchers are trying to preserve radiative function under environmental stress.

Hydrophobic surface engineering is one of the most common approaches. Fluorinated or fluorine-free silanization, low-surface-energy skins, and moisture-resistant top layers are frequently introduced to suppress water uptake, reduce dirt adhesion, and preserve pore openness under humid conditions (Song et al., 2024; Gao et al., 2023; Ben Akka et al., 2026). In the best cases, these treatments improve water repellency and self-cleaning behavior without fully blocking the pore structures that contribute to solar scattering. However, their long-term robustness is still not uniformly established. A hydrophobic layer may itself crack, lose adhesion, or degrade under UV and abrasion, meaning that the gain in wet-state performance must be considered together with the stability of the treatment itself.

Mineral or oxide hybridization is another major pathway. Additives such as SiO_2 , CaCO_3 , ZnO , and related inorganic phases are often introduced not only to enhance scattering, but also to improve UV tolerance, fire behavior, humidity robustness, or structural stability during aging (Parker et al., 2023; Chen et al., 2025; Du et al., 2023; Li et al., 2023). This strategy is attractive because it may align optical and durability benefits in the same design move. At the same time, the literature does not yet support a universal causal ranking showing that hybridization alone guarantees better long-term performance across all material classes. In many studies, additives are

introduced together with changes in pore architecture, thickness, binders, or testing conditions, which makes isolated attribution difficult.

A third pathway is structural reinforcement. Mechanically supported aerogels, layered composites, dual-pore networks, and breathable protective skins all aim to preserve optical function while reducing collapse, cracking, or loss of surface integrity. These approaches are especially relevant for highly porous CDMs, where fresh-state optical performance may be strong but mechanical fragility remains a barrier to handling and outdoor use. In several cases, the practical value of these designs lies less in improving peak reflectance than in slowing the loss of function after humidity cycling, contamination, or repeated handling.

For this reason, retention is more informative than fresh-state performance alone. A material that begins with slightly lower reflectance but retains its optical function after UV exposure, wet-dry cycling, or cleaning may be more relevant to sustainable cooling deployment than a more spectacular material that degrades rapidly outside controlled conditions. The literature increasingly points in this direction, even if the supporting evidence is still uneven. What remains missing, however, is a standardized basis for comparing post-aging performance across studies. Durability durations, stress intensities, sample formats, and measured endpoints are still too heterogeneous to support a rigorous cross-study ranking of mitigation strategies.

Accordingly, the most defensible interpretation is not that one design family has definitively solved durability, but that the field is gradually converging toward retention-oriented material design, in which optical performance, environmental stability, and maintenance tolerance are considered together rather than sequentially.

Climate-specific stress interpretation and the limits of current evidence

The distinction between arid and humid climates is often useful when thinking about the service behavior of radiative-cooling materials, but in the current CDM literature it should be interpreted cautiously. At present, the available evidence supports a qualitative distinction between dominant stress pathways in dry versus humid environments, but it does not yet constitute a climate-resolved engineering analysis based on psychrometric datasets, quantified atmospheric-window

modelling, or standardized multi-climate validation. Within that limitation, a broad pattern does emerge. In arid and high-solar-load environments, the main concerns tend to be ultraviolet exposure, dust accumulation, and thermal cycling. Under these conditions, optical retention may depend strongly on photostability, cleanability, and resistance to cracking or chalking at the exposed surface. A highly reflective porous system may still function well if it remains clean and structurally intact, but repeated dust deposition or UV-induced embrittlement can progressively erode its usefulness even when humidity is low.

In humid conditions, the stress picture changes substantially. Moisture uptake becomes a dominant concern, especially in porous cellulose-rich formats that rely on air-filled scattering networks. Swelling, wetting, reduced refractive-index contrast, and contamination risk can all reduce apparent radiative-cooling performance, even before catastrophic structural failure occurs (Manzano et al., 2024b; Gao et al., 2023; Manzano et al., 2024). In addition, humid environments may intensify the risk of microbial colonization or persistent surface fouling in organic porous structures, particularly where drying is incomplete or cleaning is infrequent. These are not merely secondary maintenance issues; they may alter the optical and thermal behavior of the material directly.

At the same time, the literature still falls short of the evidence needed to convert these observations into robust climatic design rules. Aging durations vary widely, relative humidity windows are not consistently reported, psychrometric framing is usually absent, and the atmospheric-window penalty associated with humid conditions is rarely quantified together with material degradation. As a result, the contrast between arid and humid service conditions in the present review should be read as a qualitative interpretation of reported stress tendencies, not as a quantitative deployment model.

This limitation is important because it shapes how readiness should be discussed. A material may appear promising in a dry, high-irradiance context yet remain poorly suited to humid façades, shaded urban canyons, or flexible products repeatedly exposed to moisture. Conversely, a material with slightly less impressive fresh-state cooling but better wet-state stability may be more credible in many real deployment scenarios. In this sense, climate-specific interpretation remains necessary, but it must remain proportional to the quality of the evidence actually available.

From durability evidence to qualification gaps and practical relevance

Taken together, the current durability literature suggests that cellulose-derived radiative coolers are moving in the right direction, but not yet on the basis of a uniform qualification framework. The field has clearly progressed beyond purely fresh-state demonstrations. More studies now report accelerated aging, humidity sensitivity, cleanability, UV-related changes, or post-exposure optical retention than was the case in early proof-of-concept work. This is a meaningful advance, because it shifts attention from whether a material can cool initially to whether it can retain that function under realistic stress.

However, the evidence base remains fragmented. Degradation rates, time constants, and performance decay curves are rarely reported in a way that supports robust comparison across studies. Aging durations differ. Endpoints differ. Some papers report reflectance retention, others focus on surface temperature change, others on contact angle or visible appearance, and others only on qualitative post-exposure stability. In many cases, the absence of standardized decay reporting is more limiting than the absence of high fresh-state performance. Without clearer retention trajectories, it remains difficult to estimate how rapidly functionality is lost, under which stress combinations, and whether one material class is truly more stable than another.

This is why the role of Figure 5 in the present review should remain interpretive rather than probative. It helps organize the available durability evidence into stressors, mitigation strategies, and broad retention-related trends, but it should not be mistaken for a formal ranking system derived from standardized TRL, cost, LCA, or multi-climate field validation. The current literature does not yet support that level of objectivity. What it does support is a more cautious set of conclusions: first, that retention of function is now a central criterion for judging material relevance; second, that porous cellulose architectures require stabilization if they are to remain credible outdoors; and third, that durability evidence must be made more comparable before strong deployment claims can be justified.

A practical implication follows from this. Materials that combine acceptable optical performance with some degree of humidity protection, hybrid reinforcement, mechanical support, or cleanability

are presently more convincing as near-term candidates than delicate architectures that perform exceptionally well only under controlled handling or idealized exposure. This does not mean that highly porous aerogels, adaptive systems, or multifunctional optical structures lack value. Rather, it means that their scientific promise still exceeds their qualification depth in many cases.

Overall, the durability literature now supports a transition in how CDM-PDRC materials should be evaluated. The central question is no longer only whether the material cools when new, but how quickly and under which stresses it loses the properties that made it attractive in the first place. This is precisely why the next section becomes necessary: once retention, comparability, and qualification gaps become central, the field can no longer rely on isolated optical metrics alone. It needs standardized testing, reporting, and staged validation logic capable of linking laboratory performance to credible application pathways.

STANDARDIZED TESTING, REPORTING, AND QUALIFICATION NEEDS

The rapid diversification of passive daytime radiative cooling materials has not yet been matched by an equally mature framework for testing, comparing, and qualifying them under realistic operating conditions. This gap is especially consequential for cellulose-derived materials, whose performance depends strongly on porosity, surface chemistry, thickness, humidity sensitivity, and substrate coupling. In such systems, small differences in measurement protocol can translate into several points of reflectance or several degrees in reported surface-temperature reduction, making cross-study comparisons far less reliable than they often appear. As a result, the field still faces a recurring problem: high-performing laboratory prototypes are frequently reported with insufficient metadata, limited durability context, and weak connection to building-scale or application-relevant performance (Raman et al., 2014; Zhu et al., 2015; Li et al., 2025a).

This problem is not merely academic. Without a consistent test-and-report framework, it becomes difficult for modelers, standards bodies, building designers, and procurement teams to distinguish robust, deployment-ready technologies from fragile proof-of-concept materials. For cellulose-derived radiative coolers, this issue is

particularly important because the same properties that enable strong optical performance—high porosity, low density, and complex multiscale scattering—can also amplify sensitivity to moisture, contamination, and test geometry. In this context, Figure 6 should be understood as a qualification framework rather than a simple illustration. Panel 6(a) defines the minimum optical and thermal measurement stack; panel 6(b) organizes climate-informed durability and aging tests; and panel 6(c) introduces a gated readiness funnel that links laboratory characterization to field validation and, ultimately, to practical deployment. Taken together, these elements provide a structured basis for moving CDM-PDRC research from scattered demonstrations toward comparable, reproducible, and application-relevant evidence.

Core optical and thermal measurement stack

The first requirement for meaningful comparison is a standardized measurement stack for optical and thermal performance. At minimum, radiative cooling studies should report hemispherical solar reflectance across the solar spectrum, band-resolved emissivity in the atmospheric window, and outdoor thermal performance under clearly documented meteorological conditions. These three categories are complementary and should not be substituted for one another. Solar reflectance remains essential because daytime cooling begins with suppression of absorbed short-wave heat; mid-infrared emissivity is equally necessary because radiative heat rejection depends on strong emission through the 8–13 μm atmospheric window; and outdoor temperature reduction or net-cooling measurements are needed to verify that the spectral properties translate into meaningful thermal response in practice (Orel et al., 1993; Raman et al., 2014; Chen et al., 2022a).

As indicated schematically in Figure 5(a), this measurement stack should include not only headline values but also the context needed to interpret them. For optical data, that means specifying the measurement method, spectral range, integrating-sphere or directional setup, substrate condition, and whether the reported values correspond to fresh or aged samples. For thermal data, it means reporting more than a single peak ΔT value. At minimum, ambient temperature, solar irradiance, relative humidity, wind speed, sky condition, sample geometry, thermal insulation beneath the test coupon, and duration of exposure should

be provided. This level of reporting is especially important for cellulose-derived materials because hygroscopicity, thickness, and pore morphology can produce significant variation in apparent performance even when nominal reflectance values are similar. A material tested on a highly insulated coupon under dry, low-wind conditions cannot be compared directly with one tested on a conductive substrate under humid outdoor exposure without acknowledging those differences.

Another issue emphasized implicitly by Figure 6(a) is the need to move beyond “hero metrics”. Reporting only the highest solar reflectance or the largest midday temperature drop creates an incomplete and sometimes misleading picture. For qualification-oriented assessment, more useful descriptors include retained reflectance after aging, emissivity stability under humidity, diurnal or multi-day temperature traces, and side-by-side comparisons against reference surfaces under matched conditions. In other words, the goal of the core measurement stack is not to maximize one number, but to produce a dataset that can support fair comparison, simulation input, and practical decision-making.

Climate-informed durability and aging protocols

The second pillar of qualification is durability testing that reflects real climatic stress rather than isolated single-factor aging. This need follows directly from the evidence reviewed in the previous section: for cellulose-derived materials, humidity, ultraviolet exposure, soiling, abrasion, and mechanical handling can degrade performance even when fresh-state optical metrics are excellent. Figure 6(b) is useful here because it organizes aging not as a single generic requirement, but as a climate-informed matrix of stressors and thresholds. This is a more realistic way to think about qualification. A coating intended for a hot-arid roof should not necessarily be judged by the same exposure priorities as a porous façade material intended for hot-humid operation.

In practical terms, a standardized aging framework for CDM-PDRC systems should include at least four categories: ultraviolet and photo-oxidative stability; humidity and moisture-cycling resistance; soiling/cleanability; and mechanical integrity, including adhesion or abrasion where relevant. For each category, what matters is not simply whether degradation occurs, but how

optical and thermal performance are retained after testing. That is why retention metrics are more useful than fresh-state values alone. Reporting the fraction of initial solar reflectance, atmospheric-window emissivity, and outdoor ΔT retained after aging provides a common language across different chemistries and architectures, even when absolute performance differs (Baetens et al., 2011; Zhao et al., 2025).

This climate-informed approach also helps avoid a common mistake in the current literature: assuming that all degradation data are equally relevant to all applications. A cellulose aerogel may perform very well in dry climates yet remain unsuitable for humid deployment without additional protection. Conversely, a slightly less reflective hybrid film may be more deployment-ready if it preserves its performance under moisture and repeated cleaning. For this reason, the durability matrix proposed in Figure 6(b) should be interpreted not only as a testing checklist, but as a qualification filter that links material class, climate family, and application type. In the case of CDMs, such a filter is especially valuable because it makes visible the real trade-off between optical ambition and environmental robustness.

Field-validation tiers and deployment gates

Laboratory and accelerated-aging data are necessary, but they are not sufficient for deployment claims. A third pillar of readiness is progression from coupon-scale evidence to validated field performance, and this progression is formalized in Figure 6(c) through the proposed M0-M3 readiness funnel. This is one of the strongest conceptual elements of the section because it converts scattered evidence into a recognizable development pathway.

At the base of the funnel, M0 corresponds to laboratory-only materials. These systems are valuable for mechanistic understanding and early-stage innovation, but they lack the outdoor thermal data and durability evidence needed for application claims. Many cellulose-derived prototypes still fall into this category: they demonstrate excellent spectral properties, yet are not tested under sufficiently realistic environmental conditions to support broader conclusions (Chen et al., 2022a; Zhao et al., 2025). M1 corresponds to qualified coupons, meaning materials that satisfy basic optical criteria, show at least acceptable durability under one representative climate

family, and provide outdoor ΔT data on insulated or controlled small-scale test rigs. At this level, the material becomes appropriate for pilot comparison and more serious benchmarking, but not yet for strong building-energy claims (Raman et al., 2014; Zhu et al., 2015).

M2 represents assembly-level validation. Here, materials are no longer tested as isolated coupons but as part of realistic roof, façade, textile, or laminated assemblies on relevant substrates. Evidence at this tier should include stable outdoor cooling response over at least one seasonal cycle, acceptable adhesion or integrity on the intended substrate, and compatibility with thermal modeling sufficient to estimate building-energy implications. Finally, M3 corresponds to pre-commercial deployment. At this stage, products are supported by independent or third-party testing, multi-climate or multi-season monitoring, and integration into procurement, warranty, or rating frameworks such as cool-roof criteria or low-energy building guidance (Santamouris, 2016c; Rehman et al., 2025).

For cellulose-derived radiative coolers, the usefulness of this funnel lies in its realism. It acknowledges that many current systems are scientifically promising but not yet commercially qualified, while also showing that progress toward deployment does not require a reinvention of standards from scratch. It requires disciplined graduation: better outdoor data, stronger retention

reporting, realistic substrates, and clearer coupling between material measurements and application-level outcomes.

Reporting templates, labels, and procurement tools

Standardized testing becomes truly useful only when the results are communicated in a format that non-specialist stakeholders can understand and apply. This is the final contribution of Figure 6 and the natural end point of the qualification logic. Municipal agencies, building owners, social-housing providers, and project developers cannot be expected to interpret raw FTIR spectra, spectral files, or loosely described aging experiments. What they need is a compact reporting format that translates laboratory evidence into intelligible performance, durability, and readiness information (Matthews and Wynes, 2022).

A practical reporting template for CDM-PDRC products should therefore condense the information stack developed in Figure 6(a-c) into a one-page datasheet. At minimum, that datasheet should include fresh and aged values for solar reflectance, 8–13 μm emissivity, and representative outdoor ΔT ; the climatic context of the test; a simplified durability summary for different stress categories; the current readiness level (M0-M3); and recommended maintenance or cleaning intervals

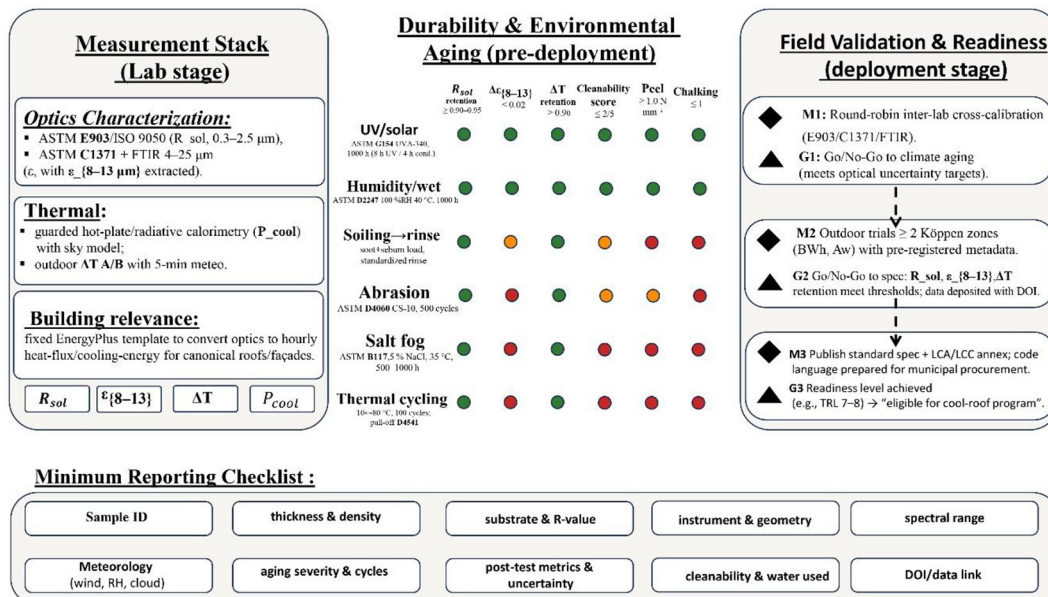


Figure 6. Standardized testing, reporting, and qualification framework for cellulose-derived passive daytime radiative cooling materials: (a) core optical and thermal measurement stack; (b) climate-informed durability and aging matrix; and (c) readiness funnel linking laboratory evidence to field validation and deployment

where known. An icon-based pass/marginal/fail summary by climate family could be particularly helpful for building-envelope decision-making. Such a format would not replace detailed characterization, but it would make the results more usable for selection, tendering, and early-stage deployment screening.

This reporting logic also has an important policy implication. If procurement and specification remain based only on initial optical metrics, then materials that look impressive in the laboratory but degrade quickly may be favored over systems with better retention and lower life-cycle risk. By contrast, if reporting templates include retention, maintenance, and readiness information, the field shifts toward persistence rather than record chasing. For cellulose-derived systems, this shift is especially important because their sustainability narrative depends not only on renewable feedstocks, but on whether those materials can remain functional long enough to justify deployment at scale. In that sense, standardized reporting is not a bureaucratic afterthought; it is the mechanism by which promising CDM-PDRC prototypes become specifiable, comparable, and credible sustainable-cooling technologies.

Overall, the framework summarized in Figure 6 shows that the next stage of the field depends on coordination rather than on isolated breakthroughs alone. Better materials will still matter, but equally important will be the adoption of shared measurement stacks, climate-relevant durability thresholds, staged field-validation gates, and reporting tools that link optical data to real cooling applications. For cellulose-derived radiative coolers, these steps are now essential if the literature is to move from promising prototypes to technologies that can be confidently modeled, specified, procured, and deployed.

CONCLUSIONS

This review establishes that cellulose-derived materials now constitute more than a peripheral bio-based variant of passive daytime radiative cooling. The evidence reviewed here shows that they have evolved into a distinct and scientifically meaningful material platform, with performance governed by a combination of porous light-scattering architectures, intrinsic mid-infrared-active chemistry, and increasingly sophisticated

hybridization and surface-engineering strategies. In this sense, the main objective of the review was achieved: the literature can now be interpreted not as a scattered collection of isolated demonstrations, but as a coherent field structured by recurring material families, structure–property relationships, durability challenges, and application-oriented design logics.

At the same time, the review also shows that the available evidence supports this platform unevenly. The proposition that cellulose-derived materials are credible candidates for sustainable cooling is strongly supported at the level of optical design and proof-of-concept thermal response. It is only partially supported, however, at the level of durability, qualification, and deployment relevance. Across the literature, many cellulose-derived systems now reach competitive solar reflectance and strong mid-infrared emissivity, and several studies demonstrate meaningful daytime cooling under outdoor or quasi-outdoor conditions. Yet the evidence becomes much weaker once the discussion moves from fresh-state performance toward retained performance, standardized comparison, service-life behavior, and application-level validation. In other words, the field has convincingly answered whether cellulose can cool; it has not yet answered with equal rigor which cellulose-derived architectures can remain reliable under realistic environmental and operational stress.

The principal contribution of this review is therefore not simply to summarize recent studies, but to clarify the present maturity structure of the field. Compared with broader PDRC reviews, the synthesis developed here fills a more specific gap by treating cellulose-derived systems as a distinct class and examining them simultaneously through four lenses: structure–property relationships, cross-family material evolution, durability under climate-relevant stressors, and relevance to sustainable cooling applications. This makes visible a key finding that was less explicit in previous reviews: the real bottleneck in CDM-PDRC is no longer the demonstration of cooling functionality itself, but the transition from optical feasibility to retained, qualified, and application-relevant performance.

A second important conclusion follows from this analysis. The most promising near-term pathway does not appear to lie in the most visually striking or optically extreme laboratory architectures, but rather in those material formats

that combine adequate radiative performance with stabilization, cleanability, substrate compatibility, and scalable processing. In this respect, supported opaque systems, hybrid coatings, protected porous films, and reinforcement-assisted cellulose composites currently appear more credible for practical cooling deployment than fragile high-porosity architectures whose performance remains strongly dependent on idealized handling or short-duration tests. This does not diminish the scientific value of aerogels, adaptive systems, transparent optical woods, or multifunctional photonic cellulose structures; rather, it places them more accurately on the current maturity spectrum.

The review also reveals a methodological gap that now limits further progress. Cross-study comparison remains hindered by non-uniform reporting of ΔT , heterogeneous outdoor protocols, incomplete environmental metadata, and scarce durability kinetics. Degradation rates, time constants, and decay curves are still rarely reported in a form that supports rigorous comparison across studies. Likewise, claims related to cooling-energy relevance, deployment readiness, or climatic suitability often advance faster than the available qualification evidence. For this reason, the field now needs fewer isolated record metrics and more standardized retention-focused evidence.

Taken together, the literature supports a clear but qualified conclusion: cellulose-derived passive daytime radiative cooling materials are already a credible research platform for sustainable cooling, but they are not yet a uniformly validated deployment platform. Their future importance will depend on whether the field can connect material innovation to comparable testing, multi-climate outdoor validation, durability-aware design, and assembly-level performance assessment. The next phase of progress should therefore prioritize four directions: harmonized reporting of optical and thermal performance under clearly specified boundary conditions; systematic durability evaluation including post-aging retention and degradation kinetics; validation on realistic substrates and application-relevant assemblies; and stronger coupling between material-level measurements and building- or use-case-level outcomes. If these priorities are addressed, cellulose-derived cooling materials are likely to move from a promising bio-based niche toward a genuinely robust and low-carbon family of sustainable thermal-management technologies.

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REFERENCES

1. Aili, A., et al. (2024). Passive daytime radiative cooling: Moving beyond materials towards real-world applications. *Next Energy*, 3, 100121. <https://doi.org/10.1016/j.nxener.2024.100121>
2. Baetens, R., Jelle, B. P., Gustavsen, A. (2011). Aerogel insulation for building applications: A state-of-the-art review. *Energy and Buildings*, 43(4), 761–769. <https://doi.org/10.1016/j.enbuild.2010.12.012>
3. Bai, Y., Jia, X., Shan, Z., Huang, C., Wang, D., Yang, J., Pang, B., Song, H. (2024). Sustainable cellulose foams for all-weather high-performance radiative cooling and building insulation. *Carbohydrate Polymers*, 333, 121951. <https://doi.org/10.1016/j.carbpol.2024.121951>
4. Ben Akka, L., Gлити, O., Bejjaji, Z., Naoui, B., Tiftafi, A., Taouraout, A., Mouilly, M., Mehdioui, S., Aouane, M. (2026). Machine-learning-assisted multi-objective environmental modelling of trace metal and mineral pollution in drinking water: A case study from Kénitra, Morocco. *Ecological Engineering & Environmental Technology*, 27(4), 176–190. <https://doi.org/10.12912/27197050/218862>
5. Bi, Y., Luo, X., Yin, Y., Tang, F., Sun, H., Huang, L., Chen, L., Li, J. (2024). Robust, stable cooling cellulose composite: Coupling nano-SiO₂ and cellulose acetate in natural cellulose. *International Journal of Biological Macromolecules*, 277, 133728. <https://doi.org/10.1016/j.ijbiomac.2024.133728>
6. Buratti, C., Belloni, E., Merli, F., Zinzi, M. (2021). Aerogel glazing systems for building applications: A review. *Energy and Buildings*, 231, 110587. <https://doi.org/10.1016/j.enbuild.2020.110587>
7. Cai, C., Chen, W., Wei, Z., Ding, C., Sun, B., Gerhard, C., Fu, Y., Zhang, K. (2023). Bioinspired “aerogel grating” with metasurfaces for durable daytime radiative cooling for year-round energy savings. *Nano Energy*, 114, 108625. <https://doi.org/10.1016/j.nanoen.2023.108625>
8. Chen, M., Pang, D., Chen, X., Yan, H., Yang, Y. (2022). Passive daytime radiative cooling:

- Fundamentals, material designs, and applications. *EcoMat*, 4(1), e12153. <https://doi.org/10.1002/eom2.12153>
9. Chen, Y., Zhang, J., Zhuang, Z., Zhou, J., Peng, Y., Dang, B., Sun, Q. (2024). Ion-dyed cellulose-based radiative cooling structural material. *Industrial Crops and Products*, 220, 119094. <https://doi.org/10.1016/j.indcrop.2024.119094>
 10. Du, H., et al. (2025). Unlocking smart wearable applications: the “potential code” of cellulose-based radiative cooling materials. *Renewable and Sustainable Energy Reviews*, 115792. <https://doi.org/10.1016/j.rser.2025.115792>
 11. Fan, Y., Feng, K., Xie, P., Tian, H., Wu, Y., Zhou, F. (2025). Recyclable cellulose nanocrystals xerogel with thermally insulating and radiative cooling. *Sustainable Materials and Technologies*, 43, e01334. <https://doi.org/10.1016/j.susmat.2025.e01334>
 12. Feng, K., Zhang, L., Liu, Y., Hu, K., Ma, Z., Pei, X., Wu, Y., Zhou, F. (2024). Iridescent transparent passive radiative cooling enabled by cellulose nanocrystal assemblies. *Chemical Engineering Journal*, 488, 151176. <https://doi.org/10.1016/j.cej.2024.151176>
 13. Gamage, S., Banerjee, D., Alam, M. M., Hallberg, T., Åkerlind, C., Sultana, A., Shanker, R., Berggren, M., Crispin, X., Kariis, H., Zhao, D., Jonsson, M. P. (2021). Reflective and transparent cellulose-based passive radiative coolers. *Cellulose*, 28(14), 9383–9393. <https://doi.org/10.1007/s10570-021-04112-1>
 14. Gao, H., Li, Y., Xie, Y., Liang, D., Li, J., Wang, Y., Xiao, Z., Wang, H., Gan, W., Pattelli, L., Xu, H. (2024). Optical wood with switchable solar transmittance for all-round thermal management. *Composites Part B: Engineering*, 275, 111287. <https://doi.org/10.1016/j.compositesb.2024.111287>
 15. Gliti, O., El Idrissi, M. C., Igouzal, M. (2024). Intelligent design of an ultra-thin near-ideal multilayer solar selective absorber using grey wolf optimization linked to deep learning. *Ecological Engineering & Environmental Technology*, 25(2), 70–87. <https://doi.org/10.12912/27197050/175785>
 16. Gliti, O., Igouzal, M., El Idrissi, M. C. (2023). Development of a sustainable solar water desalinator using a novel hollow hemispherical grid shell solar selective absorber designed via phasor particle swarm algorithm. *Ecological Engineering & Environmental Technology*, 24(9), 130–149. <https://doi.org/10.12912/27197050/173510>
 17. Halysh, V., et al. (2022). The technical and economic feasibility for the production of cellulose from non-wood raw materials. *Ecological Engineering & Environmental Technology*, 23(6), 99–103.
 18. Hanif, M., Mahlia, T. M. I., Zare, A., Metselaar, H. S. C. (2014). Potential energy savings by radiative cooling system for a building in tropical climate. *Renewable and Sustainable Energy Reviews*, 32, 642–650. <https://doi.org/10.1016/j.rser.2014.01.053>
 19. Hu, H., Feng, J., Jiang, C., Hou, Q., Liu, W., Zhao, D., Wang, Y. (2025). Cellulose nanocrystal composite films with bioinspired structural color for mechanically robust passive daytime radiative cooling. *Carbohydrate Polymers*, 368, 124079. <https://doi.org/10.1016/j.carbpol.2025.124079>
 20. Hu, X., Zhang, Y., Zhang, J., Yang, H., Wang, F., Fei, B., Noor, N. (2022). Sonochemically-coated transparent wood with ZnO: Passive radiative cooling materials for energy saving applications. *Renewable Energy*, 193, 398–406. <https://doi.org/10.1016/j.renene.2022.05.008>
 21. Jaiswal, A. K., Hokkanen, A., Khakalo, S., Mäkelä, T., Savolainen, A., Kumar, V. (2024). Thermochromic nanocellulose films for temperature-adaptive passive cooling. *ACS Applied Materials & Interfaces*, 16(12), 15262–15272. <https://doi.org/10.1021/acsami.3c18689>
 22. Jaramillo-Fernandez, J., Yang, H., Schertel, L., Whitworth, G. L., Garcia, P. D., Vignolini, S., Sotomayor-Torres, C. M. (2022). Highly-scattering cellulose-based films for radiative cooling. *Advanced Science*, 9(8), 2104758. <https://doi.org/10.1002/advs.202104758>
 23. Ji, C., et al. (2026). Promising radiative cooling materials and their application in construction and building. *Polymers*, 18(5), 596. <https://doi.org/10.3390/polym18050596>
 24. Jiang, C., Qing, Y., Yang, J., Cao, Y., Liu, Y., Zhang, Y., Feng, R. (2025). Integrated BN@ZnO/cellulose acetate composite films with enhanced thermal conductivity and daytime passive radiative cooling. *Composites Science and Technology*, 271, 111347. <https://doi.org/10.1016/j.compscitech.2025.111347>
 25. Li, L., Zhang, Q., Liu, G., Shi, R., Zhao, H., Huang, K., Zang, Y., Xu, Y., Li, C., Wu, L., Zhang, Y. (2025). Advanced passive daytime radiative cooling: From material selection and structural design to application towards multifunctional integration. *Advanced Composites and Hybrid Materials*, 8(1), 97. <https://doi.org/10.1007/s42114-024-01127-7>
 26. Li, T., Zhai, Y., He, S., Gan, W., Wei, Z., Heidarinejad, M., Dalgo, D., Mi, R., Zhao, X., Song, J., Dai, J., Chen, C., Aili, A., Vellore, A., Martini, A., Yang, R., Srebric, J., Yin, X., Hu, L. (2019). A radiative cooling structural material. *Science*, 364(6442), 760–763. <https://doi.org/10.1126/science.aau9101>
 27. Liao, M., Banerjee, D., Hallberg, T., Åkerlind, C., Alam, M. M., Zhang, Q., Kariis, H., Zhao, D., Jonsson, M. P. (2023). Cellulose-based radiative cooling and solar heating powers ionic thermoelectrics. *Advanced Science*, 10(8), 2206510. <https://doi.org/10.1002/advs.202206510>

28. Lin, K.-T., Han, J., Li, K., Guo, C., Lin, H., Jia, B. (2021). Radiative cooling: Fundamental physics, atmospheric influences, materials and structural engineering, applications and beyond. *Nano Energy*, 80, 105517. <https://doi.org/10.1016/j.nanoen.2020.105517>
29. Liu, L., Wang, J., Li, Q. (2024). Passive daytime radiative cooling polymeric materials: Structure design, fabrication, and applications. *Applied Materials Today*, 39, 102331. <https://doi.org/10.1016/j.apmt.2024.102331>
30. Lv, T., Huang, J., Liu, W., Zhang, R. (2020). From sky back to sky: Embedded transparent cellulose membrane to improve the thermal performance of solar module by radiative cooling. *Case Studies in Thermal Engineering*, 18, 100596. <https://doi.org/10.1016/j.csite.2020.100596>
31. Manzano, C. V., Díaz-Lobo, A., Gil-García, M., Rodríguez de la Fuente, Ó., Morales-Sabio, Á., Martín-Gonzalez, M. (2024). Performance and relative humidity impact of cellulose-derivative networks in all-day passive radiative cooling. *Advanced Optical Materials*, 12(22), 2400551. <https://doi.org/10.1002/adom.202400551>
32. Mitique, A., Hachimi, H., Qanza, A., Hmimou, A., Igouzal, M. (2024). Hydraulic Modeling in the Vadose Zone of an Agricultural Area under Water Stress (M'nasra, Morocco). *Russian Meteorology and Hydrology*, 49(10), 888–895.
33. Mitique, A., Hmimou, A., Draoui, Y., Igouzal, M. (2025a). Drip irrigation modelling for young cork oaks in Maâmora forest (Morocco). *Ecological Engineering & Environmental Technology*, 26(5), 43–52.
34. Mitique, A., Draoui, Y., Igouzal, M. (2025b). Assessing human impacts on degradation of Maâmora forest (Morocco). *Ecological Engineering & Environmental Technology*, 26(6), 215–223.
35. Munday, J. N. (2019). Tackling climate change through radiative cooling. *Joule*, 3(9), 2057–2060. <https://doi.org/10.1016/j.joule.2019.07.010>
36. Mylokost, S., et al. (2025). A new approach in the production of cellulose membranes. *Ecological Engineering & Environmental Technology*, 26(4), 334–341. <https://doi.org/10.12912/27197050/202223>
37. Orel, B., Gunde, M. K., Krainer, A. (1993). Radiative cooling efficiency of white pigmented paints. *Solar Energy*, 50(6), 477–482. [https://doi.org/10.1016/0038-092X\(93\)90108-Z](https://doi.org/10.1016/0038-092X(93)90108-Z)
38. Pérez-Lombard, L., Ortiz, J., Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394–398. <https://doi.org/10.1016/j.enbuild.2007.03.007>
39. Perera, A. T. D., Nik, V. M., Chen, D., Scartezzini, J.-L., Hong, T. (2020). Quantifying the impacts of climate change and extreme climate events on energy systems. *Nature Energy*, 5(2), 150–159. <https://doi.org/10.1038/s41560-020-0558-0>
40. Raman, A. P., Anoma, M. A., Zhu, L., Rephaeli, E., Fan, S. (2014). Passive radiative cooling below ambient air temperature under direct sunlight. *Nature*, 515(7528), 540–544. <https://doi.org/10.1038/nature13883>
41. Santamouris, M. (2016). Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. *Solar Energy*, 128, 61–94. <https://doi.org/10.1016/j.solener.2016.01.021>
42. Shanker, R., Ravi Anusuyadevi, P., Gamage, S., Hallberg, T., Kariis, H., Banerjee, D., Svagan, A. J., Jonsson, M. P. (2022). Structurally colored cellulose nanocrystal films as transreflective radiative coolers. *ACS Nano*, 16(7), 10156–10162. <https://doi.org/10.1021/acsnano.1c10959>
43. Skelhorn, C. P., Levermore, G., Lindley, S. J. (2016). Impacts on cooling energy consumption due to the UHI and vegetation changes in Manchester, UK. *Energy and Buildings*, 122, 150–159. <https://doi.org/10.1016/j.enbuild.2016.01.035>
44. Steven Brown, J., Domanski, P. A. (2014). Review of alternative cooling technologies. *Applied Thermal Engineering*, 64(1–2), 252–262. <https://doi.org/10.1016/j.applthermaleng.2013.12.014>
45. Sun, X., Wei, J., Pan, C., Li, W. (2024). Recent advances in passive daytime radiative cooling coatings: Fundamentals, strategies and prospects. *Progress in Organic Coatings*, 196, 108694. <https://doi.org/10.1016/j.porgcoat.2024.108694>
46. Suyasa, I. W. B., et al. (2025). Potential of cellulose extracted from sweet corn stalks (*Zea mays saccharata* Sturt) as a microplastic filter membrane. *Ecological Engineering & Environmental Technology*, 26(4), 97–107. <https://doi.org/10.12912/27197050/200658>
47. Tian, Y., Shao, H., Liu, X., Chen, F., Li, Y., Tang, C., Zheng, Y. (2021). Superhydrophobic and recyclable cellulose-fiber-based composites for high-efficiency passive radiative cooling. *ACS Applied Materials & Interfaces*, 13(19), 22521–22530. <https://doi.org/10.1021/acsmi.1c04046>
48. Wang, Y., Tan, X., Yang, X., Qi, G., Tu, Y. (2024). Hydroxypropyl cellulose thermochromic hydrogel with efficient passive radiative cooling and adjustable visible light transmittance. *Solar Energy Materials and Solar Cells*, 271, 112871. <https://doi.org/10.1016/j.solmat.2024.112871>
49. Xu, C.-L., Yuan, C., Yang, Z., Xu, X., Wang, G., Yang, Z., Cheng, Z., Zhang, S., Li, T., Lv, G., Cai, J., Qi, X. (2024). Nonflammable superhydrophobic passive cooling Cellulose-CaCO₃ film. *Journal of Colloid and Interface Science*, 671, 529–542.

- <https://doi.org/10.1016/j.jcis.2024.05.174>
50. Yue, X., Zhang, T., Yang, D., Qiu, F., Wang, X., Zhang, J., Hu, T., Yang, D. (2022). Superhydrophobic waste paper-based aerogel as a thermal insulating cooler for building. *Energy*, 245, 123287. <https://doi.org/10.1016/j.energy.2022.123287>
51. Zhao, Z., Zhao, S., Xu, J., Wu, X., Guo, Z., Huang, Y., Zhang, R. (2025). Progress in passive daytime radiative cooling from spectral design to real application. *Carbon Future*, 2(1), 9200033. <https://doi.org/10.26599/CF.2025.9200033>
52. Zhong, S., Song, L., Ren, W., Liu, W., Yuan, S., Xu, T., Xu, L., Zhang, J., Cai, Y., Yi, L. (2024). Radiative cooling cellulose-based fabric with hierarchical structure for outdoor personal thermal management. *Chemical Engineering Journal*, 489, 151482. <https://doi.org/10.1016/j.cej.2024.151482>
53. Zhu, L., Raman, A. P., Fan, S. (2015). Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody. *Proceedings of the National Academy of Sciences*, 112(40), 12282–12287. <https://doi.org/10.1073/pnas.1509453112>