

---

# Radiative Cooling Coating Aging Prediction and Its Role in Passive Building Design: A Survey

---

[www.surveyx.cn](http://www.surveyx.cn)

## Abstract

This survey paper explores the aging prediction of radiative cooling coatings, which are critical in enhancing passive cooling and energy efficiency in buildings. Radiative cooling coatings facilitate heat dissipation through infrared radiation, reducing reliance on active cooling systems and aligning with sustainable building practices. The survey delves into predictive modeling techniques, emphasizing AI-based emissivity prediction and mechanically tunable materials, to assess the longevity and performance of these coatings under diverse environmental conditions. Key findings highlight the significant cooling power and temperature reduction capabilities of advanced materials like photonic structures and metamaterials, underscoring their potential to improve thermal management and energy efficiency in building applications. The integration of evaporative and radiative cooling methods is explored for synergistic effects, enhancing overall cooling efficiency. Challenges such as high production costs, environmental adaptability, and durability are identified, with future research directions focusing on optimizing material properties, hybrid cooling systems, and scalable fabrication processes. The survey concludes that strategic application of radiative cooling technologies is essential for advancing energy-efficient and environmentally friendly building solutions, contributing to climate change mitigation and sustainable architectural practices.

## 1 Introduction

### 1.1 Concept of Radiative Cooling Coatings

Radiative cooling coatings represent a significant advancement in energy-efficient building design, enabling effective heat dissipation through thermal radiation. These coatings are meticulously engineered to achieve nearly perfect broadband and omnidirectional absorption and emission properties, thereby optimizing their cooling efficiency [1]. The core mechanism involves the emission of infrared radiation, facilitating heat transfer from surfaces to a cooler external environment by exploiting the atmospheric transparency window [2]. This passive cooling method operates without external energy input, making it a vital component of sustainable energy strategies with considerable potential for both terrestrial and extraterrestrial thermal management [3].

The aesthetic flexibility of radiative cooling coatings is notable, allowing operation below ambient temperatures while accommodating various exterior colors, including black. This is crucial for integrating advanced nanoparticle-based coatings into diverse architectural designs, ensuring that their superior cooling performance—capable of reducing energy consumption by up to 60

Material science innovations have further broadened the capabilities of radiative cooling technologies. The development of photonic structures, for instance, allows surfaces to achieve sub-ambient temperatures even under direct sunlight, marking a substantial leap in daytime radiative cooling [4]. Moreover, the concept of visible-infrared compatible camouflage (VICC) introduces a dual-functionality approach, addressing the dual challenges of effective visible camouflage and low infrared emittance for improved thermal management [5].

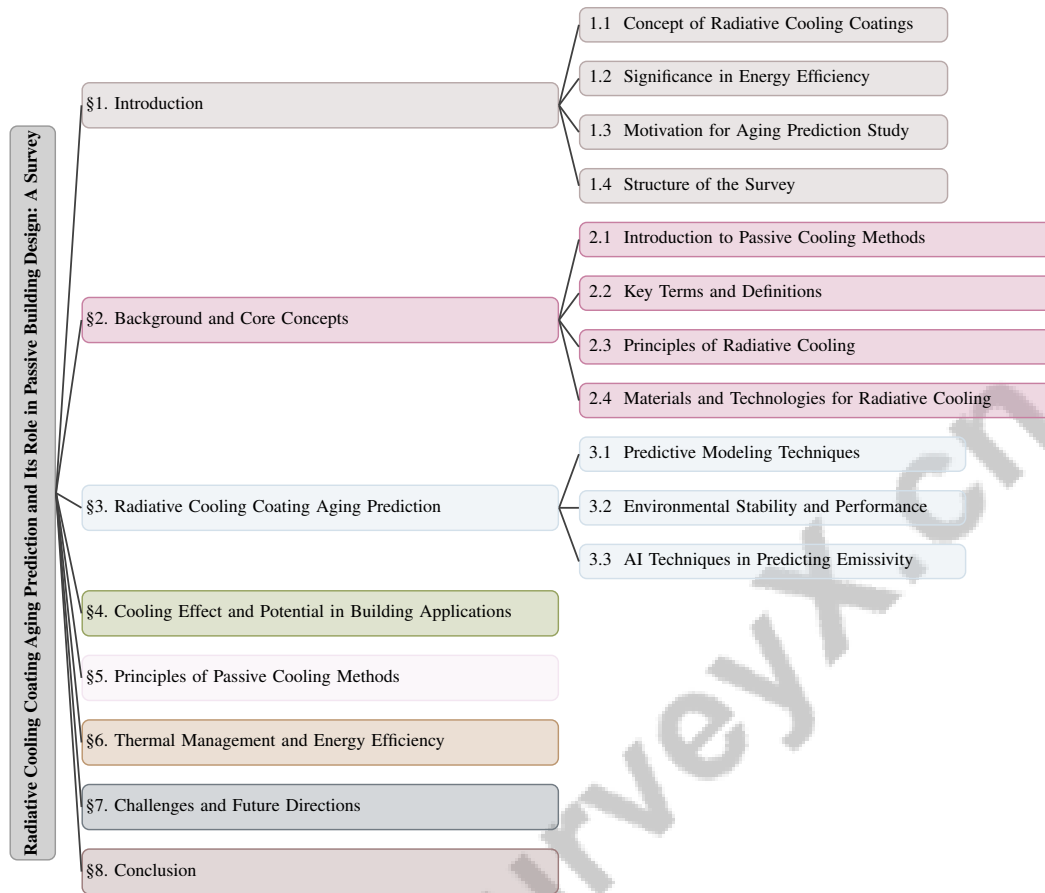


Figure 1: chapter structure

The strategic integration of radiative cooling coatings into building systems not only diminishes reliance on conventional air conditioning but also aligns with broader energy conservation and environmental protection goals. This is particularly relevant for passive building cooling, which is essential for minimizing energy consumption and promoting sustainable architectural practices. As controlling the radiative thermal load of outdoor structures becomes increasingly critical for energy efficiency and human health, the role of radiative cooling coatings in modern building design continues to expand [6].

## 1.2 Significance in Energy Efficiency

Radiative cooling coatings are pivotal in enhancing energy efficiency in buildings by reducing reliance on active cooling systems like air conditioners. By effectively emitting thermal radiation, these coatings facilitate a passive cooling mechanism that lowers indoor temperatures, thereby decreasing energy consumption associated with mechanical cooling [1]. Designed to exploit the atmospheric transparency window, they enable heat escape into outer space without atmospheric absorption, a key factor for achieving sub-ambient cooling [2].

Integrating radiative cooling technology into building envelopes can yield substantial energy savings, particularly in regions with high solar insolation. By maintaining cooler surfaces and interiors, these coatings reduce the cooling load, electricity demand, and operational costs [3]. The ability to maintain performance across various colors, including high-absorption colors like black, ensures aesthetic considerations do not compromise energy efficiency.

Advancements in materials such as photonic structures and bilayer designs have further optimized cooling efficiency, allowing coatings to achieve lower temperatures even under direct sunlight. This is crucial for maximizing energy efficiency during peak daytime conditions, when cooling demands

---

are highest [4]. Innovations like visible-infrared compatible camouflage (VICC) also enhance energy efficiency by providing thermal management alongside aesthetic integration [5].

The deployment of radiative cooling coatings aligns with sustainable building practices, enhancing energy efficiency and contributing to greenhouse gas emission reductions. Given that buildings account for a significant portion of global energy consumption, the widespread adoption of these coatings can profoundly impact energy conservation efforts and climate change mitigation. Their strategic application in architectural design is integral to advancing energy-efficient and environmentally friendly building solutions [6].

### 1.3 Motivation for Aging Prediction Study

The impetus for investigating the aging prediction of radiative cooling coatings stems from the need to enhance the durability and performance of these materials under varying environmental conditions. Current radiative cooling systems often operate statically, consistently radiating thermal power without adapting to fluctuating thermal environments—a limitation significant for both terrestrial and extraterrestrial applications [3]. This static operation highlights the necessity for dynamic systems capable of adjusting thermal properties to maintain efficiency over time.

Aesthetic diversity is another critical factor motivating the aging prediction study. Practical applications of radiative cooling technologies necessitate coatings that not only perform efficiently but also offer a range of colors to meet architectural preferences [7]. However, achieving vivid colors often increases heat absorption, potentially compromising cooling efficiency [8]. Thus, developing materials that balance aesthetic appeal with functional performance is essential.

The variability in thermal load associated with colored objects, due to their interaction with solar radiation and thermal emission, poses a significant challenge in maintaining consistent cooling performance [6]. This challenge is exacerbated by the intrinsic limitations of existing passive cooling methods, such as the need for additional water supplies in evaporative cooling and the low cooling power of radiative cooling [9]. Therefore, developing coatings that can sustain their cooling properties without external resources is crucial.

Moreover, effective management of both visible and infrared light is vital for high-temperature applications, necessitating materials that efficiently handle these wavelengths to optimize thermal management [5]. The challenge of dissipating excess heat from devices, particularly in solid-state electronics and solar energy systems, further underscores the importance of advanced cooling solutions [10].

Addressing the core issue of achieving effective daytime cooling with radiative technologies, which traditionally struggle to maintain sub-ambient temperatures under direct sunlight, is a primary focus of aging prediction studies [4]. By overcoming these limitations, radiative cooling coatings can significantly contribute to energy consumption reduction and enhance the sustainability of building designs.

### 1.4 Structure of the Survey

This survey is meticulously structured to provide a comprehensive exploration of radiative cooling coatings and their implications in passive building design. It begins with an introduction to the concept of radiative cooling coatings, emphasizing their significance in enhancing energy efficiency and the motivation behind studying their aging prediction. This is followed by a detailed background on passive cooling methods and core concepts, including an introduction to passive cooling, key terminologies, principles of radiative cooling, and the materials and technologies employed in these applications.

Subsequently, the survey delves into aging prediction in radiative cooling coatings, exploring predictive modeling techniques, the impact of environmental stability on performance, and the application of AI techniques in predicting emissivity. The analysis focuses on the cooling effects and potential applications of advanced daytime radiative cooling technologies in building design, emphasizing their cooling power, temperature reduction capabilities, and seamless integration into passive building strategies. This includes innovative materials such as photonic structures and nanoparticle coatings, which can enhance energy efficiency by reflecting over 90

---

The paper provides an in-depth analysis of passive cooling methods, focusing on the principles underlying various cooling technologies. It categorizes these technologies into distinct groups and explores the synergistic effects of evaporative and radiative cooling, highlighting recent advancements in photonic nanostructures that enhance cooling performance. Additionally, the discussion includes the role of innovative materials developed for daytime passive radiative cooling, which effectively reflect solar radiation and emit heat through the atmospheric window, thereby reducing energy consumption in buildings and improving thermal comfort [10, 11, 7, 12, 4]. This is followed by an exploration of thermal management and energy efficiency, emphasizing material design, dynamic thermal management systems, and the role of radiative cooling coatings in broader thermal strategies.

The survey concludes by addressing challenges and future directions in radiative cooling coatings, identifying current technological and environmental challenges, and exploring potential advancements and research areas. The concluding section summarizes key findings and underscores the importance of radiative cooling coatings in advancing energy-efficient building design. The following sections are organized as shown in Figure 1.

## **2 Background and Core Concepts**

### **2.1 Introduction to Passive Cooling Methods**

Passive cooling methods are crucial for sustainable building design, leveraging natural processes to maintain indoor comfort without mechanical systems. Traditional methods, such as moisture-wicking fabrics, often fall short in efficiency and sustainability, prompting innovations like bio-inspired materials. A notable advancement is a polyethylene aerogel laminated with polydimethylsiloxane, which reflects sunlight and emits heat, achieving sub-ambient cooling during the day [13, 9]. This design draws inspiration from biological systems, such as bilayer porous polymer structures mimicking human skin, enhancing passive cooling capabilities.

Recent innovations include integrating passive radiative cooling materials into architectural elements like double-pane skylights, enhancing thermal regulation [12]. These advancements not only improve cooling efficiency but also seamlessly integrate into modern architectural designs. The evolution of passive cooling techniques signifies a leap in sustainable practices, focusing on energy conservation through technologies like photonic structures and bilayer porous polymers. These methods aim to reduce reliance on traditional air conditioning by employing mechanisms like daytime radiative and evaporative cooling, addressing challenges posed by climate change [4]. By leveraging heat reflection and emission processes, passive cooling methods provide viable solutions for decreasing the energy footprint of buildings while ensuring thermal comfort.

### **2.2 Key Terms and Definitions**

Understanding key terms related to radiative cooling is essential for effective thermal management and energy efficiency in building design. Radiative cooling involves a surface emitting infrared radiation to dissipate heat into the cooler atmosphere or outer space, effectively lowering its temperature without external energy input. This process, particularly effective at night, utilizes materials designed for selective thermal emission, achieving significant temperature reductions even without solar radiation [10, 4, 7].

Emissivity is a critical parameter, indicating how efficiently a surface emits thermal radiation compared to a perfect blackbody at the same temperature. High emissivity materials are vital for effective heat dissipation, particularly in technologies like thermophotovoltaics and adaptive thermal control systems [10, 14, 3, 12]. High emissivity enhances heat dissipation rates, while solar reflectance minimizes heat absorption, contributing to cooler surface temperatures during the day.

Radiative cooling technologies significantly reduce energy consumption through passive means, potentially cutting cooling energy demands by up to 60

A comprehensive understanding of radiative cooling technologies is crucial for developing energy-efficient and environmentally sustainable building designs. These technologies utilize advanced materials and structures, such as photonic nanostructures, to reflect over 90

---

## 2.3 Principles of Radiative Cooling

Radiative cooling uses the natural emission of infrared radiation to dissipate heat from surfaces to cooler surroundings or outer space, relying on materials with high emissivity to achieve sub-ambient cooling without external energy input [15]. This process is most effective at night, when the sky functions as a vast heat sink, enabling heat escape through the atmospheric transparency window.

Advanced material designs, such as dielectric multilayer structures, enhance radiative cooling by allowing tailored spectral and directional emissivity, optimizing thermal radiation capabilities [16]. Mechanically tunable radiative cooling methods exploit the properties of thermoplastic polyurethane (TPU) through flexible electrospun nanofiber membranes, enabling precise tuning of emissivity and enhancing passive cooling efficiency [17, 18, 2].

Hybrid optical-thermal devices, such as those employing Femtosecond Laser Surface Processing (FLSP), create microscale surface features that enhance absorptive and emissive properties, improving cooling efficiency [1]. Nanophotonic designs maintain aesthetic qualities while ensuring efficient thermal management by achieving high reflectivity and color saturation without excessive solar absorption [19].

Radiative cooling principles are closely tied to advancements in material science, relying on specialized materials that exhibit high thermal emissivity and strong solar reflectivity. These innovations enable effective heat dissipation into the sky without external energy input, paving the way for applications in energy-efficient technologies such as photovoltaics and passive cooling systems [13, 10, 11, 3, 12].

## 2.4 Materials and Technologies for Radiative Cooling

The exploration of materials and technologies for radiative cooling is a dynamic field utilizing advanced material science to improve thermal management capabilities. Photonic structures allow precise control over thermal emission and reflectance properties, with silica opals serving as photonic crystals that enhance both colorization and thermal emission [8].

The Radiative Infrared Emission (RINE) system exemplifies a multi-layer configuration designed for daylong sub-ambient cooling while enabling diverse color expression, integrating a spectrally selective filter, a selective heat transfer layer, and a thermal emitter [7]. ZnO/Ag/ZnO films in a photonic crystal structure with a periodic array of apertures balance visible and infrared compatibility, essential for effective thermal management [5].

Innovative technologies like the triple-mode mid-infrared modulator (TMIM) employ a biaxially strained elastomeric film to switch between emission, reflection, and transmission modes, providing versatile thermal regulation [20]. Optical wood (OW) with a hierarchically porous structure and cellulose nanofibers enhances dynamic thermal property control [17]. Microporous glass coatings combining low-melting point glass and aluminum oxide particles demonstrate enhanced solar reflectance and infrared emissivity [11].

Using lossy optical cavities with thin platinum layers to control thermal emissivity via topological phase transitions illustrates cutting-edge advancements in material design for localized thermal emission [21]. Photonic structures address the challenge of maintaining cooling efficiency while satisfying aesthetic demands [6].

The materials and technologies in radiative cooling applications blend aesthetic appeal with high functional performance, particularly through innovative photonic nanostructures and advanced materials like polymeric aerogels. These advancements enhance cooling system efficiency by achieving sub-ambient surface temperatures in direct sunlight, contributing to sustainable and energy-efficient building designs and addressing the challenges posed by rising ambient temperatures and increasing energy demands [13, 4].

## 3 Radiative Cooling Coating Aging Prediction

Understanding the factors influencing the aging and performance of radiative cooling coatings is crucial for enhancing their durability and effectiveness. This section explores various predictive modeling techniques essential for evaluating the longevity and functionality of these coatings. Advanced

methodologies allow researchers to examine how material composition and environmental conditions impact the performance of radiative cooling systems over time. The following subsection delves into predictive modeling techniques that enhance our understanding of these processes, setting the stage for a comprehensive discussion on the future implications for radiative cooling technologies.

### 3.1 Predictive Modeling Techniques

Benchmark	Size	Domain	Task Format	Metric
-----------	------	--------	-------------	--------

Table 1: The table summarizes key benchmarks for evaluating predictive modeling techniques in radiative cooling coatings. It includes the benchmark name, size, domain, task format, and the metrics used for assessment. This comprehensive overview aids in understanding the diverse methodologies and evaluation criteria applied in the field.

Predictive modeling techniques are vital for assessing the aging and long-term performance of radiative cooling coatings across diverse environmental conditions. Artificial intelligence-based emissivity prediction (AI-EP) utilizes machine learning algorithms to relate surface features and fabrication parameters with total hemispherical emissivity, enabling precise predictions of emissivity changes over time and aiding in the design of more durable coatings [14].

Mechanically tunable materials, such as stretchable thermoplastic polyurethane (TPU) nanofiber membranes, enhance predictive modeling by providing dynamic control over optical properties. The Es-TPU membrane, for instance, achieves a reflectivity of 95.6

Hybrid Optical-Thermal Antennas (HOTA) demonstrate the potential to predict and enhance thermal emission properties by analyzing optical and thermal characteristics interactions, crucial for anticipating cooling efficiency changes over time [15]. Techniques incorporating dielectric Bragg reflectors with femtosecond laser surface processed (FLSP) aluminum surfaces offer precise emissivity control, forming a basis for predicting surface modifications' impact on cooling coatings' aging [1].

The triple-mode mid-infrared modulator (TMIM) uses mechanical strain on an elastomer to achieve various thermal management modes, providing a unique perspective on aging prediction by evaluating mechanical and thermal stresses on material performance over time [20]. The Topologically Protected Thermal Emitter (TPTE) manipulates thermal emission by adjusting a platinum film's thickness to achieve unity emissivity at a critical thickness, representing an advanced method for managing thermal properties and predicting aging effects [21]. The Multi-band Graphene-based Metamaterial Absorber/Emitter (MGM) employs a MIM grating structure with a single-layer graphene layer, allowing tunable absorption characteristics in thermal IR applications, offering a flexible framework for assessing environmental changes' effects on radiative cooling coatings' aging [22].

These predictive modeling techniques are crucial for understanding radiative cooling coatings' aging processes, enabling the development of materials with enhanced durability and performance across diverse applications. The survey categorizes existing research into four main technological clusters: multilayer planar photonic structures, metamaterials and 2D-3D photonic structures, polymers for radiative cooling, and paints for radiative cooling, providing a comprehensive framework for future advancements in the field [4]. Additionally, Table 1 provides a detailed overview of the benchmarks used in predictive modeling techniques for assessing the aging and performance of radiative cooling coatings.

As illustrated in Figure 2, the study of radiative cooling coating aging prediction through predictive modeling techniques is an emerging field with significant implications for energy efficiency and material longevity. The examples in Figure 2 demonstrate diverse approaches in this domain. The first subfigure compares the spectral emission of a real surface with that of a blackbody, highlighting the complexities in real-world surface emissions that predictive models must address. The second subfigure explores innovations in flexible and stretchable materials designed for solar energy harvesting and smart textiles, underscoring the necessity for predictive models that accommodate material deformation and its effects on reflectivity and emissivity. The third subfigure presents thermal imaging and spectral reflectance data for a solar collector, showcasing the practical application of predictive modeling in optimizing solar energy systems. Collectively, these examples emphasize the importance of advanced modeling techniques in predicting the aging and performance of radiative

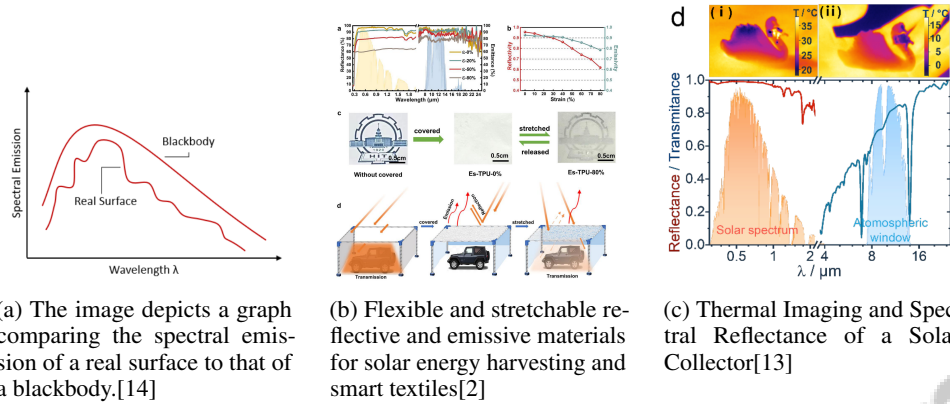


Figure 2: Examples of Predictive Modeling Techniques

cooling coatings, which are crucial for developing sustainable energy solutions and advanced material technologies [14, 2, 13].

### 3.2 Environmental Stability and Performance

The environmental stability and performance of radiative cooling coatings are critical factors influencing their longevity and efficacy across diverse climatic conditions. A primary challenge is the current methodologies' inability to dynamically adjust thermal emission in response to environmental changes, which can lead to inefficiencies and potential damage to sensitive equipment [3]. This limitation is particularly evident in metamaterial structures, which lack adjustable resonances, constraining their adaptability to fluctuating environmental conditions [22].

The inherent properties of materials also significantly influence the performance of radiative cooling coatings. For example, silica opals have demonstrated the ability to maintain cooling efficiency under direct sunlight, as evidenced by experiments measuring temperature variations [8]. This highlights their potential for effective thermal management in outdoor applications, where environmental factors such as sunlight exposure are prevalent.

Photonic crystals further enhance environmental stability. Evaluations under controlled heating conditions have shown their capability to sustain thermal management performance, emphasizing the need for precise environmental control during application [5]. However, the static nature of these materials remains a challenge, restricting their adaptability to changing environmental conditions.

To ensure practical applications of radiative cooling coatings, it is essential to develop materials that exhibit high thermal emissivity within the atmospheric transparency window (8–13  $\mu\text{m}$ ) and high solar reflectivity (0.2–3  $\mu\text{m}$ ), while also demonstrating long-term environmental stability and resilience against humidity, UV radiation, and temperature fluctuations. Recent advancements in nanomaterials and metamaterials have led to innovative coatings capable of effectively reducing energy consumption for cooling by reflecting over 90

### 3.3 AI Techniques in Predicting Emissivity

The application of artificial intelligence (AI) techniques in predicting the emissivity of radiative cooling coatings marks a significant advancement in material science, offering a sophisticated approach to understanding and forecasting the aging and performance of these coatings. AI-based emissivity prediction (AI-EP) models effectively correlate the morphological characteristics and fabrication parameters of functionalized surfaces with their emissivity properties, enabling precise predictions of how emissivity may change over time, which is vital for designing coatings that maintain cooling efficiency under diverse environmental conditions [14].

These AI techniques leverage advanced machine learning algorithms to analyze extensive datasets of surface features, facilitating the detection of complex patterns and relationships often overlooked by traditional analytical methods. For instance, in emissivity prediction for functionalized surfaces,

---

AI can accurately estimate emissivity based on 3D surface morphology images and correlate it with fabrication parameters, addressing challenges posed by conventional methods that struggle with intricate interactions affecting thermal radiation. This innovative approach enhances the precision of emissivity predictions and broadens the applicability of thermal management solutions across various engineering fields [21, 14]. By leveraging these insights, researchers can optimize the material composition and structural design of radiative cooling coatings to improve durability and thermal management capabilities.

Moreover, AI-driven models facilitate the exploration of new materials and surface treatments, accelerating the development of coatings with tailored emissivity profiles. This capability is crucial for developing adaptive cooling systems that can dynamically adjust to fluctuations in environmental conditions, thereby enhancing the longevity and efficiency of coatings used in both terrestrial and extraterrestrial applications. Such systems leverage innovative designs, including mechanically tunable radiative cooling technologies that allow for significant reductions in thermal emission through structural adjustments. By employing these advanced photonic structures, effective passive heat management can be achieved, ultimately reducing reliance on traditional refrigeration methods and improving thermal control in varying climates [3, 4].

The integration of AI techniques into the study of emissivity and aging prediction offers a powerful tool for advancing the field of radiative cooling. By enhancing our understanding of the various factors influencing emissivity, these advanced techniques play a crucial role in developing innovative cooling solutions that improve energy efficiency and contribute significantly to sustainable building design, particularly in the context of rising ambient temperatures and the increasing demand for effective thermal management in buildings. Recent advancements in photonic nanoscience have enabled the creation of materials that reflect over 90

## 4 Cooling Effect and Potential in Building Applications

Advancements in cooling technologies, notably radiative cooling coatings, have become pivotal in enhancing energy efficiency within building applications. These coatings are integral to managing thermal loads and improving indoor comfort, emphasizing their role in passive thermal management strategies. As illustrated in Figure ??, the figure underscores the significant role of radiative cooling coatings in building applications by focusing on their cooling power and temperature reduction capabilities. It also highlights the integration of these technologies into passive building design, showcasing key materials that enhance energy efficiency and occupant comfort. This section examines the cooling power and temperature reduction capabilities of these coatings, further emphasizing their substantial impact on building energy dynamics and occupant well-being.

Figure 3: This figure illustrates the role of radiative cooling coatings in building applications, focusing on their cooling power, temperature reduction capabilities, and integration into passive building design. Key technologies and materials are highlighted, emphasizing their potential to enhance energy efficiency and occupant comfort.

### 4.1 Cooling Power and Temperature Reduction

Radiative cooling coatings are crucial for passive thermal management in buildings due to their significant cooling power and temperature reduction capabilities. Their effectiveness is based on solar radiation reflection and thermal radiation emission. For instance, the Es-TPU membrane achieves a cooling power of 118.25 W/m<sup>2</sup> in its high-reflectivity state [2], while dielectric Bragg reflectors integrated with femtosecond laser surface processed aluminum surfaces reach 97.79 W/m<sup>2</sup> [16]. Optical wood technology offers 81.4 W/m<sup>2</sup>, showcasing switchable solar transmittance's role in thermal regulation [17]. A bilayer film design achieves approximately 151 W/m<sup>2</sup>, with a temperature drop of around 6 °C [9].

Colorful radiative coolers (CMRCs) demonstrate temperature reductions between 3.4°C and 4.4°C [19], and photonic crystal designs show a 12.2 °C decrease compared to low-emittance aluminum foil [5]. For nighttime applications, electrically tunable metamaterials, such as a multi-band graphene-based absorber/emitter, achieve net cooling power over 18 W/m<sup>2</sup> [22], while hybrid optical-thermal devices enhance body cooling rates by at least 23 W [15].



---

These diverse materials and technologies, including photonic structures, metamaterials, and nanoparticle-based coatings, often achieve temperature reductions exceeding 5 °C in urban environments while reflecting over 90

## 4.2 Integration into Passive Building Design

Integrating radiative cooling coatings into passive building design is transformative, enhancing thermal comfort and minimizing energy consumption. These coatings are strategically applied to building envelopes like roofs and facades, leveraging their thermal emissivity and solar reflectance to reduce thermal loads and dependence on conventional cooling systems. Recent advancements in nanoscience and metamaterials have optimized passive radiative cooling performance, enabling effective temperature regulation under direct solar exposure [9, 12, 4], particularly in high solar insolation regions where cooler building surfaces yield substantial energy savings.

Advanced materials utilizing nanotechnology and metamaterials facilitate precise control over thermal emission and reflectance, allowing for aesthetically pleasing and functionally effective coatings suitable for various architectural applications [12]. Performance metrics assessing cooling efficiency and durability in real-world environments strengthen the integration of these coatings. Bilayer porous polymer films and photonic structures demonstrate significant passive cooling through evaporative cooling and radiative heat emission, achieving sub-ambient temperature drops of approximately 7 °C under direct sunlight [11, 9, 12, 4]. Nanoparticle-based coatings enhance cooling through high solar reflectivity and effective thermal emission, promoting energy efficiency and sustainable building practices by reducing reliance on traditional air conditioning systems.

Strategic integration of advanced radiative cooling coatings into passive building design offers a sustainable approach to enhance thermal comfort and reduce energy consumption, potentially decreasing cooling energy requirements by up to 60

## 5 Principles of Passive Cooling Methods

### 5.1 Categorization of Cooling Technologies

Cooling technologies are categorized into active and passive methods. Active cooling, like air conditioning, uses mechanical systems to transfer heat, consuming energy in the process. In contrast, passive methods lower temperatures through natural processes and materials without energy input. Recent advancements in passive daytime radiative cooling exemplify this distinction, employing materials that reflect over 90% of solar radiation and emit heat through the atmospheric transparency window, potentially reducing cooling demands by up to 60% [15, 10, 11, 12, 4]. These innovations underscore the need for sustainable solutions to address growing energy needs and climate change challenges.

Radiative cooling is notable among passive strategies for dissipating heat via infrared emission into the cooler atmosphere or outer space, achieving sub-ambient cooling [2]. This technology employs diverse materials and designs such as photonic structures, metamaterials, and polymers, each optimized for thermal emission and solar reflectance [4]. Other passive methods include evaporative cooling, which lowers air temperatures through water evaporation, and thermal mass cooling, which uses materials with high heat capacity to absorb and release heat, particularly effective in climates with significant diurnal temperature variations [13, 10, 7, 12, 4].

Hybrid technologies combine active and passive methods to enhance efficiency. For instance, systems integrating evaporative and radiative cooling achieve synergistic effects that improve thermal comfort while minimizing energy use [5]. The classification of cooling technologies reveals innovative strategies for managing thermal environments, including passive daytime radiative cooling systems that utilize photonic materials to significantly reduce energy use and improve indoor comfort, contributing to climate change mitigation [3, 11, 4]. Understanding each method's advantages and limitations enables stakeholders to choose the most appropriate solutions for specific applications, fostering sustainable and energy-efficient building designs.

---

## 5.2 Synergistic Effects of Evaporative and Radiative Cooling

Integrating evaporative and radiative cooling methods creates a synergistic approach to building thermal management, leveraging the complementary mechanisms of these passive strategies. Evaporative cooling uses the latent heat of vaporization; as water evaporates, it absorbs heat from the surrounding air, reducing ambient temperatures, particularly effective in arid climates with low humidity [5]. Conversely, radiative cooling dissipates heat by emitting infrared radiation through the atmospheric transparency window, achieving sub-ambient temperatures without energy input [2]. Combining these methods significantly enhances cooling efficiency, as evaporative cooling lowers surrounding air temperatures, decreasing the thermal load on radiative systems. This synergy not only boosts overall cooling power but also extends the operational range of radiative coatings, especially during peak solar radiation.

Advanced materials and technologies further support these strategies' integration. Photonic structures and metamaterials are engineered to maximize solar reflectance and thermal emission while facilitating water evaporation, enhancing cooling performance [4]. Additionally, materials with high water absorption capacity sustain evaporative cooling, complementing radiative efforts.

The combined effects of advanced evaporative and innovative radiative cooling techniques, particularly those utilizing recent advancements in photonic nanoscience, offer a highly effective means for achieving energy-efficient thermal management in buildings. By employing water evaporation's latent heat alongside radiative cooling's passive heat dissipation, these methods significantly improve indoor thermal comfort and reduce energy consumption during peak heat events [10, 4]. This integration reduces reliance on active systems, lowers energy consumption, and enhances thermal comfort, aligning with sustainable building practices and climate change mitigation efforts.

## 6 Thermal Management and Energy Efficiency

### 6.1 Material Design and Thermal Management

Effective thermal management is essential for enhancing energy efficiency and sustainability in buildings. Femtosecond Laser Surface Processing (FLSP) exemplifies innovative methods, creating highly emissive surfaces that significantly improve heat dissipation and energy efficiency [1]. Advanced materials, such as photonic structures and metamaterials, are engineered to optimize solar reflectance and thermal emissivity, reducing surface temperatures and cooling loads. Incorporating bilayer porous polymers and photonic structures into roofs and facades can achieve temperature reductions of about 7 °C and cooling powers around 150 W·m<sup>2</sup> under direct sunlight, minimizing reliance on active cooling systems through evaporative and radiative methods [9, 12, 4]. This approach not only saves energy but also mitigates environmental impacts associated with traditional cooling methods.

Hybrid optical-thermal devices showcase the potential for dynamic thermal management by integrating light manipulation with thermal control. These devices enhance performance through resonant interactions with light across visible and infrared frequencies. For instance, hybrid optical-thermal antennas focus light at sub-wavelength scales, increasing intensity at specific wavelengths while reducing operating temperatures via light recycling. Innovative fabrics, opaque to visible light but transparent in the infrared, facilitate efficient thermal energy dissipation from the human body, highlighting diverse applications in personal thermal management and building energy efficiency [15, 16]. By modulating optical and thermal properties in response to environmental conditions, these materials enhance the adaptability and efficiency of thermal management systems.

Material design for thermal management is pivotal for achieving energy-efficient building solutions. By improving emissivity and reflectance through technologies like artificial intelligence and photonic nanostructures, these innovations significantly enhance passive daytime radiative cooling, potentially reducing cooling energy consumption by up to 60

### 6.2 Dynamic Thermal Management Systems

Dynamic thermal management systems, utilizing advanced radiative coatings, adaptively regulate thermal conditions, surpassing traditional static systems. These systems are particularly valuable in applications like spacecraft thermal management, where extreme temperature fluctuations threaten equipment integrity. Mechanically tunable designs effectively reduce thermal emissions through

---

simple mechanical strain, promoting cost-effective passive heat management in terrestrial settings and reducing dependency on inefficient artificial cooling technologies [3, 4].

A key component of these systems is the integration of AI techniques, enabling emissivity prediction and adjustment based on complex datasets. AI-based models reveal hidden relationships between surface characteristics and emissivity, allowing precise control over thermal properties [14]. This capability is crucial for developing coatings that dynamically respond to changing thermal conditions, maintaining optimal cooling efficiency across various environments.

Mechanically tunable materials, such as stretchable thermoplastic polyurethane (TPU) nanofiber membranes, exemplify dynamic systems' potential. These membranes transition between high and low reflectivity states through mechanical stretching, achieving a reflectance of 95.6

Hybrid optical-thermal devices underscore dynamic systems' potential, employing advanced material designs like dielectric multilayers and nanophotonic structures to dynamically adjust thermal emission properties in real-time. Tailored resonant interactions with light across visible and infrared frequencies enhance light intensity and facilitate efficient energy dissipation. For instance, hybrid optical-thermal antennas utilize whispering-gallery modes within optical microcavities to improve thermal management, while specialized fabrics opaque in the visible spectrum yet transparent in the infrared enable effective thermal energy release from the human body. Additionally, innovative topological approaches allow precise control over thermal radiation characteristics, leveraging topologically protected states to achieve near-unity thermal emissivity, with applications in energy harvesting and thermal camouflage [15, 21]. By leveraging these advanced materials, dynamic thermal management systems optimize cooling performance and enhance energy efficiency in building applications.

Dynamic thermal management systems represent a significant advancement in radiative cooling technologies, utilizing advanced photonic structures to sustainably enhance energy efficiency. These systems facilitate substantial reductions in indoor and outdoor temperatures while decreasing dependence on traditional active cooling methods, such as air conditioning. By employing materials engineered for optimal thermal emission, these systems adapt their cooling capabilities to varying environmental conditions, providing a versatile and effective solution for heat management in terrestrial and extraterrestrial applications [10, 3, 4]. Through the integration of AI techniques and advanced materials, these systems contribute to developing energy-efficient buildings that prioritize environmental responsibility and occupant well-being.

## **7 Challenges and Future Directions**

### **7.1 Challenges and Limitations**

Radiative cooling coatings face significant challenges that impede their performance and adoption. High costs of advanced materials and complexities in scaling production limit accessibility, particularly in large-scale projects where cost-effectiveness is crucial [10]. Manufacturing advanced photonic structures is challenging in humid climates, where atmospheric conditions can degrade performance [4]. Current passive systems lack dynamic tuning capabilities essential for maintaining thermal comfort in varying weather conditions [2], highlighting the need for advancements in material design.

Durability and long-term performance of passive cooling systems are inadequately addressed in literature. Optimizing material properties for consistent performance over time, both day and night, is essential [12]. Reliance on specific materials, such as phenylethanol in optical wood technologies, raises concerns about stability and environmental impact [17]. Mechanically tunable methods face challenges with uniform strain application over large surfaces, affecting performance [3]. The Femtosecond Laser Surface Processing (FLSP) technique may experience reduced emissivity at higher fluence values, limiting its applicability [1].

Dependence on specific material properties, such as emissivity, complicates passive radiative heating and cooling strategies [20]. Maintaining efficiency is further challenged by absorption of thermal radiation outside the atmospheric window [16]. Structural imperfections, such as in self-assembled opals, can lead to significant absorption and affect performance [8]. The photonic crystal approach faces limitations, including performance reduction due to edge damage [5]. The effectiveness of Radiative Infrared Emission (RINE) systems may vary based on environmental conditions and specific materials [7].

---

Future research should prioritize optimizing radiative cooling designs to enhance thermal performance and adaptability to various conditions. Developing dynamically tunable systems capable of adjusting thermal emission based on mechanical strain can significantly improve efficiency across applications, from urban heat management to spacecraft thermal regulation. Expanding operational conditions can enhance utility and effectiveness, addressing challenges posed by rising global temperatures and extreme heat events [3, 4]. Overcoming these challenges is essential for advancing the field and realizing the full potential of radiative cooling coatings in sustainable building design.

## 7.2 Future Directions in Radiative Cooling

Future research in radiative cooling aims to enhance performance and applicability across diverse environments. Key focus areas include optimizing material properties through new nanomaterials and advanced photonic structures to improve passive cooling technologies in varying climates. Significant advancements involve extending wavelength ranges for thermal emitters and exploring chiral edge modes in various materials. Hybrid optical-thermal devices optimize light interaction across visible and infrared frequencies, enhancing thermal management and cooling efficiency. Functionalized aluminum surfaces produced via femtosecond laser processing exhibit near-unity broadband emissivity, while designs incorporating dielectric Bragg reflectors allow precise control of thermal emission spectra, improving daytime cooling performance. The use of opals as colorful radiative coolers demonstrates potential to minimize solar absorption while maintaining aesthetic appeal, broadening applications in personal thermal management and energy-efficient building designs [15, 8, 16].

Advancements in processing techniques, particularly FLSP, are anticipated to enhance the versatility and effectiveness of radiative cooling technologies. FLSP enables creation of functionalized metallic surfaces with near-unity broadband omnidirectional emissivity, ideal for passive daytime cooling applications. Recent studies show tuning laser parameters can optimize thermal emission spectra, improving performance under direct solar irradiation. Integrating dielectric multilayer structures can tailor spectral and directional characteristics of thermal radiation, addressing challenges associated with visible and near-infrared absorption that limit daytime cooling applications. This approach not only expands potential uses of radiative cooling technologies but also contributes to energy efficiency in thermal management systems [1, 11, 14, 16, 12]. By optimizing processing parameters and applying these techniques to a broader range of materials, researchers can improve scalability and performance. Exploring mechanically tunable designs and developing scalable fabrication processes will be essential for implementing these systems in diverse environmental contexts.

Integrating radiative cooling with traditional cooling methods through hybrid systems is another promising research direction. Such systems can leverage strengths of both passive and active cooling strategies, potentially leading to more efficient and cost-effective thermal management solutions [4]. Enhancing tunability of electrically tunable metamaterials and exploring scalability will further enable practical applications in real-world thermal management systems.

Advancements in intricate photonic structures that effectively manage thermal responses while maintaining aesthetic color qualities will be critical, as these innovations can significantly enhance energy efficiency in outdoor applications such as buildings and vehicles. Research indicates that radiative thermal load for colored objects can vary dramatically, with temperature differences exceeding 47.6 °C among structures of the same color, highlighting potential for tailored photonic designs to optimize both thermal management and visual appeal [15, 6, 8, 19, 16]. This includes exploring new materials and designs to enhance performance of bilayer cooling systems, offering improved efficiency and adaptability. Improving durability of photonic crystal structures and investigating additional applications in energy and thermal technologies will contribute to long-term viability and effectiveness of these systems.

Future research directions also encompass optimizing self-assembly processes and investigating new materials to enhance cooling efficiency and color variety of radiative coolers. Advancing cost-effective materials and optimizing designs for specific applications, alongside innovative technologies for harnessing radiative cooling, will be crucial for enhancing accessibility and widespread adoption. This includes developing photonic structures and materials that effectively dissipate heat to the sky, improving performance of temperature-sensitive devices such as photovoltaics, thermophotovoltaics, and infrared detectors, while addressing challenges posed by rising ambient temperatures and energy consumption in cooling systems [10, 4].

---

Collective research directions reflect a sustained commitment to advancing radiative cooling technologies, aiming to address current challenges such as limited material performance and manufacturing feasibility. Recent innovations in photonic nanoscience have led to development of advanced materials and structures, including metamaterials and polymeric coatings, that significantly enhance solar reflectance and long-wave infrared emission. These advancements promise to reduce energy consumption in buildings by up to 60

## **8 Conclusion**

The exploration of radiative cooling coatings underscores their pivotal role in advancing passive cooling technologies through material science innovations, such as nanoparticle coatings and metamaterials. These advancements are instrumental in enhancing energy efficiency and fostering environmentally sustainable practices. The survey highlights the transformative potential of these coatings in reducing the thermal load of optoelectronic devices, thereby underscoring the importance of ongoing research to refine materials and optimize design for enhanced performance.

Radiative cooling coatings stand out as key contributors to passive building design by significantly reducing reliance on active cooling systems. Their ability to maintain lower surface and interior temperatures not only improves thermal comfort but also boosts energy efficiency. Integrating these coatings into architectural designs aligns with sustainable building practices and supports climate change mitigation efforts by curtailing greenhouse gas emissions. The strategic application of radiative cooling technologies is thus essential for promoting energy-efficient and eco-friendly building solutions.

---

## References

- [1] Andrew Reicks, Alfred Tsubaki, Mark Anderson, Jace Wieseler, Larousse Khosravi Khorashad, Jeffrey E. Shield, George Gogos, Dennis Alexander, Christos Argyropoulos, and Craig Zuhlke. Near-unity broadband omnidirectional emissivity via femtosecond laser surface processing, 2021.
- [2] Xin Li, Zhenmin Ding, Giuseppe Emanuele Lio, Jiupeng Zhao, Hongbo Xu, Lorenzo Pattelli, Lei Pan, and Yao Li. Strain-adjustable reflectivity of polyurethane nanofiber membrane for thermal management applications. *Chemical Engineering Journal*, 461:142095, 2023.
- [3] Andrew Butler and Christos Argyropoulos. Mechanically tunable radiative cooling for adaptive thermal control, 2022.
- [4] Mattheos Santamouris and Jie Feng. Recent progress in daytime radiative cooling: is it the air conditioner of the future? *Buildings*, 8(12):168, 2018.
- [5] Saichao Dang and Hong Ye. A visible - infrared compatible camouflage photonic crystal with enhanced emission in  $5.8\ \mu\text{m}$ , 2021.
- [6] Wei Li, Yu Shi, Zhen Chen, and Shanhui Fan. Photonic thermal management of coloured objects. *Nature communications*, 9(1):4240, 2018.
- [7] Suwan Jeon, Soomin Son, Seokhwan Min, Hyunjin Park, Heon Lee, and Jonghwa Shin. Daylong sub-ambient radiative cooling with full color exterior, 2022.
- [8] Hyeon Ho Kim, Eunji Im, and Seungwoo Lee. Opals as colorful radiative coolers, 2019.
- [9] Chunzao Feng, Peihua Yang, Huidong Liu, Mingran Mao, Yipu Liu, Tong Xue, Jia Fu, Ting Cheng, Xuejiao Hu, Hong Jin Fan, et al. Bilayer porous polymer for efficient passive building cooling. *Nano Energy*, 85:105971, 2021.
- [10] Xingshu Sun, Yubo Sun, Zhiguang Zhou, Muhammad Ashraful Alam, and Peter Bermel. Radiative sky cooling: fundamental physics, materials, structures, and applications. *Nanophotonics*, 6(5):997–1015, 2017.
- [11] A solution-processed radiative c.
- [12] G Gangisetty and R Zevenhoven. A review of nanoparticle material coatings in passive radiative cooling systems including skylights. *energies* 2023, 16, 1975, 2023.
- [13] Meng Yang, Weizhi Zou, Jing Guo, Zhenchao Qian, Heng Luo, Shijia Yang, Ning Zhao, Lorenzo Pattelli, Jian Xu, and Diederik S. Wiersma. Generalized bioinspired approach to a daytime radiative cooling "skin", 2020.
- [14] Greg Acosta, Andrew Reicks, Miguel Moreno, Alireza Borjali, Craig Zuhlke, and Mohammad Ghashami. Emissivity prediction of functionalized surfaces using artificial intelligence, 2022.
- [15] Svetlana V. Boriskina, Jonathan K. Tong, Wei-Chun Hsu, Lee Weinstein, Xiaopeng Huang, James Loomis, Yanfei Xu, and Gang Chen. Hybrid optical-thermal devices and materials for light manipulation and radiative cooling, 2015.
- [16] Andrew Butler, Andrew Reicks, Dennis Alexander, George Gogos, Craig A. Zuhlke, and Christos Argyropoulos. Tailoring the spectral and directional emissivity of functionalized laser processed surfaces, 2024.
- [17] He Gao, Ying Li, Yanjun Xie, Daxin Liang, Jian Li, Yonggui Wang, Zefang Xiao, Haigang Wang, Wentao Gan, Lorenzo Pattelli, and Hongbo Xu. Optical wood with switchable solar transmittance for all-round thermal management, 2024.
- [18] Jonathan K. Tong, Xiaopeng Huang, Svetlana V. Boriskina, James Loomis, Yanfei Xu, and Gang Chen. Infrared-transparent visible-opaque fabrics for wearable personal thermal management, 2015.

- 
- [19] Shenghao Jin, Ming Xiao, Wenbin Zhang, Boxiang Wang, and Changying Zhao. Daytime sub-ambient radiative cooling with vivid structural colors mediated by coupled nanocavities, 2022.
- [20] Haoming Fang, Wanrong Xie, Xiuqiang Li, Kebin Fan, Yi-Ting Lai, Bowen Sun, Shulin Bai, Willie J. Padilla, and Po-Chun Hsu. A triple-mode mid-infrared modulator for all-surface radiative thermal management, 2021.
- [21] M. Said Ergoktas, Ali Kecebas, Konstantinos Despotelis, Sina Soleymani, Gokhan Bakan, Askin Kocabas, Alessandro Principi, Stefan Rotter, Sahin K. Ozdemir, and Coskun Kocabas. Localised thermal emission from topological interfaces, 2024.
- [22] Ataollah Kalantari Osgouei, Hasan Kocer, Halil Isik, Yilmaz Durna, Amir Ghobadi, and Ekmel Ozbay. Electrically tunable radiative cooling performance of a photonic structure with thermal infrared applications, 2023.

---

**Disclaimer:**

SurveyX is an AI-powered system designed to automate the generation of surveys. While it aims to produce high-quality, coherent, and comprehensive surveys with accurate citations, the final output is derived from the AI's synthesis of pre-processed materials, which may contain limitations or inaccuracies. As such, the generated content should not be used for academic publication or formal submissions and must be independently reviewed and verified. The developers of SurveyX do not assume responsibility for any errors or consequences arising from the use of the generated surveys.

www.SurveyX.cn