Smart Building Skins for Urban Heat Island Mitigation: A Review

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Abstract: The urban heat island (UHI) effect has detrimental impacts on building cooling demand, public and ecological health, and climate change. Because UHIs are caused by the concentration of construction materials that absorb and retain heat, buildings in urban areas present challenges and opportunities to mitigate them. Specifically, innovative building skin solutions, such as those covered with smart materials (SMs) that respond to environmental stimuli with their dynamic time and temperature-dependent behaviors, have significant potential to reduce the UHI effect. This research provides a review of the state-of-the-art applications of SMs in building skins for urban heat island mitigation (UHIM). It highlights the knowledge gaps and opportunities for future research with an extensive literature review and in-depth analysis. This research classifies the application of skin-integrated smart materials (SISMs) for UHIM into five main groups that included thermal, light, air pollution, humidity and ventilation control, and energy generation, and highlights their challenges and prospects. **DOI:** 10.1061/JAEIED.AEENG-1784. *© 2024 American Society of Civil Engineers.*

Author keywords: Adaptive facade; Building skin; Smart materials; Urban heat island.

Introduction

Building envelope materials, especially in dense urban fabrics, contribute to urban heat islands (UHIs) by absorbing and re-emitting heat and solar radiation. Therefore, using proper materials could play a noticeable role in mitigating UHIs. Specifically, building skins that are integrated with materials, which have great potential to adapt to changing environmental conditions, could be an innovative smart solution to indicatively address UHIs. Therefore, this research aims to investigate the role of smart materials (SMs) and study their potential performance in mitigating UHIs.

UHI Effect: An Overview

Urban built environments are characterized by imbalanced microclimates that are caused by high building density, the concentration of building materials, few green surfaces, and excessive anthropogenic heat generation. These parameters lead to a higher temperature in urban areas (e.g., a UHI) by affecting the radiant surface heat balance, convective heat exchange between the ground and buildings, wind flows, and evapotranspiration processes (Kandya and Mohan 2018). The UHI was coined by the British climatologist Gordon Manley in the 1950s (Adamowski and Prokoph 2013; Manley 1958). However, the study of the effects of urban structures and human activities on temperature in urban and suburban areas dates back to the nineteenth century when Luke Howard, the British chemist and meteorologist, examined the climate of London (Howard 1833).

The intensity of a UHI is measured as the difference in temperature between the downtown and suburban areas and is up to 5°C–10°C higher in the downtown areas of cities such as New York (Gedzelman et al. 2003) and London (Bohnenstengel et al. 2011). The current trends in global warming and the anticipated increase in global temperature above 1.5°C and 2°C are going to affect the extreme heat events in cities and exacerbate UHIs (Hoegh et al. 2018). For example, Lee et al. (2021) examined the uncertainty of nonstationary heat wave extremes in Korea and concluded that the intensity of the extreme heatwave events would probably increase in the range of 1.23°C–1.69°C in 2050. In addition, the combined effects of UHIs and extreme heatwave events negatively impact public health and increase heat-related hospitalization and mortality risks, particularly in the elderly and those with existing health conditions (Heaviside et al. 2017). In addition, reports of a reduction in cold-related mortality risks due to UHIs in winter seasons exist (Vardoulakis et al. 2014). de Moraes et al. (2022) showed that the risk of mortality among adults above 65 years was high during the extreme air temperature from 2006 to 2015 in Sao Paulo, Brazil. Another study demonstrated that Madrid's, Spain urban population, compared with rural populations, was more susceptible to heatwave mortality during 2000–2020 (López-Bueno et al. 2021). Abadie and Polanco-Martínez (2022) evaluated the probability distributions of mortality between 2025 and 2100. They showed that an attributable mortality of 1,614 people is expected under representative concentration pathways (RCP 8.5) for 2100 in Madrid, where temperatures in excess of 3.6°C over the 38°C threshold are anticipated.

An UHI could cause thermal discomfort inside and outside buildings and affect the well-being of urban residents (Kandya and Mohan 2018) in different climates (Leal Filho et al. 2018; Mazzeo et al. 2023; da Silva Espinoza et al. 2023). In Manaus, Brazil, for example, a 6°C heat index difference between urban and rural areas and a nighttime UHI of 4°C is reported to have caused significant outdoor thermal discomfort (da Silva Espinoza et al. 2023). In addition, the UHI intensity in Beijing, Shanghai, and Guangzhou, China is reported to have increased by 0.9°C, 0.3°C, and 0.8°C, respectively (Jiang et al. 2019).

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In addition, a UHI has bilateral relationships with energy consumption and climate change; where the increased temperature in urban areas leads to greater cooling energy demand in the building sector and a feedback loop is created when higher energy consumption and the corresponding carbon dioxide (CO_2) emissions lead to anthropogenic climate change and aggravated UHIs (Kamal et al. 2023; Wang et al. 2022). Specifically, the literature reports a 20%–100% growth in cooling energy consumption due to UHIs (Kandya and Mohan 2018; Santamouris et al. 2001). Other environmental impacts that are associated with UHIs include a contribution to ozone layer depletion (Bartholy and Pongrácz 2018), deterioration in the living environment (Sadik-Zada and Gatto 2022), increase in ground level smog (Fallmann et al. 2016), and the concentration of air pollutants (Santamouris and Osmond 2020).

To mitigate UHIs and their adverse impacts on the environment and public health, multidisciplinary collaboration is required among architects, engineers, urban planners, health professionals, and other stakeholders at local, regional, and national levels. Architects, planners, and engineers affect UHI parameters with their professional decisions and, therefore, play important roles in urban heat island mitigation (UHIM). Some decisions include materials that are selected for building skins, the building height-to-width ratio, sky view factor (Zhang and Yuan 2023), or wall and roof areas, which all affect the absorbed and reflected solar radiation (Dirksen et al. 2019). Building skins and their materials are especially important for UHIM, because roof surfaces make up approximately 20%–25% of urban surfaces (Akbari and Matthews 2012), and facades cover approximately double the building footprints (Köhler 2008).

SMs: An Overview

The SMs (Bahl et al. 2020) are materials with the ability to change shape and properties in response to environmental, mechanical, chemical, electrical, or other stimuli (Bandyopadhyay and Sinha Ray 2012). A SM is a sensor and actuator (Sobczyk et al. 2022). Therefore, they could sense (i.e., receive a stimulus and respond with a signal) and actuate (i.e., produce a certain action in response) simultaneously (Newnham 1997). Cao et al. (1999) suggest that SMs have sensing, actuating, and control functions; for instance, they possess "an optimized control algorithm that could guide the actuators to perform required functions after sensing changes." The terms *smart* and *intelligent* are sometimes used interchangeably in the literature to refer to SMs. However, Liu et al. (2020) suggest that SMs are different from intelligent materials because the ability of SMs to sense and respond does not extend to self-optimizing. In addition, Newnham (1993) distinguished intelligent materials in that they integrated sensing and actuating with information processing, feedback circuitry, and power supply.

Addington and Schodek (2004) suggest that five characteristics distinguish SMs from conventional non-SM materials: (1) immediacy (i.e., real time responsiveness); (2) selectivity (i.e., discrete and predictable responsiveness); (3) transiency (i.e., responsiveness to more than one environmental condition); (4) self-actuation (i.e., internal intelligence); and (5) directness (i.e., local responsiveness). The SMs are different in their level of intelligence, based on responsiveness and agility in response and recovery (Laws and Parachuru 2021) and could be classified based on their response to external stimuli. Some SMs change properties (e.g., chemical, optical, mechanical, electrical, or thermal), and others could exchange energy, discretely change in size and location, or change directions (Addington and Schodek 2004). Newnham (1997) classified SMs into three categories that include passive, active, and very smart materials. Passive SMs, such as fiber optics, function as sensors, not actuators. Active SMs, such as shape memory alloys (SMAs), magnetostrictive, piezoelectric, and electrorheological fluids, function as sensors and actuators as they modify geometry or properties in response to external stimuli and could inherently transduce energy. Ritter (2013) grouped SMs into property-changing, energy-generating or exchanging, and matter-exchanging classes. In addition, López et al. (2015) classified building SMs as light, temperature, humidity, and CO_2-reactive materials.

The SMs are proposed for a wide range of applications in the building sector. For example, phase change materials (PCMs) experience phase changes (e.g., solid to liquid or liquid to solid) when exposed to heat and could be used in the building skin to fluctuate temperature variations. The SMA deforms when exposed to heating or cooling and stress and could be used in reinforced concrete to sense and heal cracks. Thermoresponsive hydrogels could be used in the building skin for cooling (Rotzetter et al. 2012). Considering the fluctuations in the buildings' surrounding environments, SMs could be integrated into building skins to adaptively respond to the changing thermal and lighting conditions, enhance indoor environmental regulation, increase building energy efficiency, and reduce UHI effects. Previous studies on skin-integrated smart materials (SISMs) focused on common cool materials, and limited literature exists on the direct or indirect effects of building SMs on urban overheating. Previous studies have investigated the role of SMs in regulating air temperature and solar absorption, such as the use of smart cool mortar (Rosso et al. 2017), photochromic coating based on a sol–gel mesoporous coating matrix (Wu et al. 2017) and quantum dots (QDs) for building passive cooling (Garshasbi et al. 2020). Some noticeable examples of SM applications in building skins include the integration of microalgae photobioreactors (PBR) in the building facade of the BIQ House (Wurm 2013) or the application of different smart glasses in buildings (Al-Qahtani et al. 2022; Gao et al. 2023).

The main goal of this research is to review the UHIM performance of SMs that are integrated into building skins by exploring their performance in adapting to changing ambient conditions and urban overheating. In addition, this research will investigate the underexplored aspects of the UHIM performance of SMs and their potential to integrate with building envelopes to alleviate UHIs.

Following the "Introduction" section that provides a survey of UHIs and SMs, this research proceeds to the "Methods" section, where the key research objectives and the methodology of the research are presented. The main body of this research then presents a survey of the UHI parameters and smart building skins and classifies SMs based on their effect on UHIM. This research concludes with a "Discussion and Conclusion" section that presents the knowledge gaps for future research.

Methods

The key objectives of this research were to identify the main building skin design parameters that directly and indirectly affect UHIs, present various SMs for UHIM applications with a focus on underexplored SMs, and review the challenges when incorporating SMs into building skins for UHIM. Specifically, the combinations of main keywords in the study of UHIs, building envelopes, and SMs were used during the search for relevant publications in ScienceDirect, Scopus, Web of Science, Springer, and Google Scholar. Multiple keywords that include urban heat island, building envelope, and building facade were used to identify climatic, building, and urban-related parameters that affect UHIs. To identify the SM literature for UHIM, the keywords used in the search included smart material, intelligent material, and adaptive material. In addition, "AND" and "OR" queries were used to yield a comprehensive search. Finally, the challenges and limitations of incorporating SMs and their opportunities when integrated with the building skins to realize UHIM were presented, and the knowledge gaps for future research were identified. Fig. 1 shows the methodological framework of the review.

UHI Parameters

An UHI could affect the surface and air temperatures (Fig. 2). A surface urban heat island (SUHI) is characterized by temperature differences between the surfaces in the urban environment, which is commonly examined by the satellite land surface temperature data (Zhou et al. 2019). In addition, air temperature could be studied at the urban canopy (UCL) and urban boundary layers (UBL). The UCL is measured from ground level up to approximately the mean building height (WMO 2023), and the UBL refers to the air layer that extends just above the UCL (Tabatabaei and Fayaz 2023).

Parameters that affect UHIs could be categorized into two groups: (1) uncontrollable; and (2) controllable (Kotharkar et al. 2019) (Table 1). Uncontrollable parameters are natural climatic and environmental parameters that cannot be regulated at a macro scale, and controllable parameters include built environment and anthropogenic parameters that could be changed by human interventions in the built environments at building and urban scales (Rizwan et al. 2008). In addition, these parameters could be categorized based on their direct or indirect effects on UHIs (Rizwan et al. 2008). Direct effects refer to direct changes in the temperature of the ambient environment, and indirect effects indirectly change air temperature through changes in energy consumption and greenhouse gas (GHG) emissions. As given in Table 1, incident solar radiation, for example, is an uncontrollable parameter with a direct UHI effect. Solar radiation is a parameter that is naturally uncontrollable at the macroscale; its effects could be controlled using design interventions

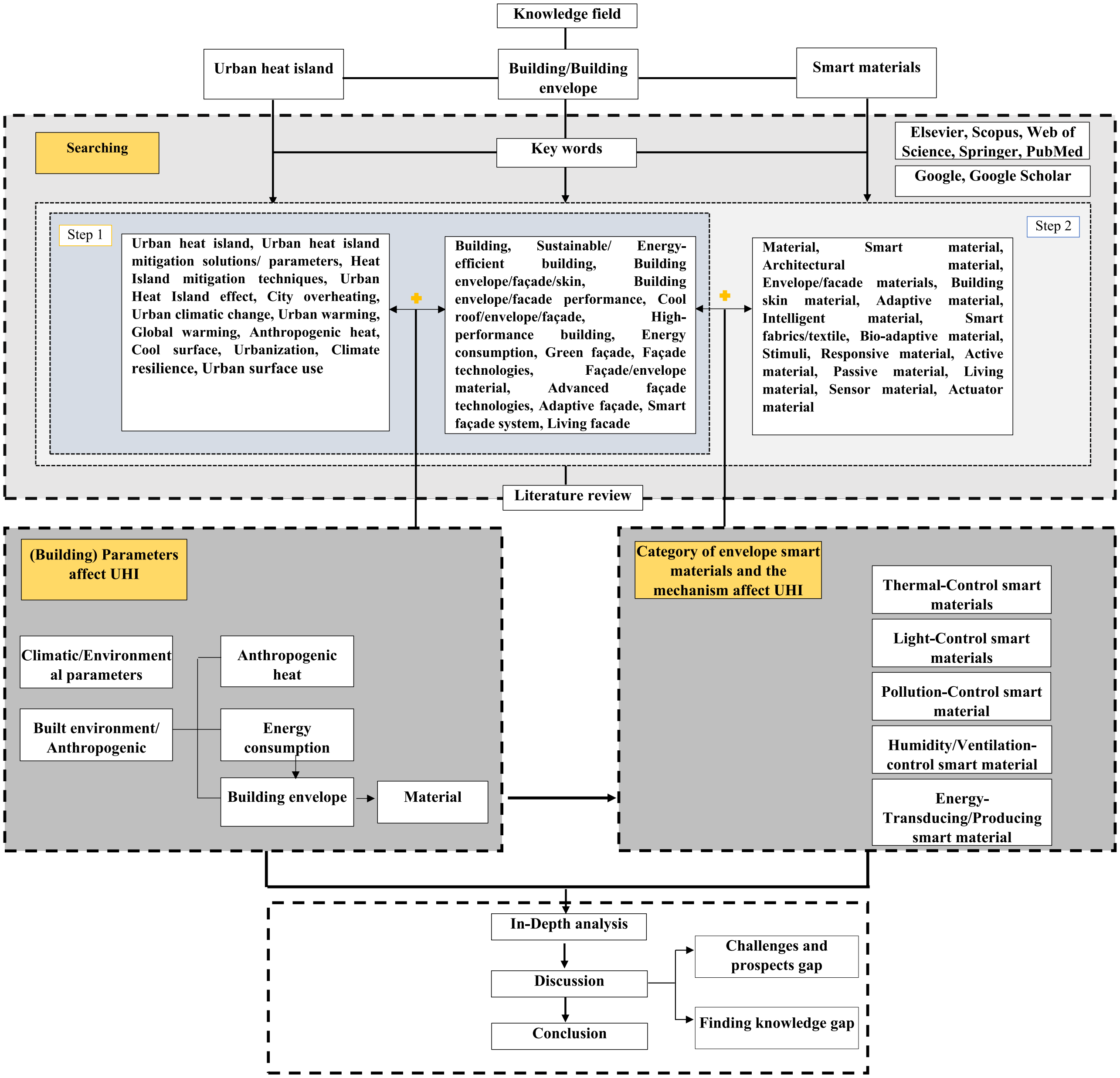

Fig. 1 Research framework.

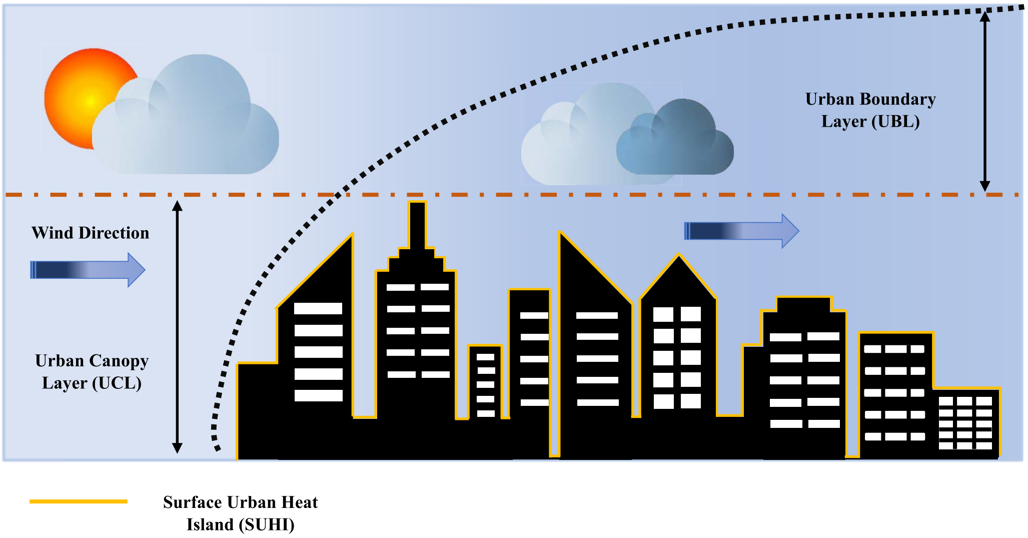

Fig. 2 Different types of UHI.

such as material albedo. Solar radiation and anthropogenic heat that is released from sources such as vehicles, power plants, and air conditioners could be the main sources of heat in an area (Rizwan et al. 2008). To examine the contribution of anthropogenic heat to UHIs, the following formula can be used (Dudorova and Belan 2022):

$$\Delta T_{\mathrm{UHI}} = \frac{Q_F l}{C_p \rho h_{\mathrm{UHI}} V} \quad (1)$$

where Q = anthropogenic heat (W/m^2); l = linear city dimension based on wind direction (m); h_{UHI} = UHI height; V = wind speed (m/s); C_p = specific heat capacity (J/kg°C); and ρ = air density (kg/m^3).

Design parameters, such as surface albedo, sky view factor, and total height-to-floor area ratio (building massing), are critical controllable factors that directly affect UHIs and energy efficiency (Giridharan et al. 2004). Albedo (i.e., the ratio of diffuse reflection of solar radiation to total solar radiation) is very low in cities due to

Table 1. Key parameters that contribute to UHIs

		UHI effect		Controllability		
Category	Parameters	Direct	Indirect	Controllable	Uncontrollable	References
Climatic and environmental parameters	Anticyclone conditions	x	x	—	x	Akbari et al. (2015)
	Incident seasonal solar radiation	x	—	—	x	Akbari et al. (2015)
	Diurnal conditions	x	—	—	x	Rizwan et al. (2008)
	Wind speed	x	—	—	x	Akbari et al. (2015)
	Cloud cover or sky condition	x	—	—	x	Akbari et al. (2015)
	Geographical location	x	x	—	x	Wang et al. (2021)
Built environment and anthropogenic parameters	—	—	—	—	—	—
Urban scale	Skyview factor	x	—	x	—	Bernard et al. (2018) and Rizwan et al. (2008)
	Surface materials (e.g., green, water, and construction)	x	x	x	—	Rizwan et al. (2008)
	Urban size, form, and density	x	x	x	—	Santamouris (2015) and Wang et al. (2021)
	Population	x	x	x	—	Santamouris (2015)
	Anthropogenic heat (e.g., vehicles)	x	—	x	—	Han et al. (2020)
	GHG emissions	—	x	x	—	Wang et al. (2021)
Building scale	Location	—	x	x	—	Mert and Saygin (2016)
	Orientation	—	x	x	—	Mert and Saygin (2016)
	Form (e.g., floor area and height)	—	x	x	—	Mert and Saygin (2016)
	Using natural ventilation	—	x	x	—	Mert and Saygin (2016)
	Using solar radiation	x	x	x	—	Mert and Saygin (2016)
	Skin material characteristics	x	x	x	—	Lassandro and Di Turi (2017) and Mert and Saygin (2016)
	HVAC systems	—	x	x	—	Alsharif et al. (2021)
	User behavior	—	x	x	—	Alsharif et al. (2021)
	Anthropogenic heat	x	—	x	—	Santamouris (2015)

Note: x = Yes; HVAC = heating, ventilation, and air conditioning.

building surface materials and street canyon configurations (Feng et al. 2022). It could be regarded as a main parameter that directly affects UHIs (Li et al. 2021). Some other controllable parameters with direct effects on urban overheating include the high roughness of manufactured structures and limited green space in urban areas, which are caused by land use patterns and lead to reduced convective heat removal (Rizwan et al. 2008). In addition, UHIs are strongly affected by environmental parameters such as wind speed, cloud coverage, cyclonic or anticyclonic conditions, and local meteorological features (Akbari et al. 2015; Santamouris 2013). Strong winds provide higher cooling rates that lead to UHIM in urban and rural areas, especially during nighttime (Rajagopalan et al. 2014). The heat islands prevent the sea breezes from moving inland (Sakaida et al. 2011), and clouds could reduce the surface UHI (Liao et al. 2022).

Building Skin Materials and UHIs

The extant literature has extensively studied the relationships between the building design, which includes skin materials and climate change, and UHIs (Steenbergen et al. 2012; Zuo et al. 2015). A study in Beijing, China has shown that the anthropogenic heat flux in urban environments, a main contributor to UHIs, is primarily caused by the contributions from buildings (45%), traffic (30%), industrial activities (20%), and human metabolism (5%) (Sun et al. 2018). With urbanization leading to urban population growth and increased industrial activities, greater demand for building construction and higher use of mechanical air conditioning systems are expected. This increases the urban cooling energy consumption of the building sector (Sun et al. 2018), generates waste heat as a byproduct of the air conditioning systems, and causes UHIs. The building skin and its materials directly affect cooling energy consumption and, in turn, associated waste heat generation by regulating conductive, convective, and radiant heat flow through the skin. The solar radiation that falls on buildings is reflected and absorbed differently and depends on the material properties that are used in building skin surfaces. Two important material properties include albedo and thermal emittance. Albedo is the fraction of incident solar radiation that is reflected off the surface of a material and ranges between zero and one. Thermal emittance is the ability of a material to re-emit the absorbed heat.

Therefore, building skin surface materials could be selected via their albedo and thermal emittance to reduce UHIs directly through the reflection of solar radiation and maintain low temperatures at the building surfaces and ambient air. Applying high albedo light-colored materials with high solar reflectance (SR) is a traditional solution for regulating building and urban thermal balance (Santamouris and Yun 2020). Reflective materials with high SR and infrared emittance are considered cool materials, because they experience lower temperatures than conventional materials under the same outside conditions and offer UHIM potential (Hernández-Pérez et al. 2014). Cool materials could be grouped into four categories: (1) white or light-colored coatings; (2) cool-colored materials with high near-infrared (NIR) reflectance; (3) white or colored cool coatings that incorporate nanomaterials with high sensible or latent heat storage capacity; and (4) cool materials with dynamic optical characteristics and capability to change reflectivity based on incident solar radiation and ambient temperature (Santamouris et al. 2011). The literature reports a 5°C–14°C temperature difference between the surfaces of cool materials and conventional materials in summertime (Levinson et al. 2007; Santamouris et al. 2011). Revel et al. (2014a) developed a new cool material for building skins, which consists of ceramic tiles, acrylic paints, and bitumen roof membranes. They improved the NIR reflectance of black ceramic tiles by applying an NIR transparent layer onto a highly reflecting base coat. Their research showed that the proposed improved material enhanced the thermal performance of the building and led to greater indoor thermal comfort (Revel et al. 2014b). Uemoto et al. (2010) studied the thermal performance of cool-colored acrylic paints with infrared reflective pigments and compared it with common acrylic paints of similar colors. This experiment demonstrated a lower surface temperature and decreased radiation heat flow because of higher NIR reflectance and lower absorbed solar radiation. Santamouris et al. (2018) studied the advantages of UHIM strategies, such as global albedo materials (0.1–0.6) in cities, and showed a decrease in the ambient temperature by 0.3°C and 3°C in Sydney. Synnefa et al. (2007) showed that cool-colored coatings with NIR reflective color pigments have greater potential to reflect solar radiation compared with those of the color-matched, conventionally pigmented coatings. Although reflective materials provide great UHIM advantages, they are associated with limitations such as aging problems when exposed to sunlight, glare, and increased discomfort in urban spaces (Santamouris et al. 2017). In addition to directly reducing UHIs, as discussed previously, building skin materials could indirectly affect urban overheating through their effects on building energy consumption (Mangkuto et al. 2016). Other factors that affect building energy consumption include location and climate (Santamouris et al. 2001), orientation, form (Mangkuto et al. 2016), energy systems (Alsharif et al. 2021), occupant behavior (Delzendeh et al. 2017), and socioeconomic characteristics. The increase in fossil fuel energy consumption increases the concentration of GHG emissions in the atmosphere. It leads to global warming by trapping heat within the lower atmosphere (Yoro and Daramola 2020), which worsens the UHI effects (Maxwell et al. 2018). Facade cladding materials with the ability to capture CO_2 emissions, such as green walls (Pérez et al. 2018) or bioreactive facades (Talaei et al. 2020), could reduce GHG emission concentration and, therefore, reduce urban overheating directly and indirectly. Stache et al. (2022) reported that typical urban materials convert more than 92% of the absorbed radiative energy into convectional heat, and urban green surfaces convert 27%– 50% of it into latent heat. By applying external insulation, PCMs, green walls, and cool materials as retrofitting and UHIM solutions, Lassandro and Di Turi (2017) concluded that green walls surpass other systems by improving building performance and mitigating UHI, simultaneously.

Smart Building Skin for UHIM

In their capacity as the mediator between inner space and the surrounding environment, building skins are constantly exposed to varying conditions of the external environment, and SMs could be applied to sense, respond, and adapt to these conditions. Examples of these skins include climate-adaptive building shells (Loonen et al. 2013), adaptive facades (Tabadkani et al. 2021), bio-inspired interactive kinetic facades (Hosseini et al. 2021), smart building skins (Kim and Kim 2017), and user-responsive microalgae facades (Talaei et al. 2022). Smart building skins could regulate solar absorption and temperature fluctuations and reduce building energy use and UHI effects.

The application of SMs in mitigating UHIs has been explored in previous literature. Santamouris and Yun (2020) studied the potentials of cool and super cool SMs (e.g., natural, light color, infrared reflective, PCM-doped, thermochromic, fluorescent, photonic, and plasmonic materials) for UHIM. Feng et al. (2022) reviewed the state-of-the-art techniques to raise high albedo in cities, which included advanced SMs (e.g., cool materials, thermochromic coatings, PCMs, and fluorescent materials). Casini (2016a) investigated the effects of reflective coatings on building energy efficiency and UHIM and reviewed the advanced adaptive building skins. In addition, he categorized adaptive skin facades into two main categories, which included temperature, light, and humidity-reactive systems (or evaporative facade systems). The SMs have been well studied by previous research that was based on their performance type or the stimulus; a limited number of studies have considered the performance of smart building skins in mitigating this. In this research, the performance of smart building skins in UHIM was reviewed under five classes: (1) thermal-control SMs; (2) light-control SMs; (3) pollution-control SMs; (4) humidity or ventilation-control SMs; and (5) energy-transducing or producing SMs (Fig. 3).

Thermal-Control SMs

A thermal-control SM for UHIM applications is a material that acts as an actuator and sensor and interactively decreases the UHI directly by reducing the air temperature and indirectly by regulating the heat transfer to the inner space and reducing the cooling load of the building. The PCMs are examples of thermal-control SMs that have drawn attention, because of their capability to store and release heat as latent heat through a reversible process.

From four groups of PCM materials that include solid–solid, solid–liquid, gas–solid, and gas–liquid, solid–liquid PCMs (e.g., organic, inorganic, and eutectic) are commonly applied in buildings due to their compatibility with building materials (Aridi and Yehya 2022). Various studies (Yang et al. 2019; Zhang and Yang 2019) (Table 2) confirmed that the symbiosis between PCM-integrated building coatings and urban surfaces could lead to building energy efficiency, thermal comfort, and UHIM (Karlessi et al. 2011). For example, the PCM cool roof systems could contribute to UHIM directly by decreasing the ambient temperature and indirectly by providing energy efficiency in the building (Yang et al. 2019). Although PCMs provide cooling benefits when integrated with buildings, their efficiency depends on the climate and PCM type (Aridi and Yehya 2022). Future research is required to study the PCM-integrated facades in buildings with dominant cooling loads.

The SMA is another type of thermal-control SMs that reacts to thermal conditions by changing shape when exposed to relatively low temperatures and recovering when heated (Formentini and Lenci 2018). By elastocaloric cooling, these materials contribute to energy saving (Chen et al. 2021) and directly affect UHIs. In addition, they have great potential to act as actuators or sensors and regulate daylight transmittance (Yi and Kim 2021), temperature, natural air circulation (Formentini and Lenci 2018), solar heat gain, and shading (Koukelli et al. 2022) and, therefore, lead to building energy efficiency and UHIM when integrated with building facades. In addition, SMAs could be used as actuators in self-shaping adaptive facade systems to control indoor daylight and thermal conditions. The main challenges in building applications of SMA materials include limitations in shape remembering, the high cost of materials, and anticipating the behavior modeling (Yi and Kim 2021). In general, SMA-integrated building skins, especially as the actuator, are in their infancy and require further investigation. Table 2 lists a selected number of previous experimental and theoretical research on thermal-control SMs for UHIM.

Light-Control SMs

Light-control SMs are SMs that control the UHI indirectly by providing shading for interior spaces, reducing energy consumption, directly reflecting solar radiation, and decreasing heat gain.

Chromogenic materials that have gained popularity as light-control SMs in smart windows (SW) include electrochromic-like polymer-dispersed liquid crystals (Dahman 2017), liquid crystal dispersion SWs (Castellón and Levy 2018), and photochromic, thermochromic, and gasochromic materials (Shchegolkov et al. 2021). Thermochromic materials are smart optical materials that regulate solar radiation by reversibly changing colors in response to different thermal conditions (Feng et al. 2022). They are suitable for locations with fluctuating temperatures (Pérez et al. 2021). Therefore, these materials have high SR in summertime and high

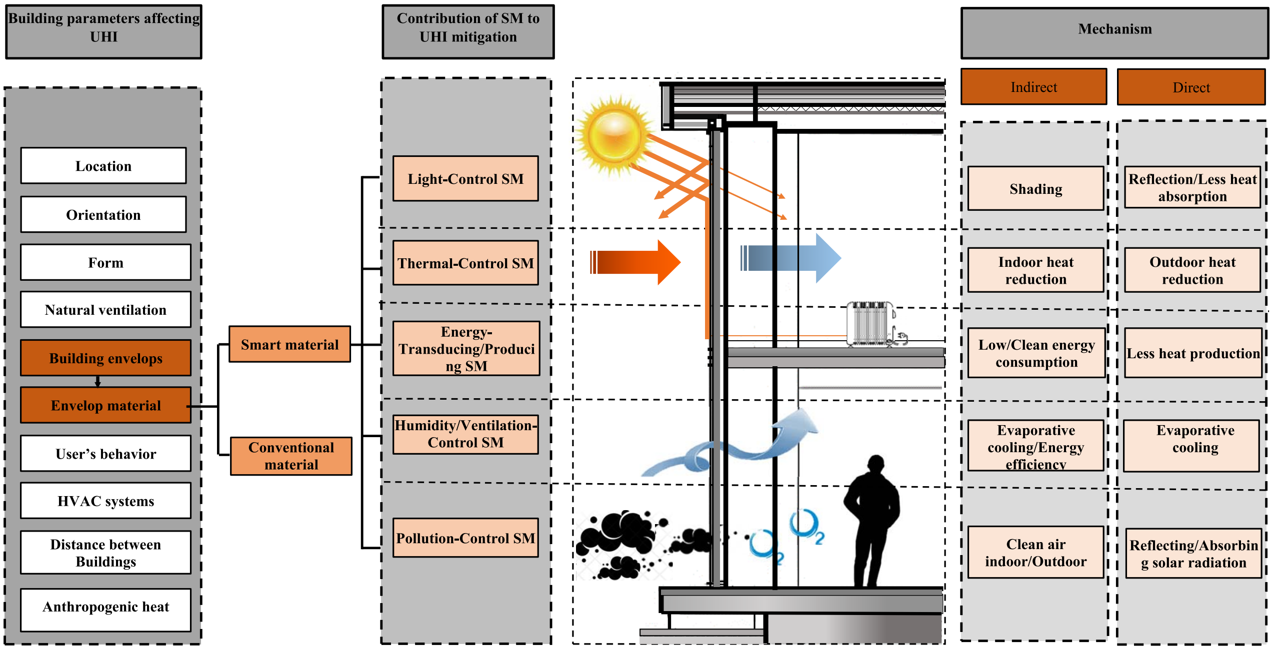

Fig. 3 Contribution mechanism of SMs to UHIM.

Table 2. Selected studies on thermal-control SMs

Name of SM or project	Placement in building	Key findings	Research method				Directly considered UHI	References
			Experimental	Simulation	Numerical	Mathematical		
Organic PCMs or PCM-doped cool-colored coatings	Building skin or urban fabric coating	PCM coating cools surface by 8°C compared with common coating of the same color	x	—	—	—	x	Karlessi et al. (2011)
PCM	Roof	Reduces surface temperature by 2.5°C, 4.5°C, and 5.7°C in winter, midseason, and summer, respectively	x	x	x	—	x	Yang et al. (2019)
	Roof	Average temperature reduction in the surface by 6.8°C	x	x	—	—	x	Yang et al. (2017b)
	Roof	PCM-incorporated roof surpasses cool roof technology by showing maximum 54% lower roof heat gain flux and 40% lower sensible heat flux for different albedo	—	x	—	—	x	Roman et al. (2016)
SMA	Actuator	Improves indoor environmental conditions by effectively regulating indoor daylight intensity	x	x	—	—	—	Yi and Kim (2021)
	Actuator or shading	Provides energy-efficient daylight or ventilation regulation for buildings	—	x	x	—	—	Khezri and Rasmussen (2022)
	Actuator or shading	Contributes to creating sustainable buildings by omitting fossil fuel energy sources	x	x	—	—	—	Mansourizadeh et al. (2021)
	Shading	Reduces approximately 40% of the reflected portion of the total solar radiation and 21% of building cooling load, respectively	—	x	—	—	x	Koukelli et al. (2022)

Note: x = Yes.

solar absorptance in wintertime, which leads to low energy consumption in buildings. Thermochromic materials are classified into two main groups: (1) dye-based thermochromic materials, which act based on the interplay between components; and (2) nondyed thermochromics that act based on molecular rearrangements or nanoscale optical effects (Garshasbi and Santamouris 2019; Manni et al. 2022). Garshasbi and Santamouris (2019) studied various advanced thermochromic SMs, which included QDs, plasmonics, photonic crystals, conjugated polymers, Schiff bases, liquid crystals, and nano-optical filters for leuco dyes. They showed that leuco dyes were applied in the built environments with the potential to reduce thermal loads with high SR in warm temperatures and low SR in cold temperatures.

Plasmons, another light-control SM, are promising materials for integration with building skins due to their daytime radiative cooling potential, which makes them favorable for dry climate zones (Santamouris and Yun 2020). These materials are collective oscillations of the electrons that exist at the bulk/surface of conducting materials and in juxtaposition with conducting particles (Mochán 2016). These materials could be used in asymmetric electromagnetic windows, which reflect solar irradiation and emit thermal radiation at the same time (Wong et al. 2018). An example of this technology is plasmochromic SWs, which have demonstrated improved energy efficiency and thermal and visual comfort in buildings (Cots et al. 2021). Thermochromic SMs perform better on the northern facade of a building compared with a conventional facade coating (Pérez et al. 2021). In addition, researchers have studied the performance of thermochromic materials, such as PCM-integrated thermochromic glazing systems (Jin et al. 2022), thermochromic glazing or windows (Teixeira et al. 2022), and thermochromic mortar (Pérez et al. 2021), paints (Soudian et al. 2020), and coatings (Zhang and Zhai 2019).

Photoluminescent components are one type of light-control SMs that remarkably reduce the conversion of light to heat by converting light to photons instead (Chiatti et al. 2022a). Photoluminescent materials could be fluorescent or phosphorescent (Sobczyk et al. 2022). A fluorescent coating provides cooling by re-emitting the absorbed light with a longer wavelength (Feng et al. 2022), and a phosphorescent coating stores the received light and re-emits it after the light source stops omitting light (Al-Qahtani et al. 2022). Fluorescents are categorized into two main groups: (1) bulk fluorescents, such as rubies, which have fixed fluorescent properties; and (2) nanofluorescent materials, such as QDs, which present versatile properties. An advanced algorithm was developed to improve the optical properties of QDs and showed temperature reduction with a photoluminescence peak at 1,100 nm from 5.8°C to 15.1°C (Garshasbi et al. 2019). Therefore, QDs could play a key role in UHIM. Of note, the photoluminescence characteristics of QDs diminish as the temperature increases, which prevents them from being fully effective for heat mitigation. However, the photoluminescence feature is enhanced when integrated with specific polymers that could make them favorable for heat reduction (Goswami et al. 2012; Santamouris and Yun 2020). Previous studies that focused on the integration of QDs into building skins mainly focused on incorporating them into solar cells to enhance energy production and building glazing for improved daylight and visual comfort regulation (AbouElhamd et al. 2019; Rastkar Mirzaei et al. 2023), which could have an indirect role on UHIM.

Gasochromic windows could change their transmittance by employing a tungsten oxide (WO_3) layer that is covered by a thin layer of platinum (Hemati et al. 2013). This window changes to blue when exposed to an argon and hydrogen mixture. This process reverses to create a transparent window state when exposed to argon and oxygen (O_2) (Feng et al. 2016). Gasochromic SW with WO_3 received wider attention at the start of the twenty-first century, compared with electrochromic windows, due to the low-cost layer configuration, simplicity, and higher solar transmittance (Feng et al. 2016). However, this attention has largely faded. The energy efficiency of building-integrated gasochromic windows was highlighted by Feng et al. (2016). However, it was suggested that due to the difficulty of gas provision and high life service costs, it was sufficient to change status based on extreme weather conditions.

Electrochromic light-control SMs materials could be applied to building glazing to control light transmittance by changing the optical properties by voltage variation. Transparent-reflective switchable (TRS) glass is an SW that could effectively contribute to the regulation of light transmittance and building thermal loads (Tong et al. 2021). The performance of different TRS, which include metal hydride-based (Maiorov 2020), reversible electrodeposition mirrors (Han et al. 2020), cholesteric liquid crystal-based (Zhang et al. 2019), and micro shutters (Mori et al. 2016), have been investigated in previous studies. In addition, electrochromic windows have been shown to surpass thermochromic and photochromic windows with lower power consumption, more thermal comfort provision, and controllability potential (Rauh et al. 2001). Various studies have demonstrated the energy-saving potential of electrochromic windows (Bui et al. 2021; Ganji Kheybari et al. 2022; Isaia et al. 2021) and other switchable glazing systems (Table 3). However, these systems must be selected based on the climatic conditions and control strategies to achieve maximum energy efficiency. Therefore, future research is required to demonstrate the efficiency of different window systems in various climate zones.

Bio-SMs with light-controlling applications, such as microalgae, have not been extensively studied for UHIM. The UHIM advantages of microalgae PBRs as smart facades glazing or systems potentially occur with energy savings that are achieved by adaptively controlling daylight with variations in culture densities in response to the environmental conditions, which include light and temperature and producing biomass for biofuel production (Kerner et al. 2019). In addition, these windows could absorb CO_2, produce O_2 via photosynthesis, and contribute to reducing GHG emissions (Özbey 2019), which could potentially contribute to UHIM. However, further research is required to document the UHI and climate change mitigation potentials of microalgae PBR windows.

Air Pollution-Control SMs

Air pollution-control SMs contribute to UHIM by decreasing air pollution and removing GHG emissions, especially CO_2 (Table 4). Aside from plants that are integrated with facades as vertical gardens, CO_2-responsive polymers and CO_2-capturing materials actively contribute to decreasing GHG emissions (Lin and Theato 2013). The CO_2-responsive polymer surpasses other polymers that respond to common stimuli (e.g., light and temperature) by directly absorbing CO_2 from the air (Lin and Theato 2013). One architectural application of these polymers is in the Open Columns Project (Khan 2010), in which nonstructural composite urethane elastomers respond to the CO_2 content of the air. These materials have been applied in architectural systems, which integrate them with building facades; however, their possible performance has not been explored extensively and demands further investigations (Juaristi et al. 2018).

As another example of CO_2-absorbing systems in buildings, Azari and Asadi (2019) [R. Azari, and M. Asadi, "Artificial leaf-based facade cladding system for energy production and carbon sequestration" US Patent No. WO2020005483A1 (2019)] invented artificial leaf-based facade cladding, which absorbs CO_2 and produces energy by the integration of photovoltaic (PV) and electrochemical cells. Another example is SolarLeaf (Wurm 2013), the first bioreactive facade used in the BIQ House, Germany, where CO_2 absorption occurs via natural photosynthesis. In this project, a microalgae PBR was integrated with the building facade and contributed to CO_2 absorption and energy production by producing biomass and biogas, as well as applying a heat exchanger to exploit the heat that was produced by the PBR and transferring it into the building. Although living walls significantly contribute to mitigating GHG emissions, air pollution, and UHIs (Susca et al. 2022), common plants in these systems cannot be regarded as SMs, because their reaction to environmental conditions is not as fast as microalgae. In addition, the growth of this system is not easily reversible; however, the PBR medium density could be controlled by the dilution of the medium or by controlling the necessary factors that are used for microalgae growth. Titanium dioxide (TiO_2) is another material in this group that has been studied for its ability to increase the SR of surfaces and mitigate GHG emissions with photocatalyst processes (Khannyra et al. 2022). In addition, TiO_2 that is applied with a thermochromic coating has enhanced the surface albedo for UHIM (Karlessi et al. 2009). Saeli et al. (2017) introduced an innovative mortar-based nanocomposite with TiO_2 for use in buildings to mitigate urban pollution. Their proposed mortar reduces air pollution by photocatalytic antipollution activity and omitting NOx and volatile organic compounds, which helps create a long-lasting building facade. The synthesis of TiO_2/silicon dioxide (SiO_2) photocatalysts to create a durable self-cleaning material that is applied to concrete surfaces is suitable for outdoor conditions (Khannyra et al. 2022). In addition, the performance of TiO_2 in the self-cleaning properties of concern and its effect on decreasing ambient air pollution, especially via photocatalysis, was confirmed (Elia 2018).

Humidity or Ventilation-Control SMs

This group of SMs could control air humidity and provide cooling by latent heat storage (Table 5). Hydrogel that is incorporated in building facades, such as hydroceramic and TiO_2 coatings, are low-tech SMs that contribute to building cooling load reduction by responding to humidity and act as cooling cladding. They highly absorb and store water, which leads to their increased size (Andrade Santos et al. 2020). Because hydrogels have the potential to absorb water 500 times greater than their weight, in experimental tests, they provide significant evaporative cooling potential for the building skin by a 6°C temperature reduction and a 15.5% humidity increase after a short time (20 min) (IAAC n.d. a). In addition, researchers (Cui et al. 2016) have introduced sweating building skins by applying double-network hydrogel (DN–Gel) that is incorporated into building roofs to reduce cooling loads. Previously, TiO_2 was discussed as an air pollution-control SM and the most efficient commercialized photocatalyst material that reacts to solar radiation (ultraviolet radiation) and provides self-cleaning properties (Fernández-Mira et al. 2021). In addition, TiO_2 provides evaporative cooling by creating a hydrophilic water layer through the facade and enhancing the wettability of the TiO_2 surface. Although various studies have explored the cooling effect of TiO_2 surfaces that use sun reflection for UHIM (Fernández-Mira et al. 2021; Zhang et al. 2022), the research on evaporative cooling and UHIM performances of a TiO_2-integrated building facade is very limited. When water was sprinkled continuously on a building facade that was integrated with TiO_2 in summer and with a clear sky, the temperature decreased by 15°C and 40°C–50°C on window

Table 3. Selected research on light-control SMs

Name of SM or project	Location on building	Key findings	Research method				Directly considered UHI	References
			Experimental	Simulation	Numerical	Mathematical		
Thermochromic	Roof	Reduces cooling load by 6.59% per m^2 of roof compared with 7.84% reduction in conventional cool roof	x	—	x	—	x	Fabiani et al. (2019)
	Facade coating	Developed thermochromic mortar is promising in building energy efficiency	x	—	—	—	x	Pérez et al. (2021)
	Glazing	Annual energy use intensity was decreased by 6.3 kW·h/m^2 in Toronto and 12 kW·h/m^2 in Abu Dhabi	—	x	—	—	x	Khaled et al. (2022)
	Facade or roof paint	Decreases the peak temperature of the roof and facade by approximately 25°C and 15°C −20°C, respectively	x	x	—	—	x	Berardi et al. (2020)
	Envelope coating	Less energy consumption in heating-dominated scenarios and the thermochromic coating with low switching temperature leads to more energy efficiency in cooling-dominated scenarios	—	x	—	—	x	Butt et al. (2021)
	Envelope coating	Integrating vanadium oxide with double-skin facade controls transmission rate of solar radiation, absorbs heat during winter, and prevents overheating in summer	—	x	—	—	x	Iken et al. (2019)
	Glazing	Reduced energy use by 3%–10% and enhanced daylight introduction by 5%–20%, compared with static average glazing	x	x	—	—	x	Giovannini et al. (2019)
Electrochromic	Window	Less energy use by 9.3%–23.5% for Melbourne and 14.6%–19.6% for Texas	x	—	—	—	—	Bui et al. (2021)
	Glazing	Electrochromic glazing surpasses slightly better than solar-coating glazing	x	—	—	—	x	Ganji Kheybari et al. (2022)
	Window	Electrochromic windows and polymer-dispersed liquid crystal switchable glazing surpass single-glazed windows for energy saving by 23.56% and 22.35%, respectively	—	x	—	—	x	Chidubem Iluyemi et al. (2022)
Photochromic	Glazing	Spirooxazine-based photochromic films result in reduced cooling energy demand compared with clear glass and reduced artificial lighting compared with commercial solar control glazing	x	x	x	—	x	Cannavale et al. (2022)
Gasochromic	Window	Transmittance of gasochromic double-glazed units, which include solar and visual transmittance, was 76% and 77% in the bleached condition, and 5% and 6% in the colored condition, respectively	x	—	—	—	x	Wittwer et al. (2004)
	Window	Annual average shading coefficient of the sol–gel method-based gasochromic windows was 0.64	x	—	—	x	—	Gao et al. (2023)
	Window	WO_3-based gasochromic window reduced annual HVAC load by 25%–35%, compared with float glass	x	x	—	—	—	Feng et al. (2016)
—	—	Photoluminescent	—	—	—	—	—	—
Fluorescent	Window	Photoluminescent coating surpassed uncoated glass due to responsiveness to ultraviolet light, high durability and photostability	x	—	—	—	x	Al-Qahtani et al. (2022)
	Skin component	Translucent and photoluminescent skin decreased annual lighting electricity demand by up to 40% and provided up to 80% electricity savings	x	—	x	—	x	Chiatti et al. (2021b)
	Surface coating	Pollution and dust impact urban surfaces by reducing the efficiency of photoluminescent paints and their potential to absorb and re-emitting light energy	x	—	x	—	x	Chiatti et al. (2021a)
	Surface coating	Photoluminescence effect leads to reduced surface temperature by applying QDs. It results in 35°C lower surface temperatures	x	—	x	—	x	Garshasbi et al. (2022)
Phosphorescent	Skin surface paint	Photoluminescent paints could save cooling and annual lighting energy by up to 30% and 27%, respectively	—	x	—	—	—	Rosso et al. (2019)
	Skin	15%–30% pigments should be used in photoluminescent glass tiles	—	—	x	—	x	Chiatti et al. (2022b)
Microalgae or PBRF system	Shading	Enhances indoor environmental quality with indoor comfort improvement	x	x	—	—	—	Pagliolico et al. (2019)

Note: x = Yes.

Table 4. Air pollution-control SMs

Name of SM or project	Placement on building	Key findings	Research method				Directly considered UHI	References
			Experimental	Simulation	Numerical	Mathematical		
Artificial leaf-based facade cladding	Cladding	Integrates energy generation with CO_2 absorption in buildings, which reduces CO_2 to methane	x	—	—	—	—	Azari and Asadi (2019) [R. Azari, and M. Asadi, “Artificial leaf-based facade cladding system for energy production and carbon sequestration.” US Patent No. WO2020005483A1 (2019)]
Microalgae or SolarLeaf	Facade	Flue gas or CO_2 emissions were applied to produce biomass by microalgae, which reduced CO_2 emissions by 6 t/year	x	—	—	—	—	IBA_Hamburg (2013)
TiO_2	Facade material	TiO_2 application on half of the southern facade of a commercial building resulted in cleaning 25,666 m^3 of air per day with 20 ppb benzene, toluene, ethylbenzene, and O-xylenes	—	x	—	—	—	Li et al. (2020)
	Facade	Synthesized TiO_2–SiO_2 coating demonstrated considerable photocatalyst potentiality and the efficiency was increased by intensifying TiO_2 loading	x	—	—	—	—	Khannyra et al. (2022)
	Coating	TiO_2–SiO_2 nanocomposites could act as an active element to decrease air pollution as a self-cleaning protective material	x	—	—	—	—	Luna et al. (2022)

Note: x = Yes.

Table 5. Selected research on humidity or ventilation control SMs

Name of SM or project	Placement in building	Key findings	Research method				Directly considered UHI	References
			Experimental	Simulation	Numerical	Mathematical		
Hydroceramic	Facade component	Integrating hydrogel with evaporative cooling effect into clay resulted in temperature reduction by 5°C	x	—	—	—	—	IAAC (n.d.-a)
Sweating skin	Facade material	Using DN–Gels on a 100 m^2 roof in a residential building resulted in approximately 290 kW·h electricity demand reduction for air conditioning. 160 kg CO_2 emission decreased b evaporation	x	—	—	x	—	Cui et al. (2016)
Super hygroscopic hydrogel	Window	Changing transparency of hygrochromic window led to energy saving	x	x	—	—	—	Nandakumar et al. (2018)
Smart thermobimetal self-ventilating skin	Skin	Laminated metals reacted to temperature fluctuation with different expansion coefficients and thicknesses and provided natural ventilation	x	—	—	—	—	Sung (2011)
Cones of wooden veneer	Skin	Responded to humidity by opening or closing pores	x	x	—	—	—	Reichert et al. (2015)
SMA	Actuator or sensor	Provides energy savings for the building by natural ventilation by opening or closing the facade	x	x	—	—	—	Formentini and Lenci (2018)
PNIPAAM–alumina/alginate–alumina/gelatin–alumina hydrogels	Skin	Multiple reversible shape alternatives were provided in response to humidity or temperature and produced monolithic composites	x	—	—	—	—	Erb et al. (2013)
TiO_2	Coating	Provided cooling for the ambient environment and building along with energy efficiency	x	—	—	—	—	Hashimoto et al. (2005)

Note: x = Yes.

Table 6. Selected studies on energy-producing or transducing SMs

Name of SM or project	Placement in buildings	Key findings	Research method				Directly considered UHI	References
			Experimental	Simulation	Numerical	Mathematical		
Concentrating PV glazing system	Glazing	Provided electric energy saving (13%–53%) for heating and cooling in Tampere and Palermo, respectively	x	x	—	—	—	Barone et al. (2022)
PV	Facade or roof	Net zero energy district needed for energy was met 60% by roof solar energy harvesting and 60% by total facade area with an 11% decrease in energy production per PV unit area	—	x	—	—	x	Boccalatte et al. (2020)
	Rooftop, wall, or window	88%, 8%, and 4% solar energy is provided by the roof, walls, and window-integrated PV, respectively	—	x	—	—	—	Panagiotidou et al. (2021)
PV/PCM	Skin	PCM–PV integration results in decreasing the transient temperature of PV/indoor and impeding peak indoor temperature	x	—	—	—	—	Hasan et al. (2016)
Piezoelectric	Facade	Proposed method could be applied when optimizing more complex harvesters, which include beams and cylinders	x	—	—	x	—	Tommasino et al. (2022)
	Facade	Improving energy efficiency, reducing materials used, and building construction costs that consider wind analysis and building width or height	—	x	—	—	—	Zarrabi and Tavakoli (2018)
Thermoelectric	Facade	Thermoelectric stand-alone element is unstable, and by adding a heat sink its function for cooling or heating is enhanced	x	—	—	—	—	Aksamija et al. (2019)
	Skin	Ventilated active thermoelectric skin means no cooling or heating systems required	x	—	—	—	—	Zuazua-Ros et al. (2018)
Microalgae or SolarLeaf	Facade	Produced energy and biogas from biomass are 345 kJ/m^2/ day and 10.20 L methane/ m^2/day, respectively	x	—	—	—	—	IBA_Hamburg (2013)
Artificial leaf-based facade cladding	Cladding	Provides an artificial photosynthesis process for energy generation by PV panels and carbon removal	x	—	—	—	—	Azari and Asadi (2019) [R. Azari, and M. Asadi, “Artificial leaf-based facade cladding system for energy production and carbon sequestration.” US Patent No. WO2020005483A1 (2019)]

Note: x = Yes.

glass and black roof tile surfaces, respectively, by creating a thin water film (Hashimoto et al. 2005). The temperature of the water film was lower than that of the water due to latent heat flux. Therefore, integrating TiO_2 into building facades could potentially decrease the energy consumption in buildings. Of note, although TiO_2 is regarded as a cool material with potential in UHIM, because this ability is not smart, such as in chromogenic materials, it has not been mentioned in the light-control SM section. In addition, some SMs that were integrated into building facades could smartly control air movement and natural ventilation. Therefore, thermal comfort and energy efficiency were created in buildings. Hydromembranes are another example of controlling humidity and air movement. In addition, they are regarded as superabsorbent polymers due to their potential to restore water due to sodium polyacrylate and slowly release it by air moving within the skin, which regulates the indoor temperature and humidity (Casini 2016a; IAAC n.d. b). Other SMs, such as SMAs and thermobimetals, could regulate air movement and ventilation when applied in building facades as actuators or sensors, decrease energy consumption, and indirectly mitigate UHIs. The performance of thermobimetals is related to their anisotropic composition, in which two metal alloys with different thermal expansion coefficients are integrated to act differently when exposed to thermal conditions. This self-actuating building skin allows for ventilation by sheet curling. An example is a self-ventilating building facade that uses thermobimetals whose porosity and shape change with temperature, therefore allowing for air penetration into the building skin and natural ventilation (Sung 2011).

Wood is a moisture-sensitive biomaterial due to its cellular structure trying to gain balanced moisture leading to constant dimensional movement (Menges and Reichert 2012). Reichert et al. (2015) developed an autonomous humidity-responsive low-tech architectural system by applying the hygroscopic properties of plant cones in a wooden veneer. With long-term experiments, they evaluated the system and recorded thousands of responsive motion cycles. Erb et al. (2013) conducted experiments to test self-shaping synthetic hydrogel composites, which presented considerable reversibility and autonomous twisting and bending movements. Various studies have examined variations in building cooling loads due to evapotranspiration and ventilation in building skins; however, few have considered the effect on UHIM, especially in different climates and building forms.

Energy-Transducing or Producing SMs

Energy-transducing or producing SMs could alleviate UHIs by producing energy or changing one form of energy into another (Table 6). Several studies have investigated energy-producing building facades, such as building-integrated PV (Azami and Sevinç 2021), PV–PCM cells (Elarga et al. 2016), building-integrated piezoelectric materials (Zarrabi and Tavakoli 2018), building-integrated microalgae PBRs (Kerner et al. 2019), and thermoelectric skins (Martín-Gómez et al. 2021).

The PV elements in building skins convert solar radiation into electricity using the PV effect (Rahman 2016) and have been extensively studied. Examples include PV glazing (Barone et al. 2022), windows (Peres Suzano e Silva and Flora Calili 2021), rooftops and walls (Panagiotidou et al. 2021), and artificial leaf-based facades (Azari and Asadi 2019), “Artificial leaf-based facade cladding system for energy production and carbon sequestration.” US Patent No. WO2020005483A1 (2019)]. In addition, the PV systems have been integrated into landscaping and pavements for traffic lighting and contribute to UHIM by reducing the surface temperature by 3°C–5°C and producing 11%–12% less heat

Table 7. Categories of SMs and their mechanism and advantages to reduce UHIs

Category of smart skin material	Name of SMs or projects	Example	Key mechanism and advantages for UHIM	Mechanism		References
				Direct	Indirect	
Thermal-control SMs	PCMs	Inorganic (salt–hydrate and metals), organic paraffin, nonparaffin, and eutectic	Cool air by storing and releasing thermal energy	x	—	Karlessi et al. (2011); Roman et al. (2016); Saffari et al. (2018); Yang et al. (2019)
			Provide energy efficiency by decreasing cooling or heating energy demand	—	x	Al-Yasiri and Szabó (2021a; b)
	SMAs	Copper–aluminum (Al)–nickel (Ni), copper–zinc–Al, Ni–manganese (Mn)–gallium, iron–Mn, and Ni–Ti	Provide elastocaloric cooling and energy efficiency.	x	x	Chen et al. (2021)
			Act as actuator or actuator for controlling building thermal load that results in energy efficiency	—	x	Formentini and Lenci (2018); Yi and Kim (2021)
	Chromogenic materials	—	—	—	—	—
Light-control SMs	Thermochromic	Dye-based (dye–polymer and leuco dyes)	Provide low cooling or heating load. Controlling ambient air temperature by SR and changing color	x	x	Feng et al. (2022); Garshasbi and Santamouris 2019), Nawade et al. (2020)
		Non-dye-based (QDs, plasmonic, photonic crystals, conjugated polymers, liquid crystals, and Schiff bases)	—	—	—	—
	Electrochromic	Metal oxides of transition, in particular, WO_3, molybdenum trioxide (MoO_3), iridium oxide, nickel oxide, and vanadium pentoxide	Change color or transparency in response to altering voltage and controlling light transmittance, which results in energy efficiency	—	x	Yang et al. (2017a)
	Photochromic	Diarylethene, dithienylethene, and furyl fulgide	Changing color when exposed to light and controlling light transmittance	—	x	Shchegolkov et al. (2021)
	Gasochromic	Nanoporous WO_3 and MoO_3	Change light transmittance through a window by a thin layer of WO_3 and reducing energy demand	—	x	Shchegolkov et al. (2021)
	Photoluminescents	—	—	—	—	—
	Fluorescent	Bulk fluorescent materials (e.g., ruby), and nanofluorescent (QDs)	Providing cooling effect (fluorescent cooling) for ambient air temperature and controlling building thermal load by re-emitting absorbed light	x	x	Chiatti et al. (2021a); Ulpiani et al. (2020)
	Phosphorescent	Zinc sulfide and calcium tungstate	—	—	—	—
	Microalgae or PBRF system	Microalgae (e.g., Chlorella and Spirulina)	Change their concentration or opacity and controlling light transmittance	—	x	Wurm (2013)
Air pollution- control SMs	CO_2-responsive polymers	Three types, which include amidine, amine, and carboxyl	Use CO_2 as a green trigger and capture CO_2 directly from air	—	x	Lin and Theato (2013)
	Artificial leaf-based facade	Integrated PV and electrochemical cells	Reduce CO_2 to hydrocarbon and decrease air pollution	—	x	Azari and Asadi (2019) [R. Azari, and M. Asadi, “Artificial leaf-based facade cladding system for energy production and carbon sequestration.” US Patent No. WO2020005483A1 (2019)]
	TiO_2		Decrease air pollution by photocatalyst reaction.	—	x	Khannyra et al. (2022)
			Reduce the surface temperature by high SR	x	—	—
Humidity or ventilation-control SMs	Hydroceramic or hydrogel	—	Use hydrogel for evaporative cooling.	x	x	IAAC (n.d.-a)
	TiO_2			x	—	Hashimoto et al. (2005)

Table 7. (*Continued.*)

Category of smart skin material	Name of SMs or projects	Example	Key mechanism and advantages for UHIM	Mechanism		References
				Direct	Indirect	
			Provide evaporative cooling with a superhydrophilic feature			
	Hydromembrane or sodium polyacrylate		Evaporative cooling by absorbing humidity	x	—	Casini (2016a), IAAC (n.d.-b)
			Provide ventilation by bending through absorbing water	—	x	—
	Thermobimetal		Provide ventilation for the building by reacting to temperature, which results in material bending and air movement	—	x	Sung (2011)
	Meteorosensitive architecture or cones of wooden veneer		Provide ventilation by reacting to humidity with hygroscopic properties and closing or opening pores	—	x	Reichert et al. (2015)
	SMAs		Act as an actuator for controlling natural ventilation	—	x	Formentini and Lenci (2018)
Energy-transducing or producing SMs	Piezoelectric	Noncentrosymmetric crystals, quartz, lithium niobate, lead zirconate titanate, and lead lanthanum zirconium titanate	Converting mechanical force to electrical energy	—	x	Santamouris and Yun (2020)
	Artificial leaf-based facade	Integrated PV and electrochemical cells	Produce energy with PV cells	—	x	Azari and Asadi (2019) [R. Azari, and M. Asadi, "Artificial leaf-based facade cladding system for energy production and carbon sequestration." US Patent No. WO2020005483A1 (2019)]
	PV cells	Mono and polycrystalline silicone	Convert light energy into electricity	—	x	Azami and Sevinç (2021); Boccalatte et al. (2020); Panagiotidou et al. (2021)
	Thermoelectric	Bismuth telluride alloy, lead telluride alloy, and silicon–germanium alloy	Converting heat to electricity	—	x	Martín-Gómez et al. (2021)
	Microalgae or PBRF system	Microalgae species	Convert solar energy to biomass or biofuel	—	x	Elrayies (2018); Kerner et al. (2019)
			Convert solar energy into heat by photosynthesis	—	x	—

Note: x = Yes.

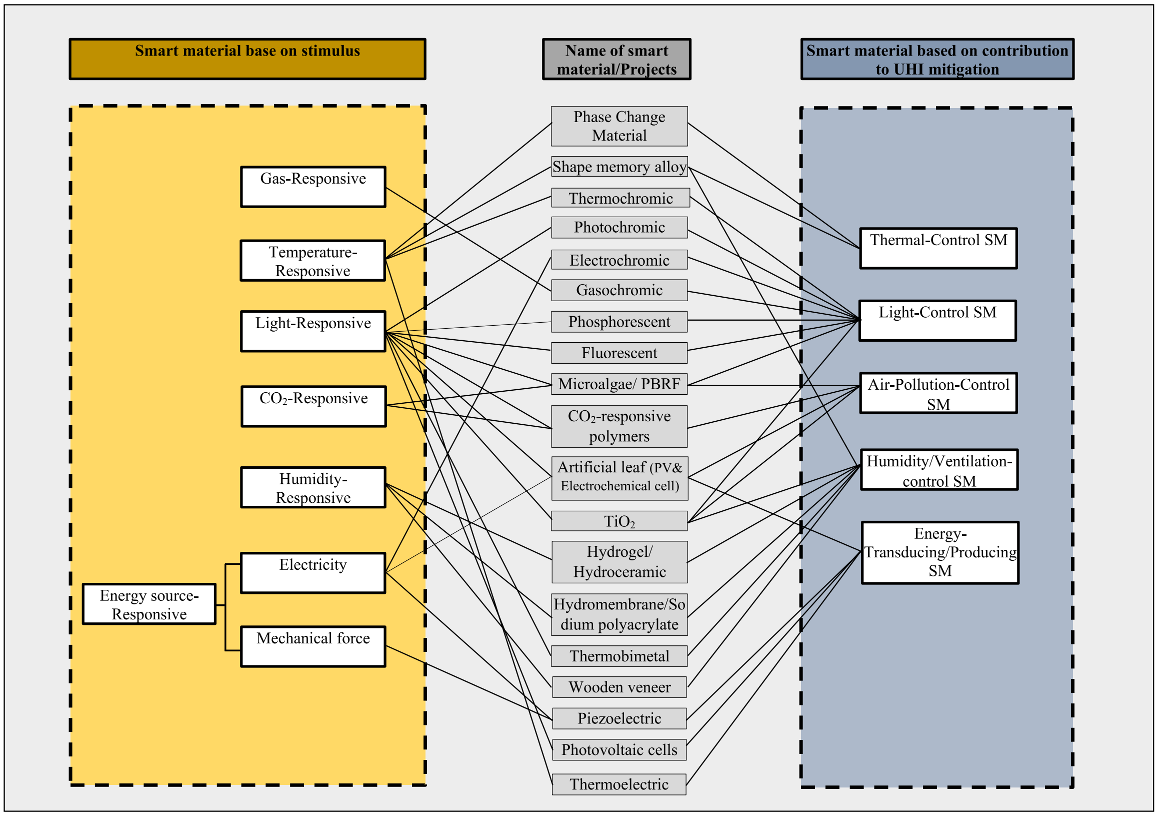

Fig. 4. Category of SMs based on their stimuli and mechanism for UHIM when integrated with building skin. EC = electrochemical cell.

output (Xie and Wang 2021). The PV-integrated rooftops provide greater solar energy for cities compared with PV-integrated windows or walls (Panagiotidou et al. 2021). In addition, incorporating PCM with PV for electrical–thermal energy efficiency could elevate electrical and thermal efficiency by up to 7.2% and 9.5%, respectively (Hasan et al. 2016).

The PV cells convert solar energy into electricity; however, thermoelectric SMs convert heat into electricity and vice versa (Steurer 2014). The conversion of thermal and electrical energy is carried out using electrons and photons (Shastri and Pandey 2021). Kim and Kim (2021) studied solar thermoelectric generators using an aerogel with high thermal insulation or solar light transmittance characteristics and stated that their optical–thermal features enhanced receiving solar energy. In addition, by integrating a thermoelectric with a PCM, the cooling coefficient of the system performance was improved by 56% (Tan and Zhao 2015). Piezoelectric materials, another type of material in this category, are energy-transducing SMs that convert mechanical energy into electricity (Bhagabati and Rahaman 2022). This process could be reversible by converting electricity to mechanical force (Addington and Schodek 2004). Zarrabi and Tavakoli (2018) studied the optimization of a piezoelectric facade layout for environmental performance. Xie et al. (2013) investigated high-rise buildings that were integrated with piezoelectric generators, which produced energy by applying the piezoelectric patch onto the cantilever. Studies on integrating piezoelectric material with building facades are very limited and require further investigation, because this symbiosis has challenges that need to be addressed that include high material costs, constructability, and energy efficiency (Gkoumas et al. 2013). A photobioreactor facade (PBRF), another example of a smart facade system, uses bio-SMs to produce energy, such as energy-generating glazing (Casini 2016b). Energy efficiency in building-integrated PBRs is provided by solar thermal collectors and light-to-biomass converters that produce biofuel and heat and adaptable shading as well as thermal insulation (Pruvost et al. 2016; Talaei et al. 2020). The more the PBRF is exposed to solar radiation, the more the microalgae concentration is increased, which could regulate light transmittance through the panel. However, excessive sun radiation leads to photosaturation and photoinhibition, which are detrimental to cell growth (Raeisossadati et al. 2019) and should be considered during the operation and design. An application of PBRs is in the BIQ House that uses 129 PBR panels and is expected to produce 30 kW·h/m^2 of biomass and 150 kW·h/m^2 of heat and lower CO_2 emissions by 2.5 t/year (Wurm 2013). Recent research on PBRFs has investigated the advantages of this symbiosis for energy efficiency and thermal regulation. However, the challenges and efficiency of this system in different climatic zones and its performance in UHIM should be investigated more comprehensively.

Discussion and Conclusions

The SMs (Table 7) that are applied on urban surfaces have received attention as an adaptation solution to address UHIM (Feng et al. 2022) due to their potential to interactively respond to the varying ambient environment (Fabiani et al. 2019; Feng et al. 2022), especially since the common cool materials present a disadvantage in winter times considering their high SR (Fabiani et al. 2019). In this research, the SMs are categorized into five main groups (Fig. 4) based on the way they contribute to UHIM directly by the reduction in the ambient environment temperature and heat absorption or indirectly by reducing building energy demand and the associated CO_2 emissions that would alleviate global warming. The SMs that are integrated into building facades have been studied for their performance in regulating light, heat, and humidity and acting as sensors and actuators; however, limited research has considered the UHIM performance of these materials. In addition, there are SISMs and adaptive facade systems (e.g., piezoelectric, hydroceramic, super hygroscopic hydrogel, and thermobimetal) whose UHIM potentials have been underexplored. Therefore, the quantitative and qualitative evaluation of the UHIM performance of different SMs in various climatic zones is required to guide the selection of SMs to address UHIs. In addition, the evaluation of the SMs for durability and resistance to climatic changes and various environmental conditions is critical when choosing suitable SMs. In addition, future research could explore the combination of various SMs to improve their performance in different climates and building facade orientations. In addition, the operational and constructional aspects, maintenance, cause of failure, fatigue, and fire safety issues that are associated with SMs that are used in buildings should be studied to improve these systems. Some SMs (e.g., PCMs) and PVs have been commercialized for integration into building facades; further commercialization efforts are needed to expand the potentials of other SMs, such as piezoelectric or bioadaptive materials such as microalgae. In addition, the industry should address the high costs for the operation and construction of some SMs that prevent them from being widely applied in building facades.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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