

## From Adaptive Skins to Adaptive Cities

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*The article explores the role of adaptive building envelopes as an innovative strategy to mitigate the Urban Heat Island (UHI) effect and enhance environmental sustainability in cities. While adaptive envelopes are traditionally studied for energy efficiency and indoor comfort, this research evaluates their potential at the urban scale by analysing their ability to dynamically interact with the microclimate through solutions such as evaporative cooling, vegetative integration, and high solar reflectance materials. Through a comparative analysis of 50 case studies (25 traditional versus 25 adaptive envelopes), the study highlights how ceramic materials, due to their high Solar Reflectance Index (0.75) and Thermal Emittance (0.90), are among the most effective in reducing surface temperatures. Additionally, the integration of active cooling systems and bioreceptive surfaces demonstrates significant potential in improving air quality and urban resilience. The findings emphasize the need to move beyond static building envelope approaches, proposing instead a model of adaptive urbanism in which architecture becomes an active agent in managing urban climate. The study concludes that, despite current limitations in quantitative data availability, adaptive envelopes represent a promising solution for addressing the climatic and social challenges faced by urban areas.*

**Keywords:** Adaptive Envelopes, Urban Heat Island Effect, Urban Sustainability, Microclimate Mitigation, Adaptive city.

### Introduction

The increase in greenhouse gas emissions and the expansion of soil consumption, direct consequences of rapid urbanization, necessitates the adoption of innovative and multidisciplinary strategies to mitigate the effects of climate change, particularly in urban areas.<sup>1</sup> In this context, the urban heat island (UHI) phenomenon constitutes an increasingly urgent environmental and social challenge.<sup>2</sup> Given these premises, adaptive envelopes, which have been the subject of research and development for several years, emerge as promising technological systems capable of improving the thermo-environmental comfort of buildings and contributing to the reduction of UHI thanks to their intrinsic requirements of adaptability to environmental stimuli.

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1. IEA (2013) Technology roadmap: Energy efficient building envelopes. Paris: International Energy Agency. <https://www.iea.org/reports/technology-roadmap-energy-efficient-building-envelopes> (Licence: CC BY 4.0).

2. Vardoulakis S, Dear K, Wilkinson P (2016) Challenges and opportunities for urban environmental health and sustainability: The HEALTHY-POLIS initiative. *Environmental Health* 15: 36.15.10.1 186/s12940-016-0096-1.

Despite this potential, their large-scale adoption remains limited and fragmented, primarily due to technological complexity and difficulties in integrating them into consolidated building and urban fabrics. The literature highlights that adaptive envelopes are mainly implemented for energy efficiency and indoor comfort, while there is a lack of comprehensive studies exploring their use at the urban scale for improving public spaces and mitigating the effects of urban heat islands.<sup>3</sup>

In the transition from the building to the city scale, the envelope presents itself as a connecting element, cooperating to improve urban quality and well-being for citizens. The concept of adaptivity transposed to the urban scale relates to the ability of a city to respond flexibly and effectively to complex and changing challenges, such as the climate crisis and environmental degradation, to name a few. Adaptive cities use the principles of complex adaptive systems theory to guide urban governance, emphasizing resilience, dynamic planning, and the integration of various indicators—environmental, social, and economic—to assess and improve urban well-being and environmental quality. This approach contrasts with traditional static urban models, focusing on continuous learning, feedback, and targeted interventions to optimize both environmental conditions and the well-being of citizens. Similar to the adaptive envelope, the city thus becomes an adaptive organism, where the envelope is a key component and primary actor. Ongoing research demonstrates that adaptive strategies can improve air quality, increase access to open spaces, and promote social cohesion, all factors linked to higher levels of urban and social well-being. Overcoming the traditional conception of the adaptive envelope as a functional element solely for indoor comfort at the scale of the dwelling unit, current research proposes an extension of the adaptive paradigm to the urban scale. In this new perspective, the envelope no longer represents just a filter between the internal and external environment but an active device within a complex urban system, contributing to the definition of resilient and climate-aware strategies. Adaptivity, understood as the capacity for dynamic response to variable environmental and energy conditions, is configured as a guiding principle for a new urban model. In this framework, the city is interpreted as an adaptive organism capable of integrating the building envelope into its ecological infrastructure. In this change of scale, the envelope is no longer limited to responding to the needs of individual buildings or dwelling units but becomes an active part of an interconnected network capable of influencing urban quality and collective well-being. Adaptive envelopes can contribute to mitigating the effects of the urban heat island, improving air quality, and optimizing the microclimate, becoming tools for environmental equity and social well-being. The study aims to offer a new interpretation of the concept of adaptivity, extending it from architectural skins to the city. The objective is to evaluate whether adaptive technologies can evolve into tools capable of improving outdoor comfort and effectively responding to the microclimatic conditions of cities. The analysis focuses on identifying even consolidated technologies present in the literature that are most compatible with this objective, contributing to outlining a more integrated design framework between the envelope, public space, and urban resilience.

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3. Aelenei L, Aelenei D, Romano R, Mazzucchelli ES, Brzezicki M, Rico-Martinez JM (2018) *Case studies – Adaptive Facade Network*. TU Delft Open.

## Research Question

Given the premises, in a policy of controlling the Urban Heat Island (UHI) effect through the choice of materials for adaptive facades, it appears fundamental to correlate not only the superficial requirements of facade components (colour, reflection, texture, etc.), but also the phenomena of mutual reflection between vertical surfaces (facades) and horizontal surfaces (road pavements and building bases). Within these considerations, what role can adaptive envelopes play in the phenomena of reflection and UHI control? These are dynamic envelopes that vary with climatic conditions; therefore, they can inherently mitigate UHI by directing solar rays away from the ground or absorbing them based on the climate and the physical-material requirements of the components (colour and surface texture). Typically, these facades are made of metal in natural, white, or reflective shades. Recent studies have shown a growing interest in the relationship between the colour of the cladding and the values of solar reflectance and emittance. Furthermore, Synnefa et al.'s 2007 research indicates that the use of low thermal inertia materials on facades can help reduce the intensity of urban heat islands.<sup>4,5</sup>

The ongoing research investigates the potential and requirements of adaptive envelopes as climatically active devices, capable of dynamically interacting with the urban microclimate and significantly contributing to the quality of urban spaces, promoting collective thermal comfort and urban resilience, also in relation to materials with high reflectance and thermal inertia. The shift from the concept of "adaptive skin" to that of "adaptive city" would transform the adaptive envelope into an urban strategy, capable of contributing to the mitigation of UHI, the reduction of energy demand for cooling, and the overall climatic quality of the built space.

## Literature Review

The implementation of effective measures to mitigate the effects of global warming following record-breaking greenhouse gas emissions aligns with the sustainability objectives established for 2030.<sup>6,7</sup> Among the sectors with the highest environmental impact, the AEC industry (Architecture, Engineering, and Construction) is widely acknowledged for its substantial consumption of materials, waste

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4. Synnefa A, Santamouris M (2007) Cool-colored coatings fight the urban heat-island effect. *SPIE Newsroom*. doi:10.1117/2.1200706.0777.

5. Gasparini K (2024) Exploring responsive and adaptive building skins: texture, materials, color, and environmental integration. In: *19th Advanced Building Skins Conference & Expo*, Bern, 28-29 October 2024, pp. 88–94.

6. *United Nations Environment Programme* (2024) Emissions Gap Report 2024: No more hot air ... please! With a massive gap between rhetoric and reality, countries draft new climate commitments. Nairobi. <https://doi.org/10.59117/20.500.11822/46404>.

7. *United Nations Environment Programme* (2024) Global Status Report for Buildings and Construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector. Nairobi. <https://doi.org/10.59117/20.500.11822/45095>.

generation, and greenhouse gas emissions.<sup>8</sup>

Research by the IPCC indicates that the construction sector accounts for 50% of global material extraction while generating 21% of total emissions. The transition toward a sustainable economy lies at the core of European strategies, with the AEC industry playing a pivotal role in this challenge.<sup>9</sup>

Concurrently, building envelope design has undergone a profound transformation, shifting toward improved indoor comfort and energy efficiency. Moving beyond static, massive construction aimed at ensuring thermal inertia, contemporary solutions increasingly embrace dynamic, modular, and technologically sophisticated approaches. The evolution of cladding systems, now engineered as high-performance industrial products, has led to the development of adaptive facades—intelligent envelopes capable of actively modifying their physicochemical properties in response to external environmental conditions. These systems represent a cutting-edge frontier in architectural and engineering research, often inspired by natural adaptation mechanisms and based on the integration of advanced materials, sensing technologies, automation, and parametric design.

Loonen et al. (2018) define adaptive facades as building envelopes that can repeatedly and reversibly alter their properties in reaction to environmental changes, thereby enhancing indoor comfort while reducing energy consumption.<sup>10</sup> The term "adaptive" is typically reserved for self-actuating systems incorporating embedded sensors and actuators, whereas "responsive elements" can also include externally controlled components.<sup>11</sup> These researchers emphasize that flexibility is central to adaptive envelopes, in contrast to the rigidity of traditional systems, and propose principles of adaptability, multi-functionality, and evolvability to address current and future demands.<sup>12</sup> There is also kinetic architecture, which involves macroscopic changes in form or configuration and represents a distinct category, as illustrated by the Acclimated Kinetic Envelopes (AKE) proposed by Wang et al. (2012).<sup>13</sup> Literature indicates that the primary objective of adaptive technologies is to optimize indoor comfort, particularly through the environmental control of the building envelope. The COST ACTION TU database reveals that the main characteristics of

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8. IEA (2013) Technology roadmap: Energy efficient building envelopes. Paris: *International Energy Agency*. <https://www.iea.org/reports/technology-roadmap-energy-efficient-building-envelopes> (Licence: CC BY 4.0).

9. IPCC (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926

10. Loonen RCGM, Trčka M, Cóstola D, Hensen JLM. Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 2013; 25:483–493. <https://doi.org/10.1016/j.rser.2013.04.016>.

11. Heiselberg P. (Ed.). *Expert Guide – Part 1: Responsive Building Concepts*. IEA ECBCS Annex 44, Integrating Environmentally Responsive Elements in Buildings. Aalborg University, Denmark, 2009.

12. Loonen RCGM, Trčka M, Cóstola D, Hensen JLM (2013) Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews* 25: 483–493. <https://doi.org/10.1016/j.rser.2013.04.016>.

13. Wang J, Beltrán LO, Kim J. From static to kinetic: A review of acclimated kinetic building envelopes. *World Renewable Energy Forum (WREF)*, vol. 5, 2012, pp. 4022–4029.

adaptive envelopes concern thermal comfort (30%) and visual comfort (24%), suggesting that over half of the analysed solutions aim to enhance indoor environmental quality. This data confirms that thermal gains and glare represent central challenges in sustainable design, particularly due to the high environmental impact of Heating, Ventilation, and Air Conditioning (HVAC) systems.<sup>14</sup> However, emerging case studies demonstrate that these technologies can extend their effectiveness beyond internal microclimate regulation, contributing to the improvement of external microclimatic conditions and the mitigation of the urban heat island (UHI) phenomenon. The UHI effect, a consequence of intensive urbanization, is characterized by significantly higher temperatures in urban areas compared to surrounding rural regions, primarily due to the replacement of natural surfaces with constructed materials and the consequent reduction in vegetation cover.<sup>15</sup> The capacity of urban surfaces to store and release heat, combined with anthropogenic heat emissions, contributes substantially to thermal accumulation in cities. Key influencing factors include soil structure, the presence of vegetation, population density, and local meteorological conditions.<sup>16</sup> Urban surface temperature plays a critical role in altering the energy balance of the built environment, thereby affecting the city's microclimate and various ecological processes. Contemporary research defines the UHI effect as an increase in summer temperatures in urban areas. UHI mitigation can be achieved through urban and architectural design strategies aimed at reducing its impact. Among the most common techniques are the use of high-albedo surfaces and reflective materials to minimize heat absorption, as well as the design of buildings and urban spaces that promote natural ventilation and mitigate the effects of urban canyons. UHI mitigation can be achieved through urban and architectural design strategies aimed at reducing its impact. Among the most common techniques are the use of high-albedo surfaces and reflective materials to minimize heat absorption, as well as the design of buildings and urban spaces that promote natural ventilation and mitigate the effects of urban canyons. Green and reflective surfaces are particularly effective, as they also enhance building energy performance. The materials used in these solutions typically exhibit high solar reflectance (SR) and high thermal emittance (TE). The combined application of reflective and green surfaces on roofs and building envelopes represents an effective mitigation strategy, wherein green surfaces reduce heat through evaporative cooling, while reflective surfaces limit net absorbed radiation. Experimental studies, such as those conducted by Akbari et al., have demonstrated that these approaches can reduce sensible heat flux compared to

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14. Aelenei L, Aelenei D, Romano R, Mazzucchelli ES, Brzezicki M, Rico-Martinez JM (2018) *Case Studies: Adaptive Facade Network*. BK BOOKS. <https://books.bk.tudelft.nl/press/catalog/book/672>

15. U.S. Environmental Protection Agency (2008) Green Roofs. In: *Reducing Urban Heat Islands: Compendium of Strategies*. Draft. <https://www.epa.gov/heat-islands/heat-island-compendium>.

16. Oke T. (1973). City Size and the Urban Heat Island. *Atmospheric Environment*, 7, 769–779. 10.1016/0004-6981(73)90140-6.

conventional concrete surfaces.<sup>17 18</sup>

Although many simulations have focused on horizontal surfaces (e.g., roofs and pavements), it is essential to recognize that urban façades interact with these surfaces through mutual solar radiation reflection. Current research has explored adaptive technologies, phase change materials (PCMs), and thermochromic materials. "Cold" materials represent a heterogeneous category that includes highly reflective natural surfaces, artificial white materials, low-temperature pigmented coatings (cold-coloured materials), and advanced nanomaterials.<sup>19 20</sup> In particular, the use of reflective or high-solar-reflectance materials on façades can contribute not only to reducing the thermal load on buildings but also to the overall radiation balance of urban spaces, in synergy with the albedo characteristics of horizontal surfaces. Supporting this, recent studies have highlighted how cool façades, thanks to their combination of high solar reflectance and thermal emissivity, are able to significantly lower external surface temperatures and reduce cooling energy demand, thereby improving indoor thermal comfort—especially in Mediterranean climate contexts where the urban heat island effect is particularly relevant.<sup>21 22</sup> This confirms the necessity of considering vertical façade treatments in climate-responsive urban design. Figure 1 illustrates three experimental projects presented as distinct case studies. Experimental projects, such as the AeroLeaf system—featuring mobile ceramic evaporative cooling components applied to residential buildings—or the bioreceptive terracotta façade developed by a multidisciplinary team comprising Henning Larsen, Thornton Tomasetti, and VS1 by Innovation Glass, which promotes moss and microorganism growth to activate climate-responsive surfaces, illustrating how living materials can enhance environmental performance, represent concrete examples of this approach.<sup>23 24</sup> Additionally, the Cool Cacti project integrates passive and

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17. Akbari H., Pomerantz M., Taha H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, 70, 295–310. 10.1016/S0038-092X(00)00089-X.

18. Akbari H., Konopacki S. (2005). Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy*, 33, 721–756. 10.1016/j.enpol.2003.10.001.

19. Cabeza LF, Castellon C, Nogues M, Medrano M, Leppers R, Zubillaga O (2007) Use of microencapsulated PCM in concrete walls for energy savings. *Energy and Buildings* 39(1): 113–119.

20. Karlessi T, Santamouris M, Synnefa A, Assimakopoulos D, Didaskalopoulos P, Apostolakis K (2011) Development and testing of PCM doped cool colored coatings to mitigate urban heat island and cool buildings. *Building and Environment* 46(3): 570–576.

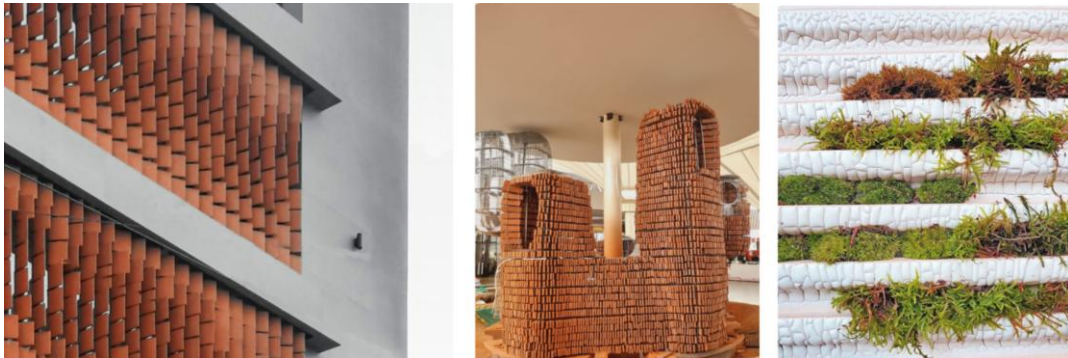
21. Pisello AL, Santamouris M, Cotana F (2013) Active cool roof effect: impact of cool roofs on cooling system efficiency. *Advances in Building Energy Research* 7(2): 209–221. DOI: 10.1080/17512549.2013.865560. <http://dx.doi.org/10.1080/17512549.2013.865560>.

22. Zinzi M (2016) Exploring the potentialities of cool facades to improve the thermal response of Mediterranean residential buildings. *Solar Energy* 135:386–397. <https://doi.org/10.1016/j.solener.2016.06.021>

23. Jayasankar P (2024) An Innovative Product for Sustainable Cooling: CoolAnt. *CoolAnt Aeroleaf: Breathing Facade*. Smart POV, 31 May 2024. Available at: <https://smart-pov.com/an-innovative-product-for-sustainable-cooling-coolant/#coolant-aeroleaf-breathing-facade> (accessed 3 August 2025).

24. ArchCeramic Workshop (2024) ACAW 2024 – Architectural Ceramic Assemblies Workshop. In *ArchCeramicWorkshop.com*. Available at: <https://archceramicworkshop.com/acaw-2023-presentations/#toggle-id-8> (accessed 6 January 2026).

evaporative cooling into a freestanding urban structure, demonstrating how adaptability can address both functional needs and shared environmental and spatial qualities. These design experiences outline a still largely unexplored area of research, in which adaptive architecture emerges as a potential climate control mechanism for urban space, expanding the scope of the building envelope to a broader territorial scale.<sup>25</sup>



**Figure 1.** *Examples of Climate-responsive Designs: (a) AeroLeaf System with Mobile Ceramic Cooling (2023); (b) Cool Cacti Passive and Evaporative Cooling (2023); (c) Thornton Tomasetti sustainable Façades with Bioreceptive Surfaces (2023)*

Source: fig. 1a-1b, courtesy by CoolAnt, 2025; fig. 1c, [www.ThorntonTomasetti.com](http://www.ThorntonTomasetti.com), 2025.

## Materials and Methods

The selection of case studies for this research is based on the database developed within the Research about the “High-Performance Ceramic Building Envelopes: Prototyping and Monitoring” University of Sassari.

This study forms part of a broader systematic review of the state-of-the-art in adaptive and ceramic building envelopes, which resulted in the collection, analysis, and cataloguing of 329 internationally selected case studies. The case study research was conducted by examining peer-reviewed articles published in scientific journals, technical manuals, and additional materials sourced from open-access repositories (Scopus, Web of Science, and Google Scholar), as well as web-based searches (Google) and journal publications.

The methodology employed integrates both quantitative and qualitative analysis, structured into three distinct phases (Table 1):

- An initial phase of data collection and systematization of the state-of-the-art on adaptive envelopes and the urban heat island (UHI) phenomenon;
- A subsequent phase dedicated to the selection of case studies and the development of a comparative database.
- A final phase focused on the critical analysis of the selected projects, aimed at identifying recurrent design patterns and effective mitigation strategies for improving the urban microclimate.

<sup>25</sup>CoolAnt (2024) CoolAnt Gallery – Façade. In *CoolAnt.co*. Available at: <https://www.coolant.co/coolant-gallery/facade> (accessed 3 August 2025).

**Table 1.** *Outline of Research Methodology Phases*

<b>PHASE 1 DATABASE</b>	<b>PHASE 2   COMPARATIVE ASSESSMENT</b>
<b>Analysis criteria</b> Analysis matrix with quantitative and qualitative indicators: 1. Material data 2. Adaptive technology 3. Physical performance 4. Climatic context 5. Degree of adaptivity	<b>Evaluation indicators</b> Key indicators (optical, physical, climatic): 1. Solar Reflectance 2. Thermal Emittance 3. Solar Reflectance Index (SRI) 4. Albedo 6. Surface temperature variation ( $\Delta T$ )
<b>Methods</b> <ul style="list-style-type: none"> <li>• Bibliographic research</li> <li>• Scientific and regulatory research</li> <li>• Deductive method</li> <li>• Direct experience and professional contacts</li> </ul>	<b>Methods</b> <ul style="list-style-type: none"> <li>• Quantitative and qualitative analysis               <ul style="list-style-type: none"> <li>• Deductive-comparative method</li> <li>• Classification by adaptivity score</li> </ul> </li> </ul>
<b>Tools</b> <ul style="list-style-type: none"> <li>• Summary sheets for analysis and data collection</li> </ul>	<b>Tools</b> <ul style="list-style-type: none"> <li>• Comparative material performance tables</li> </ul>

### Study Sample Definition

The urban heat island (UHI) phenomenon is influenced by multiple factors, including the thermophysical properties of construction materials, vegetation coverage, morphological configuration, urban density, and local meteorological conditions. The 329 case studies were initially evaluated based on their adaptivity scores and subsequently classified using optical and thermal performance indicators—specifically Solar Reflectance (SR), Thermal Emittance (TE), and Albedo—to assess the capacity of vertical surfaces to absorb, reflect, and emit thermal radiation. These parameters enable quantification of façade contributions to either mitigating or exacerbating UHI effects. This integrated analytical approach facilitates a comprehensive evaluation of bioclimatic interventions combined with specialized building envelope materials and technologies. The primary objective is to compare the environmental performance of various design solutions, establishing a quantitative foundation for developing design guidelines aimed at enhancing microclimatic resilience and reducing UHI intensity. The 329 catalogued case studies were analysed according to criteria derived from state-of-the-art research and supplemented with geographic and building envelope characteristics. Given that materials effective in UHI mitigation must demonstrate high solar reflectance (Solar Reflectance Index, SRI), high thermal emittance (TE), and adaptability (both mechanical and intrinsic), these parameters were established as key indicators for evaluating the selected case studies. The SRI criteria for the initial selection of the selected case studies were also derived from the legislation currently in force in Italy, serving as a basic reference. Ministerial Decree No. 256 of June 23, 2022, Official Journal No. 183 of August 6,

2022 (the so-called CAM Decree), which establishes the adoption of minimum environmental criteria (CAM) for buildings, thus aligning with environmental protection strategies already established internationally. Regarding the SRI, Section 2.2.6 of Ministerial Decree No. 256 establishes that, with reference to "Reduction of the impact on the microclimate and air pollution," waterproof surfaces must be made of materials with a high solar reflectance index.<sup>26</sup> In particular:

- external surfaces (e.g., pedestrian walkways, sidewalks, squares, cycle paths, tc.):  $SRI \geq 29$
- roofing materials must guarantee an SRI of at least 29 for slopes greater than 15%, and at least 76 for slopes less than or equal to 15%.

The international LEED standards, however, establish an initial SRI of at least 39 for steeply sloped roofs and a three-year SRI of 32.

For the purposes of the ongoing research, a reference SRI value for vertical surfaces was established, averaging between the two standards and ranging from 29 to 39. Therefore, the initial selection criteria are:

- $29 < SR < 39$
- Adaptivity requirements for the façade system or components (Adaptivity scoring)
- Climate range (Koppen 1991-2020/2041-2070/2071-2099)
- Visual requirements for the material (colour and texture)

A matrix of indicators was then defined to provide a second didactical analysis of the selected case studies, for optimal integration into the urban context aimed at controlling the UHI (Table 2).

**Table 2.** *Analysis Criteria Matrix*

<b>Analysis criteria</b>	<b>Description</b>
<b>1. Cladding material data</b>	
Material type	Specify if the material is: metal, composite, ceramic, stone or other
Color	Specify the color hue (white, grey, others.)
<b>2. Architectural facade data</b>	
Type of adaptivity (Inherent or mechanical)	Specify whether the construction system is mechanically adaptive or whether the material is adaptive
<b>3. Physical Requirements Data</b>	
Solar Reflectance	The fraction of the incident solar energy that is reflected by a surface.

<sup>26</sup>Ministry of Ecological Transition (2022) *Minimum environmental criteria for the assignment of building design services, construction works, and combined design and construction services*. Ministerial Decree of 23 June 2022, *Official Journal of the Italian Republic*, No. 183, 6 August 2022.

Thermal Emittance	The ability to emit energy in the form of thermal radiation
SRI - Solar Reflectance Index	Measures a material's ability to reflect solar energy and dissipate heat.
Albedo	The fraction of sunlight reflected
<b>4. Climate range</b>	The location based on Environmental requirements
<b>5. Technological integration</b>	
Plant systems integration	Integration of green facade systems (living walls) or new generation bio-inspired materials
Integration of technical systems (cooling, air, etc.)	Integration of air- or water-cooling channels

### Cataloguing

For the analysis of the case studies, a synthetic data sheet model was developed to simplify the systematization of the data. The first section focuses on the project's profile data (construction date, location, intended use, status), while the second section concentrates on the identified technological criteria, categorized and subdivided accordingly. The data collection and archiving process involved gathering both quantitative and qualitative data through the bibliographic research. The references for each case study were compiled in the corresponding data sheets. Furthermore, the information obtained through bibliographic research was supplemented by the author's direct experience, which gathered additional details through professional interactions with companies and research centres, thereby ensuring a comprehensive investigation of the subject matter.

### Research Limitations

The case study analysis revealed a significant gap in the availability of specific data based on the established criteria. This deficiency is significant because it indicates that adaptive façade design remains largely disconnected from outdoor environmental concerns, being predominantly aimed at energy savings and enhancing indoor comfort.

### Comparative Analysis of Catalogued Data

The analysis of the material composition of building envelopes revealed a total of 176 applications of metal, 72 of glass, 50 of ceramic, 39 of synthetic polymers, 26 of water surfaces, 21 of vegetation, 19 of wood, and 13 of concrete. The comparative analysis assessed the effectiveness of the selected materials in reducing the impact of the Urban Heat Island (UHI) effect. Specifically, ceramic envelopes exhibited high values of Solar Reflectance (0.75), Thermal Emittance (0.90), and Albedo (0.70), ranking among the most efficient materials in reflecting solar radiation. The Solar Reflectance Index (SRI) of white ceramic reached a value of 93.2, the highest among the analysed materials. The 50 ceramic façades present in the sample

of 329 case studies, including 25 adaptive and 25 traditional ones, were further analysed to investigate the contribution of this material within more complex adaptive strategies, integrated with evaporative cooling systems and façade vegetation, with the aim of further optimizing the environmental performance of building envelopes (Table 3-4; Figure 2).

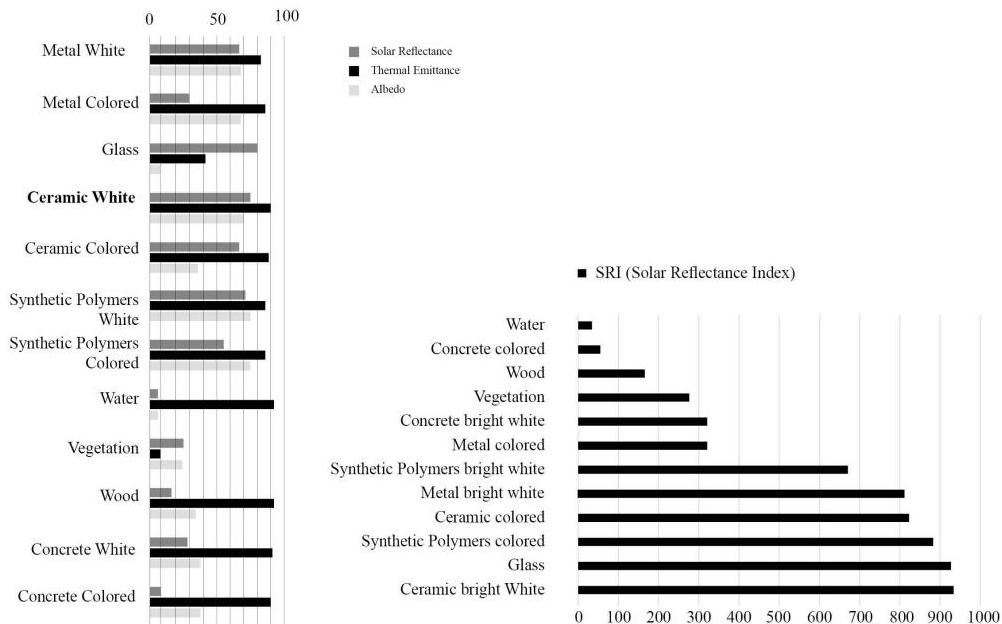
**Table 3.** Analysis of the Materials used in the Database using the indicators: Solar Reflectance (SR), Thermal Emittance (TE), Solar Reflectance Index (SRI) and Albedo

Applications	Material	Color	SR	TE	SRI	Albedo
176	Metal	Bright White	0.67	0.83	81.3	0.68
		Colored	0.30	0.86	31.9	0.68
72	Glass		0.80	0.40	93.1	0.08
54	Ceramic	Bright White	0.75	0.90	93.2	0.70
		Colored	0.67	0.89	82.3	0.36
39	Polymers	Bright White	0.72	0.87	88.7	0.75
		Colored	0.56	0.87	67.1	0.75
26	Water		0.07	0.93	3.6	0,07
21	Vegetation		0.26	0.90	27.6	0.25
19	Wood		0.17	0.93	16.6	0.35
13	Concrete	Bright White	0.29	0.92	32.1	0.38
		Colored	0.09	0.91	5.6	0.38

**Table 4.** References of Indicators used for Material Analysis in evaluating Urban Heat Island Mitigation

INDICATORS	REFERENCES
<b>SR (Solar Reflectance)</b> <b>TE (Thermal Emittance)</b>	Hoffmann, C., & Geissler, A. (2022). Climate Change and Building Materials in Urban Areas: Materials Catalog and Recommendations. Summary. Federal Office for Housing (UFAB). UNI 8477-1. (1983). <a href="https://coolroofs.org/directory/roof?key-words=glass&amp;page=2">https://coolroofs.org/directory/roof?key-words=glass&amp;page=2</a> <a href="https://www.pce-italia.it/html/dati-tecnici-1/link/tabella-gradi-di-emissione-materiali-non-metallici.htm">https://www.pce-italia.it/html/dati-tecnici-1/link/tabella-gradi-di-emissione-materiali-non-metallici.htm</a> <a href="https://www.otm.sg/complete-list-of-glass-properties">https://www.otm.sg/complete-list-of-glass-properties</a> <a href="https://www.otm.sg/sri-calculator">https://www.otm.sg/sri-calculator</a>
<b>SRI (Solar Reflectance Index)</b>	<a href="https://www.otm.sg/sri-calculator">https://www.otm.sg/sri-calculator</a>
<b>A (Albedo)</b>	Gul, MS, Kotak, YS, Muneer, T & Ivanova, S 2018, 'Enhancement of Albedo for Solar En-

	<p>ergy Gain with Particular Emphasis on Over-cast Skies', <i>Energies</i>, vol. 11, no. 11, 2881. <a href="https://doi.org/10.3390/en11112881">https://doi.org/10.3390/en11112881</a>                  H. Taha, D. Sailor, H. Akbari (1992), "High-Albedo Materials for Reducing Building Cooling Energy Use", Energy and Environment Division, Lawrence Berkeley Laboratory, University of California.</p>
<p><b>ΔT (Surface temperature decrease)</b></p>	<p>Versini, P.-A., Castellanos-Diaz, L. A., Ramier, D., &amp; Tchiguirinskaia, I. (2024). Evapotranspiration evaluation using three different protocols on a large green roof in the greater Paris area.                  Zhang, L., Zhang, R., Zhang, Y., Hong, T., Meng, Q., &amp; Feng, Y. (anno). The impact of evaporation process on thermal performance of roofs.</p>



**Figure 2.** Comparative Analysis of the Materials used in the selected Projects from the Database, based on Key Indicators to assess their Potential for Mitigating the Urban Heat Island (UHI) effect

Among the analysed case studies, three deserve in-depth examination for their potential in combining the physical-material requirements of materials, adaptability requirements, and thermal requirements. The AeroLeaf system (previously mentioned) is installed on the façade of a riverside residence in Raipur, closing off a portico. The system is particularly noteworthy due to its use of extruded ceramic elements shaped like leaves, stacked on a steel post. The ceramic elements can rotate freely and are manually adjustable. Water is dripped through a second cavity in each

"leaf" via an irrigation pipe, with the goal of moistening the ceramic pieces and enhancing cooling performance.<sup>27</sup> The bio-receptive ceramic façade designed by Make Architects in collaboration with Arup in 2024 (manufactured by Boston Valley Terracotta) is also composed of modular elements, arranged in a diagonal and curved pattern. The pattern integrates unglazed inserts with horizontal grooves designed to slow down rainwater runoff. The curved diagonal components channel airflow, while the inserts collect water in their grooves. The porous ceramic mixture used for the inserts creates a bio-receptive surface that fosters the growth of algae and other microorganisms, generating a vital layer that enhances water retention and further slows down runoff.<sup>28</sup> Also in 2024, CoolAnt developed the Cool Cacti project: an artistic installation that integrates the CoolAnt Binary evaporative cooling system. The sculpture is clad with a double zinc-coated mesh containing standard bricks, which are moistened by water poured from above and collected at the base. This system leverages evaporation to enhance cooling, combining functionality and aesthetic quality. The project achieved an adaptability score of 12, representing an example of sustainable innovation in the field of adaptive architecture.<sup>29</sup> These projects are concrete examples included in the database and represent diverse technological and material approaches that contribute to the definition of new strategies for adaptive building envelopes, with potential positive impacts on environmental sustainability.

## Results and Discussion

The investigation of a sample of 50 ceramic envelope systems, comprising 25 adaptive and 25 traditional designs, revealed that 22% of the adaptive envelopes employed effective strategies to improve the urban microclimate, a characteristic exclusive to this group. The prevalence of high-performance solutions among adaptive envelopes suggests a correlation between adaptability and environmental performance, particularly in reducing surface temperatures and enhancing urban comfort. Among the 25 adaptive projects, approximately 12% incorporated vegetation systems directly into the building envelope, while 32% featured active cooling solutions. Notably, one case (4% of the total) combined both vegetation and active cooling strategies, resulting in a hybrid system that synergistically leveraged passive and active climate control mechanisms. The integration of ceramic materials with adaptive systems, often based on plant-based or water-based elements, proved particularly effective. Indicators related to Solar Reflectance (SR), Thermal Emittance (TE), Solar Reflectance Index (SRI), and albedo did not reveal significant variations or improvements between adaptive and traditional systems. However, the surface temperature variation ( $\Delta T$  surface), based on data from studies by Versini et al. and Zhang et al., indicated a substantial reduction in façade surface temperature, equal to approximately 5.6 °C for water-based systems and 1.5 °C for vegetated façade systems. While this analysis primarily focused on surface properties and associated

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<sup>27</sup>Jayasankar, *CoolAnt Aeroleaf*, 2024.

<sup>28</sup>ArchCeramic Workshop, *ACAW 2024*, 2024.

<sup>29</sup>CoolAnt, *CoolAnt Gallery – Facade*, 2024.

temperature variations, a comprehensive assessment of the effectiveness of adaptive systems in mitigating the urban heat island effect requires the integration of microclimatic data, including ambient air temperature and environmental comfort parameters, which can be acquired through in-situ measurements or advanced microclimatic simulations. These in-depth microclimatic assessments represent a crucial future development for fully understanding the overall impact of adaptive technologies in urban contexts.<sup>30 31</sup> The comparative approach adopted enables a direct relationship between two formally similar but functionally distinct building envelope categories, isolating the role of adaptivity as an independent variable and providing a useful basis for design considerations. The focus on ceramic materials, known for their thermal and reflective properties and durability, ensures material homogeneity within the sample, strengthening the investigation's coherence. The emerging evidence suggests the opportunity to expand the study to a larger and more diverse sample, incorporating envelopes made from various materials, such as metals, composites, or natural stone, and exploring a broader range of climatic and geographic contexts.

A further area of interest concerns the integration of phase change materials (PCMs) in adaptive envelopes, analysing their thermoregulatory potential in both dense urban environments and climate-extreme zones. Expanding the database and utilizing advanced energy and environmental simulation tools could enable an objective assessment of envelope performance, integrating indicators such as surface temperature, heat flow, thermal comfort, and energy consumption. Furthermore, connecting adaptive envelopes to intelligent control systems and environmental sensors could enhance their performance, opening scenarios in which the envelope becomes an active component of a responsive and resilient urban system (Table 5-6).

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<sup>30</sup>Zhang, L., Zhang, R., Zhang, Y., Hong, T., Meng, Q., & Feng, Y. (2016). The impact of evaporation from porous tile on roof thermal performance: A case study of Guangzhou's climatic conditions. *Energy and Buildings*, 136, 119-129. 10.1016/j.enbuild.2016.12.012.

<sup>31</sup>Versini, P.-A., Castellanos, L. A., Ramier, D., & Tchiguirinskaia, I. (2024). Evapotranspiration evaluation using three different protocols on a large green roof in the greater Paris area. *Earth System Science Data*, 16, 2351-2366. 10.5194/essd-16-2351-2024.

**Table 5-6.** Analysis of the Presence of Urban Heat Island (UHI) Mitigation Strategies using Evaporative Cooling Systems, carried out on a Sample of 50 Case Studies: 25 Traditional Building Envelopes and 25 adaptive Building Envelopes incorporating Ceramic Materials. Traditional Building Envelope Table

	Project	System Type	Materials	Adaptivity Scoring:	SR	TE	SRI	Albedo	$\Delta T$ (°C)
1	Algueña Concert Hall and Music school MUCA	Ceramic pearlescent glaze	Ceramic (White)	0	0.75	0.90	92.9	0.70	0
2	Girasol	Direct fix cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
3	Biblioteca pubblica di Nembro	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
4	Center of Asian Art	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
5	Central library and municipal archives	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
6	Ceramic House	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
7	Ceramic Morphologies	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
8	Ceramic scales screen Hande	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
9	Chongwenmen M-Cube	Rainscreen cladding - sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Ceramic (White)		0.75	0.90	92.9	0.70	
10	Dearborn Residence - Filoramo Talsma LLC	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
11	Denizli Han Office Building	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
12	Dynamic terracotta	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
13	Escola Martine	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (White)		0.75	0.90	92.9	0.70	
14	Viralgen	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (White)		0.75	0.90	92.9	0.70	
15	Villa Nurbs House	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (White)		0.75	0.90	92.9	0.70	
16	Wasl Tower		Metal	0	0.67	0.83	81.3	0.68	0

		Curtain wall single skin	Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Glass		0.80	0.42	90.0	0.08	
17	Viralgen	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (White)		0.75	0.90	92.9	0.70	
18	Villa Nurbs House	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (White)		0.75	0.90	92.9	0.70	
19	Vanke Pavilion Expo 2015	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
20	TR House	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
		Ceramic	Ceramic		0.67	0.89	81.5	0.36	
21	Torrejon de Ardoz	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
22	Thin terracotta cladding	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
23	Teresianas School	Sun screen	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
24	Tarraco Arena	Rainscreen cladding	Metal	0	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
25	Spanish Pavilion Expo 2005	Metal	Metal	0	0.67	0.83	81.3	0.68	0
		Ceramic	Ceramic		0.67	0.89	81.5	0.36	

Adaptive Building Envelope Table

	Project	System Type	Materials	Adaptivity Scoring:	SR	TE	SRI	Albedo	$\Delta T$ (°C)
1	AeroLeaf facade installation	Ceramic panels	Metal	13	0.67	0.83	81.3	0.68	5.6
			Ceramic (Colored)		0.67	0.89	81.5	0.68	
			Water		0.07	0.98	6.7	0.68	
2	Bio Ceramic System - IAAC	Bioreceptive ceramic panel	Vegetation	5	0.26	0.96	29.3	0.25	1.5
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
3	Bioreceptive ceramic facade - ARUP	Rainscreen cladding	Vegetation	5	0.26	0.96	29.3	0.25	1.5
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
4	IPV Rainscreen Facade	Rainscreen cladding	Metal	1	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			PV panels (Grey)		0.72	0.87	88,00	0.75	
5	Ceramic green wall_Carnegie Mellon	Hydronic system Rainscreen cladding	Metal	7	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			"Synthetic polymers"		0.72	0.87	92.9	0.75	

6	Ceramic green wall_Eric Parry	Hydronic system Rainscreen cladding	"Synthetic polymers"	7	0.72	0.87	92.9	0.75	7.1
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Water		0.07	0.98	6.7	0,12	
			Vegetation		0.26	0.9	29.3	0.25	
7	Ceramic green wall_Henning Larsen	Curtain wall	Glass	5	0.8	0.42	90.0	0.08	1.5
			Ceramic (White)		0.75	0.9	92.9	0.70	
			Metal		0.67	0.83	81.3	0.68	
			Vegetation		0.26	0.96	29.3	0.25	
8	Kuggen - Wingårdh Arkitektkontor	Lightweight wall facade	Metal	5	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Glass		0.8	0.42	90.0	0.08	
9	Cloud House	Sun screen	Metal	1	0.67	0.83	81.3	0.68	0
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
10	Co-mida - Biophotovoltaic vertical garden	Rainscreen cladding	"Synthetic polymers"	8	0.72	0.87	92.9	0.75	1.5
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Vegetation		0.26	0.9	29.3	0.25	
11	Counter Current Heat Exchanger	Curtain wall single skin	Metal	4	0.67	0.83	81.3	0.68	5.6
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Water		0.07	0.98	6.7	0,12	
12	Cool Brick	Fired bricks	Ceramic (Colored)	5	0.67	0.89	81.5	0.36	0
13	Cool Cacti	Sun screen	Metal	12	0.67	0.83	81.3	0.68	5.6
			Ceramic (Colored)		0.67	0.89	81.5	0.36	
			Ceramic (White)		0.07	0.98	92.9	0.70	
			Water		0.67	0.83	6.7	0,12	
14	De Castillia 23 - Progetto CMR	Mass wall facade - rainscreen cladding	Metal	3	0.8	0.42	81.3	0.68	0
			Glass		0.75	0.9	90.0	0.08	
			Ceramic (White)		0.75	0.9	92.9	0.70	
15	Eau Solei - Ennead Architects	Sun screen	Ceramic (White)	4	0.07	0.98	92.9	0.70	5.6
			Water		0.67	0.83	6.7	0,12	
16	Xinjin Zhi Museum	Curtain wall	Metal	1	0.67	0.89	81.3	0.68	0
			Ceramic (Colored)		0.8	0.42	81.5	0.36	
			Glass		0.67	0.83	90.0	0.08	
17	Water Wall	Hydronic system	Metal	8	0.07	0.98	81.3	0.68	0
			Ceramic (Colored)		0.8	0.42	81.5	0.36	
			Glass		0.67	0.83	90.0	0.08	
			Vegetation		0.07	0.98	29.3	0.25	
18	Terracotta skin - Behnisch	Rainscreen cladding	"Synthetic polymers"	4	0.26	0.96	92.9	0.75	5.6
			Metal		0.72	0.87	81.3	0.68	

			Ceramic (White)		0.67	0.83	92.9	0.70	
19	Terrabyte	Mass wall facade	Water	5	0.75	0.9	6.7	0.12	5.6
			Metal		0.07	0.98	81.3	0.68	
			Ceramic (Colored)		0.67	0.83	81.5	0.36	
20	Sun louvres_BKSK	Sun screen	Water	1	0.67	0.89	6.7	0.12	0
			Ceramic (White)		0.07	0.98	92.9	0.70	
21	Spanish Pavilion Expo 2008	Sun screen	"Synthetic polymers"	5	0.75	0.9	92.9	0.75	5.6
			Metal		0.72	0.87	81.3	0.68	
			Ceramic (White)		0.67	0.83	92.9	0.70	
22	Sony City Osaki	Curtain wall	Water	7	0.75	0.9	6.7	0.12	5.6
			Glass		0.07	0.98	90.0	0.08	
			Metal		0.8	0.42	81.3	0.68	
			Water		0.67	0.83	6.7	0.12	
23	Siemens Wind Turbine Facility	Curtain wall	Ceramic (White)	4	0.07	0.98	92.9	0.70	0
			Metal		0.75	0.9	81.3	0.68	
			Ceramic (White)		0.67	0.83	92.9	0.70	
24	Selfie Facade	Curtain wall double skin	Glass	12	0.75	0.9	90.0	0.08	0
			Glass		0.8	0.42	90.0	0.08	
			Metal		0.67	0.83	81.3	0.68	
25	Sapphire	Mass wall facade	Ceramic (White)	3	0.75	0.9	92.9	0.70	0
			Glass		0.75	0.9	90.0	0.08	
			Metal		0.8	0.42	81.3	0.68	
			Ceramic (White)		0.67	0.83	92.9	0.70	

## Conclusion

The Urban Heat Island (UHI) phenomenon is one of the primary environmental concerns arising from increasing urbanization, with significant impacts on microclimatic comfort, public health, and energy sustainability in built environments. The analysis conducted on a homogeneous sample of 50 ceramic envelopes – evenly distributed between traditional and adaptive systems – revealed a clear correlation between the degree of adaptivity and the effectiveness of UHI mitigation strategies. The results indicate that only adaptive envelopes integrate significant evaporative cooling and vegetation-based solutions, confirming the potential of these approaches in reducing surface temperatures and regulating the urban microclimate. Unlike traditional passive strategies based on thermo-optical properties such as albedo, emittance, or solar reflectance, the effectiveness of the most performant solutions appears to depend on their ability to dynamically interact with the external environment through cycles of moisture absorption and release, natural shading, and active cooling. However, the analysis highlighted some limitations related to the

limited availability of quantitative data and the heterogeneity of design documentation, emphasizing the need to expand the sample and rely on advanced monitoring tools. The comparative approach enabled the isolation of adaptivity as a strategic design variable, capable of significantly impacting the climatic quality of urban spaces. In the future, the integration of innovative materials (such as Phase Change Materials), intelligent control systems, and environmental sensors can further enhance the role of envelopes as active and responsive devices. These findings open scenarios in which architecture is not just a passive element of the urban landscape, but an ecological infrastructural component, capable of interacting with the environment and contributing to the resilience of cities.

### Declaration

1. The authors declare that they contributed equally to the article. Specifically: Sara Moro wrote the introduction, literature review, and discussion, while Katia Gasparini wrote the methodological section and conclusions. Sara Moro performed the statistical analyses. All authors have read and approved the final version of the article.
2. This work utilized AI (ChatGPT-4, Grammarly, DeepL) exclusively for proofreading and linguistic polishing. All claims, data, and interpretations remain human-generated and validated by the authors

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