sustainability

Review

Sustainable Insulation Technologies for Low-Carbon Buildings: From Past to Present

Pinar Mert Cuce [1,2]

1 Department of Architecture, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey; mertcuce@gmail.com
2 College of Built Environment, Birmingham City University, Birmingham B4 7XG, UK

Abstract: Building facade insulation technologies have evolved from primitive thermal barriers to high-performance, multifunctional systems that enhance energy efficiency and indoor comfort. Historical insulation methods, such as thick masonry walls and timber-based construction, have gradually been replaced by advanced materials and innovative facade designs. Studies indicate that a significant proportion of a building's heat loss occurs through its external walls and windows, highlighting the need for effective insulation strategies. The development of double-skin facades (D-SFSs), adaptive facades (AFs), and green facades has enabled substantial reductions in heating and cooling energy demands. Materials such as vacuum insulation panels (VIPs), aerogels, and phase change materials (PCMs) have demonstrated superior thermal resistance, contributing to improved thermal regulation and reduced carbon emissions. Green facades offer additional benefits by lowering surface temperatures and mitigating urban heat island effects, while D-SF configurations can reduce cooling loads by over 20% in warm climates. Despite these advancements, challenges remain regarding the initial investment costs, durability, and material sustainability. The future of facade insulation technologies is expected to focus on bio-based and recyclable insulation materials, enhanced thermal performance, and climate-responsive facade designs. This study provides a comprehensive review of historical and modern facade insulation technologies, examining their impact on energy efficiency, sustainability, and future trends in architectural design.

Keywords: facade insulation; energy-efficient buildings; thermal performance; sustainable building materials

Academic Editors: Byung-Wook Kim, Qilong Cheng and Xin He

Received: 26 April 2025
Revised: 29 May 2025
Accepted: 31 May 2025
Published: 4 June 2025

Citation: Cuce, P.M. Sustainable Insulation Technologies for Low-Carbon Buildings: From Past to Present. *Sustainability* **2025**, *17*, 5176. https://doi.org/10.3390/su17115176

1. Introduction

The evolution of building facades is deeply intertwined with humanity's pursuit of comfort, efficiency, and sustainability. Throughout history, architectural advancements have been driven by the need to create habitable indoor environments that respond to climatic conditions while ensuring occupant well-being. From the rudimentary mud-brick walls of ancient Mesopotamia to the intricately designed timber-framed structures of medieval Europe, facades have long played a crucial role in regulating indoor conditions and protecting inhabitants from external elements. In their earliest forms, building facades were primarily structural barriers constructed using locally available stone, wood, or clay, designed to withstand environmental stresses while providing basic shelter [1]. However, as societies advanced and urban centres expanded, the expectations from building envelopes grew beyond mere protection.

Modern building facades have evolved into multifunctional systems that not only shield occupants from external weather conditions but also enhance thermal performance, contribute to energy efficiency, and integrate intelligent design technologies to reduce carbon footprints [2]. These advancements are particularly crucial given that buildings account for approximately 40% of global energy consumption, making them one of the most significant contributors to energy demands [3]. For instance, in the UK, buildings contribute to 40% of total energy use [4], whereas in India, this figure is 26%, with projections indicating a rise beyond 40% by 2040 [5]. Similarly, in China, buildings are responsible for 22% of energy consumption, while 29% of CO_2 emissions originate from the combustion of fossil fuels used for energy production [6]. Over time, this consumption has continued to rise, with non-OECD countries experiencing an annual growth of 1.3% and OECD nations seeing a 2% increase between 2018 and 2050 [7]. As a result, the total energy demand in buildings is anticipated to surge from 54.6% to 84% during this period [7,8]. A substantial portion of this energy is allocated to maintaining indoor comfort. Heating, ventilation, air conditioning (HVAC) systems and lighting account for a considerable percentage of building electricity consumption. Studies indicate that air conditioning and ventilation alone consume 50% of total electricity, while lighting requirements vary significantly, contributing 20% in residential buildings globally [9].

Given that a significant proportion of a building's energy is consumed for heating and cooling, reducing heat transfer through the building envelope is crucial for enhancing energy efficiency [10]. For instance, in a typical multi-storey building, approximately 40% of the total heat loss occurs through exterior walls and 30% through windows, followed by 7% through the roof, 6% through the basement slab, and 17% due to air leakage [11]. Figure 1 illustrates this specific distribution of heat losses, offering a visual breakdown of the relative contributions of different building envelope components for such building types. While these values may vary depending on the building design, climate, and construction practices, the figure highlights the critical role that wall and window insulation plays in thermal performance. By visualising the impact of each component, this representation supports the development of targeted insulation strategies, especially for external walls and glazing systems. The importance of reducing thermal bridges and improving envelope performance has become even more pronounced in the context of sustainable construction. Over the past decades, innovations such as high-performance insulation, ventilated facade systems, and smart glazing technologies have significantly improved the energy efficiency of buildings.

The importance of energy-efficient facades is intrinsically connected to occupant comfort and indoor environmental quality [12]. An effectively designed facade must harmonise thermal insulation, natural light ingress, air circulation, and soundproofing to establish an optimal indoor atmosphere for living and working [13]. Inadequate thermal regulation, excessive brightness, and insufficient airflow can negatively influence well-being and productivity, often leading to higher energy consumption for temperature control and artificial lighting. A facade constitutes the outermost component of a building, serving as both an aesthetic and functional barrier between indoor and outdoor conditions [1]. Typically, a facade system comprises two fundamental elements: structural components designed to absorb and transfer movement and an outer envelope that mediates environmental interactions. Its functions extend beyond mere visual appeal, as it mitigates the effects of wind and precipitation, regulates daylight exposure, and ensures the effective control of air permeability, thermal insulation, and acoustic performance. Since facades must withstand wind loads and transfer them to the primary structural framework, they are securely anchored at each floor, with connections supporting the weight of the upper sections. Depending on the construction approach, facades may be supported from below or suspended from above. In office buildings, expansive glazed sections from floor to ceiling are often integrated to maximise daylight penetration [14]. However, while extensive glazing enhances natural illumination, it can also lead to excessive solar heat gain and glare [15]. A well-conceived facade design should carefully balance these factors to achieve optimal performance. Historically, passive design strategies played a crucial role in facade construction. Thick masonry walls, timber shutters, and deeply recessed windows were common features, providing inherent insulation and facilitating passive ventilation. Although such methods proved effective to an extent, they lacked the flexibility required to adapt to evolving climatic conditions and the increasing density of urban environments. The Industrial Revolution introduced advanced materials such as steel, glass, and reinforced concrete, fundamentally transforming the facade architecture [16]. Early 20th-century modernist trends popularised curtain walls, allowing for vast glazed facades that elevated visual appeal but often resulted in significant thermal inefficiencies.

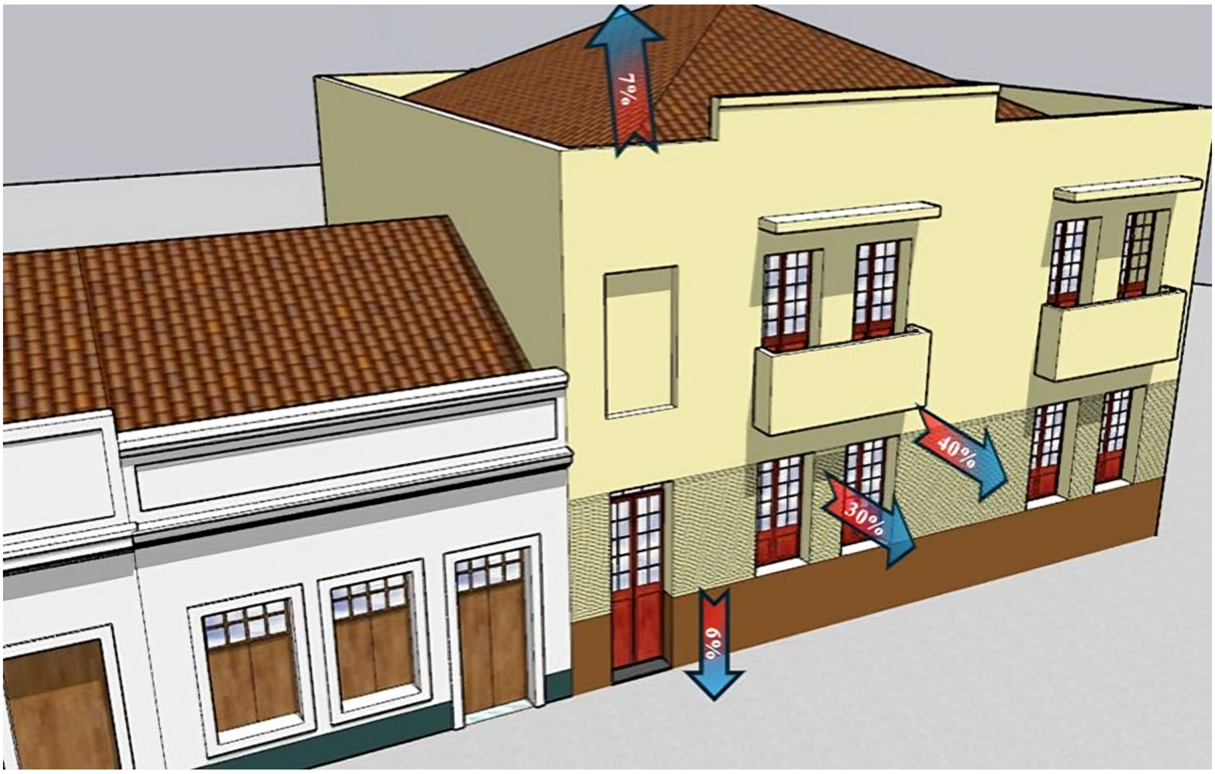

Figure 1. Contribution of facade components to building heat loss.

To address these challenges, contemporary facade engineering has prioritised high-performance insulation, adaptive shading systems, and responsive materials to mitigate energy losses while maintaining visual and functional appeal [17]. Recent advancements have introduced intelligent facade systems that dynamically adjust to environmental conditions. Technologies such as PCMs, electrochromic glazing, and D-SFS have significantly enhanced thermal regulation [18,19]. Moreover, the building integration of photovoltaics (BIPVs) within facade elements has enabled energy generation alongside insulation, turning buildings into active energy contributors rather than passive consumers [20]. Natural ventilation strategies have also evolved, with modern facades incorporating automated louvres, ventilated cavities, and green facades to improve air circulation and reduce reliance on mechanical cooling [21–23]. Innovative materials embedded with sensors and actuators enable facades to respond in real-time to climatic variations, optimising indoor thermal comfort while reducing energy loads [24].

Building Information Modelling (BIM) has revolutionised facade design and insulation strategies. By providing architects and engineers with predictive modelling capabilities, BIM allows for precise simulations of a building's thermal performance before construction begins [25]. Advanced energy simulation software such as EnergyPlus, TRNSYS, IDA ICE, and IESVE further enhances this predictive capability, enabling stakeholders to assess the energy implications of different facade configurations, materials, and insulation techniques [26]. Beyond energy modelling, BIM facilitates life-cycle assessments, ensuring that facade materials and designs align with long-term sustainability goals. The combination of computational fluid dynamics (CFD) and finite element analysis (FEA) has further refined facade engineering, allowing for a detailed analysis of thermal bridges, condensation risks, and structural integrity [27].

The future of facade insulation technologies is deeply rooted in sustainability. Emerging trends suggest a shift towards bio-based insulation materials, self-healing facades, and carbon-negative construction techniques. Aerogel insulation, vacuum glazing, and thin-film coatings are gaining traction as viable solutions to enhance thermal performance without compromising transparency or aesthetics [4,28,29]. Additionally, recent research highlights that replacing traditional building facades with optimised 3D-printed alternatives can achieve a 71.5% reduction in thermal transmittance [30]. Alongside this, advancements in 3D printing technology allow for bespoke facade designs that enhance material efficiency and minimise waste. As nations strive to meet the carbon neutrality targets outlined in agreements such as the Paris Accord, the role of innovative facade technologies becomes ever more critical. By embracing cutting-edge materials, intelligent systems, and computational tools, the built environment can significantly reduce its energy footprint while enhancing occupant comfort and architectural expression. Integrating responsive, adaptive, and self-sufficient facade technologies will define the next era of sustainable construction, ensuring that buildings consume less energy and actively contribute to a greener, more resilient future.

This study comprehensively examines the role of facade insulation technologies in enhancing energy efficiency, indoor thermal comfort, and sustainability. Given that a substantial portion of a building's heat loss occurs through external walls and windows, facade insulation is crucial for reducing energy demands and minimising carbon emissions. Historically, facade systems were primarily designed to offer protection from environmental conditions; however, their evolution has led to the emergence of adaptive and intelligent designs that actively contribute to building performance. Technologies such as D-SFSs, AFs, and green facades play a critical role in thermal regulation, while the integration of advanced materials, such as VIPs, aerogels, and PCMs, has significantly improved envelope performance. Yet, their broader implementation hinges on factors such as durability, cost-effectiveness, and regulatory integration. While several high-impact reviews have explored modern insulation materials and their thermal performance, most remain limited to technical advancements or regional strategies without offering a broader historical or architectural perspective. For example, Baetens et al. [31] have provided a detailed overview of aerogel insulation technologies, yet their analysis was confined to contemporary applications. Similarly, Jelle [32] has compared traditional and advanced insulation materials but did not consider their evolution within specific cultural or climatic contexts. Erzen et al. [33] have focused on smart and biobased materials, while Xu et al. [34] and Chu et al. [35] have provided systematic reviews of low-carbon and green building strategies—yet none of these studies engaged with the long-term architectural adaptation of insulation practices. In contrast, this study uniquely traces the 7000-year evolution of facade insulation, from Neolithic earth-covered dwellings to 21st-century energy-generating smart envelopes. By integrating passive and active systems across civilisations and mapping technological shifts against environmental and societal drivers, it fills a critical gap in the literature. This work offers a transhistorical, interdisciplinary framework that unites vernacular wisdom with modern innovation, providing architects, engineers, and policymakers with deeper insight into how insulation has historically functioned, not only to retain heat but to shape culture, space, and energy efficiency.

The overarching aim of this study is to trace and evaluate the historical evolution of facade insulation technologies and establish a comprehensive understanding of how past practices continue to inform and inspire contemporary sustainable solutions. The choice of the theme "From Past to Present" is not merely chronological but deliberately structured to reveal the continuity between ancient passive strategies and today's high-performance building envelopes. By investigating how early civilisations addressed thermal challenges using locally sourced materials and passive design features, this study seeks to highlight the enduring principles that underpin modern innovations such as VIPs, AFs, and BIPVs. Understanding these historical precedents allows researchers and practitioners to identify time-tested strategies that can be revisited, reinterpreted, or hybridised with emerging technologies. The historical review also clarifies specific research questions, such as the following: What thermal principles from ancient architecture remain valid today? How can traditional materials and methods contribute to reducing embodied carbon? What lessons can be drawn from vernacular architecture in designing climate-resilient envelopes? By weaving together historical insight with modern scientific and architectural advancements, this paper provides a unified framework that bridges past knowledge with future-oriented building practices, thereby supporting the development of low-carbon, high-performance building envelopes grounded in both innovation and tradition.

2. Historical Development of Building Facade Insulation

One of the most primitive methods to manage indoor thermal conditions involved embedding structures within the earth to take advantage of its natural insulating properties. As early as 5500 BC, communities residing in the region now known as Romania constructed subterranean or semi-subterranean dwellings. These residences were partially enveloped by soil, which served as a thermal buffer, reducing fluctuations in internal temperatures and enhancing occupant comfort. By approximately 3100 BC, ancient Egyptian builders adopted a different approach, favouring thick brick masonry to form external walls, significantly mitigating the impact of temperature extremes. These constructions not only provided robust protection against harsh environmental conditions but also laid the groundwork for more sophisticated thermal control techniques. Egyptian architects later devised an early interpretation of a cavity wall system, wherein a deliberate void between two layers of masonry acted as a barrier, impeding the transfer of heat between external and internal environments. By roughly 2650 BC, ceramic tiling was found to be applicable within the passageways of pyramids, serving dual purposes by offering both acoustic insulation and temperature regulation.

By around 500 BC, the Greeks placed considerable emphasis on solar orientation when designing residential spaces. A concept now recognised as the "Socratic House" emerged, whereby dwellings were deliberately positioned to maximise sunlight exposure, ensuring efficient passive heating during cooler months. The Romans, further refining thermal control methodologies by approximately 400 BC, introduced a heating innovation known as "Heliocaminus". This architectural feature comprised a south-facing chamber enclosed by mica-infused windows, which allowed sunlight to penetrate while minimising heat dissipation—an early precursor to greenhouse heating systems. Around 100 BC, the Essenes, a reclusive sect in what is now Palestine, established their homes within expanded caves, a strategic decision that harnessed the cooling effect of the earth during periods of intense heat.

Advancements in insulation continued throughout the medieval period. By the 10th century, Icelandic settlers developed sod-roofed homes, commonly called turf houses, to combat the severe cold of their environment. These dwellings were constructed using layers of compacted earth, stone, and organic materials, which significantly reduced heat loss, ensuring that interiors remained relatively warm despite the harsh Nordic climate. The depletion of wood resources during the 18th century further reinforced the necessity of such environmentally responsive construction methods as traditional fuel sources for heating became increasingly scarce. Across the globe, distinct cultures developed their insulation strategies. During the 1200s, China saw the rise of Tulou architecture, characterised by fortress-like, multi-storey buildings encased in exceptionally thick earthen walls. These monolithic structures provided outstanding thermal stability, maintaining a comfortable interior climate regardless of seasonal changes. By the 1500s, Leonardo da Vinci conducted pioneering investigations into air circulation and temperature control mechanisms, offering theoretical insights into material properties that would later influence modern insulation techniques. The 18th and 19th centuries marked a turning point in thermal engineering as scientific exploration into heat retention and dissipation intensified. In 1760, a Swiss physicist, Horace de Saussure, designed one of the earliest recorded solar energy collectors, a device that would lay the groundwork for subsequent developments in insulation technology. By 1855, Russian inventor Franz San Galli revolutionised indoor thermal management with the creation of the cast iron radiator. Though primarily designed as a heating apparatus, its impact on building design underscored the importance of controlled thermal regulation, ultimately shaping the progression of thermal barrier substances, as well as techniques in the modern era [36].

The employment of thermal barriers during ancient and early mechanical eras highlights humanity's persistent effort to withstand. Early humans confronted the challenge of maintaining habitable indoor conditions, which led to the development of rudimentary insulation methods using straw, clay, and wool [37]. These materials, though primitive, effectively reduced heat loss. The ancient Egyptians, for instance, strengthened earthen blocks using dried plant fibres to boost heat resistance, whereas builders in the Roman era incorporated cork and wool into edifices to optimise temperature regulation [38]. Throughout history, many construction materials inherently functioned as thermal regulators. Dense heat-retaining substances, including rock, timber, and soil, stabilised indoor temperatures by absorbing and gradually releasing heat [39]. Structures built into the earth, such as caves and semi-subterranean homes, were widely favoured due to their inherent thermal characteristics [40]. For instance, in the Neolithic Skara Brae settlement, dwellings buried under soil offered superior heat retention [41]. Building materials with significant thermal mass not only insulate but also store heat, regulating indoor climates effectively. Dense materials such as stone or thick brick walls absorb warmth throughout the day and release it at night, providing passive heating [42]. In contrast, contemporary thermal barriers such as fibreglass, polyurethane, and mineral wool are engineered to reduce heat flow rather than accumulate energy [43]. Their minimal mass limits their capacity to retain and release heat, unlike traditional materials used historically. Nonetheless, these contemporary materials excel at forming barriers that prevent unwanted heat exchange. In timber-based construction, walls were frequently built by layering wood with insulating materials like hay or mud, whilst interlocked log frameworks were sealed with braided straw to enhance thermal conservation [43]. Traditional timber structures incorporated extended corner joints to minimise thermal leakage by lengthening the path for cold air penetration. Churches constructed using these methods demonstrated remarkable durability, offering protection from cold, heat, and moisture [44]. Brick construction was developed to boost insulation, with builders adopting stacked wall designs and creating empty cavities inside the masonry and rooftop corners. Since the Roman era, outer walls commonly featured stone or brick exteriors packed with debris and lime plaster, forming a permeable centre that enhanced heat retention [45]. Such an approach was applied to vaults, where distinct construction tiers occasionally incorporated ventilation spaces to insulate interiors further. Buildings were often constructed partially below ground to protect against extreme temperatures, while multi-tiered layouts were developed to enhance thermal efficiency. In the Medieval period, building techniques increasingly incorporated the philosophical principles of space and environmental adaptation [46]. North-facing walls were often devoid of windows and doors, as this orientation was associated with cold and adversity. Instead, auxiliary chambers like sacristies or annexes served as thermal buffers, shielding the primary framework from outside factors. Medieval timber churches remained aligned with sustainable construction principles, positioning windows predominantly on the southern and eastern facades to maximise natural light and heat retention. An essential element of ancient building design was thermal retention, where substances with significant heat retention properties served as heat banks, absorbing warmth from sunlight, heating sources, and inhabitants, then slowly dispersing it over time. This principle extended to early heating systems. By the 19th century, thermal retention ideas inspired advancements like "attic airflow" mechanisms, where fresh air was warmed in advance by passing through twin-layered walls. These early heat recovery mechanisms laid the foundation for contemporary energy-efficient designs. Today, modern insulation materials primarily reduce heat transfer, whereas historical architecture often combines insulation with thermal mass storage. Contemporary energy-efficient strategies integrate both principles, insulation to limit heat exchange and high thermal mass materials for heat retention, demonstrating that ancient methods continue to inform sustainable building practices [47,48]. The evolution of insulation techniques mirrors the broader trajectory of human civilisation, highlighting an ongoing quest for optimised indoor comfort and energy-efficient construction.

The transformation brought about by the Industrial Revolution had a profound impact on construction and material sciences. Rapid technological advancements, alongside the expansion of industrial production, paved the way for the widespread use of iron, glass, and reinforced concrete. These innovations revolutionised architecture, allowing for more ambitious designs, but also introduced new challenges in regulating thermal conditions within buildings. The susceptibility of these materials to thermal expansion and permeability heightened the risk of structural deterioration. The acceleration of urban growth and industrial development led to mass migration towards cities, necessitating the rapid expansion of residential areas. The demand for cost-effective and quickly constructed housing solutions prompted the refinement of building materials and techniques. Although natural materials had been used for insulation for centuries, large-scale industrial applications were previously limited due to economic and technological constraints. Historical evidence indicates that cork was employed in construction as early as 3000 BC in Ancient Egypt [49]. Advancements in scientific understanding during the Industrial Revolution enabled a more comprehensive recognition of cork's unique attributes. Innovations in processing techniques facilitated the creation of refined cork-based products, leading to their more sophisticated applications. The introduction of multilayer boards produced from expanded cork, as well as modular construction blocks made from recycled cork waste, improved the efficiency of building assembly. These developments marked a shift from traditional methods to more technologically advanced applications. The superior characteristics of cork, low thermal conductivity, water resistance, and flexibility, were increasingly acknowledged during this era. By the mid-19th century, innovations allowed for cork granular compression using various binding agents, producing cork-based boards, bricks, and mats. With the growing emphasis on environmental sustainability and ecofriendly building practices in recent years, natural materials such as cork have regained attention. Its biodegradability and minimal environmental impact have made it an attractive option for architects and developers seeking to reduce carbon footprints and improve indoor air quality. Predominantly found in Mediterranean landscapes, cork forests serve as critical habitats for diverse wildlife, function as significant carbon sinks, and play a role in preventing soil erosion. The sustainable management of these forests highlights the balance between economic utility and environmental preservation, reinforcing cork's relevance in contemporary green architecture [50].

During the Industrial Revolution, waste generated by the wood industry found applications in facade insulation systems. The accessibility and affordability of wood by-products made them a preferred choice for insulation [51]. By the end of the 1800s and the beginning of the 1900s, substances like wood dust, timber particles, and plant fibres, typically harvested from the papermaking industry, were transformed into insulating panels. They were widely applied in facade cladding, wall insulation, and roof structures. From the 1940s onwards, cement-bonded wood chip boards became prevalent in Central and Eastern Europe, integrating Needleleaf timber fragments combined with mortar, lime, and stone-based materials to enhance facade thermal and environmental performance [52]. Wood wools have historically been utilised in facade insulation. Their thermal insulating properties, affordability, and lightweight characteristics facilitated their transition into facade construction [53]. The main architectural importance became apparent at the beginning of the 1900s, as the need for materials that conserved energy and were fireproof grew. Manufacturers produced robust, lightweight panels designed for outer cladding and thermal protection, achieved through the use of wood fibres combined with materials like cement or gypsum as binders [54]. Despite initial limitations, like flammability and instability, wood wool insulation quickly gained widespread use, particularly in facade applications with advantageous acoustic properties and thermal resistance [55]. The interwar period saw a significant improvement in hybrid wood wool facade sheets. In the early 20th century, producers started manufacturing wood wool boards bonded with cement, which enhanced fire resistance, sound absorption, and structural integrity [56]. The necessity for efficient and cost-effective facade insulation intensified after World War II, as reconstruction efforts demanded readily available materials. During this period, wood wool was widely employed across Europe and North America for insulating external walls, ceilings, and cold storage facilities. Its adaptability made it suitable for facade insulation in agricultural buildings and industrial structures. In addition, asbestos became a staple in facade insulation, often mixed with cement to produce durable panels for external applications. These asbestos cement boards, widely used for facade cladding, gained popularity due to their affordability and high resistance to weathering. In addition to exterior panels, asbestos was used in facade-related applications such as thermal insulation layers and sprayed coatings on building envelopes [43]. Unfortunately, the dangers posed by asbestos were recognised as far back as ancient times. Due to the health hazards associated with asbestos, alternative facade insulation materials have been developed [57]. Various natural and synthetic fibres have been adopted as substitutes. Mineral wool and ceramic fibres are commonly recommended for insulation boards, while cellulose, glass, and carbon fibres have effectively replaced asbestos in facade cladding [58,59]. Additionally, cement boards now incorporate cellulose, polypropylene, polyvinyl alcohol, aramid, and glass fibres as alternatives. In textile-based facade insulation, polyethene, polypropylene, polyamide, carbon, and glass fibres serve as replacements. However, some of these substitutes have also raised concerns regarding potential health risks, necessitating ongoing research into safer, more sustainable materials.

The mid-to-late 20th century witnessed remarkable progress in facade insulation technology, spurred by a heightened emphasis on energy conservation, escalating energy expenses, and the drive to enhance building efficiency [60]. This era was marked by groundbreaking developments, including introducing synthetic insulating materials and refining conventional insulation techniques geared toward improving heat insulation, flame resistance, longevity, and ecological responsibility. The energy shortages of the 1970s highlighted the global dependence on non-renewable energy sources, especially oil. The initial crisis in 1973, triggered by an embargo enforced by OPEC, caused a significant spike in fuel costs. In 1979, a subsequent crisis exacerbated disruptions in international distribution networks, exacerbating energy costs. These financial pressures forced many nations, especially in North America and Europe, to reevaluate their construction strategies with a newfound focus on energy efficiency [61]. Consequently, there was an increased focus on sealed building exteriors, energy recovery techniques, energy-efficient architectural strategies, as well as advanced exterior thermal insulation solutions. As a result, insulation materials that had been discovered earlier gained wider acceptance due to advancements in production technology and cost reductions. This change triggered the extensive adoption of established insulating substances, such as stone wool, having a major impact on the building industry. It commonly encompasses a variety of non-organic, fibre-based substances [62]. As the 20th century came to a close, increasing concerns regarding the ecological and health-related effects of different insulating substances led to a more in-depth investigation into mineral wool. Nevertheless, it continued to be considered a safer choice when compared to more dangerous options such as asbestos. Additionally, the rise of sustainable production processes contributed to this shift and further bolstered its reputation. Continuous advancements, including higher proportions of reclaimed materials and improved production techniques, suggest that mineral wool will remain integral to energy-saving exterior solutions [63]. Similarly, developed in the early 20th century, fibreglass-based insulation has evolved considerably, establishing itself as a prominent material in insulating building exteriors across both housing and business environments [64]. Produced by extruding molten glass into delicate fibres, fibreglass effectively reduces heat transfer by trapping air within its structure, serving as an economical yet efficient thermal barrier [65]. Its non-flammable properties, ease of installation, and availability in several variations, like mats, poured fillings, and air-driven insulations, were key to its broad acceptance during the middle of the 1900s. By the latter part of the century, technological improvements further enhanced fibreglass insulation's efficiency, longevity, and environmental credentials, reinforcing its role in facade insulation. With the rise of environmental awareness during the 2000s, advancements in fibreglass insulation continued, as manufacturers prioritised minimising harmful emissions and focusing on creating sustainable, high-efficiency options. Fibreglass insulation continues to be a popular choice because of its affordability, ability to conserve energy, and alignment with contemporary environmental standards. Overall, Table 1 outlines the chronological development of building insulation methods, highlighting key materials, associated civilisations, and significant milestones. From early earth-based solutions in prehistoric Romania to the sophisticated smart facades of the 21st century, the evolution reflects how societies adapted to climate conditions and leveraged available technologies to improve indoor thermal comfort. The transition from natural to synthetic and finally to intelligent systems demonstrates a continuous pursuit of energy efficiency and environmental responsiveness in building design. This development is visually summarised in Figure 2, which illustrates the chronological transition of facade insulation materials alongside the improvement in thermal performance and sustainability focus.

Table 1. Historical evolution of insulation techniques, materials, and related civilisations.

Period	Insulation Techniques	Key Materials	Relevant Civilisation	Significant Developments
5500 BC	Underground dwellings leveraging the earth's natural insulation	Earth, stone	Ancient Romania (Bordei houses)	Thermal buffering through soil
3100 BC	Thick brick masonry for external walls	Mud bricks, stone	Ancient Egypt	Passive temperature control
2650 BC	Ceramic wall linings	Ceramic tiles	Ancient Egypt	Acoustic and thermal regulation
500 BC	Sun-oriented houses for passive heating	Brick, stone	Ancient Greece	Socratic House with solar gain
400 BC	Heliocaminus (passive solar heating)	Mica, brick, stone	Ancient Rome	Early solar chamber concept
100 BC	Cave-based homes for cooling	Rock	Essenes (Palestine)	Harnessed the Earth's thermal mass
10th century	Turf-roofed houses with compacted earth insulation	Turf, stone, wood	Vikings (Scandinavia)	Natural insulation in cold climates
1200 AD	Thick earthen walls (Tulou)	Earth, wood	China	Thermal stability in communal dwellings
1500 AD	Theoretical studies on air circulation	-	Leonardo da Vinci (Italy)	Foundations of thermal design principles
1760	Solar energy collector	Glass, wood	Horace de Saussure (Switzerland)	Early solar insulation concept
1800s	Cork-based insulation blocks	Cork	Industrial Europe	Lightweight, natural insulator
1855	Cast iron radiator	Iron	Franz San Galli (Russia)	Heat regulation innovation
1900–1950	Wood fibre panels and wood wool	Wood fibre, cement	Europe & USA	Acoustic and thermal facade solutions
1940s	Asbestos cement boards	Asbestos, cement	Global	Durable facade insulation (later banned)
1970s	Energy-efficient synthetic insulation	Stone wool, fibreglass	Global	Response to the energy crisis
2000s	Sustainable fibreglass and mineral wool	Recycled glass, stone	Global	Environmental and health-friendly insulation
21st century	Smart facades integrating high-performance insulation	Aerogel, vacuum panels, BIPV	Global	Energy-generating facades with minimal thermal loss

The comparative insights drawn from this evaluation not only highlight the iterative refinement of insulation logic across centuries but also reveal the underlying continuity between ancient strategies and emerging design technologies. These parallels become especially clear when considering the conceptual lineage that informs contemporary facade systems. To substantiate this conceptual continuity with functional and technical perspectives, a comparative analysis is presented in Table 2. This table juxtaposes selected historical insulation methods with their modern counterparts, focusing on shared objectives such as thermal buffering, material use, and climate responsiveness. Each row evaluates systems not merely in terms of chronology, but through their architectural logic—emphasising passive vs. active behaviour, material mass vs. engineered performance, and simplicity vs. precision. The goal is not to idealise traditional systems but to recognise how their principles have evolved into contemporary high-performance solutions. As such, the table provides a critical lens through which the reader can assess both the legacy and transformation of facade insulation approaches across history and technology.

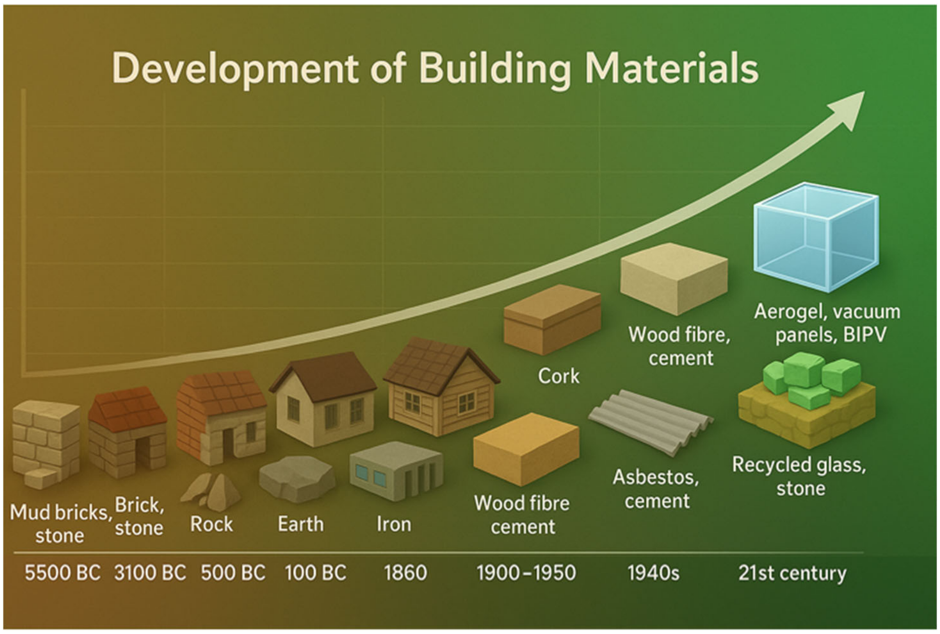

Figure 2. Development of building materials.

Table 2. Comparative evaluation of historical vs. modern insulation approaches.

System/Era	Historical Example	Modern Equivalent	Strengths	Limitations
Earth-embedded dwellings	Romanian Bordei houses (5500 BC)	Bermed earth-sheltered homes	High thermal inertia, protection from extremes	Poor daylight, high moisture risk
Thick masonry wall	Egyptian brick construction (3100 BC)	Mineral wool, masonry + aerogel	Durability, thermal mass	Weight, high embodied energy
Solar-oriented passive design	Socratic House/Heliocaminus (400–500 BC)	Passive House + BIPV systems	Solar gain, seasonal heating	No shading adaptation, reliant on static geometry
Cavity wall	Early Egyptian double brick with air gap	D-SFS with ventilated air layer	Insulation, reduced conduction	Fire safety, complex detailing
Turf and timber construction	Icelandic turf houses (10th century)	Bio-based hempcrete/wood fibre	Low-carbon, renewable	Fire risk, variable performance
Natural insulation (pre-modern)	Cork, wool, wood fibre (1800–1900s)	Aerogels, PCMs, smart coatings	Improved R-values, thinner walls	Cost, long-term stability not always proven

Each historic insulation strategy reflected a contextual response to available resources and environmental constraints. While ancient systems such as earth-sheltered or masonry-intensive designs provided exceptional thermal mass, they lacked flexibility, transparency, and scalability. In contrast, modern insulation approaches such as aerogels and PCMs enable thinner profiles with higher R-values, but often introduce new challenges, including cost, installation complexity, and lifecycle uncertainty. A notable trade-off exists between material mass and responsive control. For example, while the Socratic house depended entirely on solar orientation and mass retention, today's dynamic facades can self-regulate through smart coatings and AI-controlled shading. Yet, these systems are not universally applicable due to maintenance needs and cost barriers. Thus, the evolution of facade insulation should not be viewed as a linear technological upgrade. Instead, it represents an ongoing synthesis where vernacular principles, such as thermal inertia, cross-ventilation, or solar orientation, are reinterpreted through advanced materials and control systems. Recognising the strengths and failures of historical systems is essential to critically shaping sustainable and resilient building envelopes today.

The evolution of facade insulation from rudimentary earth-based shelters to more sophisticated mineral and fibrous systems reflects humanity's enduring response to thermal challenges using available resources. However, while these early practices emphasised material mass and passive performance, the growing demands of dense urbanisation, stricter energy regulations, and shifting climatic realities have necessitated a rethinking of facade design beyond traditional means. This transition has not rendered historical methods obsolete; instead, it has inspired a new generation of insulation technologies that reinterpret ancient principles, including thermal inertia, solar orientation, and layered construction, within contemporary material and digital frameworks. Thus, understanding historical precedents is not only a matter of architectural curiosity but a foundation for innovation. In the following section, the study explores how modern facade systems like D-SFSs, AFs, and bio-integrated designs emerge as technologically advanced yet conceptually aligned continuations of the past, aiming to meet the environmental and energy challenges of the time.

3. Modern Facade Insulation Systems

Throughout history, building facades have undergone significant transformations. Traditional insulation materials, such as stone, brick, and concrete, have been widely used for centuries; however, they no longer meet modern energy efficiency standards. Single-layer facades, due to their low thermal insulation performance, have led to excessive heat loss, negatively impacting indoor comfort and increasing energy consumption. The rapid urbanisation and population growth since the Industrial Revolution have further highlighted the shortcomings of these conventional systems. From the late 20th century onwards, global energy crises, climate change concerns, and the rising importance of sustainability have driven the construction sector towards more innovative facade solutions. Today, building facades are no longer passive structural components merely providing protection; instead, they function as active systems that integrate energy production and management. Modern facade insulation systems combine aesthetic considerations with energy efficiency, aiming to reduce the carbon footprints of buildings while enhancing occupant comfort. This transition has not occurred in isolation; rather, it has been shaped by a range of external pressures and priorities that continue to evolve. As illustrated in Figure 3, several key factors have influenced the evolution of energy-efficient facades. The increasing global energy demand has necessitated improvements in thermal performance to reduce energy consumption in buildings. At the same time, economic fluctuations have shaped material choices and technological investments, pushing the industry to balance cost-efficiency with performance. Moreover, international decarbonisation goals and environmental regulations have compelled architects and engineers to adopt more sustainable and low-emission solutions. The integration of smart technologies, such as sensors and adaptive materials, has further transformed facades into intelligent systems capable of responding dynamically to environmental conditions. These drivers collectively underline the transition from conventional, passive envelopes to high-performance, interactive building skins.

Figure 3. Factors influencing the evolution of energy-efficient facades: energy demand, economic fluctuations, decarbonisation goals, and smart technology integration.

When it comes to enhancing the energy performance of building envelopes, architects and engineers typically rely on two overarching approaches: passive design principles and active technological interventions [66]. Passive strategies revolve around utilising natural environmental factors and building design to reduce energy consumption. This involves clever choices such as orienting the building to take full advantage of sunlight, designing shading elements to limit solar heat gain, and creating ventilation pathways to encourage natural airflow. Material selection also plays a pivotal role, advanced insulation products and high efficiency glazing systems are frequently used to mitigate heat transfer and preserve indoor comfort levels. Over the years, several architectural innovations have emerged from these principles. Systems such as D-SF arrangements [67], vertical greenery installations [68], and naturally ventilated facades [69] are prominent examples of how passive strategies have evolved into fully integrated sustainable solutions. These systems not only minimise energy consumption but also contribute to healthier interior environments and aesthetic appeal. However, passive methods are not without limitations. In locations where the climate exhibits extreme characteristics, think blistering summers in arid zones or freezing winters in continental regions, passive measures often struggle to deliver consistent thermal comfort throughout the year [70]. Moreover, in places where the weather conditions shift dramatically between seasons, maintaining stable indoor environments using passive means alone becomes an uphill battle. This climatic volatility can lead to erratic energy demands that exceed what passive designs can feasibly manage. Compounding the issue is the fact that certain building types, including hospitals, laboratories, or data centres, operate under strict environmental requirements. These facilities depend on precise control over the indoor temperature, humidity levels, and air purity to ensure safety and functionality. In such cases, the reliance on passive techniques alone is not just insufficient; it can be operationally detrimental. To bridge these performance gaps, active systems come into play [71]. These strategies rely on mechanical and electronic technologies that interact dynamically with the building's conditions. High-efficiency HVAC units regulate temperature and airflow, while photovoltaic (PV) systems generate renewable electricity on-site. Additionally, automated shading devices, sensor-driven control systems, and responsive facades adapt to real-time environmental changes, optimising energy use without compromising occupant well-being [72]. Far from being mere add-ons, these technologies are now embedded into the architectural fabric, creating a synergy between structure and function that defines the buildings of tomorrow.

This section focuses on three key modern facade systems, D-SFSs, AFs, and green facades, due to their distinctive operational principles, architectural integration methods, and relevance to current sustainable building practices. Each represents a unique pathway towards energy efficiency: D-SFSs for ventilated thermal buffering, AFs for climate-responsive automation, and green facades for nature-based passive insulation. Their comparative strengths, technological maturity, and real-world applicability warrant a dedicated analysis.

3.1. Double (Dual) Skin Facade

The D-SFSs consist of two layers of skin forming an insulated building facade with a ventilated air space in between, allowing for improved airflow [73]. This air space not only enhances thermal insulation and sound attenuation but also shields extensively glazed structures from excessive solar radiation [74]. The D-SFSs are gaining traction as a contemporary design feature, extensively utilised in modern glass structures across the globe. Typically, the outer skin is completely covered with glass and fortified, whereas the internal layer features less glazing to improve both thermal efficiencies, as well as visual comfort [75]. As illustrated in Figure 4, when solar radiation strikes the outer skin of the D-SFSs, part of the radiation is reflected into the environment, some is absorbed, and the remainder is transmitted toward the interior facade along with the inside environment. The thermal energy captured by the external layer is released into the surrounding atmosphere and the ventilated space. Upon reaching the inner glazing, solar radiation raises its temperature, prompting the emission of longwave radiation. This radiation is then partially absorbed and reflected by the outer skin, with a portion becoming trapped within the cavity, leading to overheating. Consequently, the removal of thermal energy via the air gap reduces heat transmission into indoor spaces, thereby lowering the energy demand for cooling a structure. Additionally, the thermal energy released from the enclosed area can contribute to reducing heating loads in winter, provided the introduced air temperature remains within occupant comfort levels [76].

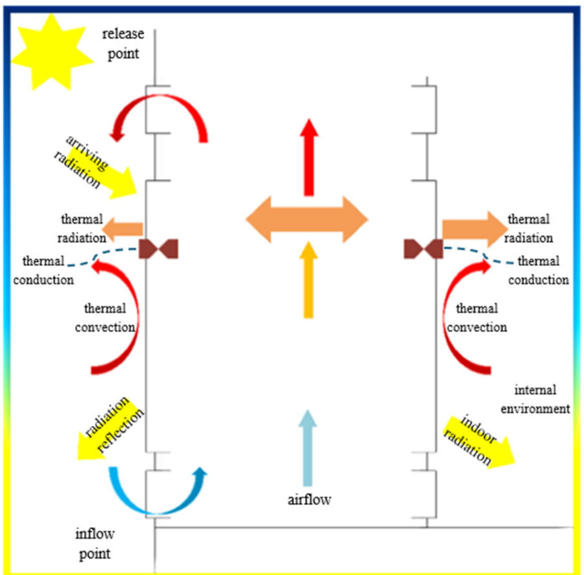

Figure 4. Illustrative representation of the airflow channel within the D-SF [76].

In addition to this, Table 3 provides a comparative overview of different D-SF typologies, outlining their structural characteristics, airflow mechanisms, advantages, and limitations. The box window system offers high acoustic insulation and individual ventilation control but is less effective in overall air circulation. The shaft-box configuration enhances energy efficiency by utilising the stack effect for natural ventilation, though it requires additional fireproofing. The corridor-based facade facilitates lateral airflow at each level, making it easier to maintain but less effective in noise insulation. Lastly, the multi-storey variant maximises natural ventilation and passive climate control, even though it lacks acoustic benefits and comes with higher installation costs. When selecting a D-SF type, climatic conditions play a crucial role. In cold climates, the multi-storey system is highly beneficial as it retains heat efficiently, while the shaft-box system can also aid thermal management. The corridor-based facade allows for controlled ventilation in hot climates, reducing overheating risks. The box window system is preferable for urban environments with high noise levels due to its soundproofing capabilities. Ultimately, the choice of D-SFS should align with the specific environmental needs, energy efficiency goals, and building function.

Table 3. Comparative overview of D-SF types: structural characteristics, airflow strategies, and performance considerations.

D-SF Types	Structural Features	Airflow Strategies	Key Benefits	Potential Drawbacks
Box Window System	-the air cavity is segmented into multiple individual compartments, separated by horizontal and vertical divisions. -openings in the external facade regulate the intake and release of air. - Internal glazing panels can be opened for ventilation.	-airflow remains confined within each segmented unit. -can incorporate mechanical or passive ventilation, depending on the design.	✅ superior noise reduction due to enclosed cavities. ✅ individual control over ventilation improves user comfort.	❌ limited efficiency in overall air circulation. ❌ cleaning the enclosed sections may be difficult.
Shaft-Box Configuration	-consists of a sequence of compartmentalised sections, each connected to a shared vertical ventilation shaft. -warm air is expelled into the shaft, which enhances thermal regulation. -relies on a stack effect to improve airflow.	-rising air creates a natural ventilation cycle, improving internal climate control.	✅ enhances energy efficiency by aiding heat dissipation in summer and retention in winter. ✅ encourages a more uniform temperature distribution.	❌ requires additional fireproofing measures. ❌ more complex to install and maintain.
Corridor-Based Facade	-the cavity is divided floor by floor, forming continuous horizontal air channels. -fire and vibration barriers can be incorporated to improve safety. -the corridor space is often wide enough to allow access for maintenance purposes.	-air circulates laterally at each level, preventing heat accumulation on upper floors.	✅ allows for natural ventilation without overheating the upper storeys. ✅ simplifies upkeep compared to other D-SF types.	❌ restricted vertical airflow limits thermal performance. ❌ less effective in noise reduction compared to the box window type.
Multi-Storey Variant	-the air cavity spans multiple floors without internal partitions. -large ventilation openings at the bottom and top allow continuous airflow. -functions as an air intake in winter and an exhaust channel in summer.	-rising warm air creates a powerful chimney effect, driving airflow throughout the entire facade.	✅ maximises natural ventilation across the building. ✅ improves passive heating and cooling efficiency.	❌ provides minimal acoustic insulation. ❌ higher installation costs due to its large-scale design.

✅ indicates a key benefit; ❌ highlights a potential drawback.

Advancements in lightweight building envelopes, curtain wall technology, and intelligent facades have facilitated the widespread adoption of prefabrication techniques. D-SFSs offer several environmental benefits, including energy savings, enhanced ventilation, improved airflow, optimised thermal comfort, glare and solar protection, superior sound insulation, noise reduction, and aesthetic enhancements. Moreover, their long-term economic benefits include reduced operational costs [74]. The effectiveness of D-SFSs in minimising HVAC usage has been demonstrated, as they help to mitigate heating demands in winter and prevents thermal overheating in summer [77]. The air cavity, which can be ventilated naturally or mechanically, typically ranges from 200 mm to over 2 m in width [78]. The architectural design of office buildings significantly influences occupant thermal comfort and energy consumption. The facade functions as an exterior filter, acting as a passive energy conservation device and climate barrier [79]. D-SFSs are particularly suitable for high-rise buildings due to their potential for improved daylighting, reduced heat gain, and enhanced natural ventilation [80]. In the context of hot climates, Aldawoud et al. [81] found that implementing D-SFSs in place of conventional curtain walls in Dubai could lead to a 22% reduction in annual cooling loads. Similarly, Ascione et al. [82] demonstrated that when PV panels are installed over 80% of the D-SF's outer skin, buildings may experience up to a 20% reduction in total energy consumption. This approach illustrates how the combination of passive architectural features and active energy systems can create synergistic outcomes in energy-efficient design. Beyond performance gains, D-SFSs also serve an aesthetic function. The use of transparent or translucent materials introduces depth and lightness to the building envelope, enhancing its visual appeal and potentially increasing its market value [83]. Pomponi et al. [84] further highlight that even simple D-SF configurations can decrease heating energy demand by up to 90% and cooling loads by 30%. At the same time, operable shading systems integrated within the D-SFS can further optimise energy performance.

For energy-efficient buildings, the building envelope must provide thermal and air insulation. Studies indicate that D-SFSs enhance insulation properties, thereby reducing energy consumption by improving thermal comfort. Several experiments across different climatic regions have evaluated the system's efficacy in glazed buildings. Matour et al. [85] investigated the performance of a newly developed interstitial slat-blind D-SFSs (IntSD-SFSs) in Brisbane's hot climate, demonstrating its potential in mitigating overheating risks. Their findings highlight that airflow velocity within the cavity is the most significant factor in controlling excess heat, while slat angles have a minimal impact. The study suggests that IntSD-SFSs can significantly improve thermal conditions and lower the energy requirements for cooling, positioning it as a suitable alternative for both newly built and renovated structures in warmer regions. Lin et al. [86] examined a novel D-SF with adjustable glazed louvres in a temperate continental climate, demonstrating that an open external skin nearly doubled wind speed in the cavity, enhancing daytime ventilation. At night, the interior ventilated configuration improved indoor airflow, increasing wind speed by 40%. The study found that switching configurations based on temperature thresholds rather than fixed time periods maximised energy efficiency. Ultimately, the optimised louvre-type D-SFSs achieved energy savings of 11.9% during the day and 5% at night, effectively mitigating summer overheating risks.

The D-SFSs concept dates back to the early 1900s, with Richard Steiff implementing it in 1903 at the Steiff factory in Germany to enhance heating efficiency against extreme cold weather and strong winds. Despite its potential, the D-SFS remains under-researched, and its widespread adoption is hindered by the lack of standardised design and performance assessment guidelines [87]. A common D-SF configuration includes a standard building facade, a ventilated space, and an outer layer of glass. A shading system is often integrated within the cavity to regulate solar heat gain. Key factors influencing air movement within D-SFSs include external wind forces and the thermal buoyancy effect, where warm air inside the cavity rises due to density differences, creating a thermal chimney effect [88]. Properly designed D-SF systems promote natural ventilation, improving indoor air quality and thermal comfort while reducing electricity demands [89]. However, designing D-SFSs for naturally ventilated buildings is complex, as thermal interactions and airflow mechanisms depend on multiple variables, including the facade's structural properties and the building itself [90].

Despite its advantages, the D-SFSs also present challenges, including high initial costs for design, construction, and maintenance, increased structural weight, potential sound transmission through the cavity, fire safety concerns, and a reduction in usable office space [74]. Nonetheless, the D-SF is widely applied in commercial and public buildings due to its superior thermal performance. A common D-SF variation involves installing an additional glass layer at a set distance from the traditional wall, significantly affecting indoor temperatures by modifying air layer dynamics. In winter, the D-SF reduces heat loss, enhancing energy efficiency, while in summer, excessive solar radiation can overheat the cavity, increasing cooling energy demands [91].

Mitigating D-SF overheating issues requires strategies such as low-emissivity (low-e) glass, shading devices, air ventilation, and evaporative cooling. The low-e glass reflects infrared radiation, reducing solar heat gain, while adjustable louvres influence convection, conduction, and radiation heat transfer within the cavity [92]. Studies show that a blind inclination of 80° enhances natural ventilation by 35%, while horizontal shading at 30°, 60°, and 90° angles can reduce energy use by 0.4%, 2.6%, and 6.4%, respectively [93].

Recent advancements in D-SFSs have positioned them as viable alternatives to traditional facade solutions for energy retrofits. Studies have investigated D-SFSs' thermal behaviour, ventilation efficiency, and energy performance across various climates, including cold, Mediterranean, tropical, and moderate zones. Shading devices within D-SF cavities effectively reduce total energy consumption and environmental impacts [94]. The integration of intelligent control systems, PV technology, and PCMs has further enhanced D-SFS's energy performance [95]. Moreover, naturally ventilated D-SFSs (NVD-SFSs) represent an evolution of traditional D-SFSs, incorporating advanced control systems to optimise energy savings. NVD-SFS shading devices can reduce cooling energy demands by 24–76%, whilst PV-NVD-SFSs can decrease energy consumption by 50–84% in subtropical climates [96,97]. Various control mechanisms, including passive, manual, active, and hybrid systems, regulate heat transfer and air distribution within NVD-SF cavities. Integrating automated shading, mechanical ventilation, and low-e glazing further enhances the NVD-SFS's energy-saving potential [98].

To comprehensively evaluate the suitability and practical trade-offs of D-SFSs, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is presented in Figure 5. This framework highlights not only the environmental and thermal benefits of D-SFSs, such as effective thermal buffering and integration potential with photovoltaic or smart-glass technologies, but also contextual limitations, including high capital costs and complex fire safety considerations. The analysis further emphasises the emerging opportunities for AI-integrated control and growing relevance in dense urban environments.

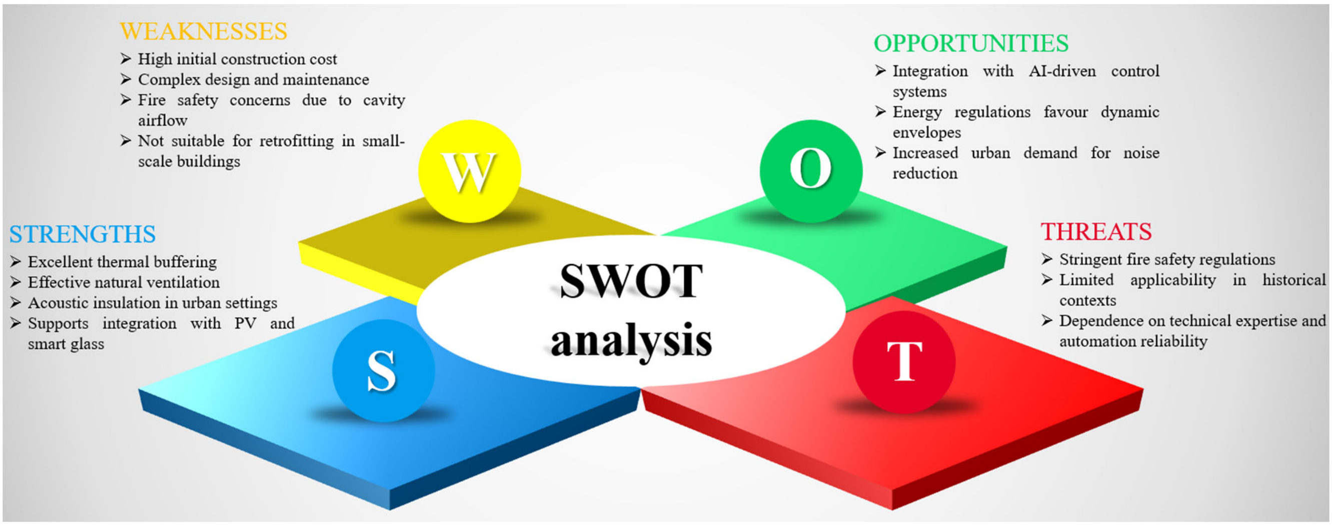

Figure 5. SWOT analysis of D-SFS.

3.2. Adaptive Facades

AFs represent a paradigm shift in architectural design, introducing advanced building envelopes capable of responding to environmental conditions and user needs. These systems serve multiple functions, such as controlling daylight, thermal insulation, ventilation, shading, and aesthetic appearance, while dynamically adjusting to changing external and internal conditions [99]. By managing performance parameters such as heat, ventilation, vapour flow, precipitation control, sunlight use, noise control, fire resistance, and structural stability, AF systems aim to optimise both energy efficiency and indoor environmental comfort. They provide a dynamic structure to the facade, which allows for movement and adaptation to both external climatic factors and internal comfort needs, ensuring the most appropriate solutions for maintaining optimal conditions within the building [100]. Increasing the energy performance inside the building, ensuring daylight requirements, and providing the highest levels of thermal comfort are fundamental goals in facade design. Movement capabilities in AFs can be achieved through either manual or automatic digital systems, with the latter being the more efficient and sustainable solution for achieving high performance and continuous operation. Moreover, facade design should be tailored to the specific climatic conditions of the building, with initial climate analysis and simulation tools guiding architects and designers in the selection of suitable adaptive systems. In this process, cost–benefit analyses are essential to ensure the long-term viability and effectiveness of these solutions [101,102]. The success of AF technologies lies in perceiving the building envelope not as a static element, but as an integrated, responsive system. Thus, AFs should not merely be seen as structural components but as vital contributors to overall building performance. They are often defined as prefabricated or site-assembled holistic systems, capable of continuous environmental interactions [103].

Commercially available AF solutions encompass a wide range of technologies, including operable shading devices (e.g., venetian blinds, louvres, roller blinds), electrochromic glazing, PCMs, NVD-SFSs, green facades, and green roofs [3,104–106]. These systems are designed to help manage daylight, reduce overheating and glare, and optimise energy consumption, all while maintaining a visual connection with the outdoor environment [107]. Their functional diversity enables architects and engineers to address multiple performance goals simultaneously, particularly in projects that prioritise sustainability and occupant comfort. However, the increasing use of expansive glazing in contemporary architecture has brought forth new challenges, especially in balancing the benefits of natural daylight and outdoor views with the risks of solar heat gain, glare, and elevated energy demands.

AF systems are thus emerging as critical tools to reconcile these conflicting design priorities [108]. In this context, two principal strategies have shaped AF development: one based on mechanical components, such as operable shading devices and screens, and the other relying on advanced materials optimised for light transmission and thermal performance, such as low-e glazing and intelligent coatings [109]. Whilst these strategies can effectively regulate heat transfer and reduce the need for active heating or cooling, they may limit passive solar gains in cold climates, underscoring the need for climate-sensitive design approaches. Among these solutions, adaptive opaque facades stand out for their ability to actively control thermal exchange between indoor and outdoor environments. Nevertheless, the widespread adoption of AF technologies in the construction industry remains limited. A significant barrier is the absence of standardised, system-level performance assessment protocols [110]. Current standards often focus only on isolated components or materials, ignoring the complex interactions and holistic behaviour of the facade system as a whole. This gap contributes to design uncertainties, as each building requires a unique response tailored to its specific climate, location, and user needs. To overcome these barriers, integrating AF systems into early-stage design processes is vital, supported by simulation tools and performance-based decision-making frameworks [111]. Moreover, if AF-integrated buildings are indeed achieving improved energy performance and higher user satisfaction, their real-world outcomes need to be rigorously documented and communicated to relevant stakeholders [112].

AFs represent one of the most advanced insulation configurations, capable of responding dynamically to climatic and operational inputs. Figure 6 summarises the strategic advantages and critical challenges of AFs through a SWOT framework. While their integration with sensors, automation, and AI allows for the real-time optimisation of indoor conditions, issues such as cost, system complexity, and limited standardisation may hinder widespread adoption. This evaluation also pinpoints growth opportunities in smart cities and occupant-centric design approaches.

Figure 6. SWOT analysis of AFs.

3.3. Green Facade

Urban areas are responsible for between 60% and 80% of global energy consumption and nearly 75% of CO_2 emissions, positioning cities as both primary contributors to anthropogenic climate change and highly susceptible to its consequences [113]. With ongoing urbanisation and rising global temperatures, cities increasingly face complex challenges including heat stress, air and noise pollution, biodiversity loss, and serious public health risks [114]. In response, urban green infrastructure has garnered growing attention as a nature-based solution capable of addressing these multifaceted issues. Given the spatial limitations in dense cities, vertical greening systems, particularly green facades and living walls, offer innovative methods for incorporating vegetation into the urban fabric [115]. Greening building envelopes, especially facades, offer a suite of spatial, ecological, thermal, and aesthetic benefits, contributing significantly to the creation of resilient and sustainable urban environments [116]. Among various vertical greening systems, green facades are increasingly favoured due to their cost-effectiveness, simplicity, and ease of maintenance compared to living walls [117]. While living walls require modular systems with integrated irrigation and substrates, green facades employ ground-based climbing plants that grow either directly on facades or with structural support such as trellises, cables, or rods [118]. This fundamental difference makes green facades more scalable and resource efficient.

Functionally, green facades offer diverse benefits by altering the thermal exchange processes between buildings and their environment. They reduce building energy demands by insulating the structure, cooling facades during summer, and retaining heat in winter, thus contributing to the mitigation of the urban heat island effect and reducing greenhouse gas emissions through shading, evapotranspiration, and photosynthesis [119]. Vegetation on facades also helps block warm ambient air from entering buildings, while storing solar energy during the day and releasing it at night, which adds thermal benefits during colder seasons [120]. The performance of green facades is significantly influenced by vegetation characteristics, particularly the leaf area index (LAI), the ratio of leaf surface area to ground area (m^2/m^2), as higher LAI values generally indicate greater shading and cooling capacity, leading to improved energy performance [121]. Another key indicator is the coverage rate, which denotes the proportion of the building surface covered by vegetation and further enhances insulation and thermal performance [122].

Experimental and empirical studies strongly support the thermal and energy-saving potential of green facades. Olivieri et al. [123] explore the impact of a green facade under summer conditions in a continental Mediterranean setting using two full-scale test modules differing only in the addition of a plant layer on the south-facing wall. Their findings reveal that the green facade maintains interior surface temperatures at around 5 °C lower and indoor air temperatures approximately 4 °C cooler than the non-vegetated counterpart. The study highlights how such systems delay peak heat loads, enhance natural ventilation potential, and contribute to improved indoor thermal comfort while lowering the need for mechanical cooling. In Spain's Mediterranean continental climate, green walls and double skin green facades achieved energy savings of 58.9% and 33.8%, respectively during summer months, with no added energy demand during winter [124]. Likewise, envelope-integrated green systems have been shown to lower both cooling and heating energy use by 25% and 18%, respectively, when compared with standard facades [125]. In the UK, the winter energy demand is reduced by up to 21% for the first winter, as well as 37% for the second, using vegetation-based systems [126]. In addition, to accurately assess the thermal performance of green facades, mathematical models incorporate multiple physical parameters such as solar and infrared radiation exchange, heat conduction, convection, evapotranspiration, and heat storage [127]. However, successful implementation requires the consideration of various design and environmental factors, including plant-specific traits such as the growth rate, sun exposure preferences, winter hardiness, and fire safety risks [128]. Proper irrigation is also essential to prevent plant desiccation and reduce fire hazards. Species such as *Hedera helix*, *Parthenocissus quinquefolia*, and *Ficus pumila* are commonly employed due to their climbing abilities and resilience in urban conditions [129].

On the other hand, despite their many advantages, green facades face multiple implementation challenges. One key issue is economic feasibility. The initial installation and maintenance costs tend to be higher than conventional cladding systems due to the need for specialised plant material, irrigation systems, structural supports, and nutrient provision [130]. However, life-cycle cost assessments reveal that when long-term environmental, social, and health benefits are factored in, green facades may prove economically viable and even cost-effective over time [131]. Government incentives such as tax benefits and subsidies have been proposed as mechanisms to enhance affordability and increase adoption rates [132]. Technical barriers may also keep going. Irrigation systems can be costly and water-intensive, but drip irrigation and the use of drought-tolerant, climate-appropriate plants can mitigate these concerns. High-rise applications pose additional challenges, such as the need for frequent pruning to control weight and ensure structural safety. Using slow-growing or woody species can help minimise ongoing maintenance. Fire safety is another critical issue, especially in indirect systems where non-fire-resistant materials could exacerbate fire risks. In response, some countries have updated fire safety codes to mandate non-combustible materials like aluminium for supporting structures [133]. Furthermore, green facades can inadvertently serve as habitats for pests or even snakes. To address this, practitioners are advised to begin installations at a certain height from the ground, use indirect systems, apply physical barriers around windows and doors, and perform regular vegetation maintenance [125]. These systems also help foster more attractive urban landscapes and improve overall well-being for city residents. Their aesthetic and architectural contributions, combined with functional sustainability benefits, make green facades a compelling option for modern urban development. In the context of retrofitting, green facades can be as a powerful strategy to reduce energy use and emissions, particularly in existing commercial structures like ageing shopping malls [134]. As part of broader urban renewal trends, green facade retrofitting addresses not only environmental concerns but also enhances visual appeal and urban comfort. Studies have shown that such retrofits are particularly well-suited for large, sun-exposed building facades, common in commercial buildings, allowing for significant improvements in thermal regulation and energy savings [135].

Table 4 presents a comparative overview of the thermal performance and energy efficiency impacts of various green facade types, including the plant species used, across different climate zones and building types. Overall, findings from the reviewed studies demonstrate that green facades have significant potential to reduce indoor temperatures, decrease heat flux, and lower cooling demands. Investigations conducted in diverse climatic conditions and building typologies consistently highlight the positive effects of these systems on building thermal performance.

Table 4. Summary of recent experimental and modelling studies on green facades: facade types, climatic conditions, test setups, key findings, advantages, limitations, and future research directions.

Ref.	Research Type	Facade Type/ Plant Species	Climate	Building Type/ Test Setup	Key Findings	Advantages	Limitations	Recommendations/ Future Work
[136]	Experimental and CFD simulation	Indirect green facade with *Pyrostegia venusta* 	Warm	Two identical test cells, one with a green facade	The green facade reduced indoor air temperature by 4.57–5.64 °C and heat flux by 7.84–16.79 W/m^2. CFD results were validated with low MPE, MBE, and RMSE values. Seasonal effectiveness was observed, with temperature reduction highest in autumn (5.64 °C). LAIV > 2.5 had a minimal additional effect; air gap size was less significant.	Substantial cooling effect across all seasons Improved thermal comfort Effective thermal barriers in summer and spring Validated CFD models for predictive use	Study limited to a single plant species and a warm climate Full-scale building application not tested Limited variation in plant types and growth stages	Assess green facades in various climate conditions Use full-scale buildings to study energy consumption and comfort Explore different vegetation types to determine optimal LAIV and air gap configurations
[137]	Experimental	DSGF/ *Rhyncospermum jasminoides* 	Mediterranean	Test wall prototype at the University of Bari, Italy. South-oriented hollow brick wall with white plaster, divided into three parts: two vegetated, one bare (control)	The green facade reduced surface temperatures by up to 9.9 °C and increased relative humidity by 18.7% during daytime. At night-time, a warming of up to 2.1 °C was observed. Energy flux through the vegetated wall was reduced by 62% compared to the bare wall. Solar radiation absorbed was 86% lower for the covered wall. A time shift between the temperature peaks of the covered and bare walls was noted. A simplified equation was proposed to estimate latent heat based on net radiation.	Enhances cooling and air humidification during daytime Reduces solar heat gain; improves microclimatic conditions Supports urban greening strategies	Findings apply to double-skin green facades with climbing plants only Further investigation is needed for other vertical greening systems such as living walls	Further tests are recommended for more complex green facade types (e.g., living walls) to assess their thermal behaviour and broader applicability
[138]	Experimental	Direct and indirect green facades using *Parthenocissus quinquefolia*, *Humulus scandens*, and a 1:1 mixture 	Hot summer	Four identical lab rooms (one control and three with greenery), movable metal frames used for green facade adjustments	Indirect green facades significantly improve thermal insulation and energy efficiency. Maximum surface temperature drop of 23.1 °C and indoor temp. reduction of 1–5 °C. The highest energy saving of 45.75% was observed with *Parthenocissus quinquefolia* in an indirect setup.	Improves thermal comfort and reduces energy consumption Particularly effective on south-facing facades Most effective during high solar radiation	Limited number of test rooms Short experiment duration (5 days per test) Lack of LAI data Densely arranged site affecting environmental parameters Not all facade types tested under identical conditions	Conduct experiments under various weather conditions Extend testing duration; measure LAI values Isolate and repeat facade types under identical external conditions for higher accuracy

Table 4. *Cont.*

Ref.	Research Type	Facade Type/ Plant Species	Climate	Building Type/ Test Setup	Key Findings	Advantages	Limitations	Recommendations/ Future Work
[139]	Experimental	Green facade using *Epipremnum aureum* 	Warm and humid	Two identical test cubicles made of burnt brick, plastered with cement, installed on a rooftop at TKM College of Engineering, Kollam, Kerala. Southern wall used for applying different insulation types	Dry coir mat showed highest heat mitigation (41.45%), followed by coir + green facade (40.3%), wet coir mat (36.3%), and green facade alone (6.15%). The dry coir mat effectively reduced indoor temperature below 28 °C for 7 h, and the coir + green facade extended it to 8 h. The green facade alone was ineffective during non-solar hours. Dry coir mat delayed heat transfer for up to 13 h.	Dry coir mat is cost-effective, easy to install, and has high heat-rejection capacity during both solar and non-solar hours due to its porosity. The coir + green facade combination enhances insulation efficiency	Green facade alone has poor performance during non-solar hours Limited effectiveness without combination with coir mat	Future studies may explore optimising green facade design or combining it with other insulation types. Further long-term field studies are recommended to validate performance in real buildings
[140]	Experimental and modelling	Green facade with *Rhyncospermum jasminoides* 	Mediterranean	Prototype building with a south-oriented facade equipped with green infrastructure Evapotranspiration measured using load cell and energy balance methods	The study developed formulae to quantify latent heat exchange due to evapotranspiration. The green facade provided significant cooling (average of 16.2 MJ/m^2 daily), with shading contributing roughly twice as much as evapotranspiration. Plant coefficients were established for summer (1.3) and spring (2.0). Model validation showed good agreement using Penman–Monteith and Deardorff equations.	Provides cooling through both shading and evapotranspiration Reduces energy consumption in buildings Useful plant coefficients were identified Can inform building energy simulations specifically for green facades	Results are limited to Mediterranean climate and *Rhyncospermum jasminoides* Cooling effects vary with orientation, plant type, season, and location Results may not be directly generalisable	Future research should investigate other climates, plant species (e.g., deciduous), orientations, and seasonal behaviours Formulae developed can be integrated into energy simulation models to enhance building design tools for green facades

Table 4. *Cont.*

Ref.	Research Type	Facade Type/ Plant Species	Climate	Building Type/ Test Setup	Key Findings	Advantages	Limitations	Recommendations/ Future Work
[121]	Experimental	Green facades with *Wisteria Sinensis*, *Hibbertia scandens* Additional ground covers: *Drosanthemum hispidium*, *Hardenbergia violacea* 	Hot summer Mediterranean	Ten pilot-scale facades with different orientations, constructed at Bentley Primary School External wall, ambient air and gap temperatures measured	During hot sunny days, external wall temperatures behind the green facade were up to 7 °C cooler than behind shade sails. The green facade also cooled the air gap up to 11 °C below ambient, with evapotranspiration accounting for 25–35% of gap cooling. Shading was not the sole cooling factor; transpiration and humidification contributed significantly. Nighttime and rainy periods showed slightly warmer surfaces behind green facades. Solar radiation was identified as the strongest driver of evapotranspiration cooling.	Effective reduction of wall and air gap temperatures Demonstrated potential as a nature-based solution for urban heat mitigation, energy use reduction, and improved thermal comfort	Results are specific to selected orientations and plant species Limited data on other directions, climates, and LAI variations Theoretical models not fully validated with continuous surface temperature and radiation measurements	Future studies should explore facades with other orientations and plant species with varied LAI and coverage Investigate potential energy savings through cooled air intake for HVAC Optimise irrigation schedules to enhance transpiration Continuously monitor surface temperatures and radiation emissions to better model longwave interactions and select optimal vegetation
[141]	Experimental and numerical	Indirect green facade/*Trachelospermum jasminoides* 	Warm and temperate Mediterranean	Two identical full-scale prefabricated modules at the University Campus of Catania, one equipped with a green facade on the west wall and one without Simulations validated with experimental measurements.	The green facade reduced peak indoor air temperature by up to 1.5 °C during the hottest hours of the hottest week; the nighttime indoor temperature trend remained similar to the reference module.	Demonstrates effectiveness of green facades as nature-based solutions for improving indoor thermal comfort in lightweight buildings	Cooling effect limited to hottest hours Negligible influence at night	Suggests further studies on energy savings potential Variation in LAI values to be considered West wall orientation confirmed as optimal for summer cooling Potential for broader implementation of validated green facades in warm climates

Table 4. *Cont.*

Ref.	Research Type	Facade Type/ Plant Species	Climate	Building Type/ Test Setup	Key Findings	Advantages	Limitations	Recommendations/ Future Work
[142]	Experimental	Green facade/*Dolichandra unguis-cati* 	Tropical	Two identical rooms at the Faculty of Integrated Technologies, Universiti Brunei Darussalam: one with a green facade, and one with a bare wall The green facade installed on the east-facing wall with a 50 cm gap between the facade and wall, using a modular trellis and wire mesh system; equipped with an automatic weekly watering system	The green facade significantly reduced the indoor temperature Mean and maximum air temperature reductions in the facade cavity were 2.2 °C and 19.8 °C, respectively, while indoor reduction was around 1.0 °C. The reduction is primarily due to the shading effect and improved thermal insulation from the vegetation layer.	Demonstrates notable passive cooling performance Contributes to energy efficiency Recyclable materials used Potential to mitigate UHI effects	Temperature reduction indoors was relatively limited Study only conducted in one season Long-term plant performance not evaluated	Future work should explore integration with renewable energy technologies and smart building systems City-scale implementation strategies recommended Long-term impact assessment and seasonal performance analysis are needed to maximise environmental benefits
[143]	Simulation	Green facade/*Hedera helix* 	Cold semi-arid	Simulated 30 different green facade scenarios with varied density (20–100%) and distance (0–50 cm) to examine daylight and thermal loads	Increased greenery density reduces daylight autonomy, maximum useful daylight illuminance and cooling loads, but increases heating loads. Distance between the facade and greenery has minimal effect, though slightly more relevant at low densities. The facade density has a greater impact than spacing in terms of regulating indoor environmental parameters.	The use of *Hedera Helix* offers high adaptability to the local climate. High greenery density significantly reduces cooling loads and improves indoor visual comfort	Higher greenery density reduces daylight and increases heating load. Facade distance has a negligible impact on the tested variables. Visual comfort may be compromised at very high densities due to excessive shading	Further research should investigate the seasonal effects of Leaf Area Density and its interaction with orientation, distance, and density to optimise thermal and lighting performance throughout the year. Green facades should be designed carefully around windows and skylights to balance light and thermal benefits

Table 4. *Cont.*

Ref.	Research Type	Facade Type/ Plant Species	Climate	Building Type/ Test Setup	Key Findings	Advantages	Limitations	Recommendations/ Future Work
[144]	Experimental	Indirect green facade/*Pyrostegia venusta* 	Subtropical	The test chamber is created on the rooftop in Cuernavaca, México. Performance assessed during winter and spring.	The green facade reduced indoor air temperature by 5.1 °C in winter and 5.3 °C in spring. Interior and exterior wall temperatures dropped significantly. It intercepted 56.4% of solar radiation and reduced heat flux by 10.7 W/m^2 in winter and 28.3 W/m^2 in spring. South orientation was optimal. The system improved thermal conditions, although it did not fully eliminate the need for air conditioning. Demonstrated strong adaptability of *Pyrostegia venusta* and confirmed economic viability.	Enhances indoor thermal comfort, reduces energy consumption, delays heat transfer, and provides economic viability. Easily adapted and improves sustainability in low-insulated buildings	Does not fully achieve optimal thermal comfort Air conditioning is still needed. Other tested species showed poor adaptability and pest resistance	Suggests the use of numerical models and building energy simulation tools to evaluate green facade performance in varying conditions. Encourages integration of green facades into urban design and further studies on species adaptability and seasonal performance

represents building type/test setup; shows a key finding; symbolises an advantage; describes a limitation; is recommendation/future work.

In particular, studies conducted in hot climates observe a marked reduction in indoor temperatures and heat flux through the implementation of green facades [136,138,142]. For instance, a study using *Parthenocissus quinquefolia* reports a maximum energy saving of 45.75% [138]. It is also noted that indirect green facade systems offer greater insulation benefits compared to direct systems. Similarly, research focused on the Mediterranean climate reveals that green facades not only significantly reduce surface temperatures but also improve microclimatic conditions by increasing the relative humidity [137,140]. In this context, evapotranspiration, when combined with shading, is emphasised as a powerful cooling mechanism, although its effectiveness varies depending on orientation, plant type, and season [140,141]. However, some studies are limited to short-term experiments and do not adequately investigate the influence of different LAI values or plant species [121,138,141]. Furthermore, it is reported that the cooling effect of green facades remains limited during night-time or in periods without direct sunlight [139,141]. These observations suggest that the passive cooling benefits of green facades fluctuate depending on the time of day and season. In a simulation study conducted in a cold semi-arid climate, the vegetation density on facades is found to have conflicting impacts on heating and cooling loads, as well as daylight availability. While dense vegetation reduces cooling loads, it restricts daylight penetration and consequently increases heating demands [143]. This highlights the need for green facades to be carefully designed not only in terms of thermal performance but also regarding visual comfort. In general, green facade systems offer promising passive design strategies for reducing indoor temperatures, lowering energy consumption, improving thermal comfort, and mitigating the urban heat island effect. Nevertheless, most existing studies are limited in duration and scope, often focusing on specific plant species and facade orientations. Therefore, future research should involve long-term, full-scale studies that cover a range of climatic conditions, plant types, seasons, and orientations. Moreover, integrating green facades with smart building systems and renewable energy technologies is also recommended to develop more sustainable and effective solutions [142,144]. In conclusion, green facades stand out as multifunctional elements of sustainable urban infrastructure, offering thermal regulation, ecological services, aesthetic enhancement, and significant potential for retrofitting applications. While there are financial, technical, and regulatory challenges to be addressed, continued research, supportive policies, and thoughtful design strategies can facilitate their broader adoption and help transform urban environments into greener, more resilient spaces.

Beyond conventional vegetation-based green facades, the integration of algae and microalgae into building envelopes has emerged as a novel bioactive strategy for sustainable and energy-efficient architecture. These systems utilise photobioreactors (PBRs) to cultivate microalgae within translucent panels, offering a range of environmental and architectural benefits such as solar shading, carbon dioxide sequestration, oxygen release, wastewater treatment, and biomass generation. Talaei et al. [145] provided a comprehensive review comparing microalgae facades with traditional green walls and D-SFSs, highlighting their superior thermal regulation and bioenergy potential. However, optimisation remains crucial in areas such as culture density, cavity geometry, and ventilation pathways. Complementing this, Elrayies [146] identified the multifaceted environmental advantages of PBR facades, including decentralised energy production, GHG emission reduction, and urban wastewater treatment, while also acknowledging integration challenges such as initial costs, limited vision, and the lack of design regulations. From a performance modelling perspective, Pozzobon [147] developed a numerical framework that integrates biological growth, heat transfer, and weather data to simulate facade behaviour. The study concluded that turbidostat operation offers the best compromise between biological yield and visual comfort in office applications. A follow-up study by the same author proposed system optimisation strategies, including module standardisation and the dynamic control of algae reservoirs across climate zones, opening the door to scalable facade applications. In a complementary study, Pozzobon [148] also investigated bioprocess control procedures such as semi-batch and turbidostat operation modes, evaluating their effects on algae biomass output, optical transparency, and system overheating. The study concluded that turbidostat control is preferable for applications prioritising visual comfort, whereas semi-batch mode yields higher biomass productivity. The research also emphasised that reservoir thickness and pigment content modulation play a vital role in balancing biological and thermal performance, reinforcing the need for localised optimisation and life-cycle modelling of bio facade systems. On the design side, Talaei and Mahdavinejad [149] investigated physical and environmental damage mechanisms in the SolarLeaf microalgae facade panels. They categorised internal failures such as bio-chemical degradation and sealant erosion and external threats including climatic loads and constructional defects, emphasising the urgent need for regulatory guidelines and robust connection detailing. Meanwhile, Talaei et al. [150] proposed a smart bioreactor panel with the user-adjustable algae medium height, allowing thermal performance to be dynamically adapted based on the occupants' thermal needs. The system demonstrated measurable short-term temperature reductions, particularly in semi-arid climates. Poerbo et al. [151] and Martokusumo et al. [152] explored algae facades in tropical buildings where solar exposure is high. Their studies demonstrated improvements in indoor air quality through biogenic CO_2-to-O_2 conversion and added shading in East/West orientations. Martokusumo further highlighted the potential for colour modulation through LED-integrated systems, merging aesthetics with energy functions. On a material level, Roudbari [153] reviewed algae-based construction composites and confirmed their environmental value in reducing carbon emissions, enhancing durability, and aligning with circular economy goals. Ahmad et al. [154] positioned microalgae within the context of green cities, focusing on urban wastewater reuse, carbon capture, and biomass conversion into biochar and biofertiliser, linking these systems to the broader agenda of urban resilience. Finally, Warren et al. [155] conducted a human-centric study on the psychological and behavioural impacts of microalgae facades. While no statistically significant differences in creativity or mood were observed compared to glazed control environments, participants exposed to algae-integrated spaces proposed greener design concepts, suggesting a subtle biophilic influence on environmental awareness and sustainability perception. Collectively, these studies frame microalgae facades as multifunctional, intelligent, and regenerative components of the building envelope. From responsive shading and bioenergy generation to human-centred design and climate-positive infrastructure, microalgae integration stands as a promising trajectory for the future of facade technology. Future research must continue bridging engineering design, biotechnological optimisation, human factors, and regulatory frameworks to fully realise their potential across scales and geographies.

As shown in Figure 7, the SWOT analysis for green facade systems offers a structured insight into the dual ecological and thermal roles of vegetative envelopes. These systems provide aesthetic, acoustic, and microclimatic benefits while contributing to biodiversity and urban heat island mitigation. However, maintenance demands, irrigation complexity, and climate sensitivity present significant implementation challenges. The analysis also identifies new opportunities for integration with greywater systems and green policy incentives, making them especially attractive in dense, temperate urban zones.

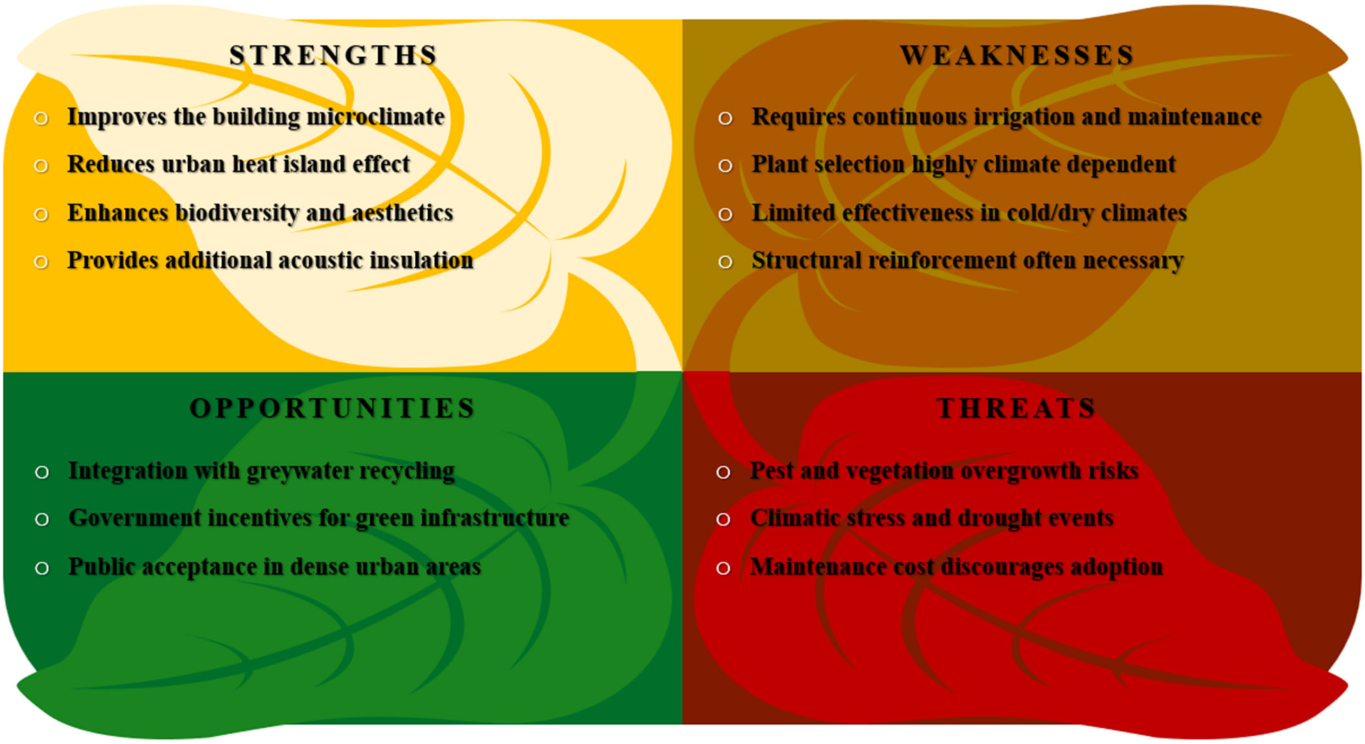

Figure 7. SWOT analysis of green facades.

3.4. Comparative Evaluation of Modern Facade Systems

Modern facade systems offer varying performance profiles shaped by their thermal logic, operational complexity, and technological maturity. As synthesised in Table 5, green facades [125], D-SFSs [74], and AFs [156] each represent established strategies with proven potential for energy savings, ranging from 10–25% in vegetation-based systems to up to 40% in intelligent, sensor-driven envelopes. The emergence of complementary technologies such as smart coatings [157], nanomaterials [158], BIPV [159,160], and PCM [161] has further expanded the design spectrum, enabling tailored performance across climates and building functions.

Table 5. Comparative evaluation of contemporary facade insulation technologies in terms of energy performance, thermal responsiveness, cost, maintenance, and application suitability.

Criteria	Green Facade [125]	D-SFS [74]	AFs [156]	Smart Coatings [157]	Nanomaterials [158]	BIPV [159,160]	PCM [161]
Energy savings (%)	10–25	10–30	20–30	Up to 30	Up to 90% mitigation	20–80	Up to 30
Thermal reactivity	Passive via vegetation	Ventilated cavity buffering	AI-driven dynamic	Thermochromic/ electrochromic	Ultra-low conductivity	Solar absorption + electric output	Latent heat storage
Cost	Low–Medium	High	Very high	Medium	Very high	High	High
Maintenance	High	Medium	Very high	Low	Low	Medium	Low
Maturity	High	High	Medium	Commercialised	Low	Commercial	Mature
Best usage	Urban greening, visual comfort	Offices, dense urban	Museums, smart buildings	Climate-adaptive glazing	Envelope nano-enhancement	Solar-active facades	Thermal stabilisation in hybrids

Whilst green facades offer cost-effective and ecologically beneficial passive cooling, their long-term viability depends heavily on the maintenance infrastructure, plant viability, and urban microclimates. These systems excel in dense urban areas where space is limited and ecological performance is prioritised, yet they are less effective in colder climates where heating demand dominates. In contrast, D-SFSs provide robust thermal and acoustic buffering, particularly in commercial buildings. Their dual-layer envelope and ventilated cavity create a microclimate that modulates interior heat gain. However, their reliance on precise structural integration and their relatively high capital expense poses constraints in retrofitting projects or smaller-scale buildings.

AFs elevate performance through responsiveness. By employing sensors, actuators, and artificial intelligence, these systems modulate building-envelope behaviour in real time, providing high levels of comfort and energy savings. Nevertheless, the operational complexity of such systems, along with their maintenance demands and relatively limited deployment track record, means they are typically confined to flagship smart buildings and high-tech institutional contexts. Meanwhile, smart coatings and electrochromic systems offer an elegant middle ground, passive modulation of solar gain without the need for active controls, making them particularly appealing for facades requiring minimal intervention post-installation.

The role of nanomaterials is rapidly gaining attention, especially in the domain of ultra-insulating solutions. Aerogels and nano-enhanced composites offer unprecedented thermal performance in thin layers, with thermal conductivity reductions of up to 90% compared to traditional materials. However, their integration into real construction remains experimental, often hindered by high costs, fragility, and the absence of clear design standards. PCMs, in contrast, have seen broader implementation, particularly within interior wall linings and curtain wall cavities. Their ability to shift peak thermal loads makes them ideal for climates with significant daily temperature swings.

Perhaps the most transformative development is the integration of photovoltaics directly into the building envelope. BIPV systems represent a convergence between passive thermal management and active energy generation. Their effectiveness varies between 10 and 20% energy gain, depending on orientation and solar access, but their primary appeal lies in enabling buildings to function as decentralised energy generators without sacrificing aesthetic or spatial requirements. As energy codes tighten and net-zero standards proliferate, BIPV is likely to shift from innovation to necessity.

Beyond technical performance, the strategic application of these systems must be contextualised. Passive systems like green facades or PCMs are ideal for low-tech climates or regions where simplicity and resilience are prioritised. Conversely, active strategies such as AFs and nanomaterial-integrated skins demand controlled conditions, skilled maintenance teams, and substantial up-front investment. Hybridisation offers a way forward: for instance, pairing D-SFSs with smart glazing or integrating PCMs into AFs can balance system responsiveness with thermal inertia.

Several knowledge gaps remain. The field validation of emerging technologies, especially nanomaterials and AI-based control systems, is scarce. Most performance claims are drawn from simulation or small-scale tests, limiting their generalisability. Additionally, standardised methods for comparing lifecycle cost, embodied carbon, and climate-specific efficiency are urgently needed to guide practical decision-making. Interoperability between active systems and passive enhancements also requires further design research, particularly in relation to real-time control algorithms and failure mitigation strategies. Looking ahead, the evolution of facade systems will likely be shaped by three interdependent priorities: decarbonisation, digitalisation, and climate adaptability. Facade technologies must not only minimise the operational energy but also address embodied emissions, especially in retrofit applications where material reuse and lightweight solutions are paramount. At the same time, AI and data-driven optimisation will increasingly be embedded within facade logics, shifting envelopes from static barriers to responsive, interactive systems. Furthermore, a climate-resilient design will necessitate facades that can both protect against intensifying heat waves and buffer interior conditions during power outages or system failures. To conclude, the comparative synthesis of contemporary and emerging facade systems underlines the need for integrated, context-aware approaches in envelope design. Moving forward, research and practice should jointly prioritise hybridisation, field-based validation, standardisation, and automation as the pillars of future facade innovation. Rather than viewing systems in isolation, architects and engineers must consider how layering strategies, technologically, climatically, and functionally, can yield envelopes that are not only energy-efficient but also intelligent, resilient, and adaptive.

4. Insulation Performance and Comparative Analysis

In the evolving context of sustainable architecture and energy-efficient buildings, the thermal performance of facade materials plays a critical role in achieving the EU's 2030 and 2050 climate neutrality targets. The analysis of 49 distinct wall and glazing materials used in various facade systems reveals not only a progressive shift towards thermal resistance enhancement but also a broader trend in innovation within the building envelope sector. Figure 8 illustrates a comparative visualisation of U values across traditional, modern, and hybrid facade solutions, highlighting how technological advancement has enabled lower thermal transmittance even with reduced material thickness.

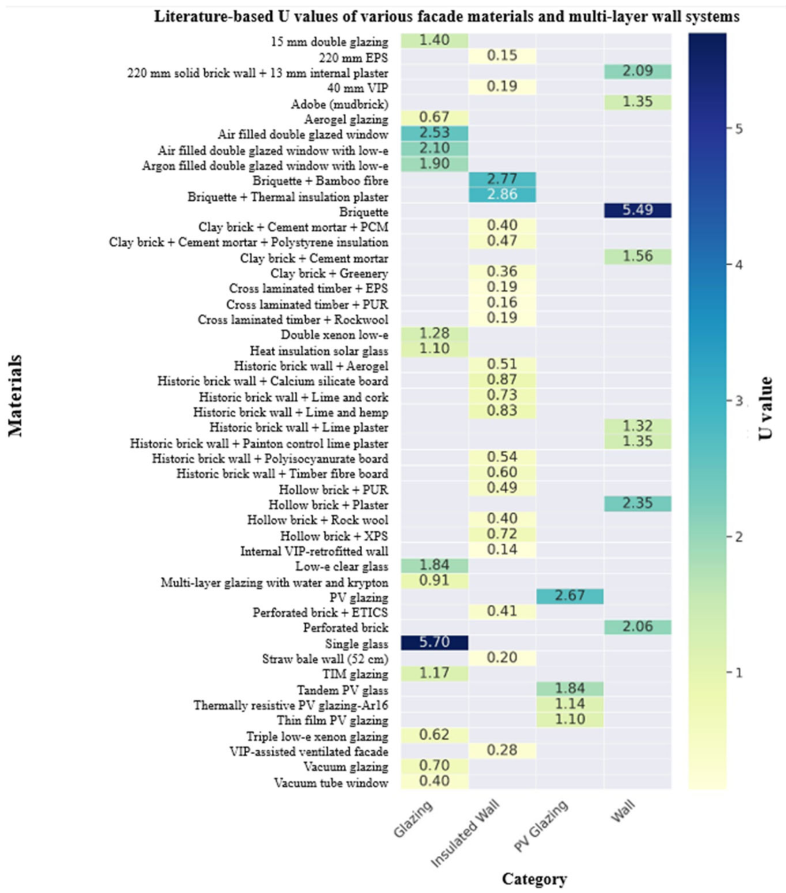

Figure 8. Comparative U-values of selected composite facade systems based on literature-reported configurations [10,28,162–184].

Remarkably, modern materials demonstrate a substantial increase in thermal resistance (i.e., lower U values), despite a general reduction in material thickness, a clear indication of improved material efficiency, and technological advancement. For instance, 15 mm double glazing (1.40 W/m^{2}K) [162], 200 mm EPS (0.15 W/m^{2}K), and 40 mm VIP (0.19 W/m^{2}K) [163] demonstrate how high thermal resistance can be achieved without excessive bulk. Traditional constructions such as historic brick walls with lime plaster (1.32 W/m^{2}K) [164] or adobe (1.35 W/m^{2}K) [165] exhibit significantly higher U values when compared to hybrid solutions like historic brick combined with aerogel (0.514 W/m^{2}K) [173] or polyisocyanurate boards (0.540 W/m^{2}K) [173]. This underscores the effectiveness of material integration strategies where conventional facades are retrofitted with advanced insulating materials, thereby enhancing performance without compromising heritage aesthetics. Similarly, the thermal performance of glazing systems has improved substantially. Aerogel glazing, with a U value of 0.67 W/m^{2}K, represents one of the most efficient solutions available [166]. Conventional single glazing, with a U value of 5.70 W/m^{2}K, performs poorly by comparison. Incremental improvements were achieved with earlier-generation double glazing technologies, such as air-filled double glazing (2.53 W/m^{2}K) and low-e air-filled glazing (2.10 W/m^{2}K) [167]. More refined systems, including argon-filled low-e glazing (1.90 W/m^{2}K) and TIM glazing (1.17 W/m^{2}K), offer further enhancements in thermal performance [168]. Briquette (5.49 W/m^{2}K) [169] is another example of high transmittance in traditional systems; however, thermal resistance can be achieved by incorporating sustainable materials such as insulating plaster and bamboo into construction materials.

In terms of bio-based innovations, materials such as cross laminated timber paired with PUR (0.162 W/m^{2}K), EPS (0.186 W/m^{2}K), or Rockwool (0.116 W/m^{2}K) [170] showcase that bio-based structures, when combined with modern insulation, can outperform even synthetic systems. The use of PCMs in conjunction with clay brick and cement mortar (0.40 W/m^{2}K), and the application of green facades (0.36 W/m^{2}K) [171], not only reduce thermal transmittance but also contribute to passive temperature regulation and urban biodiversity. Heat-insulation solar glass (1.10 W/m^{2}K) [172] is another emerging solution. Historic wall assemblies combined with natural insulation such as hemp, cork, or timber fibre now perform competitively, with U values ranging between 0.601–0.870 W/m^{2}K [173]. Hollow brick improved with PUR (0.49 W/m^{2}K) or plaster (2.35 W/m^{2}K) [174], and with rock wool (0.40 W/m^{2}K) [175], further demonstrates the role of insulation in optimising outdated systems. Thermally resistive glazing options like low-e clear glass and tandem PV glass both register at 1.84 W/m^{2}K [176]. Meanwhile, PV glazing (2.67 W/m^{2}K) [177] and straw bale walls (0.20 W/m^{2}K) [178] mark the extreme ends of thermal performance. Thermally resistive PV glazing with argon (1.14 W/m^{2}K) [179], thin-film PV glazing (1.10 W/m^{2}K) [180], and VIP-assisted ventilated facades (0.28 W/m^{2}K) [181] reveal how active functions are increasingly embedded in facade materials. Vacuum tube windows (0.40 W/m^{2}K) [182], and perforated bricks (2.06 W/m^{2}K) that drop to 0.41 W/m^{2}K with ETICS enhancement [183] show the transformative potential of intelligent retrofits. Triple low-e xenon glazing (0.62 W/m^{2}K) and double xenon low-e glazing (1.28 W/m^{2}K) [184] finalise the advanced glazing innovations.

Overall, the figure supports the conclusion that there is a consistent downward trend in U values across the examined systems, with innovative combinations and emerging materials demonstrating superior performance. This comprehensive material review illustrates a broader shift in the building envelope design: from merely achieving code compliance to actively contributing to decarbonisation goals. The movement towards materials with lower U values reflects the growing demand for higher thermal resistance, even as constructions become thinner and more lightweight. This is aligned with the necessity for flexible retrofitting, ease of installation, and lifecycle sustainability in future building stock. As it is looked ahead, it becomes clear that the facades of tomorrow will not only serve as thermal barriers but also as complex systems integrating insulation, energy production, light transmission, and environmental responsiveness. Thus, material selection and facade design are becoming increasingly strategic decisions in the global pursuit of energy-positive, low-emission architecture.

5. Future Trends and Research Areas

The future of facade insulation technologies is set to be defined by the unprecedented integration of smart systems, advanced materials, and holistic design approaches. Unlike traditional building envelopes that serve as static barriers, next-generation facades are envisioned as active participants in energy management and environmental stewardship. A confluence of drivers, from urgent carbon reduction goals to rapid progress in material science and digital technology, is pushing researchers and practitioners to rethink facade insulation in fundamentally new ways. This section offers a novel perspective on emerging trends, highlighting not only the opportunities they present but also their limitations and the actionable steps needed to realise their potential in practice. Emphasis is placed on the interdisciplinary nature of these advancements, recognising that architecture, engineering, climate science, and public policy must converge to achieve truly sustainable and high-performing facades.

5.1. Smart and Adaptive Facade Systems with AI Integration

One of the most transformative trends is the development of smart and AFs that can respond in real time to changing environmental conditions. These systems incorporate intelligent materials and devices—from electrochromic glazing to sensor-driven ventilation panels—to dynamically regulate heat, light, and airflow. For example, modern electrochromic or thermochromic windows can modulate their tint based on sunlight intensity, thereby controlling solar gain and glare without manual intervention. Likewise, automated shading devices and louvres, guided by light sensors and occupant feedback, continuously adjust to maintain optimal daylight and thermal conditions indoors. Such innovations effectively turn the facade into a climate-responsive skin that minimises heating and cooling loads while enhancing occupant comfort. Importantly, these adjustments can be orchestrated by AI algorithms that learn from building usage patterns and weather forecasts. AI-driven predictive control can anticipate thermal load changes and pre-emptively modify the facade's configuration—for instance, by pre-cooling spaces at night or closing insulation shutters before a heatwave—resulting in significant energy savings and peak load reduction. In essence, the facade moves from being a passive assembly of materials to an active, learning system that continuously optimises building performance. This level of adaptivity offers immense opportunity, but it also introduces complexity: ensuring reliability, fail-safe operation, and cybersecurity for AI-controlled facades will be critical challenges requiring ongoing research and robust design standards.

The integration of IoT technologies is a key enabler of these smart facades. Small, inexpensive sensors embedded in insulation layers and exterior surfaces can monitor the temperature, humidity, solar radiation, and even the structural health of facade components in real time. By networking these sensors to a central building management system, a facade can "sense" its environment much like a living organism. For instance, IoT-based sensors might detect localised heat buildup on a sunny facade section and trigger cooling measures or adjust the position of shading elements [33]. Coupled with machine learning, such systems can refine their responses over time, adapting to seasonal changes and usage patterns. A notable example of combining AI with adaptive facade elements is the experimental D-SF that integrates microalgae PBRs with machine learning controls [185]. In this system, a layer of microalgae is cultivated within the facade cavity to provide dynamic shading and bioenergy generation; AI algorithms optimise the algae growth conditions by adjusting light and nutrient flow, yielding up to an 80% increase in biomass production [186]. This bio-AF concept not only insulates and shades the building but also actively captures carbon and produces renewable energy, embodying a futuristic synergy of biotechnology and AI. These kinds of innovations illustrate how AFs can dramatically expand the functionality of building envelopes. However, they also underscore new challenges: maintaining biological systems like algae or ensuring sensors and actuators remain calibrated over years of operation will demand new maintenance protocols and interdisciplinary expertise. Going forward, research must address these practical considerations, developing robust control algorithms and self-diagnostic features so that smart facades remain reliable and effective throughout their life cycle.

5.2. Digital Twins and BIM for Facade Optimisation

Hand-in-hand with smart physical systems is the rise of digital tools, especially BIM and digital twin technology, which are revolutionising how facades are designed, analysed, and managed. BIM-based design platforms now allow architects and engineers to create highly detailed 3D models of facade systems that integrate geometric, material, and thermal properties. This enables an exhaustive simulation of a facade's performance under various scenarios well before it is built. For example, designers can simulate heat loss, thermal bridging, and condensation risks across different insulation configurations or cladding attachments, identifying optimal solutions for energy efficiency and durability. The ability to refine facade designs in a virtual environment reduces uncertainties and costly trial-and-error in the field, leading to facades that are both better optimised and more innovative. Digital models also support multi-disciplinary collaboration: structural engineers, facade consultants, and environmental experts can concurrently work on the same BIM model, ensuring that thermal performance, structural integrity, fire safety, and aesthetic requirements are all balanced from the earliest design stages.

Moving beyond design, digital twins are emerging as powerful tools for the operational phase of building facades. A digital twin is a live digital replica of the physical building that continuously receives data from sensors and user inputs, mirroring the state of the facade and interior conditions in real time. By integrating the facade's sensor data (temperatures, solar exposure, etc.) with weather forecasts and even occupant behaviour patterns, the digital twin can enable advanced monitoring and control strategies. For instance, facility managers using a digital twin dashboard might observe in real time how an insulation system is performing and detect anomalies like unexpected heat loss or moisture ingress in the facade. AI-driven analytics within the digital twin can also predict maintenance needs—for example, forecasting when a PCM might saturate or when a sealant might start failing, allowing for proactive interventions before performance degrades. On a larger scale, city planners and policymakers are leveraging aggregated digital twin data to simulate city-wide retrofit scenarios and energy policies. By virtually modifying the insulation or glazing of thousands of buildings in a model city, one can predict the impacts on urban energy demands and carbon emissions. Such simulations are invaluable for crafting effective building renovation strategies aligned with climate goals. A framework that combines BIM, IoT sensor networks, and AI has been shown to accurately measure and even predict carbon emissions of existing building stocks, guiding net-zero retrofit initiatives at scale. The main limitation to the wider adoption of digital twins in facade engineering is not technology, but rather standardisation and data integration: many current applications exist in silos, and there is a lack of common standards for data sharing across different building systems and stakeholders. To address this, future research and policy should promote open data protocols and invest in training for the construction workforce, ensuring that even smaller firms can harness digital twin tools for sustainable facade management. When fully realised, digital twins will serve as a bridge between simulation and reality, continuously improving the facade performance over a building's life and informing the next generation of designs with real-world feedback [187].

5.3. Innovative Insulation Materials and Thermal Performance Enhancements

Material science advancements continue to push the envelope of what insulation can achieve, yielding lighter, thinner, and more efficient materials that were unimaginable a few decades ago. A major trend is the development of high-performance thermal insulation materials such as aerogels, VIPs, and advanced foams, which offer extremely low thermal conductivity values. VIPs, for instance, can achieve thermal resistances several times higher than conventional mineral wool or EPS of the same thickness by creating an evacuated, nano-porous core that nearly eliminates heat conduction and convection. Early VIP products were prohibitively expensive and faced durability issues (e.g., loss of vacuum over time), but research into nano-structured materials and protective envelope films has significantly reduced their cost and improved longevity. It is expected that VIPs will see wider use in facades of the future, particularly in retrofits where adding thick insulation is impractical. Similarly, aerogels—often dubbed "frozen smoke"—provide exceptional insulation in a lightweight form; silica aerogel blankets can be integrated into facade panels or cavity fill to boost thermal performance with minimal added thickness. Studies show that incorporating nano-porous structures like aerogels into insulation composites can reduce thermal conductivity dramatically while maintaining or even improving mechanical strength. Meanwhile, PCMs are being utilised to enhance thermal inertia: by absorbing and releasing latent heat during phase transitions, PCMs built into insulation layers can shave peak temperature swings, effectively flattening heating and cooling demand curves. These advanced materials collectively enable facade designs that deliver high R-values in slim profiles, preserve interior space, and potentially integrate into prefabricated panels for easier construction.

Despite their promise, each of these high-tech solutions comes with limitations that researchers are actively working to overcome. Cost and scalability remain significant concerns—for example, while aerogel prices have dropped, they are still higher than traditional insulation, and their handling requires care due to dust and fibre issues. VIPs, on the other hand, must be carefully detailed in construction to avoid puncture and often cannot be cut to size on-site, which complicates installation and design detailing. There are also questions about long-term performance: how will these materials perform over 30–50 years in a facade, especially under varying moisture conditions or mechanical stress? To address such issues, current research is exploring hybrid insulation systems that combine traditional bulk insulation with the selective use of aerogels or VIP inserts in high-heat-loss areas, balancing cost and benefit. Another avenue of research is improving the environmental profile of high-performance insulations, for instance, by developing low-cost silica sources for aerogel production or recyclable vacuum panel components. As innovation continues, it will be crucial to validate these materials under real-world conditions and develop standards and certification protocols (for fire safety, ageing, etc.) so that building codes can embrace them. In summary, advanced insulation materials are key to achieving ultra-low energy facades, but realising their full potential will depend on parallel progress in cost reduction, manufacturing, and regulatory acceptance.

5.4. Bio-Based and Recyclable Insulation Materials

In parallel with nanotechnology and high-performance synthetics, there is a strong movement toward bio-based and recyclable insulation materials to address sustainability and embodied carbon concerns. Researchers and industry practitioners are revisiting natural materials, such as wood fibre, hemp, straw bales, cork, and cellulose, which can provide good insulating value with a fraction of the environmental footprint of petrochemical-based foams. Modern processing techniques have improved the fire resistance, durability, and consistency of many bio-based insulators, making them viable for mainstream facade applications. For example, wood fibre insulation boards, produced from forestry by-products, offer not only low thermal conductivity but also hygroscopic properties that can help buffer moisture in wall assemblies, potentially improving indoor air quality. Agricultural waste fibres (like rice husks or coconut coir) and recycled textiles or paper are being transformed into insulation batts and blankets, aligning with circular economy principles by repurposing waste streams. The appeal of these materials is their low embodied energy and carbon—some, like straw or hempcrete, even act as carbon sinks during their growth phase—and at end-of-life, they pose fewer disposal issues, often being biodegradable or recyclable [188].

A particularly novel entrant in this arena is mycelium-based insulation, which uses the root structure of fungi to bind organic substrates into lightweight, foam-like panels. Mycelium composites can be grown using minimal energy and can incorporate regionally sourced agricultural waste as the feedstock, yielding an insulation material that is renewable and compostable. Recent studies have demonstrated that mycelium insulation exhibits competitive thermal properties and can significantly reduce building cooling loads in hot climates. For instance, a simulation-based study in Qatar found that retrofitting residential walls with mycelium-based insulation could save over 8 TWh of energy annually and substantially cut CO_2 emissions, thanks to the material's ability to limit heat transfer in extreme desert conditions. The mycelium's porous structure and low thermal conductivity allow it to effectively regulate heat flow, and its organic nature means it contributes almost no toxic emissions during manufacture or use. Furthermore, because the mycelium can grow rapidly and be cultivated locally, it presents a cost-effective solution for developing regions seeking to improve building insulation without heavy industrial infrastructure. However, along with other bio-based materials, mycelium insulation faces several challenges that are the focus of ongoing research. Ensuring fire safety is paramount—natural materials often need treatment or hybridisation with fire retardants to meet fire codes. Moisture susceptibility is another concern: while some bio-based insulations can buffer moisture, excessive exposure might lead to rot or mould, so facade systems must be designed to keep them dry or allow drying. Additionally, variability in natural materials can affect performance; thus, quality control and standardisation for bio-based insulation are needed so that designers and code officials can have confidence in their properties. Despite these hurdles, the push for low-carbon construction is likely to accelerate interest and innovation in bio-based insulation. In the near future, it can be expected to see more composite solutions—for example, combining mycelium or hemp fibres with aerogel particles or phase change microcapsules to create a material that marries ecological sustainability with high thermal performance. Such hybrids exemplify an original direction for research, breaking down silos between green materials and high-tech engineering to deliver insulation that is both climate-friendly and functionally superior [189].

5.5. Energy-Generating and Multi-Functional Facades

A transformative vision for future facades is that they will not only conserve energy but also generate energy, becoming active players in a building's overall sustainability profile.

BIPV is at the forefront of this trend, where photovoltaic cells are incorporated directly into facade components such as glass windows, spandrel panels, or cladding systems. This allows the vertical surfaces of buildings to produce electricity from sunlight, supplementing rooftop solar installations and significantly increasing the renewable energy output of urban structures. Traditional silicon-based BIPV modules (including semi-transparent thin films) have already been used in many projects, but the next leap is expected from perovskite solar cells (PSCs) and other emerging PVs, which offer the promise of high efficiency, flexibility, and aesthetic integration. PSCs have shown remarkable efficiency gains in laboratory settings and can be made semi-transparent or in various colours, making them attractive for facade applications where visual qualities matter. A notable real-world demonstration is the installation of flexible perovskite PV modules in the glazed facade of the Spark office building in Warsaw, which was one of the first uses of perovskite BIPV technology on a commercial building. The global BIPV market is projected to grow rapidly as these technologies mature, reflecting a paradigm shift in facade design—from passive insulator to active solar power generator.

However, integrating solar generation into facades comes with its own set of technical and practical challenges. One concern is the trade-off between transparency and efficiency: for windows or transparent facades, the opaquer the PV layer, the more power it can generate, but this reduces daylight and view, so designers must strike a balance or use innovations like selective wavelength conversion. Another critical challenge with perovskite-based facades is ensuring long-term stability and safety. PSCs traditionally contain lead and can suffer from degradation when exposed to moisture and UV over time. Researchers are actively seeking lead-free perovskite formulations and durable encapsulations to address these issues, so that future facade-integrated solar cells meet the necessary longevity and environmental safety standards. Additionally, the electrical aspects of facade PV integration require careful design—wiring, inverters, and safety disconnects must be incorporated into the building envelope in a way that is accessible for maintenance yet protected from weather. Despite these hurdles, the prospect of facades contributing to net-zero energy use is a strong motivator. In combination with superior insulation, a facade might soon both drastically reduce a building's energy demand and supply a significant portion of the remaining demand through renewables, fundamentally altering the energy balance of buildings in a sustainable direction [190,191].

Beyond solar technologies, facades are increasingly expected to perform multiple functions simultaneously, leading to concepts such as bio-reactive facades and other hybrid systems. It has already been touched on in one example: microalgae PBR facades, which illustrate how a facade can act as an insulating shade, a biofuel generator, and a carbon sink all at once. Another growing interest is in facades that improve urban environmental quality—for instance, green facades or living walls where vegetation is integrated into exterior walls. Green facades (whether via climbing plants or modular green wall systems) can provide an extra layer of insulation and shading to the building, while also cooling the surrounding air through evapotranspiration and improving urban air quality by capturing particulates. They have been shown to lower exterior surface temperatures and mitigate the urban heat island effect in cities. By combining these living systems with traditional insulation behind them, designers can create facade assemblies that address energy efficiency and urban ecology in tandem. However, making vegetated facades viable at scale involves tackling maintenance and water supply issues—ongoing research is looking into drought-resistant plant species, efficient irrigation methods, and modular systems that simplify upkeep. Some cities have begun to offer incentives or updated building codes to encourage green roofs and walls as part of climate adaptation strategies, recognising the co-benefits for insulation and the microclimate.

A critical insight for multi-functional facades is that interdisciplinary collaboration is required to unlock their full potential. For instance, designing an algae facade is not just an architectural problem but also a bioengineering and chemical engineering challenge; similarly, green wall performance depends on horticultural science as much as on facade engineering. These examples underscore that moving forward, facade innovation will increasingly occur at the intersection of fields—e.g., architects, engineers, biologists, and computer scientists co-designing solutions that are both building-worthy and biologically active. There are limitations to consider as well: living and energy-generating facades often have higher initial costs and untested lifespans. Stakeholders may be hesitant to adopt such novel systems without extensive demonstration projects proving their long-term viability and return on investment. Therefore, one actionable direction is the creation of "living labs" and pilot projects in different climates, where multi-functional facade systems can be installed, monitored, and refined. Feedback from these projects will provide invaluable data on real maintenance needs, energy yields, and user acceptance, thereby informing guidelines and standards for broader implementation. In summary, the expansion of facade functions, from merely insulating to generating power, supporting greenery, and beyond, is a hallmark of future sustainable cities, but realising it will demand both innovative engineering and practical wisdom garnered from cross-disciplinary efforts.

5.6. Self-Healing and Low-Maintenance Facade Technologies

As facade systems become more complex and multi-functional, ensuring their long-term durability and ease of maintenance is an emerging research area. One promising avenue is the development of self-healing materials and coatings for facades, which can autonomously repair minor damage and thus extend service life with minimal human intervention. Inspired by biological systems that heal after injury, engineers have created coatings with micro-encapsulated healing agents that release when the coating is scratched or cracked, effectively "healing" the damage and restoring the protective barrier. In the context of facade insulation, a self-healing coating applied to exterior render or composite panels could seal small cracks that might otherwise allow water ingress or thermal bridging, thereby preserving insulation integrity. This technology is especially relevant for extreme climates or hazard-prone areas, where facades undergo frequent thermal stress or minor impacts. By preventing the accumulation of micro-damage, self-healing facades can maintain their performance over time and reduce maintenance costs. Already, industry collaborations are making headway: for example, a Swiss materials firm working with Saint-Gobain has developed a self-healing facade adhesive system that has grown into a $120 million niche market, with a nearly 19% annual growth rate since 2020. This indicates a strong demand for solutions that can improve facade longevity and reliability [192].

Beyond self-healing, intelligent monitoring systems also contribute to low-maintenance facades. It is discussed how sensors can detect performance issues; when tied to automated maintenance protocols, the facade could potentially take action (like activating heating elements to dry out moisture spots or using drones/robots to clean solar panels or refill microalgae nutrients). Whilst such interventions are still experimental, the concept of a facade that not only signals the need for maintenance but also helps execute it is gaining traction. It is worth noting that a truly low-maintenance, self-regulating facade would alleviate one of the key barriers to adopting advanced technologies—the concern that upkeep will be too costly or technically demanding. However, it also raises regulatory and safety questions: building codes and standards will need to evolve to account for self-acting facade features (e.g., ensuring that self-healing chemicals are non-toxic, or that robotic maintenance devices do not pose risks to the public). Ongoing research and demonstration projects will be vital to refining these technologies. The actionable insight here is that stakeholders should not view maintenance as an afterthought; instead, design for maintainability is becoming as important as design for performance. By investing in materials that can prolong their own life and systems that support automated upkeep, the industry can ensure that tomorrow's high-tech facades remain safe and effective throughout their intended lifespan without imposing undue burden on building owners.

5.7. Retrofitting Strategies and City-Scale Implementation

Improving facade insulation is not only about new constructions; in fact, one of the greatest challenges and opportunities lies in retrofitting existing buildings on a massive scale. Many cities around the world have ageing building stocks with poor insulation and upgrading them is essential to meet climate targets and improve living conditions. Innovative retrofitting strategies are therefore a critical area of future development. A key trend is the use of prefabricated, modular facade retrofit systems that can be installed quickly over existing structures with minimal disruption to occupants. For example, the Energiesprong program, which originated in the Netherlands, has pioneered a method of wrapping older homes with prefabricated insulated facade panels (often integrated with windows and even solar panels) to achieve net-zero energy performance. In pilot projects, multi-unit residential buildings have been retrofitted to a climate-neutral standard while tenants remained in place, thanks to the speed and efficiency of installing factory-made facade elements. Such serial retrofit approaches illustrate how scaling up insulation improvements can be accomplished by shifting work from the construction site to the factory, leveraging automation and precision manufacturing. The benefits are twofold: higher quality installation (since panels are produced in controlled conditions and simply attached on-site), and faster project timelines that reduce labour costs and inconvenience. Early results from Energiesprong and similar initiatives show dramatic reductions in heating demand (often 70–80%) and improved comfort for residents, with retrofit costs gradually decreasing as production volumes rise. This demonstrates a viable path to upgrading millions of existing buildings using a standardised yet adaptable toolkit of facade insulation solutions [193].

While the technical means for retrofit are advancing, the economic and policy dimensions are equally crucial to address. Retrofitting at the city scale requires substantial upfront investment and coordination among stakeholders. One limitation observed is the "split incentive" problem: building owners must pay for insulation upgrades while the energy savings benefit the tenants or society at large, unless energy prices or regulations incentivise the owner. Policies such as grants, subsidies, or energy-efficiency obligations are therefore instrumental in kick-starting large-scale retrofits. Some governments have set ambitious targets (for instance, China aims to retrofit over 350 million m^2 of floor area in existing buildings by 2025 as part of its low-carbon strategy) and are providing financial incentives to reach them. Yet, progress can be slow due to various barriers: homeowners may be resistant due to the hassle or heritage concerns, contractors might lack training in new materials, and there can be regulatory hurdles for altering historic facades. A critical insight is that retrofit strategies must be tailored; different building typologies and ages require different solutions, and one-size-fits-all approaches will not work. For example, what works for a post-war apartment block (external insulation panels) may not suit a century-old masonry building (where internal insulation or aerogel-based plasters could be more appropriate to preserve facades). Thus, creating a decision-making framework for selecting the best retrofit method for each context is a priority for research. Moreover, demonstrating the co-benefits of retrofits, such as improved health from better indoor climates and increased property values, can help motivate private investment. At the city level, integrated planning is needed so that facade retrofits align with other upgrades (like HVAC modernisation or seismic strengthening), maximising synergies and cost-effectiveness. City authorities might consider mandating energy audits and phased retrofit plans for the worst-performing buildings, coupled with technical assistance programs to help building owners navigate the complex process. The interdisciplinary nature of retrofitting cannot be overstated: success hinges on architects (to devise creative solutions that respect building aesthetics), engineers (to ensure safety and performance), financiers (to develop innovative funding models), and policymakers (to create enabling regulations), all working in concert. When executed strategically, large-scale facade insulation retrofits represent one of the most impactful and tangible actions towards urban sustainability, delivering immediate cuts in energy use and greenhouse gas emissions while also invigorating the construction sector and improving residents' comfort [194].

5.8. Interdisciplinary Collaboration and Structured Foresight

The advancement of facade insulation technology sits at the crossroads of multiple disciplines, making interdisciplinary collaboration a cornerstone of future progress. Architects, engineers, material scientists, data scientists, and policymakers each hold a piece of the puzzle, and only by working together can they create facade systems that are technically sound, aesthetically pleasing, environmentally sustainable, and socio-economically viable. For instance, developing a smart, bio-based facade might involve architects and climate engineers designing the facade geometry and performance criteria, materials scientists creating a new insulation composite, biologists advising on living components (like algae or plants), and computer scientists programming the sensors and controls—all while policy experts ensure that building codes accommodate these innovations. Such breadth of collaboration is challenging, but it is increasingly facilitated by forums like green building councils, smart city initiatives, and academic–industry partnerships focusing on sustainable construction. Interdisciplinary research teams are already tackling questions like how to quantify the life-cycle carbon impact of novel insulation systems (combining expertise in material science and environmental science) or how to design climate-resilient facades that can withstand future weather extremes (bridging climate modelling with engineering design). Looking ahead, structured foresight exercises—involving scenario planning and back casting—can help stakeholders anticipate the needs of buildings in 2030, 2040, and beyond, ensuring that research today aligns with the conditions and regulations of tomorrow. This proactive approach is essential because facade technologies often have decades-long lifespans and must address not just current issues but also emerging challenges like more frequent heatwaves, new energy grid dynamics (with decentralised generation), and evolving occupant expectations.

In conclusion, the future trends outlined here show that facade insulation is evolving from a narrow technical field into a rich, integrative domain of innovation. The opportunities are immense: buildings with intelligent envelopes that self-optimise and produce energy, cities with retrofitted facades that dramatically cut carbon emissions, and materials that are at once ultra-efficient and truly sustainable. Yet, realising this vision requires critical awareness of the limitations and obstacles—technical, economic, and regulatory—that stand in the way. By acknowledging these challenges and actively formulating strategies to overcome them, researchers and professionals can ensure that the next generation of facades delivers on its promise. Below, it is distilled some actionable recommendations for key stakeholders, emphasising steps that can accelerate progress toward smarter, greener, and more resilient facade insulation in the coming years:

- For Researchers: Focus on bridging gaps between disciplines to develop holistic facade solutions. This includes exploring hybrid materials (e.g., combining bio-based matrices with nano-insulators) and validating new systems through pilot projects in diverse climates. Prioritise studies on long-term performance and the maintenance of innovative facades, such as the durability of perovskite BIPV or the performance of algae facades over seasons, to build a robust knowledge base that addresses current unknowns. Also, contribute to open data and modelling tools (for instance, digital twin platforms) that can be shared globally, enabling collective learning and speeding up innovation

- For Practitioners (Architects and Builders): Embrace an integrated design approach for new projects and retrofits, engaging energy modellers, facade engineers, and sustainability experts from the earliest stages of design. Experiment with smart facade technologies and novel materials in small-scale applications or demonstration projects now, to gain experience and provide feedback to researchers and manufacturers. In retrofitting, look to modular prefabrication strategies that can reduce the time on site and improve quality—successful examples like Energiesprong's panelised facades can be adapted and refined for different contexts. Additionally, practitioners should champion the use of life cycle assessments and environmental product declarations when selecting insulation materials, thereby encouraging suppliers to improve the carbon footprint and transparency of their products. By focusing on not just upfront performance but also long-term operation and maintenance, practitioners will deliver facades that remain efficient and safe for decades.
- For Policymakers and Regulators: Create an enabling environment for innovation in facade insulation through updated building codes, incentives, and R&D support. This could involve introducing progressive performance-based standards that allow novel materials and smart systems as long as they meet safety and efficiency criteria, rather than prescriptive rules that favour the status quo. Implement or enhance subsidy programs and green financing for deep energy retrofits of buildings, thus aligning economic incentives with carbon reduction goals. Support the development of training programs to upskill workers in installing and maintaining advanced facade systems, ensuring that the workforce is ready for the technologies coming to market. At the urban scale, invest in digital twin infrastructure for city planning agencies, so they can simulate the impact of facade upgrades across building stocks and optimise strategies for meeting climate targets. Finally, foster public–private partnerships and living labs where regulatory barriers can be safely relaxed to pilot new facade innovations—the lessons learned will inform more adaptive, forward-looking regulations. By coordinating building energy policies with climate action plans and industry roadmaps, policymakers can accelerate the adoption of facade insulation innovations and guide the transformation of cities towards sustainability and resilience.

In summary, the path forward for facade insulation is one of collaboration and creativity, grounded in scientific rigour and practical insight. The coming era will see facades that are smarter, greener, and more interactive than ever before. By proactively addressing the challenges of scalability, cost, maintenance, and regulation, it can be ensured that these future facade technologies move from vision to reality, fundamentally enhancing both the energy efficiency of buildings and the liveability of urban environments. The facade, once merely the boundary between inside and outside, is poised to become a linchpin of sustainable development, actively contributing to climate change mitigation, adapting to new conditions, and enriching the relationship between people and the built environment in the pursuit of global sustainability goals.

6. Conclusions and Recommendations

Over the course of history, facade insulation has evolved from rudimentary passive techniques into multifunctional, high-performance systems that actively contribute to energy efficiency, thermal comfort, and environmental sustainability. This review has demonstrated that building facades have become key instruments in the transition towards net-zero energy buildings, serving not only as thermal barriers but also as dynamic systems integrating renewable energy generation, environmental responsiveness, and smart technologies. The study's findings affirm that advanced materials such as VIPs, aerogels, and PCMs can drastically reduce heat transfer, while AFs and D-SFSs enhance the building's ability to respond to climatic fluctuations. Additionally, nature-based systems such as green facades and microalgae-integrated PBRs offer synergistic benefits in terms of thermal regulation, carbon sequestration, and urban resilience. Despite these technological strides, retrofitting existing buildings remains a key challenge due to structural limitations and economic constraints. Cuce and Riffat [195] further underscore this challenge, emphasising that the performance of heat recovery systems depends heavily on proper insulation and airtightness and that these systems can offer significant reductions in both energy demands and greenhouse gas emissions when well-integrated. The regulatory barriers, high initial costs, and a lack of standardisation hinder the widespread implementation of intelligent and energy-generating facades. Therefore, there is an urgent need to align technical innovation with supportive policies, financial incentives, and scalable retrofitting strategies. Looking forward, facade insulation systems must strike a balance among performance, sustainability, and affordability. The integration of IoT-enabled climate control, adaptive glazing, and bio-integrated systems opens promising pathways for future research and application. In this context, Cuce and Riffat [196] identified evaporative cooling systems as particularly promising in arid climates due to their high energy efficiency, low cost, and potential to reduce both operational energy use and emissions. Emphasis should also be placed on the lifecycle impact, recyclability, and embodied energy of insulation materials to ensure holistic environmental benefits. Cuce [197] demonstrated experimentally that desiccant-based evaporative cooling systems can reduce supply air temperature by over 5 °C while achieving a high dehumidification effectiveness, providing a cost-effective, environmentally friendly solution for humid climates. Ultimately, the transformation of facades into intelligent, responsive, and energy-positive building elements signifies a paradigm shift in sustainable construction. Cuce and Cuce [198] further support this trajectory, having shown that low-cost polycarbonate-based heat recovery systems applied to residential retrofits effectively stabilise indoor CO_2 levels and humidity, highlighting their practical and accessible contribution to indoor environmental quality. By bridging historical wisdom with state-of-the-art innovations, next-generation facades can actively shape low-carbon urban environments and support global decarbonisation targets.

Recommendations for Future Research and Implementation

Affordable retrofit solutions: Develop non-invasive and low-cost insulation technologies, particularly for older building stocks, including thin-film applications and prefabricated panels.

Smart facade integration: Enhance AFs by incorporating real-time environmental data, AI-driven predictive controls, and responsive materials.

Material innovations: Invest in the development of bio-based, self-healing, and carbon-negative insulation materials aligned with circular economy principles.

Urban sustainability: Expand the use of green facades and living walls, focusing on climate-specific vegetation, water efficiency, and biodiversity.

Energy-generating envelopes: Further explore PV-integrated facades, including perovskite-based technologies, to increase energy self-sufficiency.

Regulatory alignment: Implement stricter insulation standards, revise outdated codes, and introduce tax credits or subsidies for sustainable retrofits.

Lifecycle analysis protocols: Standardise environmental impact assessment methodologies for facade materials across their entire service life.

Design and performance guidelines: Establish internationally accepted benchmarks for evaluating dynamic facade systems under varied climatic and operational conditions.

Digital twin and BIM integration: Promote the use of simulation-based tools to optimise facade performance pre-construction.

Cross-disciplinary collaboration: Encourage joint efforts among architects, engineers, biologists, and policymakers to create innovative and context-sensitive insulation strategies.

As the global push for sustainable and energy-efficient buildings intensifies, the importance of advanced facade insulation technologies will continue to grow. The integration of high-performance materials, adaptive systems, and energy-generating facades offers a promising pathway towards achieving carbon neutrality while maintaining architectural flexibility and aesthetic value. By addressing current challenges and embracing technological innovations, future building facades can serve not only as thermal regulators but as intelligent, energy-efficient, and environmentally responsive elements of urban infrastructure.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created.

Conflicts of Interest: The author declares no conflict of interest.

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