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Smart 3D-printed facades: a review of innovations, materials, and sustainable performance

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The construction industry faces increasing pressure to enhance energy efficiency, improve occupant comfort, and promote environmental sustainability. Smart 3D-printed facades represent a promising avenue for addressing these challenges, offering the potential for innovative architectural designs with enhanced performance characteristics. This paper is a narrative review examining the landscape of smart 3D-printed facade research between 2015 and 2025, analysing 76 relevant publications. There are significant advancements in material science, 3D printing techniques, and the integration of smart technologies into facade design. These developments demonstrate a notable capacity for improved energy performance and design flexibility. Specifically, 3D printing enables the creation of complex facade geometries, providing unprecedented design freedom and functional integration. The selection of sustainable and high-performance materials is crucial for optimizing energy efficiency, durability, and environmental impact. Furthermore, the integration of sensors, actuators, and AI-driven control systems allows for the creation of responsive facades that can dynamically adapt to environmental conditions and occupant needs. Critical challenges persist, including concerns regarding long-term durability, cost-effectiveness, scalability for large-scale applications, and the establishment of standardized testing and certification procedures. Future research should prioritize comprehensive lifecycle assessments to quantify environmental impacts and focus on developing robust material performance models under diverse climatic conditions. This will pave the way for the widespread adoption of this transformative technology in the built environment.

KEYWORDS

smart facades, 3D printing, sustainable architecture, energy efficiency, additive manufacturing

1 Introduction

This paper presents a narrative review of existing literature on smart 3D-printed facades. A narrative review approach was chosen to synthesize a broad range of qualitative and conceptual insights, identify key trends, and highlight critical research gaps in this interdisciplinary and emerging field. Unlike systematic reviews, this approach aims to provide a comprehensive overview of the state-of-the-art, challenges, and future potential of smart, 3D-printed facades by exploring diverse perspectives, technologies, and applications. While systematic reviews employ pre-defined search terms and rigorous inclusion/exclusion criteria, this narrative review offers a broader scope, allowing for the identification of nuanced research gaps. To maintain rigor, the literature search was conducted across reputable databases using

relevant keywords, and the selection of studies was based on their relevance to the research questions.

The article is structured as follows: Section 1 introduces the role of smart facades in addressing modern architectural and environmental challenges, as illustrated in [Figure 1](#), highlighting energy efficiency, user comfort, sustainability, and architectural aesthetics as key drivers. Section 1.3 details the specific objectives and methodology employed in this exploration. Section 2 defines the Definition and Characteristics in smart facades, integrating literature reviews and conceptual frameworks to explore the novel categorization. Section 3 presents Results and a structured examination of smart facades. 3D Printing Technology (Section 3.3): Discusses a detailed examination of 3D printing technology and its transformative impact on the construction industry follows. The speed, efficiency, cost reduction, and design flexibility offered by 3D printing are discussed, and gaps in understanding the sustainability and economic efficiency of materials used in this process are identified. Relevant Experimental Research (Section 3.4): A comprehensive review of experimental research and case studies related to energy performance and durability is presented. This section examines various testing methods and results, including energy performance metrics, durability and strength tests, innovations, and discoveries in the field. Key gaps in research, such as the long-term effects of environmental stress conditions on facade materials, are also highlighted. Innovations and Discoveries in the Field (Section 3.4.3): Discussing recent innovations. Comparison of Different Methods of Making Smart Facades (Section 3.4.4): Providing an overview of various technologies used in responsive facade systems, categorizing them. The Impact of Smart Facades (Section

3.5): This section assesses the ecological benefits of smart facades. Discussion (Section 4): Key findings and synthesis.

Prioritized Recommendations for Future Research (Section 4.2). Conclusions (Section 5): The main findings of the review are summarized, key challenges and opportunities are identified, and potential avenues for future research are discussed. This includes exploring the long-term durability of materials, integrating advanced sensors and actuators, and addressing regulatory and standardization challenges.

Through this systematic exploration, this review aims to provide a comprehensive understanding of the current state-of-the-art, challenges, and future potential of smart 3D-printed facades in driving sustainable architectural practices and in creating more resilient, energyefficient, and human-centric buildings.

1.1 The importance of SMART facades in architecture

Smart facades are now essential in contemporary architecture, influencing both aesthetics and building performance. Integrating advanced technologies, they offer solutions for sustainability and energy efficiency. As shown in [Table 1](#), smart facades vary in type, each with unique advantages. Adaptive facades adjust to environmental conditions to improve energy efficiency. Dynamic facades use movable elements to improve comfort and aesthetics. Photovoltaic facades generate renewable energy and reduce carbon footprint. These approaches demonstrate the versatility of smart facades.

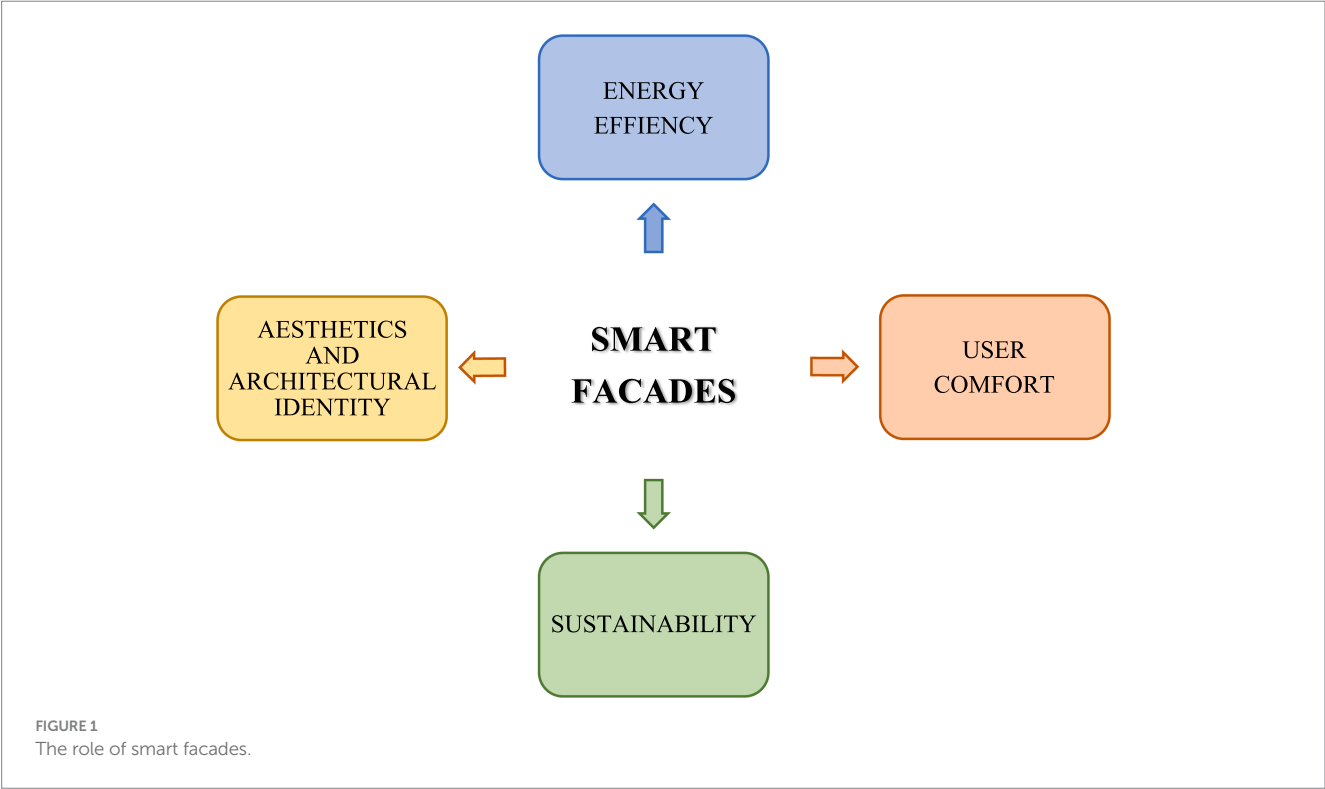


TABLE 1 Comparison of smart facade types.

Type	Characteristics	Advantages	Applications
Adaptive facades	Changes properties based on environmental conditions	Improves energy efficiency, responds to user needs	Commercial and residential buildings
Dynamic facades	Incorporates movable elements for adjusting thermal performance	Enhances user comfort, improves aesthetics	All building types
Photovoltaic facades	Integrates solar panels into the facade	Generates renewable energy, reduces carbon footprint	Buildings with high solar exposure

TABLE 2 Energy performance metrics.

Study	Technology used	Energy savings (%)	Context/conditions
Claros-Marfil et al. (2025)	Water-flow glazing (WFG)	60%	Adaptive facade under solar radiation
Wang et al. (2024)	Dynamic facade (DF)	10–50%	Varied climatic conditions
Barone et al. (2022)	Concentrating photovoltaic glazing	30–60%	Various climate zones

Despite advances, more evaluation is needed on the long-term impact of smart facades on energy efficiency, user comfort, and diverse architectural integration.

1.1.1 Energy efficiency

The building sector is a significant contributor to global energy consumption, with heating and cooling representing major energy demands. Studies indicate that smart, adaptive facades can improve energy efficiency. For example, Claros-Marfil et al. (2025) demonstrated that adaptive facades with smart-controlled water-flow glazing (WFG) reduced indoor temperatures and achieved energy savings. This research suggests the need for further optimization of control algorithms and integration of WFG facades with building climate control systems, and also highlights the importance of long-term performance and cost-effectiveness evaluations.

Given the urgency of addressing climate change, the building sector’s energy consumption necessitates innovative efficiency strategies. A review of dynamic facade (DF) typologies for zero-energy buildings by Wang et al. (2024) found that DFs can reduce energy use by 10–50% and improve comfort by approximately 80% (Wang et al., 2024, p. 1). Although machine learning (ML) is increasingly employed in DF control, further research is warranted on advanced ML algorithms and human-centered strategies.

Minimizing environmental impact is also crucial for the building sector’s energy consumption. Tahmasbi et al. (2025) reviewed energy-efficient facade technologies such as adaptive, double-skin, and photovoltaic-integrated designs. Their analysis highlights the reduction of energy consumption and carbon emissions achieved by these facades, noting the potential of smart materials. The review also acknowledges challenges related to cost-effectiveness, structural integration, and comfort, suggesting the importance of both passive and active systems for maximizing efficiency.

Innovative designs are essential to meet the global demand for efficient buildings. Barone et al. (2022) presented Concentrating Photovoltaic Glazing (CoPVG) as a method to improve facade efficiency. Simulations indicated substantial energy savings (30–60%) compared to conventional systems (Barone et al., 2022, p. 1). The CoPVG system dynamically adjusts to solar angles, generating

electricity and enhancing insulation; however, further optimization and sustainability assessments are necessary. Table 2 summarizes that Claros-Marfil et al. (2025, p.2, paragraph 1) reported 60% energy savings with Water-Flow Glazing (WFG), while Wang et al. (2024) reported 10–50% savings with Dynamic Facades (DF) (Wang et al., 2024, p. 1). These findings emphasize the importance of both context and technology. Additional research should address durability, cost-effectiveness, and control algorithm optimization.

1.1.2 User comfort

Although smart technologies offer the potential for energy efficiency, user acceptance and comfort are critical for their successful adoption. De la Barra et al. (2025) investigated user interaction with fast-switching smart glazing, focusing on the impact of transition speed and direction under overcast conditions. Their findings indicated that while user perception remained consistent regardless of speed, override behavior was significantly influenced by both factors. Specifically, a higher frequency of overrides was observed during transitions from dark states, and accelerated speeds correlated with increased overrides. Moreover, negative perceptions were reported by users who overrode the system, suggesting that transparency changes can impact user comfort and emphasize the importance of usercentered design. As illustrated in Table 3, fast-switching glazing achieved a user satisfaction rate of 75% (de la Barra et al., 2025, p.12), while reflective material reached 76% (Rizi and Eltaweel, 2019, p.15). Future research should further explore user preferences and effective adaptive control strategies.

1.1.3 Sustainability

The significant environmental impact of the construction industry necessitates the adoption of sustainable building practices. In response, Balali and Valipour (2020) focused on smart materials for facades, aligning their research with the UN Sustainable Development Goals (SDGs). By employing the Friedman test and Analytic Hierarchy Process (AHP), they prioritized materials based on performance, feasibility, acceptance, impact, and efficiency, highlighting photovoltaic, thermochromic, and photostrictive materials for Shiraz, Iran. As summarized in Table 4, these materials exhibit distinct performance characteristics, cost profiles, and

TABLE 3 Impacts of smart glazing on user comfort.

Study	Technology used	User satisfaction rating (%)
de la Barra et al. (2025)	Fast-switching smart glazing	75%
Rizi and Eltaweel (2019)	Double-sided reflective material	76%

TABLE 4 Comparative assessment of smart materials.

Material	Performance characteristics	Cost-effectiveness	Environmental impact
Photovoltaic	Generates electricity	Moderate	Low (renewable source)
Thermochromic	Changes color with temperature	High	Medium
Photo-responsive	Adjusts to light exposure	Moderate	Low

environmental impacts. For instance, they allow for electricity generation and adjustable light exposure. This approach emphasizes broader sustainability considerations beyond mere energy efficiency, advocating for a holistic perspective.

The design of tall buildings increasingly necessitates prioritizing both resilience and sustainability. Jafari and Alipour (2021) reviewed smart facades for aerodynamic performance, focusing on adaptive systems designed to mitigate wind-induced vibrations through shape modifications and bio-inspired designs. They found that integrating these systems with smart technologies creates dynamic facades that enhance structural performance, energy savings, and community resilience.

Tahmasbi et al. (2025) conducted a comprehensive review of innovative technologies for energy-efficient facades. Their analysis highlighted the role of facades in environmental interaction and carbon footprint reduction through adaptive, double-skin, and photovoltaic-integrated designs. The review further emphasized the importance of lifecycle assessment (LCA), cost-effectiveness, and occupant comfort, while also identifying key challenges such as cost and durability. This underscores the need for further research aimed at optimizing these technologies.

Integrated methods are needed that combine energy efficiency with a holistic approach to sustainability, taking into account social and economic factors.

1.1.4 Aesthetics and architectural identity

Sustainable building practices frequently necessitate innovative techniques which challenge traditional aesthetics. Na et al. (2022) addressed this challenge with a Smart Node system for irregular facades constructed via additive manufacturing (3D printing). Although primarily focusing on structural challenges, the authors also highlighted aesthetic implications. The Smart Node system, implemented in the Galleria Department Store, creates a striking curtain wall, demonstrating the potential of additive manufacturing to achieve both functional and aesthetic goals. However, further research is needed to explore broader aesthetic implications, particularly concerning scalability and adaptability. Balancing innovation with architectural expression remains a critical consideration.

Smart facades integrate technology and aesthetics to create efficient, comfortable, and sustainable buildings. Their importance has grown, offering benefits to both users and the environment. Ongoing innovations are redefining our interaction with built spaces, underscoring the need for continued research in this area.

Further research is warranted to fully explore the aesthetic implications of emerging technologies and their adaptability across diverse architectural styles.

Following this introduction, the paper proceeds with a structured exploration of the topic. The concept of smart facades will be defined, accompanied by a categorization of different types as shown in Table 1 and their operating principles. 3D printing technology will then be examined, including materials, processes, and construction advantages. Existing experimental research and case studies are reviewed, focusing on performance metrics as presented in Table 2 and innovative applications. Subsequently, the ecological benefits and impacts on user comfort, explored in relation to green facade challenges in Table 3 and energy efficiency technologies presented in Table 4, will be assessed. The paper concludes with a synthesis of key findings, a discussion of current challenges, and prioritized recommendations for future research.

1.2 3D printing technology and its impact on the construction industry

3D printing is transforming the construction industry, offering significant advantages in speed, cost, and design. Table 5 highlights its impact on speed, cost, and design. For instance, 3D printing reduces construction time through automation, offers material and labor savings, and enables complex geometries. Here’s a more detailed overview.

It is important to investigate the sustainability and economic efficiency aspects of materials used in 3D-printed construction, including the logistical and large-scale production challenges. This section will explore these aspects in detail, examining recent studies and innovations in the field.

1.3 Objectives of the review

Building on the specific objectives detailed in Table 6 – which include reviewing research from the last decade, identifying and classifying 3D printing technologies and materials, assessing performance indicators, identifying research gaps, and proposing pathways for future research – the following sections present a comprehensive literature search and analysis, using a narrative approach to summarize the current state of knowledge about facades intelligent 3D printed.

TABLE 5 Speed, efficiency, cost reduction, and design flexibility in 3D printing.

Category	Feature	Description
Speed and efficiency	Rapid construction	3D printing can drastically reduce construction time. Projects that traditionally take months can be completed in a fraction of that time.
	Automation	With automated processes, 3d printers can work around the clock, further accelerating project timelines.
Cost reduction	Material savings	3d printing uses materials more efficiently, reducing waste associated with traditional construction methods.
	Lower labor costs	The automation involved in 3d printing can lead to reduced labor requirements, saving costs on workforce expenses.
Design flexibility	Complex geometries	3d printing allows for the creation of intricate and customized designs that would be difficult or impossible to achieve with conventional methods.
	Innovative structures	Architects and engineers can experiment with new shapes and structures, leading to more sustainable and aesthetically appealing buildings.

TABLE 6 Objectives of the review.

Literature overview	To provide a comprehensive overview of the current state of research on 3D printed intelligent facades over the last decade, highlighting key advancements and trends.
Identifying technologies	To identify and categorize the various 3D printing technologies and materials used in the fabrication of intelligent facades.
Assessment of performance	To evaluate the performance metrics of 3D printed intelligent facades in terms of energy efficiency, sustainability, and user comfort.
Research gaps	To identify gaps in the existing research literature and underline areas where further experimental research is needed to advance this field.
Future directions	To propose avenues for future research and potential applications in the design and implementation of intelligent facades using 3D printing technology.

TABLE 7 Databases used for literature search.

Database	Rationale	Keywords used	Link
Scopus	Broad coverage of peer-reviewed literature in science, technology, engineering, and medicine.	Smart façade; 3D printing	[https://www.scopus.com/home.uri]
Web of Science	Comprehensive database with a focus on high-impact research across a variety of disciplines.	Sustainable architecture; Energy efficiency.	[https://www.webofscience.com/wos/]
Google Scholar	Wide-ranging coverage including scholarly literature, theses, preprints, and grey literature.	Additive manufacturing; building performance.	[https://scholar.google.com]
Frontiers	Open access publisher with a focus on science, technology, and medicine, covering a broad spectrum of research topics.	Smart building; sustainable cities.	[https://www.frontiersin.org/]

2 Methodology

To achieve these objectives, this review adopts a narrative approach to synthesize the current state of knowledge. While not strictly systematic, a comprehensive literature search was conducted to provide a broad overview of the topic. Table 7 summarizes the key databases used in this search, including Scopus, Web of Science, Google Scholar, and Frontiers, each chosen for their specific strengths in covering relevant scholarly literature. Search terms included variations and combinations of ‘smart facade,’ ‘3D printing,’ ‘additive manufacturing,’ ‘sustainable architecture,’ ‘energy efficiency,’ and ‘building performance.’

This review is based on an analysis of 76 publications, including journal articles, conference proceedings, and industry reports. These publications were selected based on their relevance to the topic of smart 3D-printed facades, their publication date (ranging from 2015 to 2025), and their presence in reputable academic databases.

The literature search was primarily conducted using the following databases: Scopus, Web of Science, Google Scholar, and Frontiers. These databases were selected for their comprehensive coverage of peer-reviewed literature in science, technology, engineering, and medicine, as well as their inclusion of conference proceedings, theses, preprints, and grey literature relevant to the topic. Finally, the bibliographies of relevant review articles and key publications were manually screened to identify additional sources.

Inclusion criteria focused on peer-reviewed journal articles, conference proceedings, and reputable industry reports published between 2015 and 2025, which provide a contemporary view of the rapidly evolving field. Exclusion criteria encompassed articles not written in English, those lacking relevance to the central theme of 3D-printed smart facades, and publications of questionable scholarly rigor.

This narrative review approach was chosen to allow for a broad exploration of diverse perspectives, technologies, and applications

within the field. While systematic reviews offer a more structured and quantitative analysis, a narrative approach is well-suited for synthesizing a wide range of qualitative and conceptual insights, identifying key trends, and highlighting critical research gaps. This approach allows for a flexible and iterative exploration of the literature, capturing the nuanced and interdisciplinary nature of this emerging field.

Identifying and analysing the detailed gaps in the existing research literature needs more extensive studies that highlight the specifics of the field and propose innovative solutions for the development of intelligent facades. Having explored the concept of smart facades in broad terms, defining their characteristics and highlighting different approaches to achieving smartness, let us now delve into the specific types of smart facades that are emerging as prominent solutions for building design and construction.

3 Results

3.1 Definition and characteristics

Attia et al. (2020) investigated adaptive facade technologies, employing literature review, expert interviews, and content analysis to overcome conventional review limitations. The study defined four categories: dynamic shadings, chromogenic, solar active, and active ventilative facades (AVFs). They developed a conceptual framework, identifying human-centred design, smart systems, service-driven solutions, circularity, and material science as key technological drivers, also highlighting multifunctionality and performance requisites. This study offers a novel categorization and framework articulating adaptive facade performance. Further exploration is needed on their implementation in diverse contexts and on understanding the limitations of categorization frameworks.

The Impact of the use of Smart Materials on the Facades of Contemporary Buildings (Sayed El Falafli, 2021) explores using smart materials to create responsive facades, including double-skin, interactive, and kinetic types, enhancing energy efficiency and aesthetics. Analysing projects in the Arabian Gulf, the research highlights environmental and technological impacts, emphasizing the potential for architects to improve designs. Long-term performance and durability in different climates require further investigation.

Saidam et al. (2017) synthesized research on integrating advanced materials in facades, focusing on a conceptual framework. Smart facades integrate materials and technologies for dynamic building envelopes, optimizing efficiency, comfort, and flexibility through responsive shading, photovoltaics, and dynamic insulation, enabling sustainable and responsive built environments. Systematic research is needed to evaluate their effectiveness across building types and establish benchmarks for smart materials.

As explored in what is an Adaptive Façade? (Romano et al., 2018), smart facades are gaining attention in sustainable building design. They represent a significant advancement, offering dynamic capabilities beyond static envelopes via IT systems, actuators, and materials. These facades adapt to changing conditions, optimizing energy and comfort, and enabling buildings to interact, regulate

energy, and contribute to sustainability. Investigating feasibility and user acceptance remains critical, as does examining effectiveness in different settings.

Attia (2018) posits that smart sensors with microprocessors and wireless networks can transform dynamic facade monitoring. The review indicates networked systems can surpass milestones in the information revolution, promising enhanced environments, user interaction, and occupant empowerment. More studies are needed on integrating sensing technologies and their real-world implications.

Smart Facades for Non-Residential Buildings: An Assessment (Panopoulos and Papadopoulos, 2017) assesses facade retrofitting techniques to achieve near Zero-Energy Building status. Reviewing smart facade technologies, the research highlights the benefits and challenges of energy upgrades.

While retrofits cannot alone achieve ZEB, they reduce emissions and align with environmental objectives. The study underscores climatic challenges in southeastern Europe and the Mediterranean. Further research is needed on performance challenges in diverse climates and tailored retrofitting strategies.

Smart facades, as explored in Advanced Techniques in Design Openings of Smart Facades in Buildings (Alsarraf and Alobaidi, 2020) integrate advanced technologies for energy efficiency and performance, utilizing dynamic systems, nanotechnology, and smart materials to respond to conditions, enhance comfort, and reduce consumption via dynamic openings, nanomaterial coatings, and systems adapting to wind/light. This integration aims to create sustainable and aesthetically pleasing buildings, marking a significant advancement. Future studies should quantify environmental benefits and explore aesthetic impacts.

3.2 Types of smart facades

3.2.1 Adaptive facades

Tabadkani et al. (2019) suggest adaptive facades enhance building performance and comfort in sustainable architecture. These dynamic envelopes modulate interactions, optimizing solar heat gain and promoting ventilation. Empirical studies show buildings significantly impact energy consumption, facades mediating thermal transfer. Adaptive Solar Facades (ASFs) offer solutions, mediating environments and providing indoor comfort without excessive consumption. Transformable shading enhances aesthetics, improves insulation, optimizes daylight, and improves energy consumption. Empirical studies are needed to assess real-world impacts on energy and comfort.

Progressive Trend in Adaptive Façade System Technology: A Review (Korniyenko, 2021) highlights adaptive facades as enhancing building efficiency and comfort. The review categorizes key technologies: climate adaptive building skins (CABS), smart glazing (SGFS), biomimetic skins (Bio-ABS), vertical greenery systems (VGS), pneumatic facades (PBFs), kinetic facades (KFs), electrokinetic pixel glazing (EPGFs), and HVAC-integrated facades. Despite benefits, challenges remain in cost, maintenance, and standardized evaluation. Ongoing research is essential.

Progressive Trend in Adaptive Façade System Technology: A Review (Zhang et al., 2022) highlights adaptive facades as enhancing building efficiency and comfort. This review classifies technologies

including climate adaptive building skins (CABS), smart glazing facade systems (SGFS), biomimetic adaptive building skins (Bio-ABS), vertical greenery systems (VGS), pneumatic building facades (PBFs), kinetic facades (KFs), electrokinetic pixel glazing facade systems (EPGFs), and facades enhanced with HVAC and electrical systems. While each technology offers unique benefits, challenges remain in terms of cost, maintenance, and their standardized performance assessment. Further research and development are needed to overcome these barriers and fully realize the potential of adaptive façades in creating sustainable and high-performance buildings.

Adaptive Façades: Review of Designs, Performance Evaluation, and Control Systems (Attia et al., 2015) examines adaptive facades (AFs) and factors hindering adoption. The study identifies limited commercial technology, unreliable data, and varying criteria hindering use. Future research should lower costs, retrofit buildings, create assessment tools, and establish uniform standards to improve implementation. Future research should focus on developing robust evaluation criteria and cost-effective retrofitting methods to facilitate the integration of adaptive facades in existing buildings.

3.2.2 Environmental responsive facades

Heidari Matin and Eydgahi (2022) explored responsive facade systems since the 1960s, focusing on control, sensing, and actuation. The authors categorize five technologies: mechanical, electro-mechanical, passive, IT, and advanced material tech. Comparative analysis informs an integrated technological framework. Identified research gaps include the necessity for more comprehensive investigations into the efficacy of diverse technologies across varying climatic contexts and the development of integrated systems that harness the optimal attributes of each technology.

Carlucci (2021) reviewed responsive technologies for high-performance buildings, emphasizing building envelopes. The study overviews energy landscape, adaptive technologies, terminology, and classification frameworks, including phase change materials, switchable glazing, and dynamic shading systems, improving efficiency and indoor quality. The study underscores the paradigm shift from static to dynamic building elements. There is a need for additional research into the interactions between responsive facade technologies and other building systems to fully optimize their performance.

Environmentally Responsive Kinetic Façade for Educational Buildings (Cho, 2019) explores sustainable development in educational buildings and proposes a kinetic façade employing mechanical moveable components, meeting aesthetic/functional needs by regulating temperature/sun penetration. The paper presents a curtain wall system, detailing the transformation mechanism, components, construction plans, and materials, aligning with architectural principles while respecting user needs and sustainability. Future studies should evaluate kinetic facades' costs and benefits in educational settings.

Comparative Analysis of Technologies Used in Responsive Building Facades (Matin et al., 2017) studies responsive facade technologies since the 1960s, identifying five categories: Mechanical, Electro-Mechanical, Passive, IT, and Advanced Material Technology. The paper examines the benefits/drawbacks associated with each category, highlighting the transition from active to passive technologies and emphasizing integrated systems. These integrated

systems combine electro-mechanical, informational, and material-based technologies, improving responsiveness and control. Research should explore the practical challenges of integrating technologies, particularly regarding costs, maintenance, and scalability.

Biomimetic Design for Adaptive Building Façades: A Paradigm Shift toward Environmentally Conscious Architecture (Faragalla and Asadi, 2022) investigates biomimetic design for adaptive building facades, highlighting the transition toward sustainable practices. It examines how biomimicry inspires sustainable facade systems minimizing energy consumption and enhancing comfort, delving into biomimetic approaches, methodologies, and materials addressing environmental challenges. Through case studies, the paper offers insights into biomimicry's implementation in building facades that are visually appealing, environmentally responsible, and functionally efficient. Additional studies are required to quantify biomimetic facade designs' environmental advantages, performance results, adaptability, and resilience in urban settings.

This study introduces Development of a performance-based design framework for multifunctional climate-responsive façades (Soudian and Berardi, 2021) for Climate-Responsive Facades (CRFs), facilitating their development by structuring the selection of technologies and creating conceptual layouts. Verified through transparent and opaque CRF modules in Toronto, Canada, the framework demonstrates applicability in decision-making, offering a generalizable approach adjusted based on criteria to promote integrating CRFs. Future work should validate this framework, examining effectiveness in real-world scenarios to enhance decision-making.

Abdelwahed Mekhamar and Halim Hussein (2021) provide an analysis of climate-responsive facades and kinetic applications, underscoring their evolution from passive components to adaptive systems. The authors categorize kinetic facades according to solar radiation and natural airflows, exploring strategies including building movement, adaptable shading, and kinetic shading with photovoltaics/wind energy collectors. The study highlights the capability of adaptive architecture/responsive facades to reduce energy consumption and improve environmental quality, while recognizing challenges. Research gaps identified more lifecycle/maintenance investigations, aiming to surmount implementation impediments and ensure sustainability.

In D1244: Design and Construction of the First Adaptive High-Rise Experimental Building, (Blandini et al., 2022) adaptive facades are explored to dynamically respond to weather/user needs, enhancing comfort. Research focuses on adjusting transparency, reflectivity, insulation, and acoustics, offering new architectural possibilities. The D1244 project will install adaptive facades in upper floors in 2022, testing glass units, ETFE, and textile-based hydroactive systems, collaborating with manufacturers.

Design and Control of Adaptive Civil Structures (Senatore and Smith, 2021) explores how buildings adapt to loading events/environmental changes through sensing and actuation. Adaptive facades can integrate electroactive polymer actuators (IEPA) in membrane skins to control ventilation/humidity and function as load sensors, allowing structural modification for control objectives, reducing material usage and environmental impact. Having outlined the concept and types of smart facades, along with technologies used

to manipulate and control them, the following section will delve into 3D-Printing technologies and the advantages of this process.

3.3 3D printing technology

3.3.1 The 3D printing process

Shahrubudin et al. (2019) explain that 3D printing, or additive manufacturing, facilitates object fabrication from geometrical data through material deposition. It has seen exponential growth, extensively implemented across healthcare, automotive, aerospace, and the food sector. The 3D printing process entails layer-by-layer deposition from a CAD model, providing a versatile manufacturing paradigm. Further studies are needed to explore the integration of advanced 3D printing technologies in various construction applications, particularly standardization and regulation.

Kumar (2022) defines 3D printing, or additive manufacturing (AM), as a process for fabricating three-dimensional objects of arbitrary geometry from digital models. This is accomplished through sequential material layer deposition under computer control. A 3D model necessitates processing by a slicer to translate it into thin layers and generate machine instructions. The 3D printer then executes these, depositing layers to construct the model from cross-sectional slices. Research should focus on optimizing the 'slicing' process for unique designs and assessing the impact of different printing methods on the quality and durability of printed objects.

Ramya and Vanapalli (2016) asserts 3D printing has materialized as a transformative paradigm in contemporary manufacturing, transitioning from rapid prototyping to the fabrication of bespoke components across industrial sectors. The 3D printing process facilitates creation of intricate structures. Technologies like SLA, FDM, and SLS cater to different material and application needs. Industrial sectors are capitalizing on 3D printing for rapid prototyping, tooling, and the production of customized products, thereby fostering innovation and augmenting efficiency. More detailed evaluations of how each technology performs under various conditions and applications are necessary to establish best practices and guidelines for specific industries.

Additive manufacturing, commonly referred to as 3D printing technology, has instigated a paradigm shift across numerous industrial sectors by facilitating the fabrication of intricate three-dimensional objects from digital design specifications. Kamran and Saxena (2016) provide a detailed examination of the 3D printing process, presenting advantages over conventional manufacturing: enhanced design flexibility, customization, and resource efficiency. The paper explores the fundamental principles governing 3D printing, its diverse applications, and technological advancements shaping manufacturing. Exploring the environmental impacts of different 3D printing materials and the long-term economic effects of widespread adoption of this technology in construction is critical.

3D Printing - A Review of Processes, Materials and Applications in Industry 4.0 (Jandyal et al., 2022) offers a detailed examination, highlighting it as an effective technology for creating engineering components. Unlike its subtractive counterpart, 3D printing significantly reduces material waste, minimizes labor, demands less post-processing, and is generally more energy-efficient. The paper explores various 3D printing processes, assessing their individual advantages and drawbacks, and materials suitable for each process.

Additionally, the paper addresses how 3D printing fits into Industry 4.0, emphasizing its capacity to facilitate automation and promote smart material development. Despite advancements, challenges such as material incompatibility and cost issues remain. Future research should aim at adapting and innovating processes to accommodate a wider array of materials and lower production costs. There is a need for research addressing challenges such as material compatibility and ongoing cost issues associated with scaling up production for industrial applications.

3.3.2 Materials used in façade printing

Grassi et al. (2019) investigated using additive manufacturing for desert climate facade design, underscoring 3D printing's versatility and efficiency but emphasizing material durability. Detailing a design-to-production workflow for an Expo 2020 pavilion shading system, the study rigorously tested polymers, proving pivotal in refining the manufacturing protocol. The project highlights additive manufacturing's significance in realizing complex morphologies for temporary structures, contributing substantially to contemporary architectural praxis. Long-term material durability and performance degradation require assessment for practical implementation.

Sarakinioti et al. (2018) explored additive manufacturing's transformative potential for future building design, underscoring its enhanced design flexibility, geometric complexity, and material optimization. Focusing on building facades, the SPONG3D project aims to produce a 3D-printed façade panel insulating and incorporating heat storage, involving design iterations and testing. The prototypes demonstrate integrating multiple functions, revealing material performance challenges and the need for larger-scale printing. Employing Fused Deposition Modelling (FDM), the authors explored printing parameters, showcasing AM's potential to innovate facade design while aligning with energy-efficient architecture. Further research is required to evaluate how complex geometries can be optimized for thermal performance and what challenges arise during their fabrication and implementation.

Printing thermal performance: an experimental exploration of 3DP polymers for facade applications (Piccioni et al., 2023) explores using 3D-printed polymers to create energy-efficient facade components, focusing on how their geometry affects thermal insulation properties. A series of prototypes were fabricated via robotic polymer extrusion, and their thermal properties were quantified. The data was used to calibrate a heat transfer simulation model, enabling a thorough understanding of conduction, convection, and radiation. The study elucidates producing polymer components with variable thermal transmittance via manipulation of internal cavity distribution and dimensional parameters. This furnishes insights into the large-scale thermal performance of polymer-based 3D-printed facades, positing that additive manufacturing demonstrates potential for high-performance, low-energy elements. Additional studies are necessary to assess the long-term thermal performance of different polymer compositions under various operating conditions.

An Overview of Transparent and Translucent 3D-Printed Façade Prototypes and Technologies (Ghasemieshkaftaki et al., 2021) discusses materials for transparency and functionality. PETG stands out for recyclability, strength, and high solar light transmission, suitable for adaptive systems. PLA is also utilized, but transparency can vary. PMMA offers clearer prints in various

colours. VeroClear resin is employed in Polyjet printing for water and heat resistance. Additionally, materials like ABS and Polycarbonate (PC), along with clear resins in SLA 3D-printing, are used, each requiring specific post-processing for optimal transparency. More research should focus on the performance characteristics of these materials in different environmental settings.

In Prototyping of 4D-printed self-shaping building skin in architecture (Yi and Kim, 2021), the focus shifts to smart materials and 4D printing for adaptive building skins. This research investigates thermo-responsive shape-memory composites (SMCs), incorporating programmed shape-memory alloy (SMA) fibres along with a 3D-printed shape-memory polymer (SMP) matrix. The resulting bidirectional motion allows for climate adaptation. While the study highlights the potential of these materials, it acknowledges limitations in technology and material development for large-scale applications, emphasizing the need for further research and substantiated engineering methods. The scalability of 4D printing technology and its integration into existing building practices warrant further exploration to fully understand its practical implications and effectiveness.

In their article 3D printing of earth-based materials: Processing aspects, published in Perrot et al. (2018) investigate the potential of adapting 3D printing techniques for earth-based construction. Recognizing the growing interest in earth-based materials due to their low environmental impact, the authors sought to address limitations such as slow production rates. They combined traditional earth materials with a fast-setting alginate binder to improve the material's green strength and enable 3D printing. The study details the mix design, including the use of fine soil and alginate powder, as well as the testing methods employed to assess workability, yield stress, and compressive strength. The findings demonstrate the feasibility of printing earth-based mortars and highlight the importance of balancing rheological properties for pumpability and structural stability. Ultimately, this research contributes to the growing body of knowledge on sustainable construction methods by exploring innovative applications of additive manufacturing with readily available and environmentally friendly materials.

In their paper 3D Printing Self-Shading Wall Structure With Earth: Enhancing thermal properties in Earthen Architecture through Computational tool path design, inspired by nature & vernacular architecture (Tohidi et al., 2024) present a compelling exploration of sustainable building practices. They detail a project aimed at rethinking housing solutions through the lens of vernacular architecture, biomimicry, and 3D printing with local earthen materials. Key to their approach is the application of an action research methodology to design and fabricate a self-shading wall, leveraging computational tools to optimize the design and enable building-scale additive manufacturing. The research identifies and addresses critical aspects including material selection, structural integrity, thermodynamics, airflow, and aesthetics. The authors showcase the potential of integrating traditional building knowledge with advanced digital design and fabrication techniques, paving the way for sustainable, affordable, and environmentally responsive earthen structures.

In Machine Use and Digitalization in Earth Building Production, Nayir and Erbil (2024) explore contemporary innovative 3D

technologies and machinery, which have been seen as essential to the evolution of green infrastructure and architecture, specifically facade construction. The paper provides an overview of the methodologies used in the article, while highlighting the challenges with the proposed design to be undertaken by the community.

Moreover, Sidorova (2022) demonstrates in Enhancing Aesthetics in Industrial Architecture That 3D printing technology is a transformative force in industrial design and manufacturing. As well, the data shows that a combination of natural materials, and new technologies, as seen in Table 8: Ecological impact of green facades can work in tandem with long-term sustainability.

3.3.3 Advantages of 3D printing in construction

El-Sayegh et al. (2020) note 3D printing is reshaping construction through automation. Faster construction, lower costs (reduced labor and waste), geometric freedom, shorter supply chains, and improved productivity result. Further studies should quantify 3D printing's impact on project timelines and costs vs. traditional methods.

Sakin and Kiroglu (2017) state 3D printing contributes to eco-friendly structures by using sustainable materials and reducing construction's environmental impact. Additive manufacturing minimizes waste and eliminates formwork. Automated tasks create safer construction sites. Socially, 3D printing leads to localized supply chains and new job opportunities. A need exists for in-depth lifecycle assessments of 3D printed elements.

Luneva et al. (2017) claim that modern 3D technologies are evolving rapidly with applications in medicine, engineering, and electronics. Benefits include high precision, rapid production, and decreased manual labor. Civil engineering embraces 3D printing for elements and entire buildings. The exploration encompasses 3D printing technologies, highlighting advantages/drawbacks, applications, and potential. Studies also examine device functionality, materials, reinforcements, and companies. More detailed investigations are necessary to explore barriers in construction, regulatory challenges, workforce training, and perception.

Hager et al. (2016) posit contour crafting, facilitates in-situ fabrication, necessitating a paradigmatic shift in design methodologies, mandating novel materials tailored for 3D printing while addressing sustainability. Realizing complex geometries is a significant advantage. While 3D printing may transform architectural practice, it must prioritize sustainability. Implementation yields reduced costs, sustainable processes, decreased injuries, and substantial time savings. Investigating contour crafting's environmental impacts and material requirements warrants further research.

Sakin and Kiroglu (2017) delineate 3D printing as an emergent construction methodology, emphasizing Contour Crafting's potential to revolutionize construction. The advantages include cost/time reductions, pollution mitigation, and decreased injuries. Integrating Building Information Modelling (BIM) with 3D printing is juxtaposed

TABLE 8 Ecological impact of green facades.

Technology type	Characteristics
Smart materials	Responds to stimuli
Mechanical systems	Automated controls
Passive elements	Utilizes natural resources

against traditional construction. Despite benefits, the study acknowledges limitations. Continuous exploration of BIM and 3D printing is needed to enhance project outcomes. Now that the Advantages and disadvantages have been discussed, let us move into some of the experimental data and review some of the case studies.

3.4 Relevant experimental research

3.4.1 Energy performance experiments

To validate the potential of smart 3D-printed facades, experimental research and case studies are essential. This section presents a comprehensive review of such studies, Ciampi et al. (2021) investigated the energy performance of extruded and 3D-printed polymers in building envelopes. Experimental testing of an ABS panel in a ventilated facade system was followed by numerical modeling. The validated model simulated refurbishment case studies, exploring polymers and manufacturing technologies. The energy performance was assessed in terms of heating/cooling demands and primary energy consumption. Future studies should assess various polymer types across climates and typologies to establish benchmarks.

Spanodimitriou et al. (2025) focused on retrofitting buildings in Italy with a second-skin façade (SSF) system, revealing energy and environmental benefits. The dynamic SSF system outperformed passive retrofits in primary energy saving (PES) and reduced carbon dioxide emissions (ΔCO_2). Dynamic fabric modules result in a PES value of 16.4% and a ΔCO_2 value of 285 tons (Spanodimitriou et al., 2025, Abstract, p.1). These results highlight dynamic SSF potential. Future research should explore SSF performance in diverse climates/ contexts, conduct pilot projects, develop dynamic models incorporating occupant behavior, investigate durability/feasibility, and carry out field surveys for comfort. There is a need for longitudinal studies on dynamic second-skin systems' durability and performance variations under different climatic conditions.

De Rubeis et al. (2024) contributes to research on 3D-printed building components, focusing on energy performance. Reviewing case studies and conducting experiments, the authors explore 3D printing to optimize building envelopes. The research involves designing/testing blocks with varying internal geometries and quantifying heat transfer. As testing methods and results summarized in Table 9 demonstrates, they focused on what conditions affected what the test. This approach provides insights into using 3D printing for energy-efficient solutions.

More research is required to explore internal geometry's implications for thermal performance and the long-term viability of 3D-printed components.

3.4.2 Durability and strength tests

Within Fabrication and durability testing of a 3D printed façade for desert climates (Grassi et al., 2019), the methodology evaluates the feasibility and durability of 3D-printed facades in desert climates. It reviews case studies and experiments utilizing 3D-printed

polymers, involving experimental testing of thermoplastic polymers, including accelerated aging tests. These tests informed material selection and design optimization for a shading system at Expo 2020 in Dubai. Further research should investigate the interaction between different thermoplastic polymers and environmental factors over extended periods to determine their long-term stability and performance.

Within 3D printing facades: Design, fabrication, and assessment methods (Leschok et al., 2023), the analysis focuses on integrating design methodologies with material and fabrication processes. The review highlights the importance of performance assessment, including durability and strength, through simulation and life cycle analysis, emphasizing the need for experimental prototyping. It identifies a gap in standardized testing of full-scale prototypes and the effects of coatings and post-processing on weather resistance. There is a need for standardized testing methodologies for full-scale prototypes and deeper analyses on how surface treatments and post-processing techniques impact durability.

The approach to the revolutionary potential of 3D printed facades requires a complex strategy, as highlighted in Validation of the Performance of 3D Printed Facades: Experimental Research, Review of Case Studies, and Durability Testing (Leschok et al., 2024). This strategy is essential for accurately assessing the thermal and manufacturing properties of 3D printed hollow core elements for lightweight facades. The validation process begins with rigorous experimental research, focusing on the thermal and mechanical properties of printed elements. A review of case studies provides insights, revealing advantages and limitations. Ultimately, durability and strength testing are vital by simulating exposure to environmental stress. This research underscores how innovative Smart Materials such as Bio-based Materials, Phase Change Materials and Nanomaterials are environmentally friendly and sustainable, improve energy storage and temperature regulation and have enhanced properties such as self-cleaning as shown in Table 10. More rigorous longitudinal studies focusing on environmental stress conditions are critical to understanding the long-term functionality and safety of 3D-printed facades, especially under extreme conditions.

3.4.3 Innovations and discoveries in the field

In the article Additive Manufacturing for Future Facades: The potential of 3D printed parts for the building envelope (Strauß and Knaack, 2016) Additive Manufacturing (AM) is highlighted as a transformative technology for facade design and construction, enabling new approaches to engineering, production, and processing. AM facilitates the creation of customized facades just in time eliminating the need for advance production and storage. Design improvements can be realized within the AM part's dataset, allowing for performance re-interpretation based on system demands rather than manufacturing limitations. This opens a new world of engineering possibilities, shifting the focus from design for production to design for function and complementing existing production processes to realize complex, algorithm-based designs with greater

TABLE 9 Case studies on energy performance.

Case study	Façade technology used	Key results	Performance metrics
Ciampi et al. (2021)	3D-Printed Polymers	Improved energy efficiency	Reduced heating/cooling demands
Spanodimitriou et al. (2025, p. 1)	Second-skin façade system	Significant carbon savings	16.4% primary energy savings

TABLE 10 Testing methods and results.

Test	Polymer used	Conditions	Results
Accelerated aging test	Various thermoplastics	High temperature, humidity, UV	Checked for cracking and expansion
Load testing	ABS	Environmental stress	Assessed structural integrity

TABLE 11 Key technologies in smart facade design.

Technology type	Characteristics	Benefits
Smart materials	Responds to stimuli	Enhances building performance
Mechanical systems	Automated controls	Improved functionality
Passive elements	Utilizes natural resources	Low energy consumption

TABLE 12 Innovations in smart materials.

Innovation	Benefits	Research gaps
Bio-based materials	Environmentally friendly and sustainable	Need for performance validation in diverse applications
Phase change materials (PCMs)	Energy storage and temperature regulation	Effects on structural integrity and long-term performance
Nanomaterials	Enhanced properties such as self-cleaning	Scalability of production and cost-effectiveness

precision and safety. As shown in [Table 11](#): Key technologies in smart facade design, there are several ways that this implementation can be realized.

Investigations into the scalability of additive manufacturing for large-scale facade production and the compatibility of printed materials with traditional construction methods are essential for broader adoption ([Table 12](#)).

In the article *Innovative Trends in Architecture – Creating Full-Scape Buildings with the 3D Print Technology* ([Ivanov-Kostetskyi et al., 2021](#)) contemporary innovative 3D technologies and machinery are highlighted as dynamically evolving and covering increasingly more aspects in architecture.

This paper conducts an in-depth assessment of various technologies and technical resources, outlining their specific advantages and limitations, while also analysing key areas for the application of 3D printers in the construction of architectural structures. It delineates prospective avenues for the advancement of high-efficiency building and structural construction technologies, encompassing the developmental contributions of construction and architectural entities in the fabrication of structures via 3D printing methodologies. The authors conduct an analysis of extant technological solutions for 3D printing in the context of real architectural structure construction, presenting pertinent data regarding the technical specifications of contemporary three-dimensional printers, conceptualizing challenges pertaining to technological development, and addressing the selection of optimal materials and engineering configurations. Identified necessitate further investigation into the complexities associated with the implementation of 3D printing in large-scale architectural projects, specifically addressing concerns related to economic efficiency and project completion timelines.

As *Enhancing Aesthetics in Industrial Architecture* ([Sidorova, 2022](#)) shows, the integration of 3D printing technology in facade design, particularly for industrial architecture, presents a transformative opportunity. This approach allows for intricate designs inspired by nature, as seen in the proposed incineration plant in

Tromsø. The use of 3D-printed facade nodes, as detailed throughout the document, enables precise creation of complex geometries, reduces material waste, and facilitates the integration of sustainable materials, aligning with the broader goals of environmental responsibility and aesthetic enhancement in modern construction. By integrating responsive features that have been proven and listed in [Table 8](#): Ecological impact of green facades.

More thorough investigations into the aesthetic implications and market acceptance of 3D printed facades in various architectural applications are warranted to promote sustainable design practices.

3.4.4 Comparison of different methods of making SMART facades

The research paper titled *Technologies Used in Responsive Facade Systems: A Comparative Study*’ ([Heidari Matin and Eydgahi, 2022](#)) presents a detailed analysis of various technologies employed in smart facade systems. It categorizes these technologies into five main groups, highlighting their evolution and distinct characteristics. Mechanical Technology represents the earliest systems, utilizing manual elements like gears, pulleys, and cables, thus offering limited adaptability. Electro-Mechanical Technology advances this by integrating electrical components for automation and remote control, albeit these systems are often complex, prone to failure, and energy-intensive. Passive Technology takes a different approach, leveraging natural resources such as wind and sunlight to function without external power; however, it lacks controllability. Information Technology introduces sophisticated control with microcontrollers and sensors, creating interconnected panels that provide scalability and adaptability, but also pose risks of computer failures and cybersecurity threats. Lastly, Material-Based Technology focuses on smart materials that react to environmental stimuli, eliminating the need for separate actuators and sensors, though they remain mostly in the prototype stage with limited programmability. The paper suggests an integrated approach that amalgamates the strengths of these diverse technologies to improve efficiency and control of facade systems. Additionally, it

emphasizes the impact of cultural and regional motifs on facade designs and underscores the need for more research in this area.

Comprehensive studies are needed to evaluate the effectiveness of integrated systems that combine different technologies and how cultural and regional factors impact the success of smart facades.

Dynamic Facades for Sustainable Buildings: A Review of Classification, Applications, Prospects and Challenges (Jamilu et al., 2024) explores dynamic facades (DFs) as a transformative element in building design. This study emphasizes the flexibility of Dynamic Facades (DFs) in adapting to environmental changes, leading to decreased energy consumption and CO2 emissions while enhancing occupant comfort. To tackle the lack of detailed information about DF design concepts and configurations, the paper presents a new classification framework. A review of 26 international case studies highlights the real-world energy-saving benefits of DF designs, advocating for in-depth techno-economic analyses that include life cycle costs (LCC) to align economic considerations with environmental advantages. The research suggests that DFs could significantly contribute to the development of energy-efficient buildings and improved indoor environmental quality. It also calls for ongoing academic exploration into the classification, performance evaluation, and economic viability of DF systems to increase their accessibility and societal benefits. The main goals of this study are to create a comprehensive DF classification framework, critically assess the energy performance and techno-economic analyses of existing DFs, compile an extensive inventory of their strengths and weaknesses, and propose directions for future research in the field of DFs.

Further research should focus on the economic viability of dynamic facade systems, including a detailed analysis of lifecycle costs and their performance benefits compared to conventional systems.

The research article titled Future Trends and Main Concepts of Adaptive Facade Systems (Attia et al., 2020) by Shady Attia, Romain Lioure, and Quentin Declaude delves into the expanding interest in adaptive facade technologies for smart, high-performance buildings, surpassing the scope of traditional literature reviews. This research utilizes an innovative conceptual framework and technological taxonomy, incorporating a thorough literature review, expert interviews, and content analysis, including detailed discussions with 27 international experts in the field of adaptive facades. The primary findings categorize adaptive facade technologies into four main families and introduce a conceptual framework that highlights human-centred design, smart building operating systems, service-oriented solutions, circularity, and materials science as key factors driving technological advancements. The study accentuates future trends characterized by multifunctionality and the fulfilment of performance imperatives such as smartness, automation, occupant comfort, and well-being. Prominent among the identified technologies are dynamic shading systems, chromogenic facades, solar active facades, and active ventilative facades (AVFs). The paper elucidates the

critical significance of adaptive facade systems in addressing climate change mitigation and reducing energy demand, presenting a consensus perspective derived from facade experts and technology developers spanning approximately 20 European nations. This comprehensive synthesis of future trends and conceptual paradigms provides invaluable insights for designers, operators, proprietors, and manufacturers operating within the adaptive facade systems sector.

More investigations of the impact of adaptive facade systems on efficiency and comfort are necessary. Having looked at both the tech and implementation side let us examine the ecological benefits.

3.5 The impact of SMART facades

3.5.1 Ecological benefits

Green facades offer a crucial step toward sustainable smart buildings. As observed by Aung et al. (2023) in their work Implementing green facades: A step towards sustainable smart buildings, there needs to be innovative solutions that enhance efficiency to green implementations. Green facades integrate vegetation and have numerous environmental benefits.

Green facades contribute to natural insulation and shading. Research indicates a reduction in the dependence on artificial systems. They also enhance air quality, there is still work to be done in examining the benefits across different environments. With the need to overcome the main hurdles and the use of Smart Materials, Mechanical Systems, and Passive Elements and reference to Table 13 a strategy is put in place to maximize the overall impact of green implementations with further research needed to look at climate variations of those designs. With Smart Materials, Mechanical Systems, and Passive Elements to the potential impact of green facades can be maximized. Possible solutions include automated irrigation and health monitoring, policy support, and guidelines. Further research should explore cost-effective maintenance and the impact of climate variability.

Implementing Green Facades: A Step Toward Sustainable Smart Buildings represents a shift toward sustainable urban environments. By harnessing benefits, planners, architects, and developers can achieve sustainability objectives and enhance quality of life. Ongoing research/collaboration are essential. Investigating policy frameworks and community engagement is essential to maximizing benefits.

Climate change necessitates solutions, and adaptive facades (AF) offer promise. The paper “Why are adaptive facades not widely used in practice? (Borschewski et al., 2023) addresses this, investigating how adaptability yields reduced energy consumption and enhanced comfort. Despite benefits, AFs lack widespread use. The acknowledged advantages primarily resonate with stakeholders possessing limited influence, necessitating compromises from decision-makers. This article demonstrates that, beyond conventional advantages, there exist

TABLE 13 Proposed solutions for green facade challenges.

Challenge	Proposed Solution	Potential Impact
High initial cost	Incentives and subsidies for green facade projects	Increased adoption and implementation
Maintenance requirements	Automated irrigation and health monitoring systems	Reduced long-term costs
Species selection	Guidelines for selecting climate-appropriate species	Improved sustainability and performance

motivating factors relevant to stakeholders. More evaluations are necessary to understand barriers to implementation.

A case study was conducted, contrasting conventional ventilation against an Adaptive Facade (AF). This resulted in reduced building height and structural weight. Specifically, a reduction of 3 meters in building height and up to 340 metric tons in material consumption was achieved, yielding a mitigated climate change impact of 110 metric tons of CO₂-equivalent (−7%). During the operational phase, 615 metric tons of CO₂-equivalent emissions were averted, and lifecycle costs were diminished by €485,000, concurrent with a 4% increase in rentable floor space.

The research, titled why are adaptive facades not widely used in practice? Identifying ecological and economic benefits with life cycle assessment, underscores adaptive facades’ potential to offer lifecycle benefits, making them attractive for investors/owners. By integrating functions traditionally realized by building equipment, adaptive facades can reduce weight, space, parts, and costs, thus justifying their application. As shown in Table 14: Energy efficient technologies, one solution to help improve the situation is to potentially reduces cooling loads and adjusting optical properties dynamically. There is a need for investigation into the economic implications of adaptive facade technologies, particularly regarding costs versus savings.

3.5.2 Increasing energy efficiency

In Switchable Façade Technology - Energy Efficient Office Buildings with Smart Facades (Platzer, 2003), the energy performance of switchable facade technologies is delineated, focusing on electrochromic and gasochromic windows. Adjustable optical properties impact heating, cooling, and lighting. A validated simulation model is incorporated, providing data for European climates. Switchable facades demonstrate comparable potential for

mitigating cooling loads as shading mechanisms, introducing visual ramifications. Occupants retain visual access through tinted glazing, whereas external solar protection may impede views.

Table 15 also demonstrated longitudinal studies that needed to be taken for adaptive facades, including: long-term user satisfaction, comparative analysis and effects on energy consumption impacts across climate variations. Consequently, this technology exhibits promising market prospects, contingent upon long-term reliability. More field studies are needed to assess energy savings compared to traditional systems.

This research underscores that switchable facades dynamically adjust optical properties for energy-efficient solutions in office buildings. Solar protection provides a permanent view and is unaffected by wind, which makes it promising for future markets, if long term results remain. As outlined in Table 16: User comfort metrics by facade type that may impact the overall effectiveness.

Investigating long-term reliability and maintenance is critical for widespread adoption. The paper, Smart Facades in Architecture: Driving Energy Efficiency and Adaptive Urban Design (Firoozi and Firoozi, 2023) explores smart facades’ transformative potential, highlighting how these skins redefine architecture, integrating energy efficiency with design, conservation, and adaptability. The study delves into the evolution of smart facades and emphasizes advanced materials/IT, enabling dynamic adjustment to conditions and optimizing consumption. While recognizing challenges, the paper emphasizes long-term advantages, including lower expenses and heightened property values. Ultimately, the research calls for collaboration and innovation to fully realize smart facades’ potential. Future studies should concentrate on integrating smart facades with existing building systems to optimize energy efficiency and assess the balance between installation costs and long-term savings.

TABLE 14 Energy efficient technologies.

Technology	Energy savings (%)	Key features
Switchable facades	Potentially reduces cooling loads	Adjusts optical properties dynamically
High-performance glazing	Reduces heating and cooling demand (See Section 4 Platzer, 2003)	Offers different levels of solar control and thermal insulation

TABLE 15 Longitudinal studies needed.

Study focus	Essential research areas	Objective
Adaptive facade performance	Long-term user satisfaction and energy efficiency	To analyze real-world effectiveness and wear
Green facade durability	Comparative analysis of plant species and maintenance	To ensure resilience and longevity
Dynamic system functionality	Energy consumption impacts across climate variations	To assess feasibility and reliability

TABLE 16 Performance comparison of static vs. dynamic BIPV shading systems [Based on Biloria et al. (2023)].

Metric	Static BIPV system	Dynamic (Adaptive) BIPV system	Source (Biloria et al., 2023)
Minimum threshold level of illuminance (Underlit Spots)	Higher percentage of underlit spots (illuminance < 300 lux)	Average daily improvement of 56.94% in reducing underlit spots (compared to static)	Figure 8, Results section
Energy generation potential	Lower	2.35% average daily improvement in energy generation (compared to static), with a maximum improvement of 21.53% in the morning (8 AM)	Figure 8, Results section
Spatial percentage of area with over-illuminance	Higher	Alleviated by up to 1.16% (reduction in area with illuminance > 3,000 lux)	Figure 8, Results section

TABLE 17 Future research directions for adaptive facades.

Research direction	Focus areas	Expected outcomes
Technology integration	Combining adaptive systems with smart building technology	Enhanced building performance and user experience
Lifecycle assessments	Detailed economic assessments of adaptive systems	Improved investment decisions for stakeholders
Adaptive control strategies	User-focused adaptive controls for personalized comfort	Increased satisfaction and energy efficiency

3.5.3 Improving user comfort

The research detailed in a user detective adaptive facade toward improving visual and thermal comfort (Rizi and Eltaweel, 2019) presents an occupant-centric approach to facade design, leveraging simulation and genetic algorithm optimization to create a dynamic system responsive to occupant preferences, addressing comfort factors. By integrating a double-sided material, the facade improves visual comfort and heat gain control, underscoring the importance of occupant needs and highlighting the potential for personalized environments. As outlined in Table 16: Future research directions for adaptive facades, technology integration, life cycle assessments and adaptive control strategies. Future investigations should explore the balance between automation and user control.

The study titled Control Strategies for Intelligent Glazed Facade and Their Influence on Energy and Comfort Performance of Office Buildings in Denmark (Liu et al., 2015) focuses on developing control strategies to optimize energy consumption and enhance indoor comfort, including thermal, visual, and air quality aspects. The researchers assessed energy/comfort performance, verified through simulations. Intelligent facades incorporate shutters, blinds, and ventilation. Results indicate intelligent glazed facades can reduce energy demand by approximately 60%, facilitating compliance with Danish standards. Additional research is needed to assess the effectiveness of control strategies across different building types.

The research investigates real-time adaptive Building Integrated Photo Voltaic (BIPV) shading systems' ability to perform in regards to visual comfort and energy generation potential within the humid subtropical climate of Sydney, Australia (Biloria et al., 2023). The study presents a simulated case scenario using computing principles to maximize energy generation and maintain visual comfort.

Now that we have completed an assessment of what enhances user comfort, let us go ahead and assess the main findings and how it is that we could make these buildings better with future research.

4 Discussion

4.1 Key findings and synthesis

This review confirms the significant potential of intelligent 3D-printed facades to revolutionize the building industry. Key findings include:

- 3D printing enables the creation of complex facade geometries, unlocking unprecedented design freedom and functional integration.
- The selection of sustainable and high-performance materials is crucial for optimizing energy efficiency, durability, and environmental impact.

- The integration of sensors, actuators, and AI-driven control systems offers the possibility of creating responsive facades that dynamically adapt to environmental conditions and occupant needs.
- Despite these advancements, several challenges remain, including:
- Scalability and cost-effectiveness: Scaling up production to meet market demands while remaining competitive with traditional facade systems is essential.
- Durability and long-term performance: Ensuring the long-term viability of 3D-printed facades under real-world conditions is crucial for building confidence in the technology.
- Regulatory frameworks and standardization: Developing updated building codes and testing/certification procedures is necessary for widespread adoption.

4.2 Prioritized recommendations for future research

To fully unlock the potential of intelligent 3D-printed facades, future research should prioritize the following areas (as informed by Table 17: Future research directions for adaptive facades):

- Long-Term Durability and Material Performance (High Priority): Rigorous longitudinal studies are needed to assess the performance of 3D-printed materials under diverse environmental conditions (UV radiation, moisture, temperature fluctuations) and to develop protective coatings/material compositions that can withstand these stresses. Specific research questions should address:
- How do different infill patterns and geometric complexities affect material degradation over time?
- What are the most effective and cost-efficient protective coatings for 3D-printed facade materials?
- How can the long-term performance of 3D-printed materials be modeled and predicted in different climates?
- Scalability and Manufacturing (Medium Priority): Addressing the practical challenges of manufacturing large-scale 3D-printed facade elements is crucial for widespread adoption. This includes:
- Developing efficient printing techniques for large-format elements.
- Optimizing transportation and assembly methods.
- Creating modular designs that can be easily customized and adapted to different building types.
- Performing cost-benefit analyses comparing 3D-printed facades with traditional systems.
- Integration of Intelligent Systems (Medium Priority): Exploring the integration of advanced sensors, actuators, and AI-driven

control systems for responsive and energy-efficient facades is essential. This includes:

- Developing miniaturized, robust sensors and efficient actuators.
- Creating sophisticated AI algorithms capable of processing real-time data.
- Investigating new functionalities such as integrated energy harvesting and air purification.

Lifecycle Assessment and Environmental Impact (Lower Priority):

Conducting comprehensive lifecycle assessments (LCA) to determine the environmental impact of various material selections and manufacturing processes.

5 Conclusion

Intelligent 3D-printed facades hold immense promise for creating more sustainable, energy-efficient, and human-centric buildings. This narrative review has explored the research landscape of smart 3D-printed facades, synthesizing 76 relevant publications from 2015 to 2025. Key findings highlight the potential of 3D printing to enable complex facade geometries, unlocking unprecedented design freedom and functional integration. The selection of sustainable and high-performance materials remains crucial for optimizing energy efficiency, durability, and minimizing environmental impact, with materials like PETG and PLA showing particular promise for specific applications (Ghasemieshkaftaki et al., 2021). Furthermore, the integration of sensors, actuators, and AI-driven control systems offers the possibility of creating responsive facades that dynamically adapt to environmental conditions and occupant needs, enhancing both energy performance and user comfort.

Despite these advancements, several challenges persist, necessitating further research and development. These include: (1) scalability and cost-effectiveness in manufacturing large-scale facade elements; (2) ensuring the long-term durability of 3D-printed materials under real-world conditions, particularly in relation to UV radiation, moisture, and temperature fluctuations; and (3) developing updated building codes and standardized testing/certification procedures. To fully unlock the potential of intelligent 3D-printed facades, future research should prioritize: (1) combining adaptive systems with smart building technology to enhance overall performance and user experience; (2) conducting detailed lifecycle assessments (LCA) to inform investment decisions; and (3) developing user-focused adaptive controls for personalized comfort and increased energy efficiency. The findings of this review have implications for a range of stakeholders, including architects, engineers, material scientists, and policymakers. By addressing the prioritized research recommendations, the building industry can pave the way for widespread adoption of this transformative technology, contributing to more sustainable urban environments and reducing the building sector's significant contribution to global energy consumption. Moreover, the integration of smart 3D-printed facades aligns with broader sustainability goals, such as reducing carbon emissions and promoting a circular economy through material selection and waste reduction.

Future research should focus on developing comprehensive lifecycle assessment models to quantify environmental impacts and optimize material selection, as well as exploring innovative materials

and design approaches that enhance both performance and durability. Furthermore, investigating the integration of 3D-printed facades with smart city initiatives and the potential for creating circular economy models could offer new avenues for maximizing their environmental and economic benefits. Addressing the research questions outlined in Section 4.2 regarding the impact of infill patterns, protective coatings, and long-term performance modeling across different climates is also critical. Ultimately, continued research and development are crucial to realizing the vision of intelligent 3D-printed facades and ensuring that these technologies deliver on their promise of a more sustainable, resilient, and human-centric built environment. The focus should shift from design for production to design for function (Strauß and Knaack, 2016), promoting the creation of complex, algorithm-based designs with greater precision and safety.

Author contributions

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

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References

- Abdelwahed Mekhamar, A., and Halim Hussein, A. (2021). Brief overview of climate responsive facades & its kinetic applications. *Eng. Res. J.* 171, 16–34. doi: 10.21608/erj.2021.193461
- Alsarraf, A. A., and Alobaidi, M. M. (2020). “Advanced techniques in design openings of smart facades in buildings,” in *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 757:012003.
- Attia, S. (2018). “Challenges and future directions of smart sensing and control technology for adaptive facades monitoring,” in *COST Action TU1403-Adaptive facades network final conference*. Lucerne, Switzerland: Lucerne University of Applied Sciences and Arts. Available at: <https://hdl.handle.net/2268/229695>.
- Attia, S., Favoino, F., Loonen, R., Petrovski, A., and Monge-Barrio, A. (2015). “Adaptive facades system assessment: An initial review,” in *10th Conference on advanced building skins, 3-4 November 2015*. Bern, Switzerland: Economic Forum, p. 1275–1283.
- Attia, S., Lioure, R., and Declaude, Q. (2020). Future trends and main concepts of adaptive facade systems. *Energy Sci. Eng.* 8, 3255–3272. doi: 10.1002/ese3.725
- Aung, T., Liana, S. R., Htet, A., and Bhaumik, A. (2023). Implementing green facades: a step towards sustainable smart buildings. *J. Smart Cities Society* 2, 41–51. doi: 10.3233/SCS-230014
- Balali, A., and Valipour, A. (2020). Identification and selection of building façade’s smart materials according to sustainable development goals. *Sustain. Mater. Technol.* 26:e00213. doi: 10.1016/j.susmat.2020.e00213
- Barone, G., Zacharopoulos, A., Buonomano, A., Forzano, C., Giuzio, G. F., Mondol, J., et al. (2022). Concentrating photovoltaic glazing (CoPVG) system: modelling and simulation of smart building façade. *Energy* 238:121597. doi: 10.1016/j.energy.2021.121597
- Biloria, N., Makki, M., and Abdollahzadeh, N. (2023). Multi-performative façade systems: the case of real-time adaptive BIPV shading systems to enhance energy generation potential and visual comfort. *Front. Built Environ.* 9, 1–14. doi: 10.3389/fbuil.2023.1119696
- Blandini, L., Haase, W., Weidner, S., Böhm, M., Burghardt, T., Roth, D., et al. (2022). D1244: design and construction of the first adaptive high-rise experimental building. *Front. Built Environ.* 8, 1–12. doi: 10.3389/fbuil.2022.814911
- Borschewski, D., Voigt, M. P., Albrecht, S., Roth, D., Kreimeyer, M., Leistner, P. (2023). Why are adaptive facades not widely used in practice? Identifying ecological and economical benefits with life cycle assessment. *Build. Environ.* 232:110069. doi: 10.1016/j.buildenv.2023.110069
- Carlucci, F. (2021). A review of smart and responsive building technologies and their classifications. *Future Cities Environ.* 7, 1–12. doi: 10.5334/fce.123
- Cho, M. (2019). Campus sustainability. *Int. J. Sustain. High. Educ.* 20, 1042–1060. doi: 10.1108/ijshs-06-2018-0107
- Ciampi, G., Spanodimitriou, Y., Scorpio, M., Rosato, A., and Sibilio, S. (2021). Energy performances assessment of extruded and 3D printed polymers integrated into building envelopes for a south Italian case study. *Buildings* 11:141. doi: 10.3390/buildings11040141
- Claros-Marfil, L. J., Vargas, V. Z., Padial, J. F., and Lauret, B. (2025). Experimental energy performance assessment of a smart controlled water-flow glazing adaptive facade in heating demand conditions. *Appl. Energy* 378:124787. doi: 10.1016/j.apenergy.2024.124787
- de la Barra, P., Luna-Navarro, A., Brembilla, E., Allen, M., Knaack, U., and Overend, M. (2025). User interaction with smart glazing: effect of switching speed under overcast sky condition. *Build. Environ.* 270:112409. doi: 10.1016/j.buildenv.2024.112409
- de Rubeis, T., Ciccozzi, A., Paoletti, D., and Ambrosini, D. (2024). 3D printing for energy optimization of building envelope – experimental results. *Heliyon* 10:e31107. doi: 10.1016/j.heliyon.2024.e31107
- El-Sayegh, S., Romdhane, L., and Manjikian, S. (2020). A critical review of 3D printing in construction: benefits, challenges, and risks. *Arch. Civ. Mech. Eng.* 20, 1–25. doi: 10.1007/s43452-020-00038-w
- Faragalla, A. M., and Asadi, S. (2022). Biomimetic design for adaptive building facades: a paradigm shift towards environmentally conscious architecture. *Energies* 15:5390. doi: 10.3390/en15155390
- Firoozi, A. A., and Firoozi, A. A. (2023). Smart facades in architecture: Driving energy efficiency and adaptive urban design. Available at SSRN 4631796. doi: 10.2139/ssrn.4631796
- Ghasemieshkaftaki, M., and Ortiz M, A., & Bluyssen, P. (2021). An overview of transparent and translucent 3D-printed facade prototypes and technologies. Available at: <https://resolver.tudelft.nl/uuid:fd2c5f3c-56d2-4f8d-83a7-d65677ba2037>.
- Grassi, G., Lupica Spagnolo, S., and Paoletti, I. (2019). Fabrication and durability testing of a 3D printed facade for desert climates. *Addit. Manuf.* 28, 439–444. doi: 10.1016/j.addma.2019.05.023
- Hager, I., Golonka, A., and Putanowicz, R. (2016). 3D printing of buildings and building components as the future of sustainable construction? *Procedia Eng.* 151, 292–299. doi: 10.1016/j.proeng.2016.07.357
- Heidari Matin, M., and Eydgahi, A. (2022). Technologies used in responsive facade systems: a comparative study. *Intell. Build. Int.* 14, 54–73. doi: 10.1080/17508975.2019.1577213
- Ivanov-Kostetskyi, S., Gumennyk, I., and Voronkova, I. (2021). Innovative trends in architecture – creating full-scape buildings with the 3D print technology. *IOP Conf. Ser. Mater. Sci. Eng.* 1203:022099. doi: 10.1088/1757-899x/1203/2/022099
- Jafari, M., and Alipour, A. (2021). Review of approaches, opportunities, and future directions for improving aerodynamics of tall buildings with smart facades. *Sustain. Cities Soc.* 72:102979. doi: 10.1016/j.scs.2021.102979
- Jamilu, G., Abdou, A., and Asif, M. (2024). Dynamic facades for sustainable buildings: a review of classification, applications, prospects and challenges. *Energy Rep.* 11, 5999–6014. doi: 10.1016/j.egy.2024.05.047
- Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., and Ul Haq, M. I. (2022). 3D printing – a review of processes, materials and applications in industry 4.0. *Sustainable Operations Computers* 3, 33–42. doi: 10.1016/j.susoc.2021.09.004
- Kamran, M., and Saxena, A. (2016). A comprehensive study on 3D printing technology. *MIT Int. J. Mech. Eng.* 6, 63–69.
- Korniyenko, S. V. (2021). Progressive trend in adaptive façade system technology. A review. *AlfaBuild* 19:1902. doi: 10.57728/ALF.19.2
- Kumar, A. V. (2022). A review paper on 3D-printing and various processes used in the 3D-printing. *Int. J. Sci. Res. Eng. Manag.* 6, 953–958. doi: 10.55041/ijserm.13278
- Leschok, M., Cheibas, I., Piccioni, V., Seshadri, B., Schlüter, A., Gramazio, F., et al. (2023). 3D printing facades: design, fabrication, and assessment methods. *Autom. Constr.* 152:104918. doi: 10.1016/j.autcon.2023.104918
- Leschok, M., Piccioni, V., Lydon, G., Seshadri, B., Schlueter, A., Gramazio, F., et al. (2024). Thermal and manufacturing properties of hollow-core 3D-printed elements for lightweight facades. *Develop. Built Environ.* 19:100485. doi: 10.1016/j.dibe.2024.100485
- Liu, M., Wittchen, K. B., and Heiselberg, P. K. (2015). Control strategies for intelligent glazed façade and their influence on energy and comfort performance of office buildings in Denmark. *Appl. Energy* 145, 43–51. doi: 10.1016/j.apenergy.2015.02.003
- Luneva, D. A., Kozhevnikova, E. O., and Kaloshina, S. V. (2017). Application of 3D printing in construction activities and its prospects. *Constr. Geotech.* 8, 90–101. doi: 10.15593/2224-9826/2017.1.08
- Matin, N. H., Eydgahi, A., and Shyu, S. (2017). Comparative analysis of technologies used in responsive building facades. *Asee Annu. Conf. Expo. Conf. Proc.* doi: 10.18260/1-2--28052
- Na, S., Kim, S., and Moon, S. (2022). Additive manufacturing (3D printing)-applied construction: smart node system for an irregular building façade. *J. Build. Eng.* 56:104743. doi: 10.1016/j.job.2022.104743
- Nayir, S., and Erbil, Y. (2024). Machine use and digitalization in earth building production. *Karesi Journal of Architecture*. 3, 101–120.
- Panopoulos, K., and Papadopoulos, A. M. (2017). Smart facades for non-residential buildings: an assessment. *Adv. Build. Energy Res.* 11, 26–36. doi: 10.1080/17512549.2015.1119058
- Perrot, A., Rangeard, D., and Courteille, E. (2018). 3D printing of earth-based materials: processing aspects. *Constr. Build. Mater.* 172, 670–676. doi: 10.1016/j.conbuildmat.2018.04.017
- Piccioni, V., Leschok, M., Lydon, G., Cheibas, I., Hischier, I., Dillenburger, B., et al. (2023). “Printing thermal performance: an experimental exploration of 3DP polymers for facade applications,” in *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 1196:12063.
- Platzer, W. J. (2003). “Switchable façade technology-energy efficient office building with smart facades,” in *Solar World Congress. Proceedings*. CD-ROM: Solar energy for a sustainable future.
- Ramya, A., and Vanapalli, S. L. (2016). 3D printing technologies in various applications. *Int. J. Mech. Eng. Technol.* 7, 396–409.
- Rizi, R. A., and Eltaweel, A. (2019). A user detective adaptive facade towards improving visual and thermal comfort. *J. Build. Eng.* 33:101554. doi: 10.1016/j.job.2020.1015542021
- Romano, R., Aelenei, L., Aelenei, D., and Mazzucchelli, E. S. (2018). What is an adaptive facade? Analysis of recent terms and definitions from an international perspective. *J. Facade Des. Eng.* 6, 065–076. doi: 10.7480/jfde.2018.3.2478
- Saidam, M. W., Al-Obaidi, K. M., Hussein, H., and Ismail, M. A. (2017). The application of smart materials in building facades. *Ecol. Environ. Conserv.* 23, S8–S11.
- Sakin, M., and Kiroglu, Y. C. (2017). 3D printing of buildings: construction of the sustainable houses of the future by BIM. *Energy Procedia* 134, 702–711. doi: 10.1016/j.egypro.2017.09.562
- Sarakinioti, M. V., Turrin, M., Konstantinou, T., Tenpierik, M., and Knaack, U. (2018). Developing an integrated 3D-printed façade with complex geometries for active temperature control. *Mater. Today Commun.* 15, 275–279. doi: 10.1016/j.mtcomm.2018.02.027
- Sayed El Falafli, M. (2021). The impact of the use of smart materials on the environment. *International Journal of Advances Engineering and Civil Research* 1, 41–54. doi: 10.21608/ijaecr.2023.214440.1010

- Senatore, G., and Smith, I. F. C. (2021). Editorial: design and control of adaptive civil structures. *Front. Built Environ.* 7, 1–2. doi: 10.3389/fbuil.2021.729752
- Shahrubudin, N., Lee, T. C., and Ramlan, R. (2019). An overview on 3D printing technology: technological, materials, and applications. *Procedia Manuf.* 35, 1286–1296. doi: 10.1016/j.promfg.2019.06.089
- Sidorova, L. (2022). *Enhancing aesthetics in Industrial Architecture: integrating 3D-printed facade structures in the design of an incineration plant in Tromsø*. Available at: <https://hdl.handle.net/10589/214551>
- Soudian, S., and Berardi, U. (2021). Development of a performance-based design framework for multifunctional climate-responsive façades. *Energ. Buildings* 231:110589. doi: 10.1016/j.enbuild.2020.110589
- Spanodimitriou, Y., Ciampi, G., Tufano, L., Scorio, M., and Sibilio, S. (2025). Evaluating the performance of fixed 3D-printed and dynamic fabric modules in a second-skin façade system: a residential case study in southern Italy at building and district scales. *Buildings* 15:189. doi: 10.3390/buildings15020189
- Strauß, H., and Knaack, U. (2016). Additive manufacturing for future facades: the potential of 3D printed parts for the building envelope. *J. Facade Des. Eng.* 3, 225–235. doi: 10.3233/fde-150042
- Tabadkani, A., Valinejad Shoubi, M., Soflaei, F., and Banihashemi, S. (2019). Integrated parametric design of adaptive facades for user's visual comfort. *Autom. Constr.* 106:102857. doi: 10.1016/j.autcon.2019.102857
- Tahmasbi, F., Khdaier, A. I., Aburumman, G. A., Tahmasebi, M., Thi, N. H., and Afrand, M. (2025). Energy-efficient building façades: a comprehensive review of innovative technologies and sustainable strategies. *J. Build. Eng.* 99:111643. doi: 10.1016/j.jobbe.2024.111643
- Tohidi, A., Goma, M., Haeusler, M. H., and Shiel, J. (2024). *3d printing self-shading wall structure with earth*. doi: 10.52842/Conf.Caadria.2024.3.121
- Wang, M., Jia, Z., Tao, L., and Xiang, C. (2024). Review of dynamic façade typologies, physical performance and control methods: towards smarter and cleaner zero-energy buildings. *J. Build. Eng.* 98:111310. doi: 10.1016/j.jobbe.2024.111310
- Yi, H., and Kim, Y. (2021). Prototyping of 4D-printed self-shaping building skin in architecture: design, fabrication, and investigation of a two-way shape memory composite (TWSMC) façade panel. *J. Build. Eng.* 43:103076. doi: 10.1016/j.jobbe.2021.103076
- Zhang, X., Zhang, H., Wang, Y., and Shi, X. (2022). Adaptive façades: review of designs, performance evaluation, and control systems. *Buildings* 12:2112. doi: 10.3390/buildings12122112

Glossary

3D - Three-Dimensional

AI - Artificial Intelligence

ABS - Acrylonitrile Butadiene Styrene

AF - Adaptive Facade

AHP - Analytic Hierarchy Process

AM - Additive Manufacturing

ASF - Adaptive Solar Facade

AVF - Active Ventilative Facade

BIM - Building Information Modeling

BIPV - Building Integrated Photo Voltaic

CABS - Climate Adaptive Building Skins

CO₂ - Carbon Dioxide

CoPVG - Concentrating Photovoltaic Glazing

CRF - Climate-Responsive Facade

DF - Dynamic Facade

ETFE - Ethylene Tetrafluoroethylene

EPGF - Electrokinetic Pixel Glazing

FDM - Fused Deposition Modelling

HVAC - Heating, Ventilation, and Air Conditioning

IEPA - Electroactive Polymer Actuator

IT - Information Technology

KF - Kinetic Facade

LCA - Lifecycle Assessment

LCC - Life Cycle Costs

ML - Machine Learning

PC - Polycarbonate

PCM - Phase Change Material

PES - Primary Energy Saving

PETG - Polyethylene Terephthalate Glycol

PBF - Pneumatic Facade

PLA - Polylactic Acid

SDGs - Sustainable Development Goals

SGFS - Smart Glazing Facade Systems

SLA - Stereolithography Apparatus

SLS - Selective Laser Sintering

SMA - Shape-Memory Alloy

SMC - Shape-Memory Composite

SMP - Shape-Memory Polymer

SSF - Second-Skin Façade

TWSMC - Two-Way Shape Memory Composite

UN - United Nations

UV - Ultraviolet

VGS - Vertical Greenery System

WFG - Water-Flow Glazing

ZEB - Zero-Energy Building