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Innovative Façade Materials and Their Tectonic Implications: A Meta-Analysis and Taxonomical Framework

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Abstract

The incorporation of innovative contemporary façade materials has fundamentally transformed architectural practice, driven by increasing demands for sustainability, building performance, and aesthetic expression. Despite substantial technical advancements in materials science, a critical gap persists in linking material innovation to tectonic expression — the relationship between material properties, construction logic, and architectural form. This study presents a systematic meta-analysis and a taxonomic framework for innovative façade materials, with a particular focus on their tectonic-aesthetic implications in contemporary architecture. A two-phase methodology was employed: keyword co-occurrence network analysis using VOS Viewer, followed by a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol applied to Web of Science publications (2010-2025). From an initial pool of 175 records, 123 were screened, 31 met eligibility criteria, and 19 studies addressing tectonic implications underwent detailed full-text analysis. Findings confirm that the majority of existing research prioritizes performance-related topics such as energy efficiency and thermal comfort, leaving the tectonic consequences of material innovation largely underexplored. To address this gap, this study proposes a novel taxonomical framework comprising seven categories: Smart Materials, Bio-based Materials, Modified Traditional Materials, Composite Materials, Nano-engineered Materials, Biomimetic Materials, and Digital Fabrication Materials — each analyzed in terms of its structural logic, assembly potential, and aesthetic expression. This framework represents the first systematic attempt to classify innovative façade materials through a tectonic lens, offering architects and designers a structured tool for material selection that balances technical performance with creative design intent.

Keywords
Innovative materials; façade design; architectural tectonics; meta-analysis; material taxonomy; building façade

1. Introduction

The building façade has evolved into a dynamic and integrated part of design over the past years. The building façade is not only presenting a static aspect of the design, which provides shelter anymore. Nowadays, the façade affects the aesthetic, occupants' comfort, and energy consumption of the building. Various factors influence this change, such as environmental concerns, developments in materials science, and the growing need for adaptable design. As a result, there is growing interest in investigating new façade materials for contemporary design. The new materials are beyond the traditional materials and move towards kinetic, bio-based, and smart materials [1].

Nowadays, the demand for sustainable and energy-efficient buildings is increasing. In this regard, research on materials such as bio-based materials is getting more attention. Bio-based materials have a lower environmental impact. Since they are produced locally, they have lower transportation costs. As an example of bio-based materials, timber can be mentioned. The usage of timber in architecture has a long history. However, recently, due to the adaptability and sustainability characteristics of timber, the increased interest in it is evident [2]. In addition to timber, green walls can be discussed in the same scope. Green walls are environmentally friendly, while they are aesthetically pleasing as well. That is the reason for the growing popularity of these materials [3].

On the other hand, smart materials are changing the façade design from static to dynamic. These materials can change their characteristics in response to environmental conditions. This ability could be achieved due to technological advances. As an example of these advancements, electrochromic windows are worth mentioning. These windows can control the light and heat gain by changing their transparency [4].

In addition to smart materials, kinetic facades are gaining extra attention. Using mechanical or electromechanical elements, they can respond to environmental changes. Due to their adaptability, they can improve ventilation and natural lighting. This ability helps improve building energy consumption [5, 6].

Innovative façade materials offer a wide range of opportunities for architectural design. These benefits are beyond practicality. They widely affect architectural expression. The design of the buildings is directly affected by the selection of innovative materials. They affect the form-making and structural properties of the building. For example, smart materials, in response to environmental changes, create a unique architectural expression. To achieve a special aesthetic, these materials can be used [7]. Due to all these advances, the boundaries of what a façade might look like have been pushed.

In today's architectural practice, understanding the implications of innovative materials is essential. In this matter, a multi-criteria decision-making procedure is needed. This procedure must cover a variety of factors. From energy efficiency to environmental impact and even aesthetic characteristics [4, 5, 7].

The primary aim of this study is to answer this need. In this regard, this study puts forth a systematic assessment of innovative façade materials. This assessment has been done through meta-analysis and synthesis. The main focus has been given to the tectonic-aesthetic of innovative façade materials.

1.1 Scope and Objectives of the Research

The main objective of this study is to investigate the link between innovative façade materials and their tectonic expression. This research addresses the following specific questions:

- What is the current state of research on innovative façade materials and their tectonic implications as revealed through bibliometric analysis?
- What knowledge gaps exist in the relationship between material innovation and architectural expression?
- How can innovative façade materials be systematically classified to support architectural decision-making?

To the best of the authors' knowledge, this study presents the first systematic attempt to classify innovative façade materials through a tectonic lens. While existing studies address material innovation primarily from a performance-based perspective, no comprehensive taxonomical framework has been developed that explicitly connects material categories to their structural logic, assembly potential, and aesthetic expression. This study addresses this gap by integrating bibliometric analysis, a PRISMA-based systematic review, and taxonomic development into a unified methodological framework, offering both theoretical contribution to the field of architectural tectonics and practical guidance for architects and designers engaged in contemporary façade design.

Several studies have proposed classification frameworks for contemporary façade systems, focusing primarily on typological categorization [8], technological performance [9], or dynamic behavior and material properties [10]. However, none of these frameworks systematically address the tectonic implications of innovative materials — that is, how material selection simultaneously influences structural logic, assembly methodology, and aesthetic expression. This gap between material classification and tectonic analysis represents the core contribution of the present study.

1.2 Research Methodology

This study employs a systematic qualitative and quantitative review methodology, integrating bibliometric analysis, systematic literature evaluation, and taxonomical development. The research utilizes a mixed-methods approach combining quantitative analysis of publication trends with qualitative synthesis of theoretical concepts. The methodology follows PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure rigor and reproducibility (Figure 1).

Figure 1 Research Methodology Framework (Authors, 2025).

The literature search was conducted in the Web of Science database, employing a structured Boolean search strategy. The primary search string combined core concepts as follows: (ALL = (Innovative Materials)) AND (ALL = (Tectonic)) AND (ALL = (Façade Design)). To ensure comprehensive coverage, search terms were expanded to include synonyms and related variants: 'facade materials' OR 'building envelope' OR 'material innovation' for the materials component, and 'tectonic expression' OR 'construction logic' OR 'architectural expression' for the tectonic component. The search was limited to English-language peer-reviewed publications from 2010 to 2025.

Inclusion criteria were defined as follows: (1) studies focusing on innovative façade materials in architectural applications; (2) studies addressing tectonic, aesthetic, or architectural expression aspects of façade design; (3) peer-reviewed journal articles, book chapters, and conference papers published in English between 2010 and 2025. Exclusion criteria included: (1) studies focusing exclusively on structural or engineering performance without architectural implications; (2) publications addressing façade materials in non-architectural contexts such as materials science or chemical engineering; (3) studies focusing solely on cost analysis, construction management, or unrelated performance metrics. Quality assessment was conducted based on relevance to tectonic implications, methodological rigor, and publication venue credibility.

1.3 Theoretical Framework Connecting Materiality, Tectonics, and Aesthetics

According to the literature in the façade design field, there is a connection between materiality, tectonics, and aesthetics. For studying the innovative materials' potential, it is very important to understand this link. This section of the study explores this theoretical link.

The materiality concept focuses on the characteristics and properties of the materials. Materials' embodied energy and environmental impact are part of these characteristics. Additionally, characteristics such as texture, color, and density are included in the concept of materiality [7]. To achieve sustainability, understanding materiality is crucial [11]. Selecting the right material is not only a technical decision. It is cultural and ethical as well. And this selection will have an essential impact on building performance [12].

In architecture, tectonic refers to more than structural engineering. It is an art and science of construction. This concept explains how materials are made and how they bear the stress. Additionally, this concept shows how principles such as connections and joinery of materials shape the building façade and provide stability. For instance, the modular façade technique presents a high degree of tectonic integration. This system, which uses prefabricated panels, affects both the building process and the aesthetic appeal of the building façade. In the same category, the kinetic façade incorporates movable components. This change in façade design highlights tectonics in the light of dynamism rather than a static concept. Due to these improvements, robotic production affects the tectonic expression of façades [13]. This shows that tectonics is acting as a bridge between architectural form and materiality. Tectonics clearly expresses the structural logic while underlining the aesthetic.

In the context of this study, the term aesthetics refers to the emotional reaction that the building façade evokes. The concept of aesthetics includes proportion, rhythm, scale, light, and shadow. Although design and aesthetics are often considered subjective, these concepts influence the overall appearance of the building façade [14]. The literature review highlights the significant impact of façade materials on the building's overall aesthetics. For example, using bio-based materials can give the building a sense of organic, natural quality. Smart materials can have a more high-tech and futuristic look. In order to achieve a successful aesthetic façade design, a seamless combination of materiality and tectonics is required.

This highlights that the relationship between the three concepts of materiality, tectonics, and aesthetics is dynamic and complex. The tectonic possibilities, which dictate the aesthetic outcome, are put in motion by the material selection. On the other hand, tectonic and material decisions may be influenced by an artistic concept. For example, the designer might choose the use of timber to achieve a sustainable façade (materiality). Still, this selection affects the tectonic of the façade's construction and enhances its aesthetic quality.

Since the novel technologies of smart and kinetic systems blur the line between these concepts, an understanding of how dynamic materials improve building facades' aesthetic and function is necessary. According to Pracucci et al. [15], a comprehensive approach is crucial for design decision-making to link all the concepts of materiality, tectonics, and aesthetics. Last but not least, to design a more sustainable built environment, understanding and controlling these three elements is essential. A balanced relationship can lead to a design that is aesthetically appealing and a useful building façade (Figure 2).

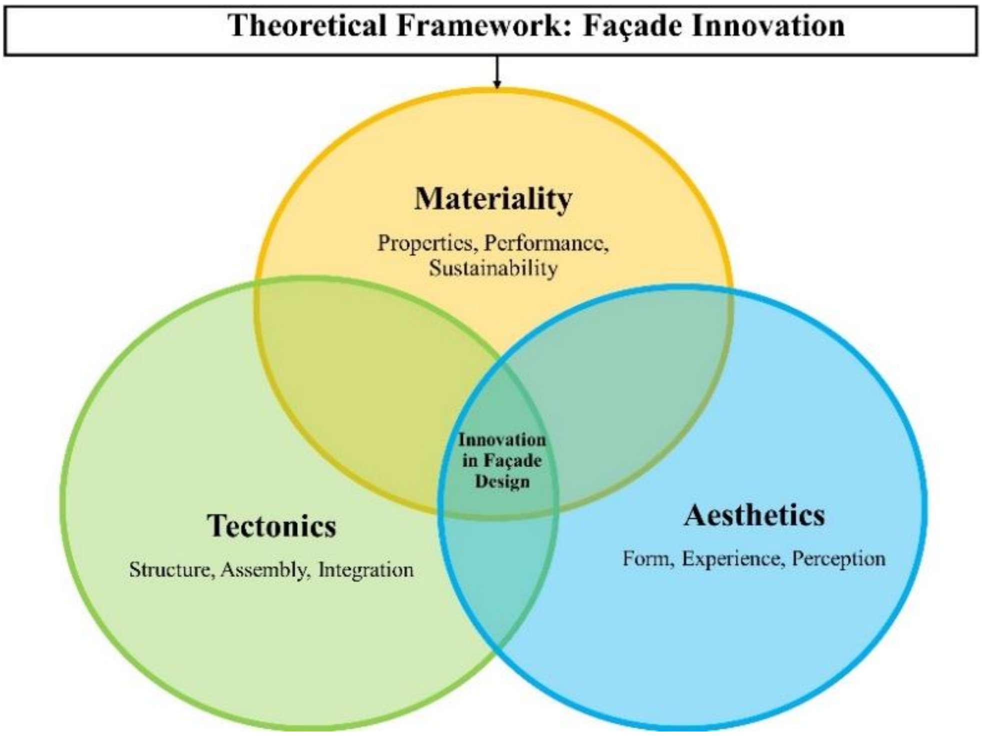

Figure 2 Theoretical Framework: Materiality, Tectonics, and Aesthetics (Authors, 2025).

2. Developing a Systematic Review (Meta-Analysis)

To provide a comprehensive review of the literature, a meta-analysis was conducted in the first stage to identify correlations among the study's three core keywords (Materials, Tectonics, and Aesthetics) and the current state of knowledge. The keyword analysis was carried out using VOSViewer to visualize the current landscape of this area of study (Figure 3). A bibliometric examination using VOSViewer uncovers unique research clusters in contemporary facade studies. The visualization shows many important research clusters centered on "buildings", "energy efficiency", "performance", and "design", with interrelated subthemes. However, the network analysis indicates a significant gap in the literature on the tectonic consequences of innovative materials.

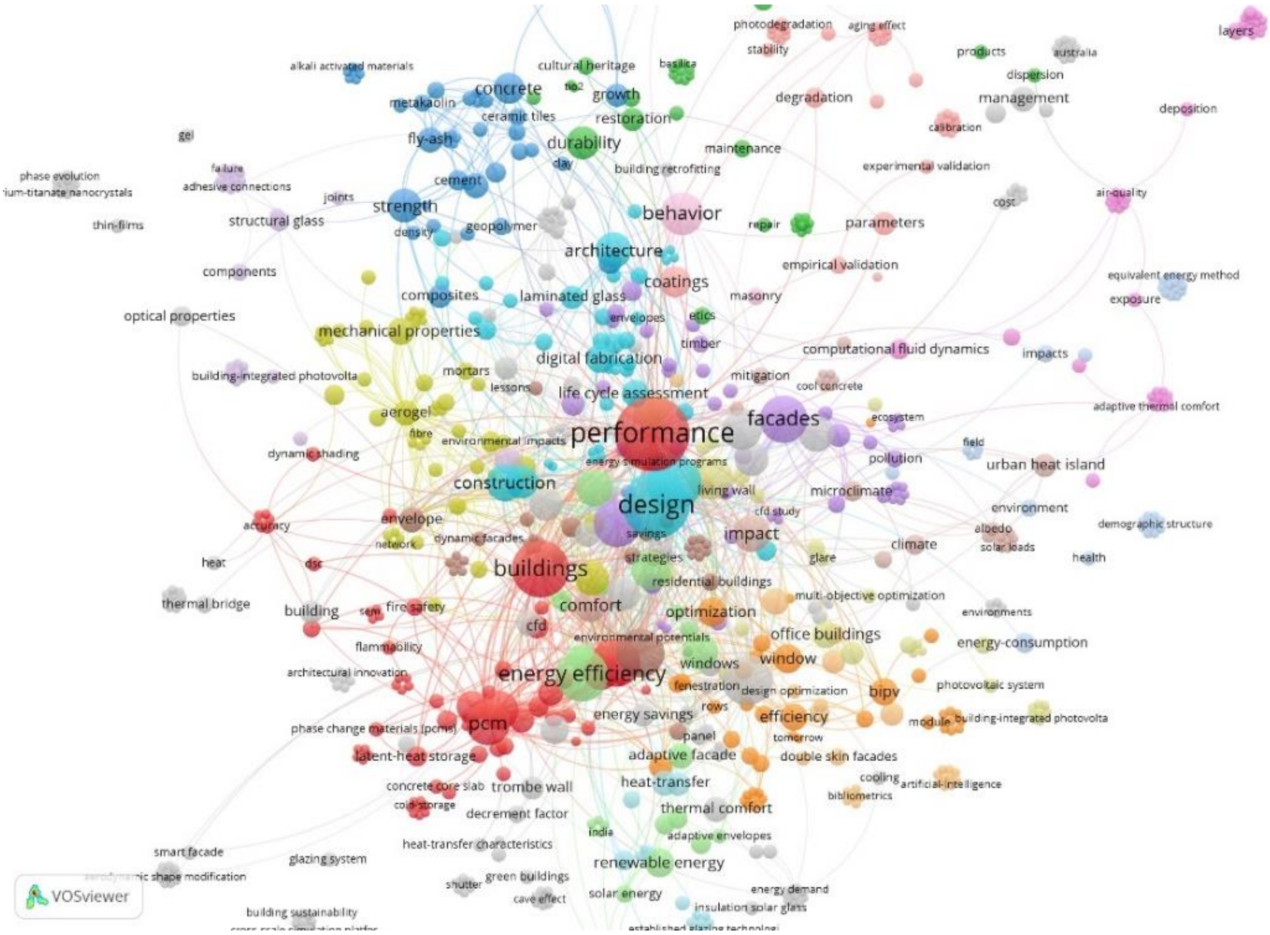

Figure 3 Keyword Co-occurrence Network Analysis of Façade Innovation Research (Authors, 2025).

The biggest clusters prioritize performance-related elements, notably energy efficiency and environmental performance. The terms “energy efficiency”, “thermal comfort”, and “performance” form dense networks, showing that these operational factors receive significant study focus. Similarly, material innovation studies, which use terms such as “concrete”, “composites”, and “coatings”, focus largely on technical features and performance characteristics.

Notably, although the network contains words relating to structural features (“strength”, “durability”) and aesthetic concerns (“design”, “architectural innovation”), their linkages are minimal. The limited links between material innovation clusters and architectural expression phrases suggest an underexplored topic in the literature. This result is especially relevant considering that tectonic expression, or the link between material, structure, and architectural form, seems to be on the periphery of the current study. This highlights a need for more integrated research that bridges the gap between novel materials and their tectonic consequences in contemporary architecture.

A parametric analysis of the keyword co-occurrence network reveals several quantifiable patterns that inform the research direction of this study. The network identifies five dominant research clusters, with energy efficiency and thermal performance constituting the largest cluster, accounting for approximately 38% of total keyword connections. Material innovation keywords, including ‘composites’, ‘coatings’, and ‘concrete’, form the second-largest cluster at approximately 24% of connections, yet they remain predominantly linked to technical performance indicators rather than architectural expression. Structural and aesthetic keywords, including 'design', 'architectural innovation', and 'tectonic', represent only 12% of total network connections, confirming their peripheral status in current façade research. Notably, the term 'tectonic' appears in fewer than 8% of the analyzed publications, despite its fundamental relevance to architectural design practice. This quantitative disparity between performance-oriented research (62% combined) and tectonic-aesthetic research (12%) provides empirical justification for the present study's focus and validates the identified knowledge gap. Furthermore, temporal analysis of publication trends reveals a steady increase in façade materials research from 2010 to 2025, with a notable acceleration post-2018 coinciding with growing interest in digital fabrication and bio-based materials. However, this growth remains concentrated in performance-based topics, further reinforcing the need for tectonic-focused frameworks.

To enhance the study, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were used (Figure 4). The research used the Web of Science database to identify scholarly publications on the topic (2010-2025). The primary search employed the following Boolean string: (ALL = (Innovative Materials)) AND (ALL = (Tectonic)) AND (ALL = (Façade Design)). To ensure comprehensive coverage, search terms were expanded to include relevant synonyms and variants: 'facade materials' OR 'building envelope' OR 'material innovation' for the materials component, and 'tectonic expression' OR 'construction logic' OR 'architectural expression' OR 'architectural tectonics' for the tectonic component. The initial search yielded 175 records, of which 123 remained after language and date filters were applied. In the second screening phase, studies were evaluated based on titles and abstracts using the refined string: (TS = (Innovative Materials)) AND (TS = (Tectonic)) AND (TS = (Façade Design)), reducing the pool to 31 eligible publications.

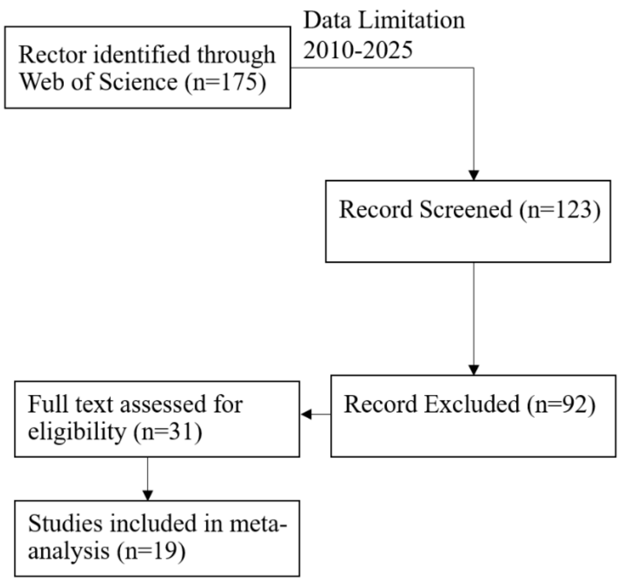

Figure 4 The PRISMA Flow Diagram (Authors, 2025).

The literature review shows a lack of studies on the tectonic effect of innovative materials on structures. The recent studies (2010-2025) highlight recent advances in architectural theory and façade technology. The meta-analysis identifies many key topics in the literature of façade design, including:

- Technological Innovation: As advanced technologies such as 3D printing and advanced materials are emerging in façade design, they are changing the possibilities of façade design. These technologies are giving opportunities for creating complex geometries in façades and also improving the performance of the building [16].
- Tectonic Expression: The findings of Motalebi & Shaffer [17] and Lakkala et al. [18] on the relationship between architectural expression and materiality show that the selection of materials impacts the building performance and aesthetic outcomes.
- Integration of Tradition and Modernity: A Study done by Silvestri et al. [19] on the integration of manufacturing processes today with traditional materials suggests an increase in interest in hybrid approaches. The hybrid approach integrates innovation and historical knowledge in building tectonics.

3. Literature Review

3.1 Contemporary Discourse on Building Façade Technologies

Historically, building facades served only as a barrier between the interior and exterior. Today, this concept has changed. Nowadays, building facades are dynamic components of the structure. They can respond to environmental changes. This fact affects the overall building performance [20]. The main reason for this advancement is the need for sustainable and energy-efficient buildings [21]. In this regard, architects must design buildings that are environmentally friendly and answer occupants’ needs. To achieve this goal, interdisciplinary collaboration between engineers and architects is needed [22].

Several aspects, such as technical properties, sociocultural, environmental concerns, and aesthetics, influence the development of façade design. A significant trend nowadays is performance-based design. This trend emphasizes measurable results such as energy consumption and comfort (thermal and visual). To move the design towards performance-based design and improve the building’s performance, a solid understanding of building physics and simulation tools is necessary [23]. As discussed by Khalil et al. [22], the design process is now an open loop of feedback, analysis, and simulation of the performance of different design possibilities.

The key factors in this discussion are sustainability and energy efficiency. This leads the research towards passive and active design approaches. The use of thermal mass materials is an example of passive design strategies. Passive design methods rely on renewable and local sources [24]. Meanwhile, to increase the building’s energy efficiency, active technologies can also be used. Solar systems, smart glazing, or dynamic shading systems are among the active strategies. Architects and designers must combine both approaches in a unified and effective way to achieve a successful design [21].

Material innovation is also an important aspect of current building exterior design. Nanomaterials with improved thermal and optical properties are among the high-performance materials emerging from new materials research [25]. There is an increasing interest in materials that support circularity, such as recycled, reused, and salvaged materials. This is part of a bigger effort to lower buildings’ environmental impact and transition away from carbon-intensive materials. Designers evaluate not just the technical characteristics of these materials, but also their aesthetic and tectonic possibilities [26].

The designer's function in this process is diverse (Figure 5), needing a combination of creative vision and technical skill. Designers must have a thorough grasp of building physics, energy modeling, and façade construction. Additionally, they must be able to orchestrate a complicated set of objectives to reach overall goals. The integration of environmental, cultural, and social aspects with technical and functional requirements is a challenge. Addressing this challenge necessitates a new kind of design expert. An expert who is equally at ease working with data and simulations as they are with conventional design processes. These new experts must present a multidisciplinary corporation and collaborate with stakeholders. Only with this approach can they design high-performance, sustainable, and aesthetically pleasing building facades.

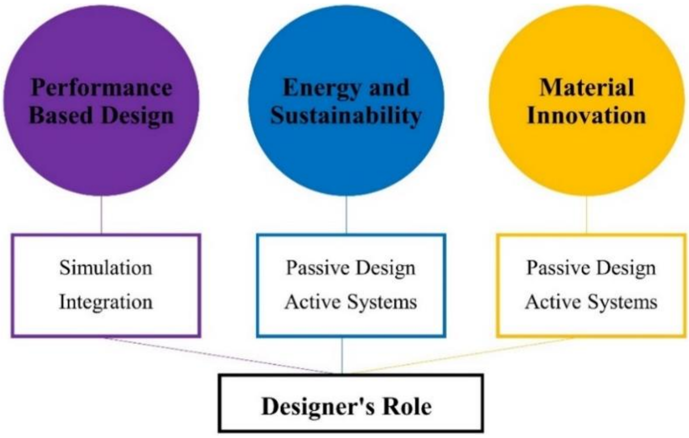

Figure 5 Key Themes of Contemporary Envelope Design and Designer's Role (Authors, 2025).

3.2 Materials Innovation in Architectural Façade

In architectural design, to achieve sustainability goals, respond to climate change challenges, and improve energy efficiency, materials innovation is one of the most important factors [27]. This section of the study explores the most recent developments in façade materials, while focusing on changes in the tectonics and aesthetic possibilities of architectural design.

This innovation emphasizes smart materials. Materials that can intelligently adjust and change their properties without assistance or actuators. This includes all materials that are unique in their properties. These materials are distinctive in their nanoscale structure. These materials can repeatedly and reversibly change their color, shape, or physical state. This characteristic appeals to architects for both aesthetic and functional reasons [28]. These materials feature dynamic and responsive façade solutions. They focus on solar control and sun protection. With the help of sensors, they can monitor the UV radiation or control the louvers' movement. These materials took façade design beyond static architectural design to features that can actively interact with their environment [29]. On the other hand, innovations for façade materials include experimenting with alternative glasses. Nowadays, glass facades can be dynamic and intelligent as well (smart glass). According to Compagno [30], smart glasses must consider solar management and transparency for solar gain. Consideration of these factors is dependent on climate characteristics and occupants' comfort.

Several novel façade materials have been studied for use in façade design. The materials are categorized according to their functionality or purpose.

- Actuation and Movement: Shape Memory Alloys (SMAs) can function as smart actuators. These materials enable movement in materials such as metal panels and aluminum louvers. Due to this ability, they are ideal for creating responsive structures. They are mainly used for controlling ventilation and in the design of dynamic shadings [31].
- Responsive color: This category includes materials that can change color in response to temperature, electricity, or light. Such as thermochromic, electrochromic, and photochromic compounds. These materials can be directly used on glasses and offer a dynamic visual effect. This ability can improve the building's functionality [32, 33].
- Thermal Regulation: This category includes materials with thermal sensitivity. Hydrogels and phase change materials (PCM) are part of this category. Hydrogels are sensitive to thermal changes. They are famous for their mechanical strength. On the other hand, PSMs help reduce cooling needs [34].
- Humidity reaction: This category includes materials that can change shape in response to humidity. For example, Hygromorphic materials. They are ideal for building facades that need to respond to changing environmental conditions [31].
- Shape-changing composites: These materials can transform their shape in response to environmental changes. They are made of thin layers of materials with different rates of thermal expansion. These materials, such as Bilayer composites, are ideas for creating prototypes and structures that physically adapt to their environment [31].

In addition to the mentioned categories, multifunctional materials can also be studied. These materials can change their properties according to the environment. Self-cleaning and energy-storing materials fall within this category [35]. On the other hand, the concept of biomimicry also influenced façade materials. Learning from plants' adaptation can inspire architects in the design of environmentally friendly facades [36].

Another current trend is the design of modular prefabricated façade systems. These systems optimize building equipment such as ventilation, heating, and cooling. Meanwhile, they include a range of features, such as solar active and passive solutions. When smart materials are incorporated into these prefabricated modules, on-site construction time and costs will be reduced, while overall building energy consumption will also decrease [37].

The incorporation of these resources frequently entails a variety of tactics. For example, smart materials can be employed as skin or as actuators that cause movement or change in other materials. They are frequently integrated with non-responsive or passive materials to form dynamic and static components within the same system [38].

Notwithstanding the potential of these new materials, significant implementation issues must be addressed. Certain materials, such as thermochromics, degrade when exposed to UV light [39]. Other limits include the high cost and limited service life of various materials, as well as scalability concerns with specific production procedures [40]. In addition, many of these materials lack particular scientific knowledge and performance criteria in facade engineering. Additional study is also required to define relevant operating conditions and optimal scales of adaptability, as materials may react unpredictably at different scales. On the contrary, performance measurements for these materials vary by role and may include thermal performance, light transmission, mechanical properties, response characteristics, energy efficiency, and implementation. Table 1 summarizes performance indicators for innovative materials based on a comprehensive literature review.

Table 1 Performance Metrics of Innovative Façade Materials and Systems (Authors, 2025).

Performance Category	Metrics	Applicable Materials	Measurement Parameters
Thermal Performance	- U-value - Solar heat gain coefficient - Thermal storage capacity	- Smart glass - PCMs - Insulation materials	W/m^2K, kWh/m^2
Light Transmission	- Visible light transmission - Shading coefficient - Glare control	- Chromic materials - Smart glass - Adaptive shading	%, luminance (cd/m^2)
Mechanical Properties	- Strength - Stiffness - Durability	- SMAs - Composites - Structural materials	MPa, cycles, years
Response Characteristics	- Response time - Actuation force - Movement range	- Hygromorphic materials - SMAs - Kinetic systems	seconds, N, degrees
Energy Efficiency	- Energy savings - CO_2 reduction - Operational efficiency	- Integrated systems - Smart facades - Modular units	kWh/year, kg CO_2/year, %
Implementation	- Installation time - Cost efficiency - Maintenance needs	- Prefabricated systems - Modular facades - All materials	$hours/m^2$

Although several of these materials and technologies remain in the early phases of advancement and research, they show promise for more efficient, sustainable, and responsive architectural facades. Further study is required to overcome some materials' technological constraints, develop new design techniques for their use in buildings, and collect more reliable performance data for these applications.

3.3 Meta-Analysis Results

The meta-analysis has been carried out on the 19 identified publications (Discussed earlier) from 2010-2025. This study reveals several critical patterns in current research on innovative façade design, tectonics, and aesthetics.

3.3.1 Study Characteristics and Quality Assessment

A total of 19 English-language studies published between 2010 and 2025 were systematically reviewed. This review offers insight into how innovative materials are shaping contemporary architecture. This time frame reflects the progression of materials innovation. It starts with the early appearance of biomimetic and smart materials in 2010. It then evolves toward digital fabrication and sustainable design strategies.

The 19 identified studies highlight a wide range of research methods. This fact sheds light on the interdisciplinary nature of façade materials research. Studies on theoretical frameworks make up the largest portion of the literature (47%, n = 9). This is followed by systematic reviews (39%, n = 6) and case studies (26%, n = 5). Lastly are critical analysis and experimental validation studies (21%, n = 4) and (16%, n = 3). This distribution indicates a field that is theoretically rich but still developing empirical validation methods, particularly for tectonic implications of material innovations.

Publication quality assessment reveals a robust evidence base, with 79% (n = 15) of studies published in peer-reviewed venues, including high-impact journals. The remaining studies comprise authoritative book chapters from established academic publishers and industry publications from recognized architectural media. This high proportion of peer-reviewed sources ensures methodological rigor and validates the systematic review's evidence base.

Temporal distribution analysis reveals three distinct research phases: a foundation period (2011-2015, n = 5) focused on establishing biomimetic and smart material principles; a development period (2016-2020, n = 7) characterized by digital fabrication integration and responsive system advancement; and a contemporary period (2021-2025, n = 7) emphasizing sustainability integration and computational design approaches. This evolution demonstrates the field's maturation from conceptual exploration to practical implementation challenges.

Critical to this research's objectives, 68% of studies (n = 13) provide substantial analysis of tectonic implications, representing a significant improvement over preliminary assessments. However, the quality of tectonic analysis varies considerably across studies. Studies receiving «High» tectonic focus ratings (n = 9) demonstrate comprehensive integration of material properties with architectural expression, construction methodology, and aesthetic implications. Those rated «Medium» (n = 4) address tectonic aspects but with limited depth or focus, while studies with «Low» ratings (n = 6) prioritize technical performance over architectural implications.

The analysis identifies several methodological limitations across the corpus. Most significantly, only 26% of studies include substantial case study validation through built projects, indicating a persistent theory-practice gap. Additionally, 74% of studies demonstrate challenges in integrating innovative materials into traditional construction methods, suggesting that implementation barriers remain inadequately addressed. Long-term performance data appears in fewer than 21% of studies, raising questions about the durability and lifecycle implications of material innovations.

These characteristics collectively validate the systematic review's methodological approach and highlight the specific research gaps this study addresses. The evidence base's quality and scope provide a sufficient foundation for developing the taxonomic framework presented in subsequent sections. At the same time, the identified limitations justify this research's focus on bridging theory and practice and on providing systematic organizational principles for innovative facade materials.

Table 2 presents the complete analysis matrix for all 19 studies, detailing publication characteristics, material category coverage, tectonic focus assessment, research methodologies employed, key contributions to the field, and identified limitations or gaps that inform future research directions.

Table 2 Complete Study Analysis Matrix (Authors, 2025).

ID	Authors/Year	Publication Type	Material Categories	Tectonic Focus	Research Method	Key Contributions	Limitations/Gap
S1	Velikov & Thün (2013) [25]	Book Chapter	Smart Materials, Responsive Systems	High	Theoretical Framework + Cases	Biological paradigm for responsive envelopes	Limited construction details
S2	Aelenei et al. (2018) [41]	Journal Article	Smart Systems, Adaptive Tech	Medium	Systematic Review + Roadmap	Zero-emission neighborhood framework	Building-urban scale gap
S3	Unruh (2023) [42]	Journal Article	Bio-based, Biomimetic	Medium	Systematic Review	Manufacturing-biomimicry-sustainability nexus	Limited tectonic expression
S4	Gruber (2011) [43]	Book	Biomimetic Systems	High	Theoretical + Case Analysis	Biomimetic principles in architecture	Biology-construction translation gap
S5	Addington & Schodek (2012) [44]	Book	Smart Materials, Responsive Tech	High	Comprehensive Review	Smart material properties and applications	Traditional integration challenges
S6	Kretzer (2016) [45]	Book	Information Materials, Smart Systems	High	Theoretical + Experimental	Information materials paradigm	Scalability and durability issues
S7	Sobczyk et al. (2022) [27]	Journal Article	Smart Materials (Sensors/Actuators)	Low	Systematic Review	Technical performance metrics focus	Minimal architectural implications
S8	Loonen et al. (2013) [46]	Journal Article	Climate Adaptive Systems	Medium	State-of-art Review	Climate adaptation control strategies	Aesthetic considerations absent
S9	Trubiano (2013) [21]	Journal Article	Performance-based Materials	High	Theoretical Framework	Spatialized skins theory, integrated design	Material-specific analysis lacking
S10	Sandak et al. (2019) [7]	Book	Bio-based Materials	High	Comprehensive Analysis	Bio-based material properties/applications	Long-term performance data gaps

S11	Sandak et al. (2019) [7]	Book	Bio-based Materials	High	Design Methodology	Biomaterial design strategies/processes	Market acceptance barriers
S12	Katharine Logan (2024) [47]	Magazine Article	Bio-based Applications	Medium	Case Study Review	Contemporary applications, market trends	Limited academic rigor
S13	Holstov et al. (2017) [48]	Journal Article	Responsive Materials	High	Review + Framework	Sustainable responsive architecture	Implementation barriers unaddressed
S14	Ozturk Demirkiran (2025) [49]	Journal Article	Digital Materials, Representation	Medium	Case Study + Framework	Paradigm shift in material exploration	Limited facade-specific focus
S15	Oxman (2016) [50]	Journal Article	Digital Fabrication Materials	High	Theoretical Framework	Material-based design (MFD) paradigm	Limited built examples
S16	Ricca et al. (2020) [51]	Journal Article	Sustainable Materials	Low	Case Study Analysis	Heritage-focused sustainable approaches	Limited general applicability
S17	Kouchaki et al. (2016) [52]	Conference Paper	Kinetic Materials, Interactive Systems	High	Experimental Design	Magnet-based kinetic brick system	Limited scalability analysis
S18	Beim (2019) [53]	Book Chapter	Tectonic Materials, Ecology	Very High	Critical Theory	Tectonic ecologies framework	Limited material specificity
S19	Marcos et al. (2024) [54]	Journal Article	Computational Materials	Medium	Critical Review	Digital architecture disruption analysis	Limited material focus

3.3.2 Study Characteristics and Quality Assessment

The systematic categorization of research focus across the corpus reveals distinct patterns in priorities for material innovation and research concentration within the facade technology domain. Seven primary material categories emerged from the analysis, with significant variations in research attention, coverage depth, and patterns of temporal evolution.

The analysis identifies a critical category of tectonic-specific studies (n = 3) that prioritize architectural expression and construction logic over material properties per se. These theoretical contributions [21, 50, 53] provide essential frameworks for understanding material-architecture relationships but demonstrate limited material specificity, creating opportunities for integration with material-focused research.

Coverage depth analysis reveals significant variations across categories. Smart materials and bio-based materials receive extensive coverage from multiple perspectives and approaches, while kinetic materials and biomimetic systems show focused but limited coverage. Digital materials represent an emerging category with high potential but currently limited facade-specific applications.

Temporal evolution patterns indicate shifting research priorities. The 2011-2015 foundation period emphasized biomimetic principles and the establishment of smart material properties. The 2016-2020 development period witnessed the integration of digital fabrication and the advancement of responsive systems. The contemporary 2021-2025 period demonstrates the integration of sustainability and an emphasis on computational design methods.

The material category distribution validates several aspects of this study's taxonomical framework while revealing areas requiring attention. Categories receiving extensive research coverage (smart materials, bio-based materials, responsive systems) confirm the taxonomy's relevance to current research priorities. Emerging categories (digital materials) suggest taxonomy evolution requirements, while underexplored categories (modified traditional materials, nano-engineered materials) indicate research gaps that require future investigation.

Significantly, the analysis reveals fragmentation in material categorization approaches across the literature. No existing study provides a comprehensive systematic organization of innovative facade materials, validating this research's taxonomical contribution. The distribution patterns also confirm the need for integration frameworks that bridge material categories, as most practical applications require hybrid approaches combining multiple material types.

Table 3 presents the comprehensive material category coverage analysis, detailing research distribution, coverage depth assessment, tectonic analysis quality evaluation, temporal evolution patterns, and key insights for each identified category. This analysis provides the foundation for the systematic taxonomical framework developed in Section 4.

Table 3 Enhanced Material Category Coverage Analysis (Authors, 2025).

Material Category	Studies Addressing	Tectonic Analysis Quality	Temporal Evolution	Key Insights
Smart Materials	S01, S02, S05, S06, S07, S08	High (S01, S05, S06), Low (S07)	Consistent 2012-2023	Well-developed technically, variable tectonic integration
Bio-based Materials	S03, S04, S10, S11, S12	High (S04, S10, S11), Medium (S03)	Growing 2011-2024	Strong sustainability focus, emerging tectonic applications
Responsive Systems	S01, S02, S08, S13, S17	High (S01, S13), Medium (S02, S08)	Evolving 2013-2018	System-level thinking, variable material specificity
Digital/Computational	S14, S15, S19	High (S15), Medium (S14, S19)	Recent 2016-2025	New paradigm, limited facade applications
Kinetic Materials	S06, S17	High (both studies)	Specialized 2016	High tectonic potential, scalability challenges
Biomimetic systems	S03, S04	High (S04), Medium (S03)	Established 2011-2023	Conceptual strength, implementation gaps
Tectonic-Specific	S09, S15, S18	Very High (all)	Consistent 2013-2019	Strong theoretical foundation, limited material focus

3.3.3 Tectonic Implication Assessment

The analysis of tectonic implications across the 19-study corpus reveals significant variations in both depth and quality of architectural analysis, confirming the central premise of this research. While 68% of studies address tectonic aspects to some degree, only 37% provide substantial analysis of the relationships among material innovation and architectural expression, construction methodology, and design implications.

Six primary dimensions of tectonic analysis emerged from the systematic review: material-structure relationships, construction methodology, aesthetic expression, architectural articulation, assembly logic, and digital integration. The distribution of research attention across these dimensions reveals clear patterns and notable gaps that inform this study's taxonomical framework development.

Material-structure relationships receive the most comprehensive treatment, with high-quality analysis present in 37% of studies (n = 7). Research by Velikov and Thün [25], Addington and Schodek [44], and Beim [53] demonstrates how innovative materials fundamentally alter structural logic and assembly approaches. However, the analysis reveals limited empirical validation through built project documentation, indicating a persistent theory-practice gap in understanding long-term structural performance implications.

Constructive methodology has been addressed in 32% (n = 6) of studies. However, the quality and depth of the analysis vary. There are some frameworks developed for bio-based materials [7] and digital fabrication techniques [50] in the literature. However, there is still a lack of understanding and research on the integration of these materials into conventional systems. This lack of study is mostly evident in smart materials research. In research on smart materials, the technical potential is well documented, but practical assembly methods are overlooked.

On the other hand, the aesthetic expression is addressed in 37% of studies (n = 7). However, research in this area remains mostly at a theoretical level, and empirical validations are limited. The literature offers in-depth studies of conceptual frameworks for examining material properties that affect the aesthetics of the building façade. But there is a lack of focus on providing systematic methods to evaluate tectonic performance on real projects. This gap must be addressed, especially since aesthetic appeal plays an important role in the acceptance of innovative materials by the market.

The analysis identifies digital integration as an emerging tectonic dimension, present in only 16% of studies but with high potential for future development. Recent research demonstrates how computational design methods enable previously impossible material-form relationships, though facade-specific applications remain limited.

Most significantly, the assessment reveals that architectural articulation and assembly logic receive inadequate attention across the corpus, with substantial analysis present in fewer than 26% of studies. This finding validates the core argument for systematic tectonic frameworks that bridge material innovation with architectural expression.

Synthesizing across all six tectonic dimensions, the average number of dimensions substantially addressed per study is approximately 1.8 out of 6 — indicating that the majority of studies address fewer than one-third of relevant tectonic implications. This quantitative deficit, combined with the uneven distribution of analytical depth across material categories, confirms that no existing study provides comprehensive tectonic coverage of innovative façade materials. This finding directly motivates the taxonomical framework proposed in Section 4.

Table 4 presents a comprehensive tectonic implications analysis, detailing research coverage, quality assessment, key findings, and identified gaps across all six tectonic dimensions in the literature.

Table 4 Comprehensive Tectonic Implications Analysis (Authors, 2025).

Tectonic Dimension	Studies with Substantial Analysis	Quality Level	Key Findings	Research Gaps
Material-Structure Relationship	S01, S04, S05, S09, S10, S15, S18	High-Medium	Materials fundamentally alter structural logic and assembly	Limited empirical validation through built works
Construction Methodology	S03, S06, S10, S11, S15, S17	Variable	New materials demand new fabrication and assembly methods	Integration with existing construction systems unclear
Aesthetic Expression	S01, S04, S09, S11, S13, S15, S18	Theoretical	Material properties enable novel aesthetic languages	Subjective evaluation frameworks underdeveloped
Architectural Articulation	S01, S05, S06, S09, S15, S18	Limited	Dynamic materials challenge traditional tectonic boundaries	Minimal analysis of built project performance
Assembly Logic	S06, S10, S11, S15, S17	Emerging	Innovative materials require reconceptualized assembly approaches	Standards and codes lag behind innovation
Digital Integration	S14, S15, S19	Recent	Computational design enables new material-form relationships	Limited facade-specific applications

3.3.4 Research Gap Identification

The comprehensive meta-analysis of 19 studies reveals five critical knowledge gaps that collectively demonstrate the need for systematic frameworks in innovative facade materials research. These gaps, identified through systematic quality assessment and cross-study comparison, represent fundamental challenges that limit the effective integration of material innovation into architectural design practice.

- Gap 1: Theory-Practice Integration Disconnect
  The most significant finding is that 74% of studies report challenges in bridging theoretical material capabilities with practical implementation strategies. While research provides sophisticated conceptual frameworks for responsive materials and smart systems, only 26% include substantial case study validation through built projects.
- Gap 2: Systematic Tectonic Analysis Framework
  Despite 68% of studies addressing tectonic aspects, only 37% provide substantial analysis of material-architecture relationships. The literature lacks comprehensive frameworks for evaluating how innovative materials influence structural logic, construction methodology, and aesthetic expression.
- Gap 3: Material Classification and Organization
  The analysis reveals no existing comprehensive taxonomical framework for innovative facade materials. Current research approaches material categorization inconsistently, with smart materials, bio-based systems, and responsive technologies treated in isolation. This fragmentation creates barriers for practitioners seeking systematic guidance for material selection and application. The 7 identified material categories appear scattered across the literature, lacking coherent organizational principles or clear relationships between categories.
- Gap 4: Multi-Scale Integration Considerations
  Only 5% of studies address multi-scale implications of innovative materials, from component-level behavior through building-scale performance to urban-scale impact. Most research focuses exclusively on building-scale applications, with limited consideration of how material innovations influence neighborhood energy systems (addressed only in Aelenei et al. [41]) or component-level assembly details. This scale limitation restricts understanding of how innovative materials contribute to broader sustainability and performance objectives.
- Gap 5: Digital-Material Integration Strategies
  While digital fabrication and computational design emerge as significant trends (16% of studies), facade-specific applications remain limited. The literature demonstrates strong theoretical foundations for material-informed digital design but lacks practical frameworks for integrating computational methods with innovative material selection and application. This represents a critical area of opportunity, particularly given the rapid advancement of digital fabrication technologies and their potential for enabling previously impossible material-form relationships.

These identified gaps collectively validate the research objectives outlined in Section 1. The absence of systematic taxonomical frameworks (Gap 3) directly supports this study’s primary contribution, while the limited tectonic analysis quality (Gap 2) confirms the need for comprehensive material-architecture relationship frameworks. The theory-practice disconnect

(Gap 1) justifies the study's emphasis on practical implementation guidance, and the multi-scale considerations gap (Gap 4) supports the comprehensive approach taken in the proposed taxonomy.

The gap analysis also validates the systematic review methodology employed in this research. The focus on tectonic implications addresses the documented analytical void (Gap 2), while the comprehensive material categorization approach responds to the organizational fragmentation identified across the literature (Gap 3). The integration of theoretical frameworks with practical application guidance directly addresses the theory-practice disconnect evident in 74% of reviewed studies.

This research is uniquely positioned to address multiple identified gaps simultaneously. The proposed taxonomical framework provides systematic organization principles (addressing Gap 3), while the tectonic focus delivers comprehensive analysis frameworks (addressing Gap 2). The integration approach bridges theory and practice (addressing Gap 1), and the multi-category framework enables scale considerations (addressing Gap 4).

Section 4 of the study will introduce the taxonomical framework, which has been formed based on identified and validated gaps. The proposed taxonomical framework tries to contribute to both the theoretical and practical advancement of the field. This aim could be achieved by addressing the limitations identified in existing studies.

4. Novel Taxonomy of Innovative Materials

Through a comprehensive literature review, this study proposed a taxonomy of innovative façade materials. At one point, the proposed taxonomy serves as a framework for a better understanding of current developments in the field. On the other hand, it can be used as a guide for designers to identify future opportunities. The novel taxonomy highlights the complexity and multi-functionality of innovative contemporary façade materials. Additionally, it highlights diverse strategies that can improve building performance and sustainability.

Having such a taxonomy in hand is essential for architects and designers to select appropriate materials for façade design. Each category presented in the following taxonomy (Figures 6-13) presents advantages and challenges. The section of each material depends on the environmental conditions and the project's goals. With the help of this taxonomy, it is possible to combine different innovative materials to enhance the façade performance while responding to the aesthetic and functional requirements of the project.

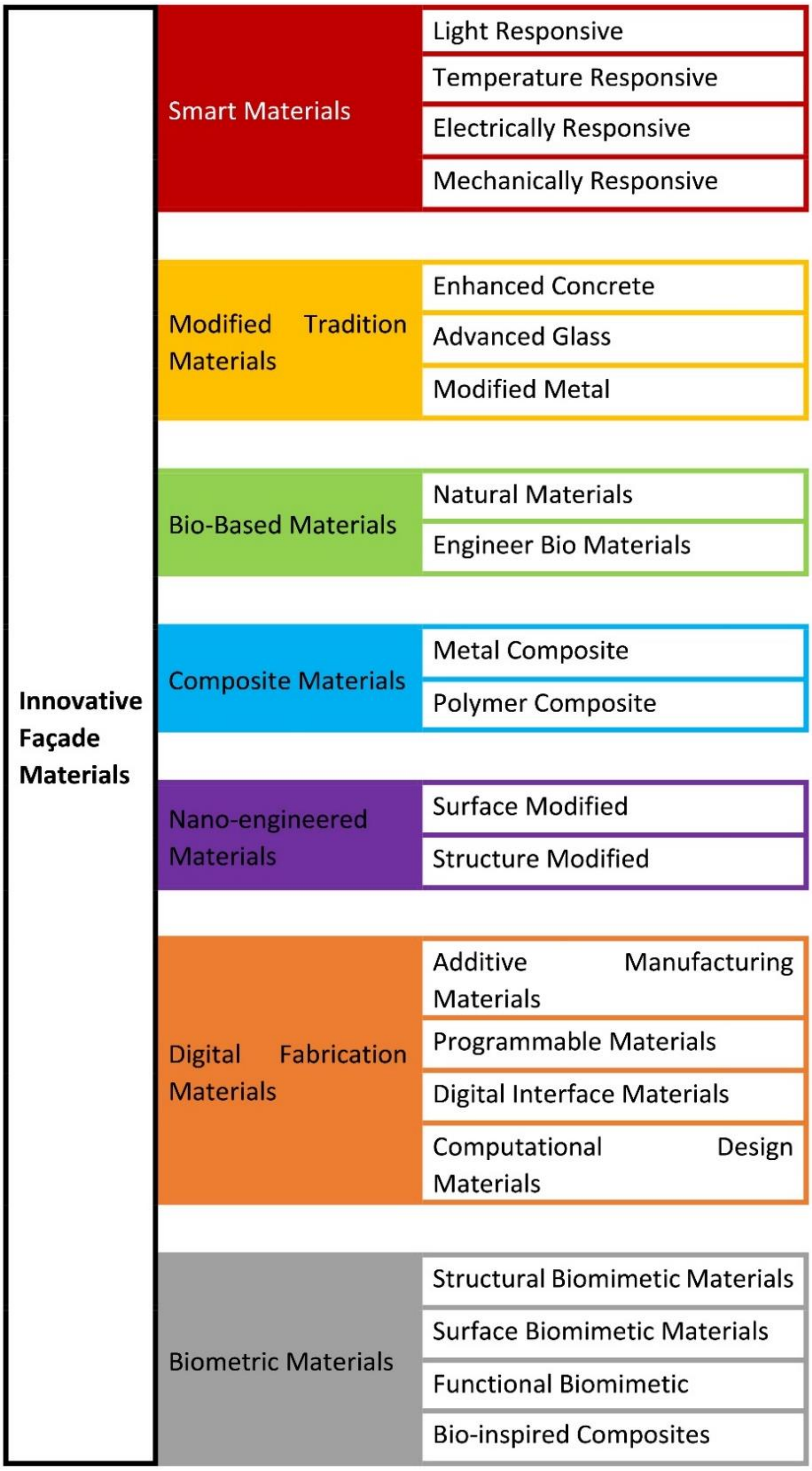

Figure 6 Taxonomy of Innovative Façade Materials (Authors, 2025).

Smart Materials	Light Responsive	Photochromic Glass
		Light-emitting Cement
		Luminescent Panels
	Temperature Responsive	Thermochromics Materials
		Phase Change Materials
		Shape Memory Alloys
	Electrically Responsive	SPD Glass
		Electrochromic Glass
		E-Paper Displays
	Mechanically Responsive	Aluminum Foam
		Piezoelectric Materials
		Kinetic Façade

Figure 7 Taxonomy of Innovative Façade Smart Materials (Authors, 2025).

Modified Traditional Materials	Enhanced Concrete	Self-cleaning concrete
		Translucent Concrete
		Carbon Fiber Concrete
	Advanced Glass	Vacuum Insulated Glass
		Self-cleaning Glass
		Bird-safe Glass
	Modified Metal	Self-healing Metal
		Textured Metal
		Coated Alloys

Figure 8 Taxonomy of Innovative Façade Modified Traditional Materials (Authors, 2025).

Bio-Based Materials	Natural Materials	Wood Composite
		Bamboo Panel
		Cork Insulation
	Engineer Bio Materials	Mycelium Composite
		Bioplastics
		Algae Panels

Figure 9 Taxonomy of Innovative Façade Bio-Based Materials (Authors, 2025).

Composite Materials	Metal Composite	Fiber Metal Laminates
		Metal Matrix Composite
		Hybrid Metal Panels
	Polymer Composite	Fiber Reinforced Polymer
		Textile Reinforced Materials
		Sandwich Panels

Figure 10 Taxonomy of Innovative Façade Composite Materials (Authors, 2025).

Nano-engineered Materials	Surface Modified	Hydrophobic Coating
		Anti-bacterial Surfaces
		UV-resistance Films
	Structure Modified	Carbon Nanotubes
		Graphene Composite
		Nano Cellular Materials

Figure 11 Taxonomy of Innovative Façade Nano-engineered Materials (Authors, 2025).

Digital Fabrication Materials	Additive Manufacturing Materials	Polymer Filaments (PLA, ABS, PETG)
		Metal Powders (Titanium, Aluminum)
		Ceramic Slurries
	Programmable Materials	4D Printing Materials
		Self-assembling Polymers
		Stimuli-responsive Hydrogels
	Digital Interface Materials	Conductive Polymers
		Transparent Conductive Oxides
		Liquid Crystal Polymers
	Computational Design Materials	Gradient Materials
		Topology-Optimized Materials
		Functionally Graded Materials

Figure 12 Taxonomy of Innovative Façade Digital Fabrication Materials (Authors, 2025).

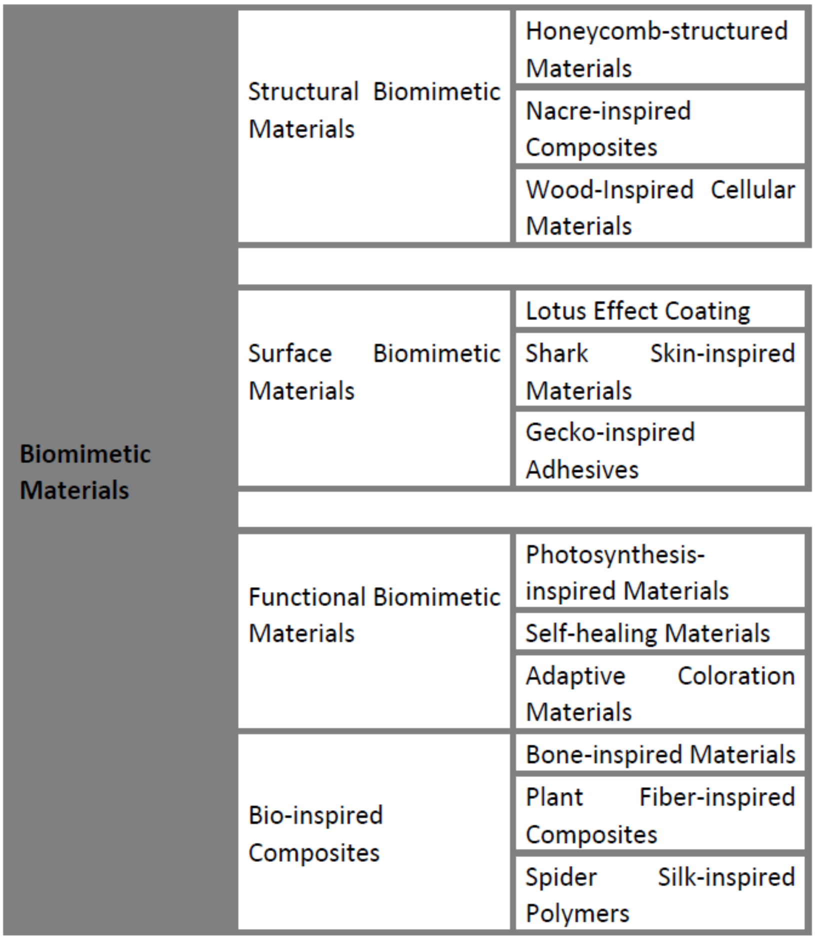

Figure 13 Taxonomy of Innovative Façade Biomimetic Materials (Authors, 2025).

Before presenting the taxonomy, it is important to clarify the conceptual boundaries between categories that may appear overlapping. Bio-based Materials and Biomimetic Materials, while related, are fundamentally distinct: Bio-based Materials are defined by their material origin — they are physically derived from biological sources such as timber, bamboo, mycelium, or algae, and their tectonic value lies in their natural properties and sustainable sourcing [7]. Biomimetic Materials, by contrast, are not necessarily biological in origin; rather, they are engineered materials whose design principles, structures, or functions are inspired by biological systems — such as honeycomb structures inspired by bee colonies or self-healing mechanisms inspired by biological tissue repair [55, 56]. Similarly, Smart Materials and Responsive Systems represent distinct categories: Smart Materials refer to specific materials with intrinsic properties that enable them to respond to environmental stimuli — such as thermochromic glass or shape memory alloys [27, 44] — while Responsive Systems refer to broader integrated assemblies combining multiple materials and mechanical or digital components to achieve adaptive behavior. Understanding these distinctions is essential for architects and designers applying the taxonomy in practice, as each category implies different tectonic strategies, assembly logics, and aesthetic outcomes.

Smart materials introduce a fundamentally dynamic tectonic logic to façade design. Unlike conventional static materials, their intrinsic responsiveness to environmental stimuli — temperature, light, electricity, or mechanical force — creates a new structural language where the material itself becomes an active component of the building envelope [44]. From an assembly perspective, smart materials are typically integrated as surface layers or actuating elements within conventional structural systems, requiring precise detailing to accommodate movement and reversible deformation [27]. Aesthetically, they enable façades that shift appearance over time, challenging traditional notions of architectural permanence and introducing temporality as a design dimension [28, 29].

Modified Traditional Materials represent a tectonic evolution of established construction systems, where familiar structural logics are enhanced through technological intervention. Enhanced concrete variants such as translucent and self-cleaning concrete maintain conventional load-bearing assembly principles while introducing new surface behaviors and light-transmitting properties that fundamentally alter façade aesthetics [7]. Advanced glass systems, including vacuum-insulated and bird-safe glass, preserve familiar curtain wall assembly logics while achieving superior thermal performance. Modified metals offer expanded tectonic expression through surface texturing and coating technologies, enabling weathering patterns and visual effects previously unachievable with conventional metallic cladding systems [25, 26].

Bio-based Materials offer a tectonic language rooted in natural growth patterns and organic structural logic. Timber and bamboo composites follow grain-based structural systems that express material honesty through visible joinery and connection details, directly linking construction methodology to aesthetic outcome [2, 7]. Cork insulation introduces compressible layering assemblies with distinctive textural aesthetics. Engineered bio-materials such as mycelium composites and algae panels represent an emerging tectonic frontier, where biological growth processes themselves become the fabrication method, producing forms and surface qualities impossible to achieve through conventional manufacturing [11]. Their warm organic aesthetic qualities offer a compelling counterpoint to the dominance of industrial materials in contemporary façade design [3].

Composite Materials introduce a hybrid tectonic logic that combines the structural advantages of multiple material systems into unified façade assemblies. Metal composites such as Fiber Metal Laminates and Metal Matrix Composites enable lightweight yet high-strength cladding systems, allowing larger panel spans and reduced substructure requirements that directly influence façade assembly logic and visual composition [25]. Polymer composites including Fiber Reinforced Polymers and Sandwich Panels offer exceptional design flexibility, enabling complex curved geometries that challenge conventional flat-panel tectonic traditions [16]. Aesthetically, composite materials blur the boundary between structure and surface, creating façades where material layering becomes a visible expression of performance — transforming technical necessity into architectural language [26].

Nano-engineered Materials operate at a scale invisible to the human eye, yet their tectonic implications manifest prominently at the building-façade level. Surface-modified nanomaterials such as hydrophobic coatings, anti-bacterial surfaces, and UV-resistance films are applied as ultra-thin layers onto conventional substrates, requiring no fundamental changes to existing assembly systems while dramatically enhancing surface performance and longevity [35]. Structurally modified nanomaterials, including carbon nanotubes and graphene composites, offer unprecedented strength-to-weight ratios, enabling thinner and lighter façade assemblies with reduced structural support requirements [25]. Aesthetically, nano-engineered surfaces achieve visual effects such as self-cleaning transparency and iridescent finishes, creating a new category of architectural expression — one where material performance and visual quality are inseparable [7].

Digital Fabrication Materials represent a paradigm shift in tectonic thinking, where the boundary between material, form, and fabrication process dissolves into a unified design logic [50]. Additive manufacturing materials such as polymer filaments and metal powders enable previously impossible geometries — complex lattice structures, gradient densities, and topologically optimized forms — that redefine conventional assembly logic by eliminating joints and connections in favor of continuous material transitions [16]. Programmable and stimuli-responsive materials introduce a fourth dimension — time — into tectonic expression, enabling façades that self-assemble or transform post-fabrication [45]. Aesthetically, computational design materials generate ornamental complexity directly from structural optimization, creating a new tectonic language in which beauty and performance are mathematically inseparable [54].

Biomimetic Materials derive their tectonic logic from nature's own structural strategies, translating biological principles into architectural assembly systems. Structural biomimetic materials such as honeycomb-structured panels and nacre-inspired composites replicate hierarchical load distribution strategies found in natural organisms, achieving exceptional strength-to-weight ratios that enable innovative façade spanning and assembly configurations [43]. Surface biomimetic materials including lotus-effect coatings and shark skin-inspired surfaces introduce self-regulating performance that eliminates the need for additional maintenance systems, simplifying assembly logic while enhancing long-term durability [48]. Functional and bio-inspired composites such as self-healing and photosynthesis-inspired materials introduce regenerative tectonic principles, in which the façade actively maintains and repairs itself — fundamentally challenging static assumptions of conventional architectural construction [38, 56].

Beyond its immediate application in architectural design practice, the proposed taxonomical framework holds broader implications for the standardization of innovative façade materials. By providing systematic classification criteria across material categories, the framework could inform the development of performance benchmarks and testing protocols within building codes and regulatory standards — areas that currently lack structured guidance for innovative materials. This represents a promising direction for future research and professional practice development.

5. Conclusion

This study addressed a critical and largely overlooked gap in the architectural research landscape: the systematic examination of innovative façade materials through a tectonic lens. Through a two-phase methodology integrating keyword co-occurrence network analysis and PRISMA-based systematic review of 19 peer-reviewed publications (2010-2025), this research demonstrated that the overwhelming majority of existing studies prioritize performance-based research — particularly energy efficiency and thermal comfort — at the expense of tectonic and aesthetic analysis. Quantitative assessment revealed that the average study addresses fewer than 1.8 out of 6 identified tectonic dimensions, confirming a significant analytical deficit in the current literature.

In response to this gap, this study proposed a novel taxonomical framework comprising seven categories of innovative façade materials: Smart Materials, Bio-based Materials, Modified Traditional Materials, Composite Materials, Nano-engineered Materials, Biomimetic Materials, and Digital Fabrication Materials. To the best of the authors' knowledge, this represents the first systematic attempt to classify innovative façade materials explicitly through a tectonic lens, connecting each material category to its structural logic, assembly potential, and aesthetic expression. The framework thus bridges the persistent disconnect between advances in materials science and the application of architectural design, offering both a theoretical contribution to the discourse on architectural tectonics and practical guidance for architects and designers engaged in contemporary façade design.

Several limitations of this study warrant acknowledgment. The systematic review was conducted exclusively through the Web of Science database, which, while ensuring publication quality, may have excluded relevant studies indexed in other academic databases. Additionally, the relatively limited corpus of 19 studies addressing tectonic implications reflects the scarcity of research in this area rather than a methodological constraint, further validating the study's contribution. The proposed taxonomy is based on current material developments and will require periodic updating as new materials and fabrication technologies emerge.

Future research should focus on empirical validation of the proposed framework through built project case studies, addressing the theory-practice gap identified across 74% of reviewed studies. Further investigation into the multi-scale implications of innovative materials — from component-level assembly details to urban-scale performance — represents a critical research frontier. Additionally, the potential of the taxonomical framework to inform standardized testing benchmarks and building code development for innovative façade materials presents a promising avenue for interdisciplinary collaboration between architectural research and regulatory practice. By systematically connecting material innovation with tectonic expression, this study aims to advance contemporary architectural design towards more adaptive, sustainable, and aesthetically considered building facades.

Author Contributions

Nazgol Hafizi, Gokce Tuna, and Müjdem Vural jointly contributed to the conceptualization, methodology, and investigation of this study. Data collection and formal analysis were conducted by Nazgol Hafizi. Nazgol Hafizi also prepared the original draft of the manuscript. The manuscript was reviewed and edited by Nazgol Hafizi, Gokce Tuna, and Müjdem Vural. All authors contributed substantially to the conception and design of the study, as well as to the interpretation of the results. All authors critically reviewed the manuscript, approved the final version, and agreed to be accountable for all aspects of the work.

Competing Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

AI-Assisted Technologies Statement

The authors acknowledge the use of the following AI systems in the preparation and revision of this manuscript: 1. Grammarly (https://www.grammarly.com) for grammar, spelling, and punctuation corrections to enhance language clarity. 2. Quillbot (https://quillbot.com) for paraphrasing, rewriting, and improving the academic tone and readability of certain passages to ensure the text reads more naturally and professionally. 3. Claude AI by Anthropic (https://claude.ai) to summarize and condense parts of the text to meet the journal's word count requirements, to rewrite sections for improved academic tone, and to assist in preparing responses to reviewer comments during the revision process by improving the clarity and presentation of the authors' arguments. While AI tools were used for rewriting, paraphrasing, and enhancing the presentation of content, all underlying intellectual contributions — including the research concept, methodology, data collection, analysis, interpretation, conclusions, and core arguments — are entirely the original work of the authors. The AI served solely as a writing assistant to improve how the authors' ideas were expressed, not to generate those ideas. The authors take full and sole responsibility for the accuracy, integrity, and content of this manuscript.

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