Review

Biomimetic Design for Adaptive Building Façades: A Paradigm Shift towards Environmentally Conscious Architecture

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Abstract: A change in thinking has been ongoing in the architecture and building industry in response to growing concern over the role of the building industry in the excessive consumption of energy and its devastating effects on the natural environment. This shift changed the thinking of architects, engineers, and designers in the initial phases of a building’s design, with a change from the importance of geometry and form to assessing a building’s performance, from structure to a building’s skin, and from abstract aesthetics to bio-climatic aesthetics. In this context, sustainable, intelligent, and adaptive building façades were extensively researched and developed. Consequently, several typologies, strategies, and conceptual design frameworks for adaptive façades were developed with the aim of performing certain functions. This study focuses on the biomimetic methodologies developed to design adaptive façades because of their efficiency compared to other typologies. A comprehensive literature review is performed to review the design approaches toward those façades at the early stage of design. Then, the theoretical bases for three biomimetic frameworks are presented to gain an overall understanding of the concepts, opportunities, and limitations.

Keywords: energy; performance; façade; adaptive; biomimetic; design; methodology

1. Introduction

The building sector consumes 40% of global energy, leading to the release of harmful greenhouse gas (GHGs) emissions [1]. Moreover, buildings are responsible for approximately 39% of the world’s carbon dioxide emissions as well as 50% of the extraction of necessary raw materials, making energy consumption an essential aspect of building construction and operations [1,2]. Additionally, the planet has limited resources, and continues to grapple with the severe impacts of climate change. Those issues necessitate paying close attention to the negative impacts of the building industry and working towards lowering energy consumption and preserving limited natural resources. In this context, it is crucial to devise approaches for the building industry to achieve sustainability goals in terms of energy efficiency and combating climate change [3]. As such, building sustainability has gained more attention and importance in architecture due to climate change and increased energy demand in the built environment [4]. In this regard, it is of the utmost importance to design buildings that lessen their environmental impact and utilize non-renewable resources. Building sustainability begins with a climate-responsive design with a passive approach to maximize the use of natural resources such as light, heat, rain, and wind [4]. In this way, sustainable architectural design solutions should be prioritized to address the adverse impacts of climate change [2,5]. Therefore, a shift in how we design buildings has been continuously ongoing to produce environmentally conscious architecture [6]. One approach for buildings to respond positively to the environment is to integrate a façade system that reacts to the dynamic outdoor environments by providing natural light, solar protection, and the ability to harness this energy and other environmental benefits [4,7].
A building’s façade is the most critical energy-regulating component of any building [8]. The significance of this component can be attributed to its nature as a medium between indoor and outdoor environments [1]. In balancing heat loss and gain between the indoor and outdoor environment, particular attention should be paid to the façade (exterior wall, door, window, and façade openings), roof/ceiling, and floor elements in proportion to heat losses. For instance, about 60% of the heat losses occurring throughout residential buildings are due to façades, 25% to roofs/ceilings, and 15% to floors [9]. Traditionally, building façades were regarded as barriers between the outdoor climate and the artificially controlled indoor environment. The efficiency of such façades was measured by their ability to isolate the building’s interior from the outdoor environment allowing the heating or cooling systems to operate as efficiently as possible [7]. This often leads to high energy consumption for the cooling or heating systems in the building, as well as occupants’ discomfort [7]. Therefore, in response to the increasing need for sustainable approaches to the deal with the surrounding environment, the building’s façade must achieve not only aesthetic and visual impact but also ensure thermal and hygrometric comfort in the indoor environment and minimize energy consumption by satisfying environmental, technological, and aesthetic requirements [1]. In this context, sustainable façades are not simply enclosures that separate the interior spaces of the building from its exteriors, but they are vital components that create inhabitable interior spaces by regulating the indoor environment and achieving user’s comfortability [10]. The design of such building façades needs to consider various performance aspects such as functional, environmental, and economical. The functional performance of the building’s façade is further divided into several categories [1,11]. Some of the building’s façade functional requirements are related to safety, such as structural stability and fire protection, while others relate to health, such as weather protection, including protection from wind-driven rainwater, moisture, and air penetration. Other performance parameters relate to the well-being of the users, such as thermal, visual, and acoustic comfort [11]. Therefore, the building’s façade has evolved into a critical and complex system for achieving the end-users’ optimal comfort and wellness standards. This is a critical issue, given that most people today spend a significant amount of time indoors [12].

To this end, façades should respond to several design and functional performance issues that may contradict each other, for example, shading vs. artificial lighting, views vs. privacy, solar gain vs. overheating, and daylight vs. glare. Thus, several environmental parameters should be considered while designing the building façade. These include [4,8]:

- **Solar gain control**: The solar radiation received through the building surfaces effects its indoor temperature and, consequently, the thermal comfort of the inhabitants [4,8];
- **Natural ventilation**: The building’s façade can regulate air exchange and circulation, thus reducing dependency on mechanical systems for the heating or cooling of the interiors, which can reduce energy consumption under certain conditions [4,8];
- **Daylighting vs. artificial lighting**: Through fenestrations and shading systems, the building envelope regulates the amount of natural light allowed into a space. These influence indoor illuminance and, as such, affects the user’s well-being. Therefore, one strategy to reduce energy consumption is to combine active and passive lighting mechanisms [4,8]. As an additional solution, daylighting strategies can be integrated into sustainable building façades, significantly minimizing the need for artificial indoor lighting, and controlling glare levels to achieve visual comfort [13]. Moreover, lighting is regarded as a primary element of space identification and quality, with significant implications on resource conservation, occupant productivity, health, and comfort [13];
- **Visual comfort**: This is defined as a state of mind representing the users’ needs, preferences, and satisfaction with the visual indoor environment, which impacts mental and physical health [8,13]. For instance, a façade’s openings connect the user of the space to the exterior environment, which serves a significant psychological function [4,8].
- **Heat control**: This relates to the regulation of heat flow between the interior and exterior of the building. This is typically done by insulating the opaque part of the façade.
However, the glazing part requires more consideration due to the degree of heat transmission through windows, which can be minimized by providing shade during high temperatures [4,8].

- **Moisture control:** The building’s façade must be designed to address two types of moisture: rain and condensation. While rain exposes the façade to humidity from the exterior, condensation forms on cold interior surfaces because of significant temperature differences due to inadequate façade insulation [4,8];

- **Noise:** The building façade must be acoustically insulated against outdoor noise caused by temporal variabilities [4,8].

There is a significant body of research regarding adaptive façade technologies in use or in the experimental stages, including biomimetic applications, kinetic, dynamic solar shading, electrochromic glazing, and phase change materials [3,14–16]. In addition, several methodologies, and typologies of adaptive façade concepts, including materials, components, and systems, have been developed. Moreover, the future holds an increase in advanced and inventive design solutions for building façades [3]. These façades are characterized by adaptability, which represents a response to the changing climatic conditions such as short-term weather fluctuations, diurnal cycles, or seasons [3,10].

Henceforth, adaptive façades have transcended the conventional role of building façades [7,17]. This new role ensures that the façade design addresses several complex functional requirements of the building’s envelope. Those requirements include heat, air, and water vapor flow, rain penetration, solar radiation, noise, fire, strength, stability, and aesthetics. Therefore, the multifunctionality of façades have become an important design goal for any sustainable building. In other words, adaptive façades would be able to perform several functions such as controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading, or humidity control [3]. As such, building envelopes’ thermophysical and optical properties contribute greatly to minimizing building energy consumption and improving the indoor environmental conditions [18].

Conventionally, environmental factors have not always been taken into consideration as constraints in the architectural design process of façades or the building as a whole [19]. In this regard, architects and designers have always focused on the classical principles of building design which are function, structure, and aesthetics, with less attention to energy and environmental considerations [17]. This presents challenges to integrating energy performance parameters into typical architectural design requirements, such as aesthetics, functionality, and structure, as well as the challenge of responding to all the contradicting functional performance parameters of façades [8,20].

To address those challenges, a holistic performance criterion must be considered simultaneously with conventional architectural design criteria during the initial design process [8,20]. Although this has been a problem in the past, there is an ongoing shift to integrate aspects of adaptive façades into the early design stage. This is driven by the potential of the adaptive façades to significantly minimize the building energy load and CO₂ emissions while preserving occupants’ thermal and visual comfort [3]. Consequently, the design approach will not only ensure the production of adaptive, intelligent, or smart envelopes which serve both the occupants and the environment, but also it can redefine the aesthetic perception of buildings, producing an aesthetics that is based on the façade’s functionality and performance, not abstract forms [21,22].

Biomimicry is considered an innovative approach for designing sustainable and adaptive building façades [15,23,24]. In this sense, the concept of biomimicry is in harmony with the concept of environmental sustainability. Moreover, adapting inventive design thinking ensures the sustainability principle is embedded at the core of the design problem’s definition from the start [25]. This is contrary to conventional design thinking, where nature’s inspiration was limited only to mimicking natural forms and shapes [26]. In this new biomimetic design thinking, designers can extract organisms’ functional and operational characteristics from a database of biological references, study the natural adaptation
strategies and then translate it into innovative, adaptive, flexible, and more efficient design solutions [25,27]. Hence, the existence of such diverse yet related biological mechanisms can inspire innovative solutions for optimal energy consumption in buildings [15]. Hence, the biological paradigm is becoming more integrated into today’s architectural design discourses [28]. In consideration of these factors, this study will review existing literature on adaptive building façades with a focus on biomimetic approaches.

Over the years, several typologies of adaptive façades have been developed with distinct technical properties and sometimes overlapping aspects [29]. Regardless of the distinctive technological aspects, adaptability is the most prominent feature among all the innovative façade typologies. This adaptability attribute is integral to biomimicry [30]. Considering that, the study will review existing literature on the adaptive building façades with a focus on biomimetic typology. Moreover, this review will explore three methodological frameworks in biomimetic design to establish a holistic framework for the design of biomimetic façades during the initial stages of the design process using the potentiality of each framework.

The paper is structured as follows: Section 2 outlines the methodology followed to generate the literature review, Section 3 describes the existing adaptive building’s façade typologies, and Sections 4 and 5 present the concept of biomimicry, biomimetic architecture, and biomimetic design. Section 6 discusses selected existing biomimetic methodologies and frameworks for adaptive façades. Section 7 explores biomimetic materials and manufacturing processes. Section 8 presents the state of the art in building simulation performance for adaptive façades. Section 9 discusses the findings of this review, and Section 10 provides conclusions and recommends areas for future research.

2. Methodology

A general overview of the advances in building façades will be presented for this review. This is followed by a critical analysis of the biomimetic adaptive façade’s typology, its design approaches, and methodologies. The papers used in this literature review were identified across three databases, including Scopus, Web of Science, and Engineering Village, between 2010 and 2022. The following keywords were used in all three search engines: adaptive façades, advanced façade, biomimetic design, parametric design, kinetic, and intelligent façade. A total of 254 studies were identified, and 104 were assessed to be of sufficient methodological quality to be included.

A critical analysis of the existing literature that focuses on intelligent and adaptive façades for all types of buildings has been included. A selection criterion has been developed to decide on the suitability of the selected papers, including:

- Literature should focus on the design of adaptive, intelligent, and biomimetic façades.
- Each research paper must analyze at least one human comfort objective, such as thermal comfort, daylight, glare, or view, and energy consumption.
- Shading systems and windows are not part of this review.

Only studies meeting the above criteria were considered for further analysis. The overall eligibility was evaluated by reading paper abstracts and the whole research paper as required. Papers were then categorized based on the typology, design methodology, and performance parameters they investigated. Figure 1 explains the framework adopted for the literature review.
Figure 1. Diagram depicting the workflow of the research methodology.

3. Façades

The term “façade” comes from the French language and means “frontage” or “face” (Simpson 1989 a, b). It refers to the exterior or skin of a building, including any special architectural features [31]. Façades are integral components of the building skin and support the building’s external architectural elements. The materials used to construct façades have evolved over time, from clay, stone, wood, and brick to steel and glass to meet various functional and climatic needs. This evolution of various materials and building techniques has resulted in the emergence of various façade typologies [5,32]. Subsequently, the understanding of the importance of the building envelope has grown over time, especially in regulating and controlling energy usage [5,33]. This means that the façade’s role is evolving from “a passive protective covering to an active regulator of a building’s energy balance” [33]. This new role necessitates the ability of façades to adapt to changing conditions [34]. In doing so, building façades must behave more like natural skins [24]. This is due to the ability to live organisms to adapt to changing weather conditions while keeping their body temperature within very narrow ranges using physiological, morphological, and/or behavioral thermoregulation mechanisms [35]. In this context, biomimicry has enormous potential as a design tool for improving a building’s sustainability [36]. Furthermore, the ability of building façades to adapt to their microenvironment would increase their versatility and improve their resilience by requiring less energy to operate and allowing for much more efficient utilization [11].

3.1. Façade Performance Indicators

In terms of the indoor environment and occupants’ biological needs, four categories of façade performance indicators could be defined: outdoor climate, biophilic requirements, and energy issues [4,8,37,38]:

- **Biological Factors**: Façade systems must be designed to respond to the biological needs on an hourly/seasonal basis of the occupants by adjusting indoor lighting and thermal environments.
- **Climatic Factors**: The response and adaptation to the outdoor climate maximize the positive relationship with exterior environments. The major climatic factors in the context of built environments are humidity, wind, solar radiation, and precipitation.
- **Biophilic Factors**: This includes responding to the following features: (1) visual and non-visual features, (2) airflow and thermal features, (3) acoustic features, (4) colors and materials, (5) shape and form, and (6) design implications and space syntax.
- **Energy Factors**: The most critical design parameter for building sustainability is the amount of energy required to regulate indoor environmental conditions. Moreover,
heating and cooling functions constitute large amounts of the energy consumed in a building, which relates to the façade’s design because most of the heat and light transmission between indoors and outdoors occurs through the façade [4,8,37,38].

3.2. Advances in Building’s Façades

Traditionally, control systems have been integrated into windows and doors using low-cost and simple-to-use manual shading or protection devices such as exterior louvers, blinds, or sunshades. These programmable devices can, for example, regulate solar thermal intrusion and minimize heat gain through windows and other glazed surfaces [38]. However, over the last few decades, various typologies of more active and less static façades have emerged over time, for instance, kinetic façades as environmental control systems capable of responding to changing environmental conditions [38]. Moreover, historically, the façade had the goal of being the primary load-bearing structural element, limited in its functionality and materiality [25].

In the modern era, the façade is often liberated from its load-bearing role. This has led to describing the enclosure as a building skin with diverse functions. These functions include regulating energy usage, providing thermal comfort, and adaptability to changing conditions, among others [15,39]. In this context, the adaptability of the building façades led to the development of various adaptive façades typologies. Those façade typologies can be defined as building envelopes that can adapt to changing boundary conditions, such as short-term weather fluctuations, diurnal cycles, or seasonal patterns [29,40,41]. Hence, the thermophysical behavior of these façades can change over time and adapt to the changing needs of the building and its occupants, considering the various boundary conditions that can occur throughout the seasons and during the day [1,22]. In terms of sustainability, adaptable building façade design is critical, considering thermal, lighting, acoustics, occupant’s comfort and well-being, aesthetics, economy, and durability [42]. Five of the adaptive building’s façade technologies that are driven by innovative responses to the environmental conditions are presented below.

1. **Advance Intelligent Façade (AIF)**

The AIF is defined as an advanced intelligent module that uses electromechanical systems to produce the appropriate response by sensing indoor and outdoor temperature, daylight, and humidity parameters using sensors. This is a performance-driven adaptive and electromechanical prototype that responds to environmental conditions and proposes critical decision and priority algorithms to incorporate ambient data to resolve conflicts in decision-making [43].

2. **Building Integrated photovoltaic Façade (BIPV)**

BIPV is a type of façade that integrates photovoltaic (PV) systems and thermal collectors, enabling the building envelope to function as an energy generator while at the same time maintaining energy efficiency. This has been supported by a significant body of research conducted to optimize the integration of solar panels in building development, including the integration of shading devices. Moreover, such façades rely on enhancing the architectural quality of solar collectors, including shape, size, and color, which are essential for successful integration. Hence, manipulating façade geometry increases the energy production potentials of PV façade integrated panels compared to typical vertical surfaces [20,44].

3. **Kinetic Façade**

This can be defined as automatic and responsive (adaptive) façades consisting of kinetic elements with distinct types of movements such as flapping, folding, transforming, rotating, sliding, scaling, expanding, extracting, and changing in response to daylight [31]. This responsive kinetic façade improves an occupant’s comfort through interacting morphologically with its surrounding environment by using built-in sensors and actuators. As
a result, kinetic façades have the potential to provide occupants visual and thermal comfort while considering dynamic stimuli, such as sun timing positions [37,45].

4. **Climate Adaptive Building Skins (CABS)**

This type of façade repeatedly and reversibly changes some of its functions, features, or behavior over time in response to changing performance requirements and variable boundary conditions, aiming to improve overall building performance. It has three different properties: adaptability, multi-ability, and evolvability [19].

**Adaptability**

Building envelopes with this characteristic can take advantage of the opportunity to act deliberately in response to changes in climatic conditions. This has the potential to save energy compared to conventional building systems because the valuable energy resources in our environment can be actively exploited, but only when the effects are deemed favorable. CABS can thus act as a climate mediator, negotiating between user’s comfort requirements and the environment’s sustainability requirements [19].

**Evolvability**

In the built environment, evolvability is also known as survivability [13]. It can be used to address changing external conditions such as climate change and changing urban environments. Despite the uncertainty in daily building operation, the future building requirements and boundary conditions are highly unpredictable or not predictable at all during the design stage. This uncertainty can be used to derive value and create envelopes that can evolve over time. Evolvability is regarded as a positive byproduct rather than a primary design goal; the ability to keep options open preserves opportunities to respond to changes in the future. Furthermore, the use of CABS increases the likelihood that the building will continue to operate as intended without being subjected to potential negative effects of unforeseeable future conditions [19].

**Multi-ability**

The concept of multi-ability stems from the existence of non-simultaneous performance requirements or the requirement to respond to changing environmental factors. In this regard, multi-ability differs from adaptability by accomplishing multiple objectives sequentially rather than concurrently. Unlike conventional systems that are designed to address a single set of conditions, it allows for addressing change via several optimized states [19].

5. **Biomimetic adaptive building skins (Bio-ABS)**

Bio-ABS is a façade typology that responds to environmental conditions by changing its morphological or physiological properties or behavior constantly to meet the building’s various functional requirements and improve its performance. The changing properties and behaviors, in this case, are inspired by biological models that offer environmentally, mechanically, structurally, or materially efficient strategies [15].

Bio-ABS typology is the integration of two aspects: biomimetics and adaptive building skins (ABS). ABS refers to imitating nature; therefore, adopting biomimetics as a design generator and ABS as the design product [15,39]. In recent years, researchers have become increasingly interested in the development of biomimetic building façades with an aim to achieve multi-regulation façades, which are multifunctional and adaptable across days and seasons [46]. Subsequently, biomimetic façades rely on biomimetic strategies that are often driven by biological adaptation mechanisms in response to environmental factors. The expression of these mechanisms in organisms is often dynamic and can produce a change in their physical or physiological conditions. Therefore, adaptability is a significant shared attribute between organisms and those types of façades [15,37].
Characterization of Biomimetic Adaptive Building Skins

Kuru et al. [47] identified four layers for Bio-ABS: (1) scale, (2) adaptability, (3) biomimetics, and (4) performance.

Layer 1: Scale

Scale is concerned with spatial scales and developmental stages. The spatial scale, which is defined as envelope, façade, façade component, and façade sub-component, determines the size of a system. The envelope refers to the entire building skin, whereas the ‘façade’ refers to the external walls. A façade component is a component of a façade that is put together to form the façade. A façade sub-component is a smaller-scale version of a façade component [47].

Layer 2: Adaptability

The adaptability of Bio-ABS determines its responsiveness to environmental factors, its functions, and its stimuli. Environmental factors are the parameters regulated by Bio-ABS by causing changes in heat, light, air, water, and energy. A shading system, for example, controls the exposure to heat and light by limiting solar gains and providing daylighting. Furthermore, the number of environmental factors that Bio-ABS regulate when activated by stimuli interdependently determines whether they are monofunctional or multifunctional systems [47].

Layer 3: Biomimetics

The biomimetic properties of Bio-ABS distinguish them from other types of ABS. Those biomimetic processes can begin by defining a design problem to be solved by a biological strategy or by investigating a biological solution to address a design challenge [47].

Layer 4: Performance

Bio-ABS performance quantifies the efficacy of operational strategies. It entails determining a performance target, conducting system analyses, and measuring and improving performance. The Bio-ABS performance target specifies the system’s functionalities to improve the building’s performance, such as indoor air quality, thermal comfort, visual comfort, or energy consumption [47].

4. Biomimetics

4.1. Definition

The term “biomimetics” can be defined as the study of biological structures, processes, and their potential technological applications [48,49]. In addition, biomimetics, as an interdisciplinary field of research between biology, technology, and design, has existed for a long time. Moreover, biomimetics is not just an imitation of an organism’s functions or materials but a conscious understanding of the biological principles to develop technological solutions [48,50,51]. In addition, biomimetics is a rapidly expanding engineering discipline and an emerging design field in architecture and engineering [35]. It operates by borrowing biological strategies from a database of mechanisms and strategies to be integrated into the design process. Those biological solutions implemented in design can be multifunctional, complex, and highly responsive and can thus replace the static concept of conventional building façades with the aim of improving energy performance in a new adaptive form [52].

Upon investigating the current biomimetic typologies, three levels of mimicry can be noted, including the organism, behavior, and ecosystem [53–57]. The organism level refers to an organism, such as a plant or animal, and may involve imitating the entire or part of the system. The second level of behavior mimicking refers to translating an aspect of how an organism behaves or relates to a macro context [53]. The final level is the replication of entire ecosystems and their operational and functional principles that allow them to function effectively [55,58].
Hence, the organism’s adaptation properties to environmental changes have drawn a lot of attention, with the hope that these properties can provide novel approaches to building technologies, particularly building façades, to improve overall energy performance [47]. Such optimized performance is achieved through the creation of interactive relationships and behaviors within the building systems that can adapt to changing conditions in nature [59]. The emphasis on building façades stem from their functionalities, which have progressed from load-bearing components to more thermal, acoustic, and visual envelopes [59]. To optimize the building’s façade performance, complex, adaptable, and transformable morphologies in nature must be examined. This will yield strategies to provide dynamic structuring in building envelopes and enhance the building’s performance by supporting building-environment interaction using smart materials [59]. In this context, recent technologies such as adaptive building façades attempt to design façades that adapt to changing environmental conditions, accommodate various functions and provide occupants with decentralized controls. Thus, increasing the user’s comfort and decreasing energy consumption in buildings [47].

To study biomimicry, there are three primary motivations [56]. First is biomimicry for innovation, in which we investigate biological systems to create modern technologies [60]. The second motivation is biomimicry for sustainability. Hence, the environmental performance of both human technologies and the built environment can be enhanced using this concept. The final motivation is employing biomimicry to enhance human well-being, which involves investigating the ability of bio-inspired designs to contribute to increasing human psychological well-being [60,61].

The knowledge transformation process from biology to design or technology necessitates collaboration [56,62]. This collaborative approach is supported by recent advances in biology. One notable advance in biology is applying physics and thermodynamics principles systematically and meticulously to explain how organisms remain and thrive within certain temperature ranges despite their constantly fluctuating environment. In this respect, biologists have demonstrated the existence of functional, adaptive thermal features that can be structural, physiological, or behavioral in nature and can also inform a building’s thermal performance [63].

4.2. Biomimetic Approaches

Two main approaches were defined in approaching biomimetics as a design field [60–64]. First is a problem-based approach, in which designers identify a design problem and then look for precedents from nature to search for inspiration. The second approach is solution-based, where the biological knowledge of scientists and biologists is the starting point rather than the human-based design problems [64]. Both biomimetic approaches can be explored in the following three levels, as illustrated in Figure 2:

- **Morphological or structural level**: Focuses on an organism’s physical properties and attributes such as shape and pattern, which aid the organism in adapting to its specific environmental constraints.
- **Physiological or functional level**: This level studies the chemical processes that occur within the organism.
- **Behavioral**: This level of biomimetics relates to how an organism interacts with its environment, most often as surviving mechanisms [65].
The biomimetic approach to design goes beyond simple inspiration or imitation of natural forms or processes [51,66–68]. As such, different complex strategies can be transformed from biology to architecture. In this regard, nature can be used directly or as a metaphor to solve design problems and develop environmentally responsive functions, systems, and solutions. Moreover, through evolutionary processes, living systems optimize their survival strategies, presenting a potential for developing sustainable and adaptive buildings [56].

4.3. Biomimicry Principles

There are a set of characteristics that are recognized in biological systems as the principles on which organisms and natural systems are formed [55]. These principles are abstract biological strategies that can be found in most organisms, some of which are obvious and self-explanatory. These principles of biological systems are divided into six (6) categories [55,69,70]:

- **Exchange with the environment**: All life forms interact with their surroundings by exchanging data, matter, and energy; locally integrating, exploiting, and improving concurrent cyclic procedures; and establishing cooperative and competitive relationships.
- **Order/structure/growth**: Organisms and natural habitats are defined by the optimization of available materials or alteration of form to function according to principles such as multifunctionality, entropy growth, or nullity.
- **Adaptability**: The primary characteristic of living systems is their ability to adapt to changing circumstances due to their increased resilience and integration of variety, redundancy, and decentralization requirements.

4.4. Comparison between Organism and Building Thermal Properties

Nature is linked to architecture because it is a factor that changes and adapts to its surroundings, just as buildings should [71]. The building envelope acts as a bridge between the internal and external environments, transferring heat between buildings and their surroundings via conduction, convection, radiation, and evaporation [72,73]. In this context, nature has more efficient thermoregulation solutions to be learned from [73]. In nature, organisms can manipulate their body temperature using behavioral or physiological means as an adaptive response to changes in their environment. Moreover, organisms must keep their body temperature within a very narrow range to survive the harsh climatic conditions [55]. In addition to producing heat metabolically, organisms exchange heat with their surroundings through conduction, convection, evaporation, and thermal radiation, sustaining a convenient body temperature [73]. As such, the organisms’ remarkable adapt-
ability to extreme environmental conditions has become a major source of inspiration for architects, engineers, and designers [34].

One of the concepts used in establishing the relationship between organism and building is skin-building techniques. In this regard, a building’s façade is considered as a skin or a thin membrane that sits on top of the structure and regulates the mechanical and electrical functions of the structure, as well as forming the interior spaces of the building, imitating the natural skin of a living organism. Moreover, both skins are made up of various layers that filter out particles and react responsively to heat, pollution, water pollution, and noise pollution. Thus, one of the primary similarities between these two types of skin is that they both maintain the condition of internal spaces while meeting the functional needs of the inner space or body [55].

To this end, environmental impact and sustainability debates influence architecture globally through new codes and measures, most notably on topics of energy efficiency and environmental impacts of buildings. As such, architects and designers today work in an increasingly complex, volatile, and interconnected industry [60,74]. Consequently, the design and construction industry has been inspired to pursue an environmental sustainability mission of responding to declining resources, eroding biodiversity, and chronic environmental health issues [60]. In this regard, architectural practices continue to seek out more sustainable design concepts, such as passive, active, energy-efficient, zero energy, green, and intelligent technologies. Moreover, due to the essential role that building skin plays in mediating external environmental conditions, a sizable portion of the design problem has been shifted to focus on building skin configurations [37,47]. Consequently, many designers are now focusing on creating a building façade that acts as a dynamic, responsive system [47,74], thus pushing the biological domain further into the center of architectural concerns [47].

5. Biomimetic Architecture

The modern-day requirements of buildings are often complex and necessitate a comprehensive approach for inventive functional and sustainable building systems, which might be attained from a more interdisciplinary field like biomimetic design [75]. In this context, the overlaps between nature and architecture inspired many researchers to adopt biological mechanisms to control environmental conditions [15,39]. Hence, biomimicry-based design has emerged as a multidisciplinary, revolutionary trend in architecture [47]. It has transformed the concept of a building into a living, interactive being, opening a new venue for architects’ innovation and creativity [47]. Moreover, the advancements in design software supported by digital fabrication and manufacturing of composite materials have allowed designs derived from nature to be realized [15,39].

Biomimetic architecture can be classified into two, structural and process biomimetics. First, structural biomimetics explores the ability of organisms to achieve resource and material-efficient morphologies as hierarchical multi-level structures with independent functional qualities. Second, process biomimetics focuses on biological functions that control physical and chemical environments. This involves controlling the building’s external climatic and related internal changes [44].

The primary advantage of using biomimicry is that designing building façades result in an efficient thermoregulatory mechanism [55]. However, there is a significant gap between biomimicry with its focus on biosystems and the architecture of human-made structures. As humans create a built environment, biomimicry is a natural evolution process. Hence, limiting the availability of cross-domain information for both biologists and architects. This has been identified as one of the significant constraints to applying biomimicry to architecture [55].
5.1. Biomimetic Design

Today, the trend toward sustainability has resulted in modern design approaches for adaptable building façades, with biomimetic design principles gaining the most attention [28]. This inspiring biomimicry design has become a promising approach, as it provides various design alternatives that achieve adaptability to environmental concerns [67]. The research field is shifting toward a qualitative process for the conceptual design phase of façades. This is in response to the need for a comprehensive framework for building façade design that considers performance and context-related parameters to achieve more adaptive façades. To create these optimal façade systems, architectural and engineering performance parameters must be outlined throughout the façade’s life cycle [40]. Therefore, the design of those systems is critical for achieving energy efficiency in buildings [75]. In this context, a focus on biological solutions is critical for gaining new perspectives for building façade design [56]. Hence, research on biomimetic design focuses on three key themes: modeling and simulation methods, transferring biological principles into building solutions and using biological structures as inspiring models for more sustainable building technologies [76].

5.2. An Approach to Biomimetic Design Decisions

The design decisions taken by the architect or designer in the initial phases of any project have the greatest impact on building performance [77]. However, the use of biomimetics in the design of adaptable façades is an iterative process involving multiple disciplines [55]. Moreover, indoor environmental quality parameters, such as thermal comfort and daylight usage, should both be considered as part of a building’s performance parameters rather than just energy efficiency requirements. In addition to that, building energy performance can be ensured by identifying the appropriate performance indicators and variables during the design process [78]. Thus, design decisions for sustainable buildings frequently involve many variables that can result in complex issues that are difficult to solve at a time [77].

Regarding abstracting biological morphologies to generate architectural forms, a gap has emerged between the methods of physical and digital form-finding that rely on nature, with most designers extracting from nature rather than adopting and learning from biological systems. This gap can be addressed by employing organism’s behavior and studying nature’s rules and logic. Furthermore, designers should not ignore the relationship between materials and the shaping processes used in the generation of the form [79].

5.3. Biomimetic Design Principles

Nature is a source of distinct integrated strategies that can be used as forms of design analogies and thinking in which aesthetic, function, form-material, and structure can be similarly considered in the pursuit of sustainable architectural solutions [80]. Those biological mechanisms are characterized by the following principles:

- Adapt to changing conditions.
- Develop survival tendencies.
- Harmonize growth with developments.
- Create self-awareness and responsibility for local needs.
- Release no harmful chemical substances to the environment.
- Manage resources sustainably.

The above design principles emphasize the need for a whole system. As systems evolve over time, they demonstrate adaptation, harmonize substructures within local constraints and conditions, and create sustainable and always modern designs while using fewer resources and causing less environmental damage. Thus, the concept of sustainability demanded that architectural design approaches be reviewed considering environmental and energy concerns [80].
5.4. Functional Integration Possibilities in Biomimetic Design

Badarnah [81] has investigated the multifunctionality of the existing design solutions inspired by nature. In general, most existing façade design solutions address a single functional parameter at a time. In practice, a building is subjected to a variety of environmental factors, necessitating the simultaneous management of heat, air, water, light, etc. Furthermore, environmental factors are frequently highly interconnected with the regulation of one factor reliant on the regulation of the others. To carefully consider the humidification of a building interior at the desired humidity level, for example, one must consider (1) air regulation, which may continuously modify the relative humidity; (2) thermal regulation, which is coupled with humidity in determining comfortable humidity levels; and (3) light regulation, which is coupled with heat regulation. In nature, some organisms have multifunctional capabilities and can deal with multiple environmental aspects at the same time. Termite mounds, for example, manage air movement while retaining heat; skink scales redirect light, preserve water, and prevent heat concurrently. As a result, when faced with the task of developing a multifunctional system, it is best to select morphologies with multifunctional abilities where integration has already been effectively developed and utilized by the organism [81].

6. Existing Biomimetic Design Methodologies

Biomimetic design processes are supported by numerous methods and frameworks. However, those frameworks are still at a conceptual level and not widely tested [82]. This section will thematically explore three different biomimetic approaches developed for the design of adaptive building façades.

6.1. Approach One: Biophysical Information Representation

Badarnah [35] proposed a model for representing biophysical information to aid designers with inadequate biological knowledge in the conceptual design stage. In this model, natural analogies are used to solve specific design problems in the biomimetic design process. Moreover, the model provides a frame for organizing and categorizing biophysical data based on hierarchy and relational connections, enabling the designer to perceive the biophysical data as a contextual map and to distinguish relevant analogies. In addition to that, the model aims to identify exemplary pinnacles and investigate viable scenarios for the design solution. Hence, this model establishes a suitable analogy between thermoregulation in both nature and buildings and provides some indications of proper aspects to adapt in the design solution. The model consists of four main components that correspond to generic functions of desired building materials and systems (Figure 3): First, functions that are analogous to building challenges in terms of heat regulation. Second, processes that present various means by which a design solution might be adapted. Third, factors: are the influential properties and, finally, the pinnacles; examples of organisms and systems for different function-process-factor combinations [35].

![Figure 3. Biophysical information representation model.](image-url)
6.2. Approach Two: The Thermo-Bio-Architectural Framework (ThBA)

To enable architects to find biological solutions which relate to the thermal characteristics and requirements of buildings, Imaniet al. [83] developed a thermo-bio-architectural framework (ThBA). This method was established and tested based on enhancing the thermal performance of existing buildings. As a result, the first step was to identify the thermal performance issues in several existing office buildings as models. This was significant because the bio-inspired design process in a problem-based approach begins with design challenges. These must be linked to biological organisms’ solutions in a systematic manner through a design process identified as design by analogy. Considering this, ThBA model was designed to have two sides relating to the distinct fields of biology and architecture, with links between them through which the analogies discovered in nature and their corresponding thermal adaptation principles could be transferred. This cross-disciplinary tool requires the identification, classification, and categorization of thermal regulation mechanisms utilized by organisms. Additionally, such categorization involves two; passive or active strategies, which were used to seek architectural analogies that eventually informed the structure of the ThBA. As a result, matching parameters in energy-efficient building design were identified for each mechanism, which were used for the architectural side of the ThBA model [83].

6.3. Approach Three: Framework to Achieve Multifunctionality in Bio-ABS

Kuru et al. [84] developed ‘multi-Biomechanism Approach’ framework aiming at achieving multi-functionality in Bio-ABS. This is a top-down approach that focuses on addressing design using metaphors from biology. Moreover, the framework is divided into four phases, and each phase is divided into sub-phases (Figure 4). The first phase is sub-divided into two: selecting a base-case scenario that includes a project’s location, microclimate, and microclimate, and then analyzing the performance of that base-case scenario and identifying a set of functional requirements to improve performance. The second phase comprises matching the functional performance parameters of the base-case scenario to the corresponding biological strategies in the database. In the third phase, the properties of the selected biological system are outlined as hierarchical and heterogeneous structures to achieve multifunctionality. This primarily means creating a multifunctional system in which multiple biological mechanisms should be chosen, whether they belong to the same biological model or not. Moreover, the importance of using hierarchy or heterogeneity as drivers at this stage cannot be overstated. This includes either positioning the preferred mechanisms at different scales or choosing varied types of morphological, physiological, or behavioral adaptations in a heterogeneous structure. Finally, a biomimetic adaptive façade will be generated with multiple functions at different scales and geometries. Subsequently, creating several biomimetic adaptive skins configurations, as well as actuation mechanisms for achieving climate-adaptability [84].

Figure 4. The multi-biomechanism approach and its stages.

7. Material Development for Adaptive Façade Design

In addition to the traditional materials used for façade design and construction, there have been significant advancements in non-conventional materials which can be used to enhance traditional façade performance. These include plastic and composite polymers, which are characterized by: the ability to be molded into free forms, and their excellent thermal and electrical insulators, among others [85]. However, in the context of biomimetic design, organisms can be used directly to create structured bioinspired-based materials.
In this regard, a limited number of biomimetic materials have been developed and used up to date [86]. The development of bioinspired materials capitalizes on the ability of the organism to self-assemble into biofilms, and hierarchical structures are critical. Furthermore, these biological materials can also be used to inspire the design of synthetic materials [87].

In traditional manufacturing approaches, the ability to integrate and assemble materials with different hierarchical levels has limited the creation of bioinspired designs. However, various adaptation strategies in plants have driven the design and development of several bio-inspired building envelope systems with multifunctional interfaces to control heat, air, water, and light. These Bio-inspired materials have been reported to have excellent energy absorption properties when compared to conventional structures [88,89].

7.1. Biomimetic Materials

Bioinspired materials can be categorized into four: (1) smart materials that change and react in response to external factors; (2) materials with innovative surface structures and enhanced functions; (3) bio-inspired materials that focus on advanced geometries and structural configurations; and (4) technologies that improve existing systems by integrating specific adaption strategies [52,88,89]. The first category is for organism-like smart materials that can alter certain properties and parameters in response to mechanical, chemical, spatial, and temporal information in various environmental conditions. The second category is for materials with surface properties such as repellant and anti-reflective properties. The third category is for material architectures with natural endoskeletons and exoskeletons. These materials represent the production of new materials with many potential applications in the initial stages of architectural design. Numerous examples of natural structural adaptations allow for the construction of lightweight structures, such as the two-layer beetle elytra, which maintain their structural integrity through a series of interconnecting components. Moreover, mimicking natural photonic structures and producing new nano-scale structures can assist architects in developing new structures and material properties. Finally, materials with targeted application technologies such as robotics and vehicle movement efficiency, as well as aid in the development of new modes of transportation. This limitation reveals the movement principles inspired by the muscular and skeletal systems. In general, these classifications can aid in the improvement of design approaches and the innovation of building façades [52,89].

7.2. Bio-Inspired Manufacturing

Advances in adaptive manufacturing (AM) present potential in the manufacturing of bio-inspired building components. AM employs a bottom-up approach inspired by nature. In this approach, the final structure of the material is encoded in precursors that self-assemble to the prescribed form. The ability of AM to easily manufacture intricate structures allows for extensive research into structure-property relationships in biological materials [87]. However, the current application of AM in biomimetic manufacturing is only limited to imitating organism structures, not the embedded bioprocesses and strategies [90].

Ideally, the manufacturing of bio-inspired materials can be conducted at distinct levels, either micro, nano, or macro-level. Furthermore, those materials or systems are manufactured from self-organization biological strategies, i.e., self-healing, self-cleaning, and self-assembly. In this regard, organisms may be cultured in a manufactured and controllable environment, and their efficient characteristics are engineered. For instance, culturing fungus to produce fungi-producing thermal insulation materials for energy-efficient façades or algal photoreceptors for energy generation [37,89].

While nature inspires adaptive, intelligent, and sustainable façades, the application of biological strategies to the building industry is limited to specific scales and technologies. Numerous functional solutions can be extracted from nature at multiple levels of biological organization. This includes strategies related to physiology, morphology, dynamics, and behavior, ranging from molecular components to whole organisms and even populations (e.g., swarms). In this respect, biological information can be identified at one scale and
deployed to another in solution transfer. However, standard, and universal parameters for scaling biological systems are still a long way off because they are heavily dependent on the functional and operational principles of organisms as well as the specificity of the final application field [40].

Biomimetic materials can be perceived as ascending scales, beginning with the cellular scale of living organisms and including, for example, material make-up and cellular growth parameters. The second scale could include the anatomical and structural qualities of the organism. The micro-environment, such as the influence and interaction with other organisms and the immediate surroundings, is included in the third scale. The macro-environment, which includes the context and ecosystem within which it survives and develops, is the fourth and final scale. Any of these scales could be useful in architecture. Significant research has been conducted on a cellular biological scale, including their shape, packing, functions, and interactions. This could be useful for the development of nanomaterials, building forms, and even urban-scale development [89,91,92].

8. State of the Art in Building Performance Simulation of Biomimetic Adaptive Building Façades

Conventional façade performance descriptors do not typically change properties over time. In conventional façades, for example, constant values are used to identify performance descriptors such as thermal transmittance, resistance, solar heat gain coefficient, or light transmittance. This is not the case with Bio-ABS, as their properties change over time, causing changes in values for performance descriptors. These changes make predicting their performance difficult [93]. In addition, simulation tools are a crucial factor limiting the prediction of the biomimetic adaptive façades’ performance. This is mainly due to the complexity of the digital modeling and simulation processes embedded in the software packages [88]. In this context, Clayton et al. [43] suggested a theoretical framework to overcome by combining dynamic building performance simulation (BPS) tools with evolutionary optimization algorithms, which has proven to be a valuable approach. In this regard, the use of multi-objective optimization (MOO) algorithms is especially useful in supporting high-performance building design because it allows for the visualization of trade-offs between two or more conflicting design objectives [43]. Hence, the main benefit of this approach is that the best trade-off solution is represented as a set of equally optimal solutions, i.e., the Pareto front, from which a single design can be selected a posteriori by taking design decision makers’ priorities into account [43].

Abdel-Rahman [93] has suggested an optimization framework with biomimetically inspired algorithms. This bio-inspired optimization tool identifies the best bio-inspired strategy to solve design problems, subsequently describing the complex shapes and geometries of the building’s façade. These algorithms could provide an optimum solution with little knowledge of the search area and simple rules. The model consists of two biomimetic algorithms; the first category contains biologically inspired algorithms, whereas the second contains non-bioinspired but still nature-inspired algorithms. However, this model remains a theoretical model and only addresses the façade’s thermal aspects [93].

9. Results and Discussion

Biomimicry has been used in building design to a limited extent to date [94]. What is effective conceptually in biomimetic transfers does not always work in practice [23,39]. This is primarily due to the failure to consider organismal design constraints and their dimensional realms. Organismal design constraints are a primary consideration in transferring solutions. Indeed, while organisms can inspire technical applications, their structural and functional strategies are not always the best solution to any situation or context [39]. Moreover, despite numerous references to nature, it is extremely rare to develop holistic architectural solutions that fully adapt to the potential of biological principles [95]. Over the last two decades, approximately seventy typologies of bio-inspired building façades have been developed, with rapid research and development of more typologies across
industry and academia [82]. The main challenge with those systems is addressing the monofunctional of the system due to the need to address multiple contradictory and complex functional aspects simultaneously [55,66,82].

Badarnah [35] has focused on the energy performance of biomimetic strategies by developing a comprehensive model for thermoregulation, including heat gain, retention, dissipation, and prevention, to aid the designers in the initial concept development [35]. Furthermore, Badarnah [81] has identified key functions for environmental adaptations, how they are done naturally, and an in-depth study into distinct morphologies and their underlying environmental processes. Besides, configurations abstracted from nature were developed to transform those environmental adaptations into design solutions and patterns. In theory, those morphological adaptations were multifunctional as opposed to mono-functional [81]. However, the translation of those theoretical adaption concepts into a functional building’s envelopes that interact with their surroundings remains a challenge [65]. The complexity of transforming biological strategies into architectural strategies requires multidisciplinary approaches, including input from biologists and architects. In this regard, Hosseini et al. [96] also proposed a multidisciplinary approach to research and design process, including kinetic façade, biomimicry, building form, energy efficiency, thermal comfort, and parametric design thinking [96].

Extensive research is required to validate the biomimetic strategies, their applications in the building sector, and their corresponding scales [65]. This is a time-consuming process as it requires undertaking active materials research to reach testing results to effectively transfer biological strategies into technical solutions.

The focus of the existing methodologies on a limited type of species, limiting the potential biological strategies adopted into buildings, is another reason for the challenge in addressing the multiple contradictory functional requirements of the building’s façade [86]. Hence, there is a need to diversify the adaptations from nature in biomimetic façades. In this sense, biology provides a vital knowledge base for diverse mechanisms to support environmental and energy regulation, with enormous potential if applied to buildings [35]. As such, multifunctionality is not fully integrated into biomimetic façades and requires further development [55,82].

In addition to the limited number of realized or prototyped buildings noted above that attempted to deploy biomimetic strategies, most studies are still in the conceptual phases and lack quantitative performance analysis [81]. Moreover, according to Badarnah, [35], most of the buildings that are already built using biomimetic methods have failed to fully retain the traits or qualities of the imitated organism or biosystem [34]. This can be attributed to the failure to fully access the biological potentials, the difficulties in representing biophysical knowledge, and the challenges in abstracting and transforming the biological mechanisms [35].

To this end, nature presents successful strategies, which in turn presents a vast database for adaptation strategies. In this context, architects are challenged to transform these adaptation strategies from nature into successful technological solutions for building façades. In addition, the inherent operational and organizational structures of engineering companies or architectural firms hinder the successful integration of bio-inspired design processes into the existing design practices [97].

Furthermore, the advancement of biomimicry in engineering and technology is restricted to specific scales for transferring biological strategies from nature to design. These constraints have narrowed the extent of the investigation, thus limiting the application of biomimicry in achieving more sustainable designs [52]. The research in biomimetic thermal solutions for buildings, categorically, provides a biophysical model and strategies to be implemented. However, a systematic representation of thermal interactions and their primary contribution to a system is lacking, which would have assisted designers in the initial phases of the design process [35]. Therefore, Badarnah [35] proposed the multifunctional model for biophysical information representation to aid designers with a limited biological background. Recently, Kuru et al. [84] proposed a hybrid model of the existing
biomimetic design frameworks and natural design principles to achieve multi-functionality in the design of biomimetic buildings [66,84].

The design and construction of buildings with AFs tend to cross multiple engineering fields, necessitating a high level of coordination among the involved professionals. This creates several process-related issues, which occur in a professional setting with procurement models that are not typically streamlined to complete such coordination-demanded tasks efficiently [98]. In addition to that, conducting a life-cycle assessment (LCA) is a significant barrier to effectively realizing the adaptive façade’s prototypes. This is because of several factors, including data collection difficulty, lack of adequate knowledge among investors, and the term market models capable of guaranteeing a return on short-term investments [99].

Other types of barriers have been identified which impede the construction industry’s adoption of adaptive building façades. The first barrier is the difficulty in evaluating the adaptive building façades performance. Moreover, there is a lack of a comprehensive performance evaluation criterion which includes testing, assessment, and monitoring. Furthermore, no prospective studies or best practices exist for assessing and documenting the performance of AFs systems. This knowledge gap is critical and requires attention from researchers to device scientifically driven assessment of AFs. The second barrier is the delivery process for such high-performance façades. The delivery process typically consists of multiple stages, including a complete design assist, construction verification, commissioning, and operations [100]. Finally, the review found that another challenge with biomimetic application in the design of AFs is the limitation of existing simulation software and methods. Moreover, the performance evaluation is affected by those AF systems in response to real-time climatic data by modifying its morphologies [35]. Hence, building performance is frequently not assessed, which can be viewed as a shortcoming [22].

10. Conclusions

A review of the biomimetic design approach for adaptive building’s façade was presented. Various issues, approaches, and methodologies in architectural design were discussed. The implementation of those conceptual frameworks for achieving multifunctionality in biomimetic façade design is the future frontier in improving the performance of those façade systems. This multifunctionality can be achieved by integrating numerous functions in one system to attain multi-regulation of diverse environmental factors such as heat, air, light, water, and energy. However, this is a challenging task, requiring extending biological references to more diverse species. Moreover, from a design standpoint, archiving multifunctionality requires an in-depth study of potential biological mechanisms. An appropriate potential biological mechanism will have to respond to complex and contradictory façade performance parameters. Hence, selecting and applying an appropriate strategy for the design of adaptive façades should be pursued at the initial stages of design.

Finally, the paper investigated several limitations of biomimetic adaptive façades that present an opportunity for the additional research needed to facilitate the successful implementation of biomimetic strategies in architecture, including: (1) investigating biomimetic façades and their performance in existing buildings, (2) examining the existing limitations of different simulation tools with respect to assessing the performance of biomimetic façades, (3) reviewing the existing knowledge on biomimetic materials, scaling, and adaptive manufacturing, and (4) studying the potential biological references and their transformation into holistic design solutions for façades design.

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