A critical review of biomimetic building envelopes: towards a bio-Adaptive Model from nature to architecture

Francesco Sommese [a, *], Lidia Badarnah [b], Gigliola Ausiello [a]
[a] DICEA – Department of Civil, Architectural and Environmental Engineering. Federico II University of Naples, Italy.
[b] Department of Architecture and the Built Environment, University of the West of England, Bristol, United Kingdom.

*Corresponding author. E-mail address: francesco.sommese@unina.it

Abstract

The building envelope has an important role in regulating the energy exchanges between the internal and external environment. In recent years, various studies on technological solutions for responsive and intelligent envelopes have been carried out. The purpose of this paper is to investigate climate-adaptive building envelopes and related biomimetic solutions, providing a critical review of the state of the art. Various examples of the adaptive envelopes are analysed and compared with examples of biomimetic envelopes. This paper demonstrates the potential of the broad database of nature to provide solutions that can be implemented in architecture to achieve design solutions that are sustainable, energy efficient, and able to adapt to environmental changes. After an initial critical review of nature's adaptation strategies, a methodological approach has been proposed: the bio-adaptive model (bio-AM). Starting from the definition of the context and the relative abiotic factors, the bio-AM identifies the essential phases to transfer the functions of plants to building technologies, using adaptive materials capable of self-activation in response to environmental factors, thus potentially emulating the adaptation of plants in technological solutions for the future of sustainable buildings.

Highlights:

- A comparative analysis of adaptive and biomimetic envelopes was developed.
- Six responsive functions of the adaptive envelope were defined.
- The potential of biomimetics in the architectural field was highlighted.
- Plants adaptation mechanisms can be implemented in the field of construction technologies.
- The bio-AM identifies the essential phases to transfer the functions of plants to building technologies.

Keywords: biomimetics, adaptive building envelope, bio-inspired solutions, architectural design, bio-adaptive model, plant adaptations, adaptive materials.

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1. Introduction

Cities play a major role in the increased greenhouse gas emissions globally [1], where buildings account for about 40% of energy-related CO_2 emissions [2][3]. To meet international target goals by 2050 [4], there is an urgent need to improve the energy efficiency of buildings and reduce the negative impact on the environment and mitigate climate change. The energy efficiency of buildings can be improved by developing designs solutions for the building envelope that represents the interface between the indoor and outdoor environment [5]. The Architecture, Engineering and Construction (AEC) sector, at the heart of European policy plans [6], [7], can play a major role in developing novel technologies and innovative solutions that will be able to adapt to changing environmental conditions and provide comfort with less energy demand. This paper aims to address this problem and propose a model for the development of adaptive solutions and in particular adaptive building envelopes inspired by nature.

Building envelopes are mainly static solutions. The concept of the adaptive envelope is still not fully applied and needs to be facilitated and more broadly employed, especially for the benefits in terms of both internal comforts and terms of mitigation of the heat island effects. The design process is particularly complex and requires the involvement of new systems and materials that can interact dynamically with the external and internal environment. The state of the art also highlights an absence of standardised procedures to assess and test the performance of adaptive building components. According to Attia et al. [8] two limits about the application of adaptive facades are identified. The first concerns the quantification of performance and the evaluation of buildings with adaptive facades; in particular, the lack of holistic performance criteria based on testing, evaluation, and monitoring. The second concerns the delivery process of an adaptive façade [8].

Nature provides a large database of morphological, physiological, and behavioural solutions for adaptation. Various strategies facilitate the different types of adaptation in nature, such as in Fig. 1. Environmental changes are shaped by different variations, such as in seasonal and daily frames, and geographical locations (latitude, altitude). Living organisms are related to their habitats and develop a high capacity for adaptation, especially through their interface with the external environment. The skin surface can provide a complex tissue or structure (hair, skin, epidermis, cuticles, etc.) which can sense and respond to the variation of environmental conditions and provide protection from extreme thermal gradients for instance [9]. Analysis of various biological strategies, such as plant adaptations to the environment, has the potential to provide the basic principles for biomimetic design of climate-adaptive building facades or envelopes [10].

Biomimetics is a rapidly growing discipline in engineering and architectural design, though with a limited scope of applications in architecture. It aims to apply functional solutions from nature to solve technical problems [11]. The majority of applications are limited to prototypes and small scale pavilions, using parametric modelling and digital fabrications [12]. Biomimetics has a potential to impact innovation in AEC sector, and provide efficient environmental solutions [13] [14]. In the AEC sector, the interest in biomimetic architectural design has been growing in the last years with more interdisciplinary interest in co-design, biology, computation, and digital fabrication. Establishing clear parallels between nature and architecture for knowledge transfer, could facilitate the development of environmentally adaptive solutions. Plants as source of information, can provide strategies that respond to variations in external conditions at different scales. Transforming natural strategies into technologies for the adaptive building envelope is still a challenge, and there is a need to provide ways that facilitate the implementations in the AEC sector.This work aims to provide a critical review of the application of biomimetic adaptive building envelopes and propose an adaptive model to facilitate early-stage design processes. In section 2, the methodological approach is discussed. In section 3, a sample of adaptive building envelopes are analysed, and their characterization are defined. In section 4, a biomimetic overview and its broad application are presented, where several biomimetic building envelopes are analysed. In section 5, a comparative analysis between adaptive envelopes and biomimetic envelopes is discussed. In section 6, an early-stage adaptive model is proposed to facilitate the exploitation of adaptive principles from nature to building envelope solutions and technologies. Finally, in section 7 the implications and findings of the study are presented, and future visions are discussed.

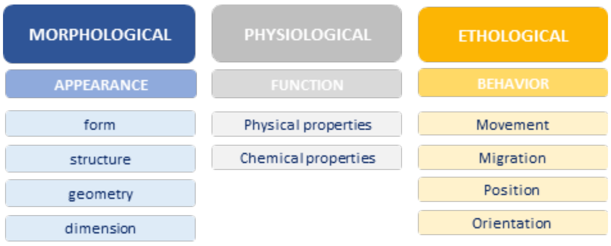


Fig. 1. Levels of adaptation in nature and relevant examples.

2. Methodology: a critical review

This study adopts a critical review approach [15], where relevant scientific literature is reviewed and appropriate case studies are analysed, from which important information is obtained to evaluate the state of the art and then propose a new methodological approach (the bio-adaptive model) to be applied in architectural design and more specifically to adaptive building envelopes. Fig. 2 shows the four phases of the methodological framework used in this paper: data collection, data screening, data analysis and synthesis, considering both architectural and natural aspects and characteristics.

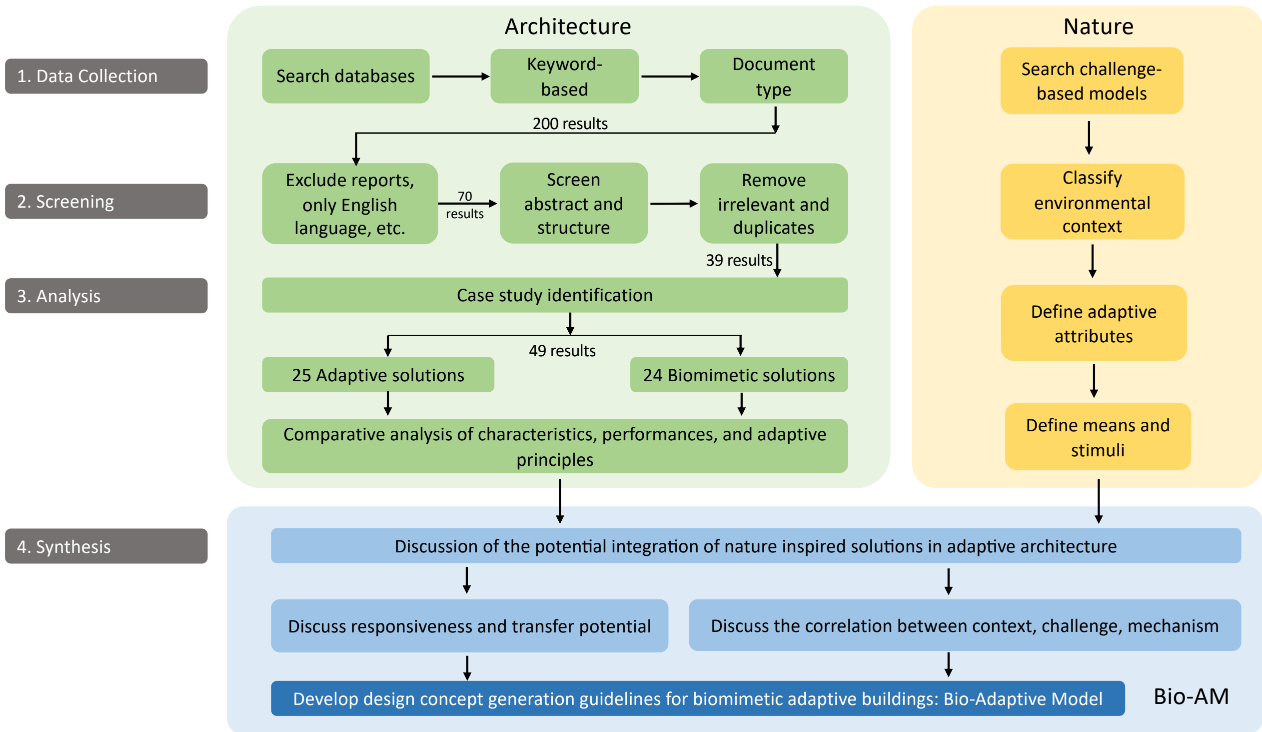


Fig. 2. Methodological framework

2.1 Phase 1: Data collection

The data was collected from online libraries and databases (such as Scopus and Google Scholar), and from official websites of some governmental institutions. Different types of documents were identified, such as books, international scientific papers, conference proceedings, and government reports on adaptive and biomimetic building envelope, using theme related keywords, such as "adaptive building envelope", "adaptive facade", "biomimetic envelope", "biomimetic adaptive building envelope", "building skins", “innovative facade”, “advanced facade”. Projects from different geographical locations were considered to inform the overview of the topic with a wider context. As the focus of this paper is on the state-of-the-art, we considered the build-up of knowledge since 2000 to the present, including references to earlier projects that were considered advanced for their time. This phase resulted in 200 outputs that were potentially considered relevant to the study.

2.2 Phase 2: Data screening

The initial screening was carried out by excluding reports and English language only, which resulted in 70 outputs. Narrowing it down to 70, helped us perform a more in-depth screening of each output by examining the relevance of title, abstract, structure of paper, and general content. The main aim was to ensure that content is relevant to adaptive building envelope design, functional and performance issues, environmental aspects, and physical characteristics. After removing duplicates and irrelevant outputs, the number of papers went down to 39.

2.3 Phase 3: Data analysis

In the refined selection of 39 papers, 49 case studies were identified as potentially relevant to this study for further analysis. The case studies are comprised of 25 adaptive envelope projects and 24 biomimetic envelope projects. This study adapts similar classification trends as in [16], Kuru et.al [17] Cruz et.al. [13], [any other related refs to classifications], such as Koppen-Geiger classification, abiotic factors, performance, responsive functions, scale, and mechanism of adaptation. The defined classification was used to compare between the case studies by mapping out their attributes and characteristics for performance purposes and identify the challenges and opportunities for potential integration of solutions from nature for adaptation.

2.4 Phase 4: Synthesis

This phase draws on the challenges, limitations, and potentials of developing adaptive solutions, and proposes the bio-Adaptive Model that aims to integrate solutions from nature into the design of adaptive building envelopes. It discusses the correlation between functions, mechanisms, environmental context for adaptation, and discusses responsive attributes for potential transfer of solutions from nature into architecture. This study considered morphological, behavioural, and physiological means of adaptation from nature, and focused on plants as a main source of inspiration due to their responsive mechanisms to changing environmental conditions in short and long terms, providing a potentially relevant insight into developing building technologies and solutions [18].

3. Adaptation in architecture: from static to dynamic model

Throughout history, buildings have evolved from simple primitive structures which provided shelter from the weather and predators to increasingly complex structures, able to adapt to the environmental context [18]. At first, the building envelope had the simple function of enclosing space and protecting the occupants from adverse weather events. Subsequently, various design strategies were implemented to ensure comfort and improve the quality of life of the occupants [19]. Vernacular architecture, defined by Rudofsky in 1964 as "Architecture without Architects" [20], is understood as an expression of a way of building linked to local traditions and using the material resources of the place [21] [22]. The orientation of the building, the internal distribution defined according to the cardinal poles, the thick masonry, the openings, and the various types of roofing, are typical elements of vernacular architecture that meet the principles of bioclimatic architecture, to ensure maximum living comfort by drawing on natural resources [23] [21].

The research on the building envelope has shifted to adaptive solutions that reflect the environmental context and thus improve the performance of building envelopes, increase occupant comfort and reduce energy consumption [24]. The Institute of the Arab World (1987) in Paris by Jean Nouvel is one of the first examples of an adaptive envelope. It is often cited in the literature as a pioneering example of an adaptive kinetic envelope [25][26]. The main facade, in glass and aluminium, has a series of diaphragms that filter the luminous flux using photoelectric cells that open and close, like the lens of a camera, at every change of hour, changing the appearance of the facade and the brightness of the interior spaces as a function of light [27][28][8].

The following sub-sections provide an overview of the main terminologies and characteristics, and an analysis of the state of the art in the context of adaptive building envelopes. The classification for the analysis is based on the findings from the various characteristic identified and building use, as well as climatic context and functional issues.

3.1 Building envelope: the concept

Sadinei defined the role of the building envelope as "*the key factor that determines the quality and controls the indoor conditions irrespective of transient outdoor conditions*" [29]. Building envelope without distinction between walls and roof have an important role in the regulation and control of energy use because it represents the interface between outdoor and indoor environment [30][27][25][31]. Therefore, the building envelope has not only the role of separating the space to divide the internal environment from the external one, but it also has the main role of filtering certain environmental factors ensuring good internal conditions [32]. It behaves similarly to the human skin which acts as a barrier between the external environment and the organism. In fact, in the literature, the words skin or envelope, are often used.

In recent years, research and development activities, about the application of components and materials for adaptive facades, have been growing [33]. In agreement with [28], in this paper, the term envelope to indicate the total building enclosure and not the term façade that describes only the vertical plane of the construction, is used. Contemporary architecture is characterized by complex and dynamic shapes, and it is not always evident the clear distinction between vertical wall and roof, because of a material continuity of the surfaces.

The environmental factors that broadly affect the envelope are solar radiation, precipitation, wind, temperatures, humidity, and noise [34]. These factors should be considered at the design stage to ensure indoor comfort, in particular thermal, visual, acoustic comfort, indoor air quality, and durability [35][36]. Some of these factors can also be used for energy generation. Each environmental factor can have more than one effect on the indoor environment, for example, solar radiation affects both visual and thermal comfort, as well as energy generation. Occupant activity and environmental factors influence the thermal comfort of buildings, in particular: air movement, humidity, temperature, solar radiation, air quality, noise [24]. The energy requirement to assess the environmental conditions inside a building is the most common design metric for the environmental sustainability of buildings. Most of the energy consumed in buildings is due to heating/cooling requirements and is related to the characteristics of the envelope as much of the heat and light transfer between inside and outside takes place through the envelope. The constantly changing external environmental conditions create new challenges for building envelopes that require appropriate solutions in line with energy efficiency requirements.

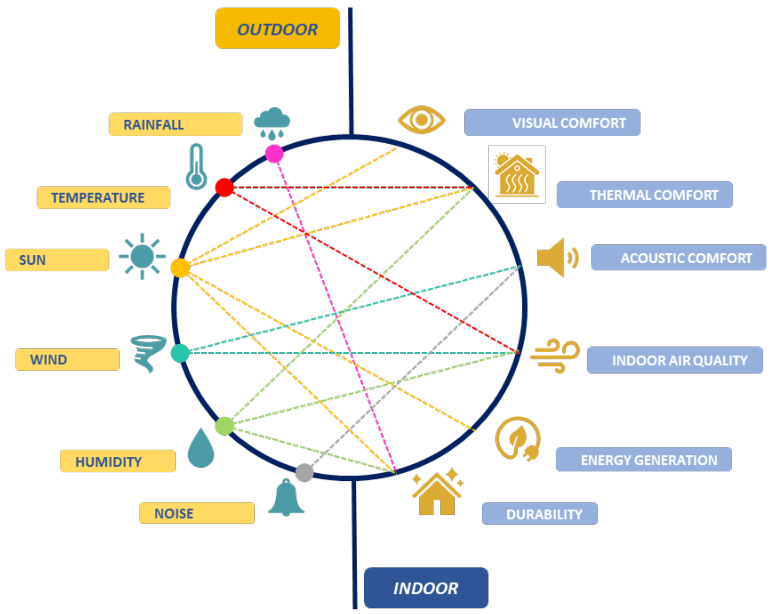


Fig. 3. The outdoor and indoor environmental factors that have an impact on users' comfort.

3.2 Terminologies and definitions of adaptive building envelopes

Various studies presented in the literature explain the concept of building envelopes that are adaptive to climate as a technological solution capable to respond to certain conditions, thus promoting higher levels of sustainability in the built environment and ensuring comfort for the occupants [37]. The main objective of an adaptive envelope is to optimize energy flows with an improvement in the performance of the building. As a result, adaptive envelope help reduce energy requirements for lighting and air conditioning, increasing air quality and comfort levels [38].

In the four years 2014-18, the European Union has activated the action plan EU COST-TU 1403, Adaptive Facades Network, that had an objective to harmonize, share and disseminate knowledge on adaptive facades and thus to facilitate sharing data and the development of technologies in adaptive facades and, more generally, in buildings with high energy efficiency [31][39][40]. The EU COST action plan defines the adaptive façade as an element of the building envelope consisting of multi-functional and highly adaptive systems capable of changing its functions over time, characteristics, or behaviour in response to performance requirements and transitional conditions, to improve the overall performance of the building.

Table 1 presents some of the adaptive envelope definitions in scientific literature: *Climate Adaptive Skin* (CAS) by Hasselaar [41], *Responsive Building Elements* (RBE) by IEA [42], *Living Envelope* (LE) by Badarnah [43], *Acclimate Kinetic Envelope* (AKE) by Wang [44], *Climate Adaptive Building Shells* (CABS) by Loonen [33] [45], *Adaptive Facade* (AF) by Attia [8] [46], *Responsive Building Envelope* (RBE) by Taveres Cachat [47]. There is a lack of a general definition for the concept of the adaptive envelope, where several aspects are considered but not consistent among the different studies. The common feature is the adaptation to climatic variations but with different responses and modes. Therefore, the definitions of the adaptive systems are very broad. In this connection, one of the aims of this study is to introduce a systematic approach to definitions about actions specifying adaptation, to give uniformity to the reading of research studies and achievements.

Table 1
Definition found in the literature.

Year	Authors	Acronym	Definition and characteristics

2006	Hasselaar [41]	**CAS**	***Climate Adaptive Skins*** *can adjust their characteristics to and mediate between the changing environments. By doing so they can provide a comfortable indoor temperature, lighting level, and air quality (parameters influencing energy consumption) without excessive use of energy.* **Environmental parameters:** Internal temperature; Lighting level; Air quality. **Aim:** Reduction of energy consumption.
2009	IEA,ECBS Annex 44 [42]	**RBE**	***Responsive Building Elements****: a building component that assists in maintaining an appropriate balance between optimum interior conditions and environmental performance by reaction in a controlled and holistic manner to changes in external or internal conditions to occupant intervention.* **Boundary conditions:** Meteorological conditions; Internal heat; Pollution loads. **Responsive action:** Heat flux; Thermal storage; Permeability; Transparency. **Function:** Reject; Redirect; Store; Admit. **Requirements building and occupants:** Heating/cooling ventilation.
2012	Badarnah [43]	**LE**	***Living Envelope****: is an adaptive building envelope inspired by nature that has the ability to adapt to the changes arising in the surrounding environment in order to maintain a comfort state for its occupants.* **Environmental regulation:** / **Functions:** Air; — Indoor air quality; Prevent air stagnation; — Exchange; Move Heat — Thermal comfort — Gain; Retain; Dissipate; Prevent Water — Water regulation and harvesting — Gain; Conserve; Transport; Lose Light — Minimize heat gain; Maximize daylight. — Filter; Illuminate; Harness
2012	Wang et al. [44]	**AKE**	***Acclimate Kinetic Envelope:*** *capable of responding to variable climatic environment by means of visible physical behaviors of building envelope components.* **Climate sources:** / **Other:** Solar responsive — Solar radiation; Sunlight/daylight; Solar electricity Air flow responsive — Air flow; Wind electricity Other — Precipitation; Air temperature
2013	Loonen et al. [33]; [45];	**CABS**	*A* ***Climate Adaptive Building Shells:*** *has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this to improve overall building performance.* **Relevant physics:** Thermal; Optical; Airflow; Electrical.
2018	Attia et al. [8] [46]	**AF**	***Adaptive Façade:*** *building envelopes that can adapt to changing boundary conditions in the form of short-term weather fluctuations, diurnal cycles, or seasonal patterns.* **Dynamic requirements of the occupants** **Changes in climatic conditions:** Weather fluctuations; Diurnal cycles; Seasonal patterns
2019	Tavares-Cachat et al. [47]	**RBE**	*A* ***Responsive Building Envelope*** *rely on integrated technologies that are designed to enable the building to respond to a range of triggers, using a combination of passive, active, and/or cognitive control strategies.*

User comfort	**Building energy performance**
Thermal comfort;	Recovery and conservation of available energy;
Visual comfort;	Energy buffering;
Acoustic comfort;	Energy storage;
Indoor Air Quality	Renewable energy integration.

3.3 Characteristics of adaptive building envelopes

This sub-section aims to identify the characteristics of the adaptive envelope as discussed in literature. Loonen et al. [33] summarized eight basic concepts that describe the characteristics of an adaptive envelope, starting by identifying the goal/purpose to which directly associates one or more of the above functions. Loonen proposed four physical domains (thermal, optical, electrical, and airflow) through which the interactions between internal and external environment through the building envelope occur [33]. According to Loonen such interactions can be managed and controlled depending on the physical domain in terms of preventing, rejecting ,or modulating solar gains, visible light or sound pressure, filtering of outside air, collecting and converting wind and solar energy [48]. Aelenei, on the other hand, simplifies interaction with the environment in four responsive functions: prevent, reject, modulate and collect [34]. Table 2 reports six new responsive functions proposed as a result of the analysis in Table 1: regulate (e.g. temperature and air), shield (e.g. cold and radiation), transfer (e.g. heat, water, light, air), reflect (e.g. radiation), store (e.g. heat and water), transform (e.g. energy). The responses depend on the input that is one of the following external environmental factors: solar radiation, temperature, humidity, wind, precipitation, and noise, which are presented in Table 2. Consequently, the performance of the adaptive envelope is described in terms of thermal comfort, visual comfort, acoustic comfort, internal air quality (IAQ), and energy generation. The input corresponds to an output intended as an adaptation action.

The adaptation response occurs in a variable time interval depending on the seasonal or daily cycle or other boundary conditions [33]. For the mechanisms of adaptation control, the same terminology used by Loonen [33] is preferred, which distinguishes them as extrinsic and intrinsic. The extrinsic controls refer to an envelope that adapts through response to external factors by sensors, processors, and actuators and then resume a dynamic mechanism that moves visible to the naked eye, resulting in modification of the aesthetic configuration of the envelope by folding, expanding, and/or sliding [49]. Depending on the type of control and adaptation mechanism, the level of visibility varies from a nanoscale to a macro scale. In intrinsic controls, the adaptive capacity becomes a characteristic of the envelope. The adaptation mechanism can be both static and dynamic. According to Lopez [49], the mechanism is dynamic when it is observable with the naked eye through a change in the material configuration, while it is static when the change is not visually observable but affects an internal property of the material that does not involve a change in the morphological configuration. A dynamic mechanism involves visible mechanisms such as expansion, rotation, curvature, and rolling that are generally manifested through automated shielding systems or through the use of smart materials, such as shape memory polymers that are configured as innovative materials that respond to external stimuli by changing their properties and geometric conformation without the use of added energy. On the other hand, a static mechanism involves reflection, absorption or energy exchange, exploiting the properties of materials such as in the case of Phase Change Materials that accumulate and release thermal energy. The type of adaptation can be achieved by an interscalar approach, then either on the entire envelope or on the single components or material that constitutes the element or the envelope itself.

Table 2

Characteristics of adaptive building envelopes.

Input Environmental external factors	Performance	Output Adaptation action	Responsive function	Responsive time	Control	Level of visibility	Spatial scale		
							Facade Systems	Component	Materials
Solar radiation	Thermal comfort	Thermal	Regulate	Seconds	Intrinsic	Nano	Curtain wall	Shading device	Thermochromic

Temperature	Visual comfort	Physical	Shield	Minutes	Extrinsic	Micro	Prefabricate module	Energy storage device	Electrochromic
Humidity	Acoustic comfort	Chemical	Transfer	Hours		Macro	Double skin facade	Air circulation device	Photochromic
Wind	Indoor Air Quality	Mechanical	Reflect	Day-night	**Mechanism**			Insulation layer	PCM
Precipitation	Energy production		Store	Seasons	Static				SMPs
Noise			Transform	Years	Dynamic				

3.4 Analysis of Adaptive Building Envelopes

This study identified 25 adaptive projects in the context of building envelopes, where they are of 25 representative examples of relevant adaptive solutions, see Table 3. The various examples have been classified according to the building use and the climatic context based on the Koppen Geiger classification [50]. The performance of the envelope was classified in terms of visual comfort (V), thermal comfort (T), indoor air quality (IAQ), energy generation (EG), acoustic comfort (A), and structural resistance (S); the mechanisms of adaptation were classified as dynamic if there is a movement, or as static if there is no movement [49]; the responsive functions were classified following Table 2 as Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), and Transform (Tm); the abiotic factors that were considered are Temperature (T) air (A), light (L), and Water (W); they represent the environmental stimulus to which the building envelope adapts.

Table 3

Analysis of building with adaptive envelope. **Climate:** Equatorial (A), Arid (B), Warm temperate (C), Snow (D), Polar (**E). Performance:** Thermal Comfort (T), Visual Comfort (V), Acoustic Comfort (A), Energy storage (ES), Indoor Air Quality (IAQ), Structural (S). **Mechanism:** Static (S), Dynamic (D). **Responsive function:** Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Abiotic factor**: Temperature (T), Air (A), Light (L), Water (W).

Year	**Case study**	**Designer**	**Building use**	**Climate**	**Performance**	**Responsive Function**	**Mechanism**	**Abiotic factor**
1987	**ARAB WORLD INSTITUTE** Paris, France	Jean Nuovel	Museum	Cfb	V, T	Reg, Sh	D	L
1993	**HELIOTROP** Freiburg, Germany	Rolf Disch	Residential	Cfb	V, T, ES	S, Tm	D	L
1996	**EASTGATE CENTER** Harare, Zimbabwe	Mick Pearce	Office	Cwb	T	Reg	S	A
1999	**GSW HEADQUARTERS** Berlin, Germany	Sauerbruch Hutton	Office	Cfb	T, A, IAQ	R, Sh	S	A
2002	**ESPLANADE THEATRES**	Dp Architects	Theater	Af	T	Reg, Sh	S	L, T

	Downtown core, Singapore							
2002	**MUSEUM OF PAPER ART** Shizouka, Japan	Shigeru Ban	Museum	Cfa	T, V	Reg, Sh	D	A, T
2004	**BIOCATALYSIS LAB BUILDING TECHNICAL UNIVERSITY** Graz, Austria	Giselbrecht + Zt Gmbh	University	Cfb	A	Reg, Sh	D	A, T
2005	**EWE ARENA** Oldenburg, Germany	ASP Architekten	Sport	Cfb	T, IAQ	Tm, R	S	L
2006	**COUNCIL HOUSE 2** Melbourne, Australia	designing	Office	Cfa	T, IAQ, ES	S	D	L
2007	**AL-BAHR TOWERS** Abu Dhabi, Arab Emirates	AHR + Arup	Office	BWh	T, V	Reg, Sh,Tm, S	D	L, T
2007	**KIEFER TECHNIC SHOWROOM** Bad Gleichenberg, Austria	Ernst Giselbrecht + Partner	Exposition	Cfb	T, V	Reg, Sh, R	D	L
2007	**CARABANCHEL** Madrid, Spain	FOA	Residential	BSk	V	Reg, Sh	D	L
2010	**ICT-MEDIA** Barcelona, Spain	Enric Ruiz Geli, Cloud 9	Office	Csa	T	Reg, Sh	D	L, T
2010	**OVAL OFFICE** Cologne, Germany	Sauerbruch Hutton	Office	Cfb	V	Reg	S	L
2010	**Q1 BUILDING OFFICE** Essen, Germany	JSWD Architectures et al.	Office	Cfb	T, V	Reg, Sh, Tr	D	L, T
2011	**BURKE BRISE SOLEIL** Milwaukee, USA	Santiago Calatrava	Museum	Dfa	V	Sh	D	L, T
2011	**KUGGEN** Gotenorg, Sweden	Wingardh Arkitektontor	University	Cfb	V, ES	Reg, Sh, R	D	L, T

2012	**ONE OCEAN** Yeosu-si, South Korea	Soma Architecture	Exposition	Cfa	V	Reg, Sh, Tr	D	L
2012	**COOLED CONSERVATORIES AT GARDENS BY THE BAY** Singapore	Wilkinsoneyre	Exposition	Af	V	Tr, Reg	D	L
2013	**BIQ HOUSE** Hamburg, Germany	Splitterwerk	Residential	Cfb	ES	Tr, S, Tm, R	D	L
2013	**IBA SOFT HOUSE** Hamburg, Germany	360grad + Architecktеn et al.	Residential	Cfb	V, ES	Reg, Tm, S, Tr	D	L, T
2014	**KOLDING CAMPUS UNIVERSITY** Kolding, Denmark	Henning Larsen Architects	University	Cfb	T, V	Reg, Sh	D	L, T
2014	**ESKENAZI HOSPITAL** Indianapolis, USA	HOK	Parking	Cfa	V	Tr, Reg	D	A
2015	**NEW LUDGATE** London, United Kingdom	Fletcher Priest Architects	Office,	Cfb	V	Sh	S	L
2017	**US EMBASSY** London, United Kingdom	Kieran Timberlake	Office	Cfb	V	Tr, Reg, R	S	L

3.5 Results: adaptive envelopes

Table 4 presents the results of the analysis of the 25 adaptive envelopes expressed in percentages. Most of them are located in warm temperate climates (C), while only few of them are located in equatorial (A), arid (B), or snow (D) climates. The external environmental factors that are generally more widely used are the sun and in rare cases wind. Consequently, regulating and shielding are the most considered responsive functions to ensure thermal, visual, and luminous comfort conditions. The shielding systems analysed in the adaptive facades need a sensor that perceives the stimulus and an actuator that activates the system to ensure the responsive function. This study didn’t identify significant solutions that draw on water or other resources.

Table 4
Results of the analysis on the adaptive envelope.

Climate		Building use		Responsive Function		Performance		Abiotic factor	
Equatorial -A	4 %	Office	28 %	Regulate	72%	Energy Storage	20 %	Light	80 %
Arid - B	8 %	Sport	8 %	Shield	60 %	Thermal comfort	56 %	Air	20 %
Warm Temp. - C	80 %	Exposure	12 %	Transfer	28 %	Visual comfort	68 %	Water	0 %

Snow -D	8 %	Residential	16 %	Reflect	24 %	Indoor Air Quality	3 %	Temperature	40 %
Polar -E	0 %	Museum	12 %	Store	20 %	Acoustic comfort	8%		
		Theater	4 %	Transform	20 %				
		University	12 %	**Mechanism**					
		Parking	4 %	Static	28 %				
				Dynamic	72 %				

4. Biomimetic building envelopes

This section focuses on building envelope solutions inspired by nature, i.e. biomimetics. Man throughout history has looked at nature and its systems as a source of inspiration for various purposes, the work by Leonardo Da Vinci and Gaudi are one of the early pioneering examples . Biomimetics in Greek means "*life*" and mimesis means "*to imitate*" [51] [52]. There is a difference between the various terminologies used in bio-inspired design (Fig. 4), where biomorphism refers to the emulation of living forms, biomimetics refers to the emulation of function, and bio-utilize refers to the utilisation of the natural material in the construction. In the last two decades the idea of making the emulation of natural processes an established applied discipline has been rapidly growing in the field of engineering and more recently also in architecture [53]. Natural strategies, mechanisms, and principles provide an extensive database of adaptation solutions that can enhance sustainability [54] [55].

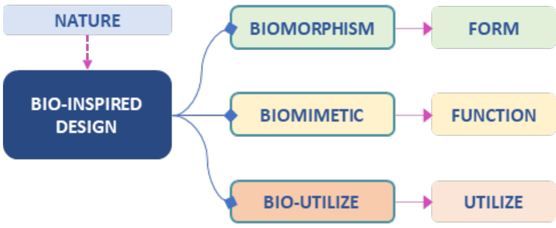


Fig. 4. Difference between the bio-discipline

Lepora et.al. 2013 [56], discussed the impact of biomimetics in the field of engineering and related sciences, and classified publications by year, journals or conferences proceedings, and subject areas, showing through their analysis how the area of research has grown rapidly from the 90s to the first decades of the 20th century. Following same approach, this paper provides an updated overview of the application of biomimetics in the various thematic areas that have been reported in scientific literature until 30/12/2021. The search, using Elsevier's Scopus database [57] with "*biomimetics*" as the search word, has resulted in 22388 items, divided by Journal, conference proceedings, and books (Fig.5). The annual production of articles on biomimetics has shown rapid growth since the 90s, confirming findings by [56]. Since 2000 publications have increased dramatically, from less than 1000 to more than 1000 per year, and inn 2021 alone, some 2500 biomimetic publications were produced (Fig. 5). The thematic areas are led by Engineering with about 9500 publications and Material Science with about 10000 publications, followed by Chemistry and Physics (Fig. 6). This paper also reports on the location of items by countries, as presented in Fig. 7, where only the countries with more than 500 publications were considered. It is noted that China and the United States occupy the first places, with about 6500 and 5000 publications respectively.

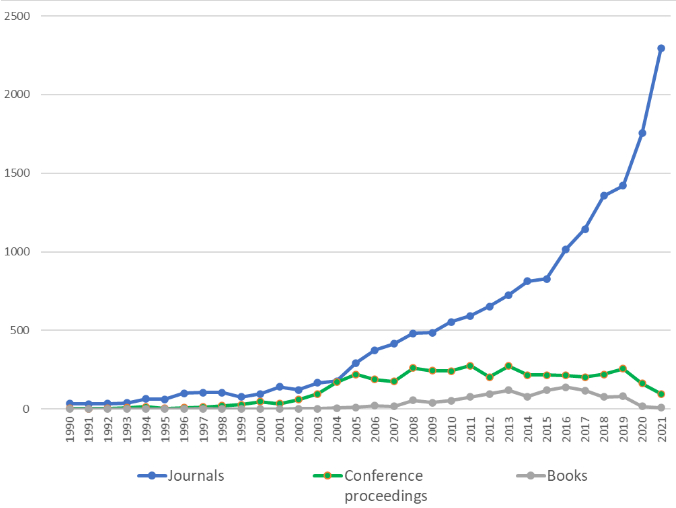


Fig. 5. Number of documents about biomimetics by year.

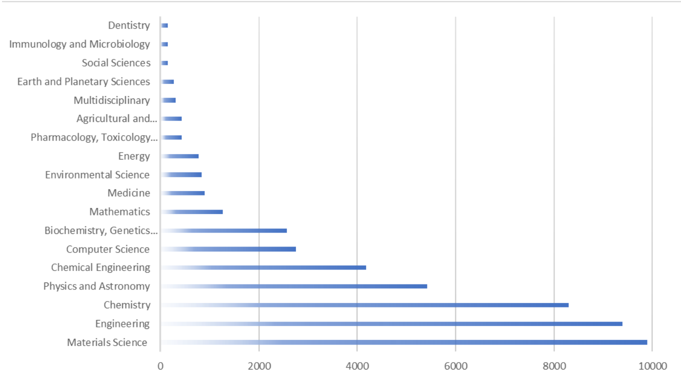


Fig. 6. Number of documents about biomimetics by subject area.

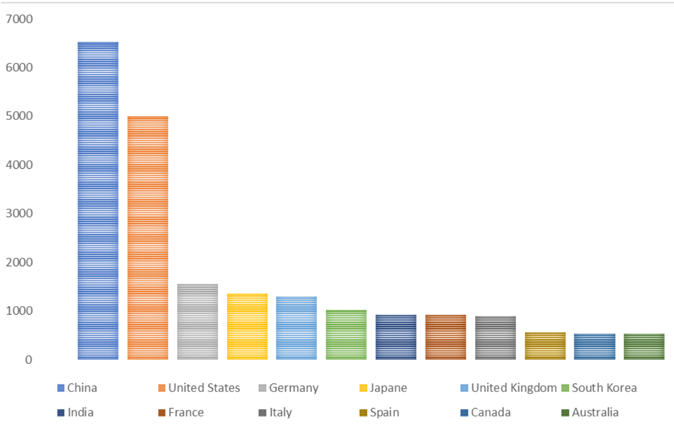


Fig. 7. Number of documents about biomimetics by country.

4.1 Biomimetics in architecture

The architectural field has been influenced by inspiration of forms, processes, and logic of the natural world. According with the definition of biomimetic, which concerns the functional emulation of natural organisms, in this section, a difference between the various types of emulation to the architectural scale is reported. In this study two types of emulation are proposed: morphological-structural and dynamic-functional.

4.1.1 Morphological-structural emulation

The morphological-structural emulation conceives mimesis from the structural point of view. In this case, the intention to copy the function is preserved by ensuring structural performance.

Various examples of this are present in the architectural field, especially in older buildings. The organic forms by the Catalan architect Antoni Gaudi are an example of structural morphological emulation, in fact, he is considered a precursor of biomimicry. The vault and the colonnade of the Sagrada Familia, reproduce the branches and Trunks of a forest to obtain a system of lighting and filtering of natural light. The roof of the Crystal Palace, designed by the English architect and botanist Joseph Paxton in 1851, is another example of nature-inspired construction [58]. The vaulted roof is inspired by the structure of the Victoria Amazonia, a plant belonging to the family of water lilies. Each leaf has a series of radial ribs stiffened by thin crossed ribs. Paxton emulates this structure for the closing arches of the building's main elevations, using iron elements to emulate radial ribs and ribs, and glass panels in analogy to leaf filling. In this way, it was possible to construct a light-wight structure, which was considered the first modern building to be inspired by the shapes of nature [59].

4.1.2 Dynamic-functional emulation

The dynamic-functional emulation tends to bring the mechanisms of adaptation typical of natural organisms to architecture. The architectural organism reacts to the environment in which it finds itself and can activate autonomously dynamics that favour the adaptation conditions, just as it happens in nature. The building is therefore "living" and "intelligent", that is, able to react to external stimuli. To ensure this is important the use of specific materials, such as natural, defined by Lopez et al. "self-activating" [49]. The pinecones, which are activated according to the humidity level by exploiting the hygroscopic and anisotropic properties of the wood, are an example of self-activation. In this case, humidity is the environmental stimulus that activates the reaction. The Hygroskin pavilion designed by Achim Menges in collaboration with Oliver David Krieg and Steffen Reichert is an example of dynamic-functional architecture. This pavilion is characterized by a steel structure covered with concave panels in spruce, each of which has a circular hole for the passage of light. These openings are characterized by thin triangular petals that open and close according to the humidity in the atmosphere [60]. When the outside air is dry, the wood fibres retreat and the petals open and the holes in the structure remain open; when the air is humid, the wood fibres are relaxed; therefore, the petals are closed and the holes in the structure remain closed [60] [61] [62] [63].

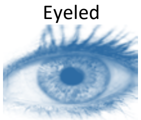
Another example is given by the special system of solar shielding without hinges called "*Flectofin*", by ITKE that is inspired by the pollination mechanism of the flower Strelitzia reginae based on the principle of elastic deflection [64]. The final patented product is made of fibre reinforced material consisting of two large foils, like the petals of the inspiring flower, without the use of hinges. The advantage of replacing hinges with elastic deformations lies in the fusion of all mechanical elements within a single folding component. The use of fibre reinforced polymers can combine high tensile strength with low flexural rigidity, thus offering a wide range of calibrated elastic deformations [65] [66]. An example of a combination of formal and functional emulation is at the scale of the building component and is represented by artificial ivy leaves. These imitate the morphology of the leaf as far as the aesthetic aspect is concerned, while for what concerns the function they behave as photovoltaic panels, therefore able to store thermal energy incidents on them [67] [68]. In addition, they can move also yielding wind energy.

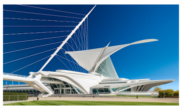
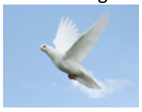
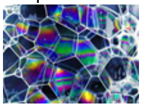
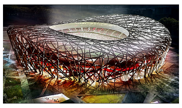
4.2 Analysis of Biomimetic envelope

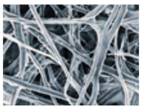
In this sub-section the analysis of 24 examples of biomimetic envelopes are presented in Table. 5. The characteristics considered are the same as those already described in the previous section, as well as the source of inspiration, the stimulus, and the scale of adaptation. The stimulus is classified as intrinsic (I) intended as a self-regulation in response to environmental factors such as temperature, relative humidity, without a mechanical or energetic activation system. Conversely, if the system is activated by means of a system of sensors and actuaries, the stimulus is extrinsic (E). The scale of adaptation represents the size of the system and is defined as building (B), façade Systems (FS), component (C), material (M).

Table 5

Analysis of building with biomimetic envelope. **Climate:** Equatorial (A), Arid (B), Warm temperate (C), Snow (D), Polar (E). **Performance:** Thermal Comfort (T), Visual Comfort (V), Acoustic Comfort (A), Energy storage (ES), Indoor Air Quality (IAQ), Structural (S). **Scale of adaptation:** Building (B), Façade Systems (FS), Component (C), Material (M). **Responsive function:** Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Mechanism:** Static (S), Dynamic (D). **Stimulus**: Intrinsic (I), Extrinsic (E). **Abiotic factor**: Air (A), Light (L) Water (W), Temperature (T).

	Case Study Year Name Location Designer	**Inspiration**	**Building use**	**Climate**	**Performance**	**Scale of adaptation**	**Responsive function**	**Mechanism** [17]	**Stimulus** [17]	**Abiotic factor**
	1851 **CRYSTAL PALACE** London, United Kingdom Joseph Paxton	Victoria amazonica 	Exposure	Cfb	S	B	-	-	-	-
	1882 **SAGRADA FAMILIA** Barcelona, Spain Antoni Gaudì	Tree 	Cult	Csa	S	B	-	-	-	-
	1936 **JOHNSON WAX BUILDING** Racine, Usa Frank Lloyd Wright	Tree 	Office	Dfa	S	C	-	-	-	-
	1951 **WALL MILL GATTI** Rome, Italy Pier Luigi Nervi	Fungi 	Production	Csa	S	C	-	-	-	-
	1956 **SPORTS HALL** Rome, Italy Pier Luigi Nervi	Schell 	Sport	Csa	S	B	-	-	-	-
	1986 **LOTUS TEMPLE** Delhi, India Fariborz Sahba	Lotus flower 	Cult	BSh	S	B	-	-	-	-
	1996 **EASTGATE CENTER** Harare, Zimbabwe Mick Pearce	Termites 	Office Commercial	Cwb	T V IAQ	B	Reg	S	-	A
	1998 **HEMISFERIC** Valencia, Spain Santiago Calatrava	Eyeled 	Cinema	Af	V T	C	Sh Reg	D	E	T

	2001 **MILWAUKEE ART MUSEUM** Milwaukee, USA Santiago Calatrava	Bird wings 	Museum	Dfa	T	C	Sh	D	E	L
	2001 **EDEN PROJECT** Cornwall, United Kingdom Grimshaw Architects	Soap formation 	Exposure	Dfb	T S	B	S Tr Reg	-	-	T
	2002 **ESPLANADE** Singapore DPA Architects, Atelier One. Micheal Wilford	Durian fruit 	Theater	Af	T V	FS M	Reg Sh	S	-	L, T
	2003 **KUNSTHAUS** Graz, Austria Peter Cook - Colin Fournier	Bubbles 	Exposure	Cfb	T	B	Reg	-	-	T
	2006 **ORQUIDEORAMA BOTANIC GARDEN** Medellin, Colombia Plan B Arquitectos + Jprcr	Honeycomb 	Exposure	Cfb	V	C	Sh	S	-	L
	2008 **WATER CUBE** Beijing, China Ptw Et Al.	Soap formation 	Sport	Dwa	T V S	B	Reg S Tr	-	-	T
	2008 **PECHINO NATIONAL STADIUM** Beijing, China Herzog & De Meuron, Arup	Bird's nest 	Sport	Dwa	S	B	-	-	-	-
	2011 **FLECTOFIN** Stuttgard, Germany S. Schieicher ITKE Stuttgard University	Sterlitzie reginae 	-	Cfa	T V S	FS	Reg Sh	D	I	L
	2012 **HOMEOSTATIC FACADE** New York, USA Decker Yeadon	Muscle 	-	Cfb	T V	M C	Reg Sh	D	I	L, T
	2012 **ONE OCEAN** Yoesu, South Korea Soma Architecture	Sterlitzie reginae 	Exposure	Cfa	T V S	FS	Reg Sh	D	I	L A
	2012 **HYGROSKIN PAVILION** Orléans, France A. Menges, S. Reichert	Pin cone 	Exposure	Cfb	T V S	FS	Reg	D	I	T, A, W
	2013 **HYGROSKIN PAVILION** Orléans, France A. Menges, O. D. Krieg, S. Reichert	Pine cone 	Exposure	Cfb	T V IAQ	C FS	Reg	D	I	T, A, W
	2014 **LANDESGARTENSHAU EXIBITION HALL** Schwaebish Gmuend, Germany	Sea urchin skeleton 	Exposure	Cfb	S	FS	-	-	-	-

	ICD, ITKE Stuttgard University									
	2019 **BUGA WOOD PAVILION** Heilbronn,Germany ICD, ITKE Stuttgard University	Sea urchin skeleton 	Exposure	Cfb	S	FS	-	-	-	-
	2019 **BUGA FIBER PAVILION** Heilbronn,Germany ICD, ITKE Stuttgard University	Cellulose 	Exposure	Cfb	S	FS	-	-	-	-
	2020 **PHO' LIAGE** Lyon, France ArtBuilt Studio	Flower petals 	Office Commercial	Cfa	T V	FS M	Reg Sh Tm	D	I	L T

4.3 Results: biomimetic envelopes

Table. 6 presents the results of the analyses of 24 biomimetic envelopes in percentages. Most of them are located in warm temperate climates (C) and in snow climates (D), while few of them are located in equatorial (A) and arid (B). Most of the examples considered are temporary office or exhibition structures; other examples instead, are at the prototype scale. Many of the natural organisms' emulations are aimed at structural performance while others at guaranteeing indoor comfort, especially thermal and visual comfort. The latter case justifies the responsive shading and filtering functions. From this analysis emerges the evolution of biomimicry over the years. The first examples considered, preceding the twentieth century, represent formal emulations with a structural function. In the 20th century, examples present more a functional dynamic emulation. This underlines the increased awareness about the potential of the biomimetic discipline and its application in the field of architectural technologies for adaptation purposes.

Table 6

Results of the analysis on the biomimetic envelopes.

Climate		**Building use**		**Scale of adaptation**		**Performance**		**Responsive function**	
Equatorial -A	8 %	Office	9,5 %	Building	33 %	Structural	36 %	Regulate	45,83%
Arid - B	4 %	Sport	14 %	Facade Systems	33 %	Thermal comfort	33 %	Shield	29,17%
Warm Temp. - C	67 %	Exposure	47 %	Component	23 %	Visual Comfort	26 %	Transfer	8,33%
Snow -D	21 %	Production	5 %	Materials	11 %	Indoor Air Quality	5 %	Reflect	0%
Polar -E	0 %	Cultural	9,5 %					Store	8,33%
		Cinema	5 %					Transform	4,17%
		Museum	5 %	**Mechanism**		**Stimulus**		**Abiotic factor**	
		Theatre	5 %	Static	12.50 %	Intrinsic	25 %	Temperature	37,50%
				Dynamic	33,33 %	Extrinsic	8,33%	Light	25%
								Air	16,67%
								Water	8,33%

5. Comparative analysis and discussion

This paper presents an analysis of 49 case studies divided into 25 examples of adaptive envelopes and 24 of biomimetic envelopes. The aim is to highlight the current trends of these technological solutions, as well as emphasizing their features and applications. Figures 8-13 shows the results of the comparative analysis of the various categories. It is evident that the examples of biomimetic envelopes of the past have the objective of emulating the morphology of natural organisms for structural functions, while more recent examples tend to mimic the behavioural or physiological function of natural organisms to ensure the ability to adapt to weather conditions. The biomimetic envelope has an added potential because it can provide in some cases the same performance as a standard adaptive envelope, without consuming much energy, enhancing a passive response to external variables and limiting the negative impact on the environment. The only adaptive casing ensures the internal comfort and well-being of users adapting to external conditions, but requires a system of sensors and actuators to activate. These, in addition to consuming energy, also entail a high cost for maintenance and management during the life cycle of the building itself.

Furthermore, the companies of façade construction, do not have all the skills suitable to design such complex systems and must resort to cooperation with companies of other sectors, such as sensors, electrical or automation more in general. To date, there are few examples of adaptive envelope, and even fewer biomimetic ones. Most adaptive envelopes have temporary, exhibition or recreational use (Fig. 9). The main destination of adaptive envelopes, on the other hand, is office or university offices (Fig. 9). and mainly used for office buildings. These are therefore buildings that need a good level of lighting to ensure activities but, at the same time, it is necessary to reduce glare and overheating of the internal environment. This explains why adaptive envelope solutions are generally dynamic shields with a filtering or shading function (Fig. 10). The analysis carried out shows that most of the applications are in climatic contexts of type C, that is, in climates with warm temperatures (Fig. 8). This justifies that the main response functions are shading and filtering (Fig. 10) and the visual comfort and thermal comfort performances which are the most needed (Fig. 11).

The concept of adaptation for the building envelope are mostly limited to a mono-functional approach. Not only one environmental factor should be considered at a time, but all other environmental factors should be considered, as well as other sustainable natural resources to generate energy for the benefit of users. The qualitative analysis shows that only 20% of the envelopes analysed have performances capable of storing energy. Otherwise, it is limited to a simple automated shielding mechanism.

The analysis regarding biomimetic envelopes identified that natural organisms, especially plants and animals, inspired the examples considered in this study. Exploiting principles from natural organisms has a strong potential , where they can perform multiple functions at the same time. The biomimetic examples analysed show that the approach is still of a monofunctional type. There are rare envelopes in which it is possible to find a solution capable of performing multiple functions at the same time as it occurs in nature. This is certainly a limit, already identified several times in the literature, yet to be developed.

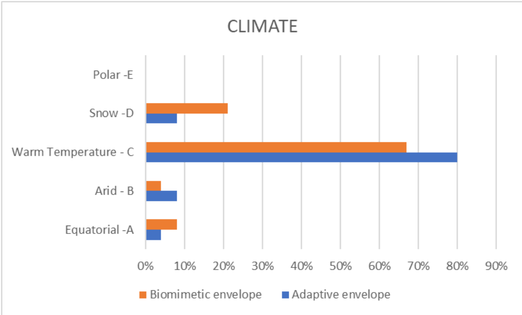


Fig. 8 Comparative analysis about climate

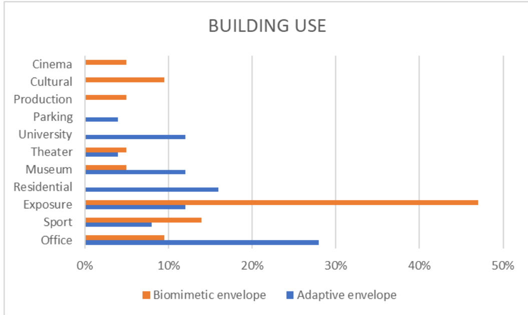


Fig. 9 Comparative analysis about building use

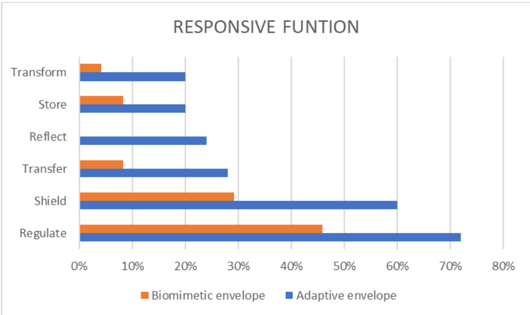


Fig. 10 Comparative analysis about responsive function

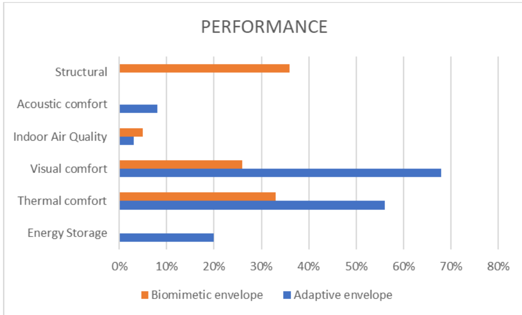


Fig.11 Comparative analysis about performance

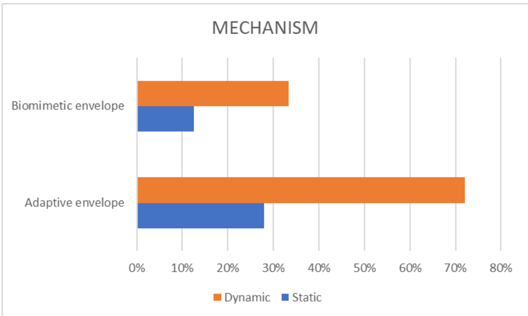


Fig. 12 Comparative analysis about mechanism

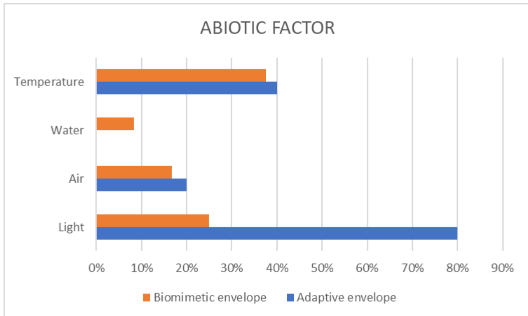


Fig. 13 Comparative analysis about abiotic factor

6. The bio-adaptive model (bio-AM): from nature to architecture

Strategies of adaptation are effectively employed by organisms at various scales, where several factors can affect their performance capabilities. The main aim of the proposed model in this study is to facilitate the transfer of responsive principles and mechanisms from nature to technological solutions for adaptive buildings. This study focuses on solutions inspired by plants due to their unique structural and morphological characteristics, where clear dynamic parallels with buildings can be established. The following sub sections explain the construction logic and the general guidelines of the bio-AM and discuss the potential integration of responsive solutions into architecture.

6.1 General outline of bio-AM

The bio-AM builds on existing problem-based approaches in biomimetic design, such as [69] and [43], and further defines specific phases to facilitate the transfer of adaptive mechanisms from nature into architecture. The iterative nature of the design process is mapped out in Fig. 14, where it starts with a scoping phase to define the design problem or challenge; then a research phase to investigate potential solutions from nature and select relevant features; and finally, an implementation phase to transfer knowledge, create and validate prototypes. Table 7 describes in more detail the various phases and steps of the process.

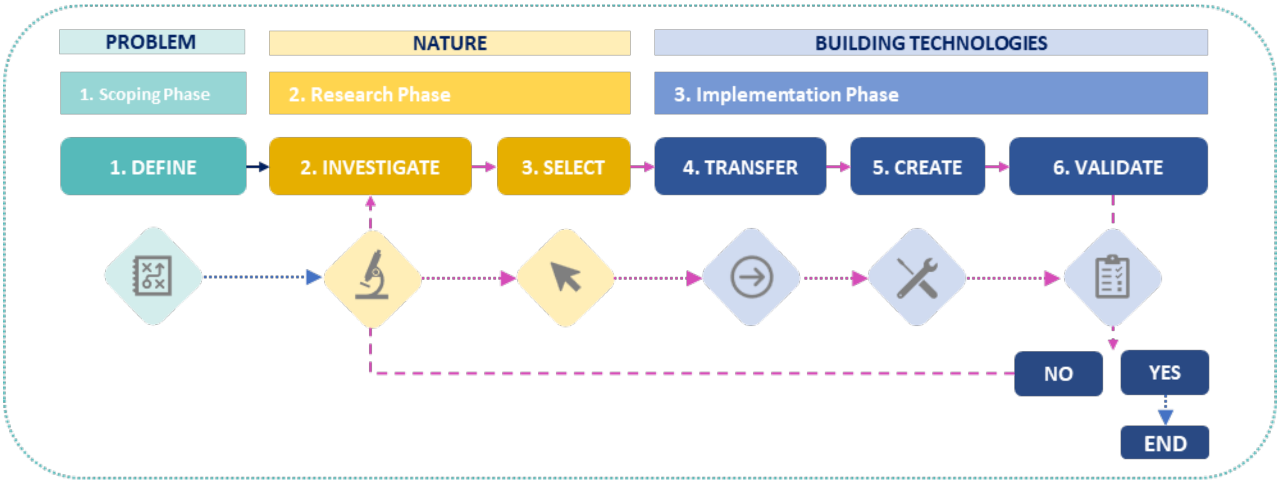


Fig. 14. General scheme of the bio-adaptive model (bio-AM).

Table 7

Description of six phase of the bio-adaptive model

Domain	Macro – phase	Phase	Procedure	Description
PROBLEM	Scoping Phase	1. DEFINE	What is the challenge?	The first step of the proposed approach is to define the problem or challenge. In this phase, it is necessary to analyze the context in which the solution will be realized, the available resources, the social and economic issues, and eventual constraints.
NATURE	Research Phase	2. INVESTIGATE	How does nature react?	In this phase, it is necessary to investigate the natural world to understand how natural organisms perform certain functions and adapt to certain challenges. At this stage, it is necessary to ask questions such as: how does nature exploit the natural resources present in each context? What strategies does nature implement to survive in a specific climate? Therefore, this is a very delicate phase, it takes the necessary time and the advice of experts in the field of biology to properly understand biological strategies and classify them according to the function performed.
		3. SELECT		After understanding how natural organisms perform one or more functions, one of them is selected for emulation. The level of adaptation is defined.
BUILDING TECHNOLOGIES	Implementation Phase	4. TRANSFER	How to transfer the previous information into technologies?	This phase consists in transferring the adaptation solutions identified in the following phases, in the field of building technologies. Obviously, it is necessary to consider the spatial scale, the material, and the technological characteristics of the new solution. To do this you must use the professional skills of the specific thematic area of application of the solution.
		5. CREATE		Creation of a full-scale, reduced-scale prototype, or by simulation with advanced software.

	6. VALIDATE	The final step is to test the proposed solution. In particular, the performance of the prototype is evaluated in terms of mechanical, physical, or chemical properties. Various simulations with advanced software are necessary to evaluate the performance and evaluate the comfort inside the building, also in terms of energy efficiency. If the test gives a negative result, it is necessary to return to phase 2 and identify a new solution.

6.2 Scoping phase: challenge and context definition

Defining the challenge is the first step in the biomimetic process. It means defining the objective as a function or strategy to which the final solution must respond. For example, understanding how to shelter from high temperatures or how to survive in snowy climates. The strategies vary according to the context in which they are applied. A strategy that works well in one context may not work in a different context. This happens because each context has varying factors and different resources availability. Therefore, it is important to understand the context in which the project will fit. From the characteristics of the context comes the challenge. For example, if the building is in a tropical environment the challenge will be to protect the occupants from high temperatures and humidity or adjust light intensity. It is crucial to consider the climate, abiotic factors and biotic factors that together make up an ecosystem. Abiotic factors are the non-living parts of an environment, such as sunlight, temperature, wind, water, and soil as well as natural events, including storms or volcanic eruptions, which are divided into chemical and physical. Biotic factors, on the other hand, are the living parts of an environment, such as plants, animals, and micro-organisms. Fig. 15 presents the main climatic contexts, environmental aspects, biotic e abiotic factors, and responsive functions that were considered in developing the biomimetic adaptive model in this study.

Therefore, depending on the climate and the ecosystem it is possible to define the specific challenge. Having to apply our model in the field of construction technologies, the challenges must be overcome by the architectural envelope, which acts as an adaptive interface between the internal and external environment.

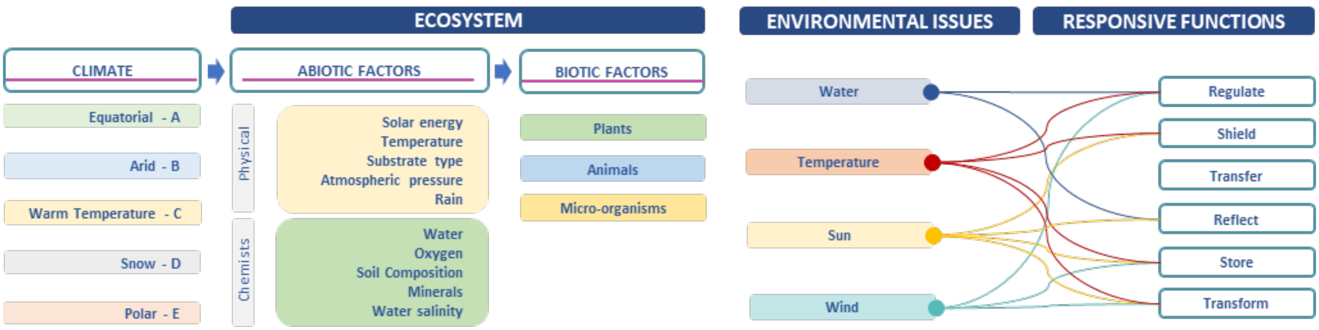


Fig. 15. Classification of the climatic context and of biotic and abiotic factors. Link between environmental issues and responsive functions. From left to right: five climatic zones [50] – equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E); Factors related to ecosystem – Abiotic factors and Biotic factors; Environmental issues – water, temperature, sun, and wind; the responsive functions are defined to allow the building envelope to act as an adaptive interface, such as regulate, shield, transfer, reflect, store, and transform.

6.3 Research phase: adaptation in plants

The second macro phase consists of deepening the understanding about biological strategies and identifying the relevant mechanisms to emulate. Therefore, it is essential to start from the analysis of the adaptive mechanisms present in nature. As mentioned earlier, plants are selected for this phase due to their static location, like buildings, but with responsive adaptation qualities. Plants are excellent climate indicators. In fact, the Koppen-Geiger classification is based on the values of temperatures and precipitation of five vegetation groups determined by the French botanist De Cabolle [70] [71]. The five Koppen vegetation groups distinguish between plants from the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E). In the case of plants, the control and tolerance of environmental factors are necessary for survival, in the case of buildings it is necessary for the comfort of users.

Plants' growth and structure are shaped by the stresses of their local environment and climatic conditions [72] , where various movement responses can be characterised [73]. Plants control various environmental factors by regulating temperature, access to light, controlling solar energy gain and water absorption or simply protecting themselves from the wind [74]. The presence of stomata on leaves facilitates the gas exchange between the plant and the atmosphere during the photosynthesis process, as well as the water vapor exchange to decrease the temperature during hot periods [75]. Plants adapt to environment by morphological, physiological, and/or ethological means, for example they activate a dynamic mechanism through valve movements in response to certain stimuli (physiological and ethological). An interesting example of morphological and physiological adaptation are succulents, where they have thick fleshy tissue that has adapted to the storage of water [76]. Cacti are capable to surviving in arid or semi-arid climates because of their spiny leaves that reduce evaporation and their enlarged stem acts as a reservoir of water [96][97]. To reduce the loss of water due to transpiration, cacti close the stomata during the day and open them during the night when the temperature is lower, and the relative humidity is higher.

Regarding behavioural adaptation, plants exhibit different types of movements, such as tropic, nastic, and nutation[72]. Tropic movements are directional responses that induce a variation of the orientation according to the direction of the stimulus. Nastic movements are induced by variation in turgor or cell growth regardless of the direction of the stimulus [72]. Nutation movements are oscillating or rotating movements of the organs of the plant (leaves, flowers, stems, etc.) during their growth process, due to the variation in turgor and the rate of growth of cells found on different sides of the organ itself [72].

Several studies have investigated the unique mechanisms of plants' movement, and some used these to inform new solutions [78][74][79] Fig. 16 provides a summary of the main plants and their strategies that are discussed in literature. The elastic opening of *Strelitzia reginae* has inspired a hinge-less solar shading system called "Flectofin" [80]. Lopez [27] instead, introduced various plants with particular properties: *Salvia officinalis* that, like all plants with hairy leaves, reflect sunlight from the surface and avoid overheating of the leaf surface; *Mimosa pudica*, whose leaves bend inward in response to physical contact [81]. La Rocca [72] describes the thermonastic movement of *Eranthis hyemalis* ; the flower petals open , during the day with increasing temperatures and remain closed , at night when temperatures are low. *Leontopodium alpinum*, on the other hand, is covered with a layer of down. In this case, however, the hair does not serve to protect the plant from low temperatures, but have the function of counteracting the loss of water and limit the transpiration [82]. For this reason, the *L. alpinum* , can live in arid places and subject to strong winds.

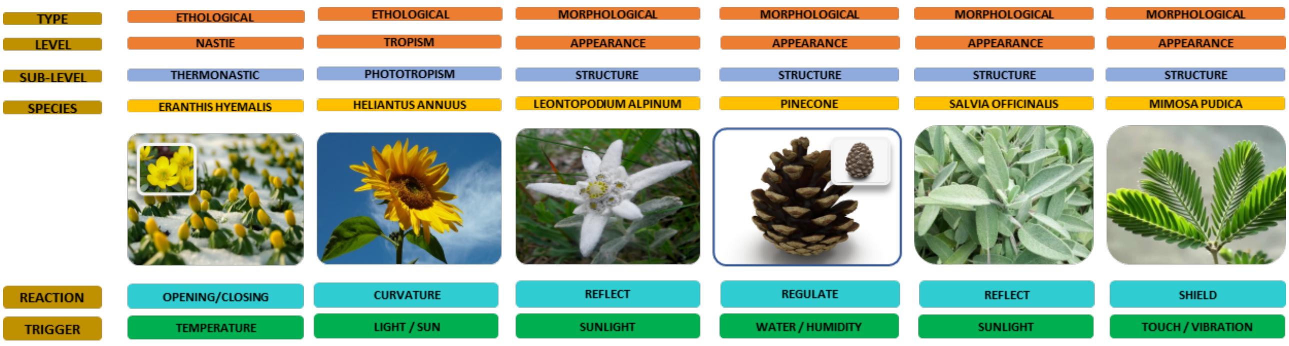


Fig. 16. Examples of responsive strategies and mechanisms in plants.

6.4 Implementation phase: parallels of adaptation for the development of the bio-AM

The third phase aims to transfer knowledge from nature, systematically, to an adaptive solution for buildings. The context has a significant factor on the shaping of the solution, where morphological, physiological, and ethological means through appearance, function, and behaviour should be clearly defined at the early stages. The environmental factors (sun, water, temperature, wind) represent the external stimulus that induce the particular response in terms of adaptation. Several strategies and mechanisms for responsive adaptation have been identified in plants, which can be classified based on the challenge that is faced by the intended solution. An overall classification of the framework is presented in Fig. 14. with relation to the responsive functions.

The transfer of responsive functionalities can be facilitated by using appropriate technologies and materials. For the context of bio-AM, materials that self-adjust as a response to environmental stimuli without the need for extra energy are preferred, such as smart materials. Smart materials constitute a class of innovative materials that make it possible to design architectural solutions that respond to the environment [37]. They are capable of providing a real-time response to stimuli and activate without requiring external control systems [83]. Shape memory alloys (SMA), shape memory polymers (SMP), electrochromic and piezoelectric materials are among the most widely used smart materials [84]. This work excludes smart materials based on an electrical stimulus from the model and considers only those capable of being activated through an intrinsic modification of properties. The choice of smart and self-activating materials allows to transfer functionality from nature to technology, and to direct the design towards low energy consumption, in line with the objectives of climate neutrality by 2050.

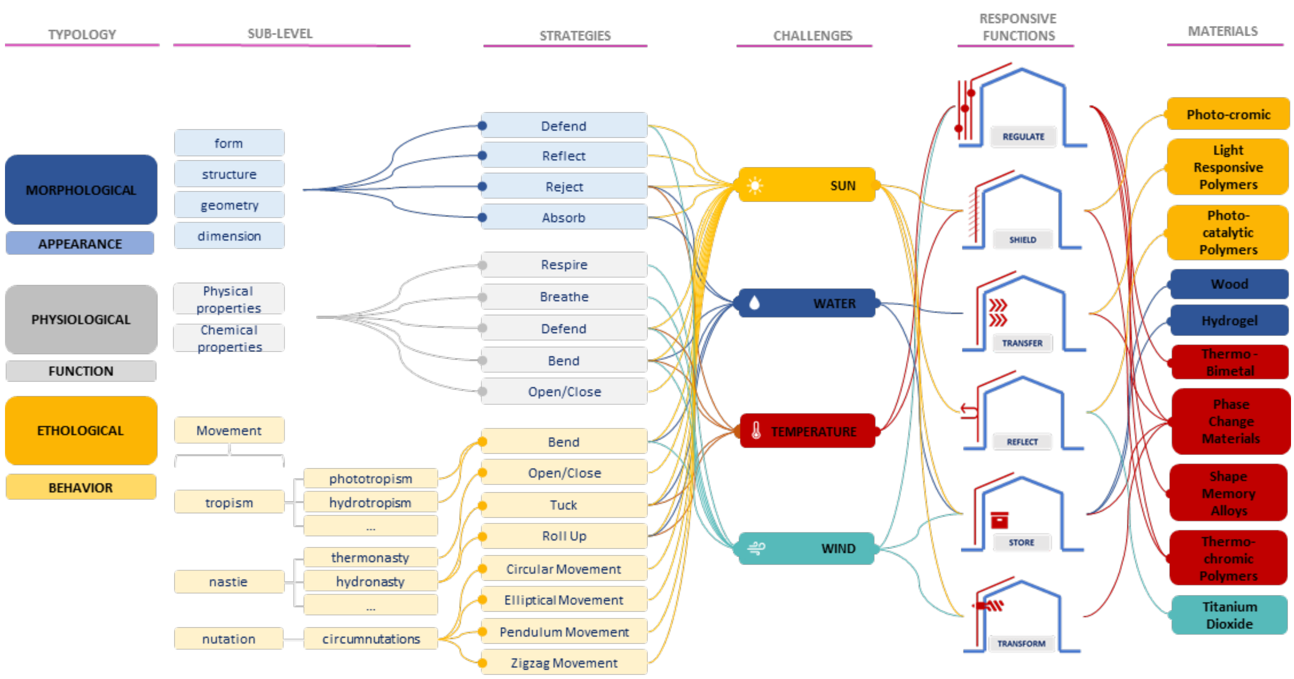


Fig. 17. The initial framework for developing the bio-AM.

7. Conclusions and visions

The building envelope has a significant role on the energy consumption in buildings, where a great of the negative impact on the environment can be mitigated if envelopes are properly designed. due to their static nature (in most cases), traditional solutions fail to meet the challenges of the current climate changes and crisis. The adaptive biomimetic approach, applied to building envelope technologies, could reduce energy consumption for air conditioning and lighting, adapting to the needs of users based on the climatic conditions surrounding the building. Several examples of adaptive envelopes were analysed to provide an overview of the progress of the application of biomimetic principles in the AEC sector, especially in the architectural field. This study provided an overview of the related characteristics that were used to inform a new biomimetic model, defining the steps to move from biological principles to architectural technologies.

The adaptation strategies of plants implement relevant mechanisms for survival and have clear analogy to buildings in terms of static location and climatic conditions. The analysis of adaptive and biomimetic envelopes has made it possible to define the limitations and potentials of biomimetics, with a clear potential in the architectural field for energy efficiency and environmental considerations. Nevertheless, adaptive biomimetic applications are still limited and mostly prototypes. Existing examples of adaptive envelope are limited to shading systems and limited to an emulation of structural morphologies, while only a small part of these are dynamic-functional emulations in prototypes or in temporary structures such as pavilions.

The proposed initial framework for developing the bio-AM aims to facilitate the efforts towards developing solutions for adaptive building envelopes in a systematic way and implement novel design solutions for a more sustainable and resilient future. The transfer of biological principles to building envelopes that can interact with the environment is still a challenge but has the potential to change the way we design sustainable solutions and to reduce the impact on the environment, and eventually contribute to achieving climate neutrality by 2050.

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Author Contributions

Francesco Sommese: Conceptualization, Data Curation, Methodology, Analysis, Investigation, Writing – original draft preparation, reviewing & editing, Visualization. **Lidia Badarnah**: Conceptualization, Methodology, Analysis, Visualization, Supervision, Writing – reviewing & editing. **Gigliola Ausiello**: Supervision.

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