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*Edited by Gulden Kokturk  
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# **INTERDISCIPLINARY EXPANSIONS IN ENGINEERING AND DESIGN WITH THE POWER OF BIOMIMICRY**

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## **Interdisciplinary Expansions in Engineering and Design With the Power of Biomimicry**

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# **Biomimetic Facade Applications for a More Sustainable Future**

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Ayça Tokuç, Fatma Feyzal Özkaban and  
Özge Andiç Çakır

Additional information is available at the end of the chapter

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## **Abstract**

Mankind has often taken inspiration from the nature to solve problems since nature has sophisticated processes, refined for thousands of years. While manmade systems are unsustainable, natural processes embody sustainability principles; therefore, there are many things to learn from nature in order to solve design problems and create a more sustainable future. This is the promise of a biomimetic design approach. Another design approach is biodesign, and it also involves utilizing natural elements inside the design. The building façade is a problematic research area since it is at the intersection between living spaces and natural environment; thus it faces many problems especially regarding energy-air-water transition between indoors and outdoors. Application of key sustainability concepts in architecture such as energy requirements, form and structure, and sustainability considerations can be enhanced by learning from natural processes. This chapter looks at cutting-edge design principles, materials, and designs in building façades through the lens of biomimetics and biodesign. First, the design principles and then the materials and some cases are explained. The concepts of biomimicry and biodesign are in harmony with the concept of sustainability; however, to reach sustainable façade solutions, the sustainability principles should be at the core of the design problem definition.

**Keywords:** adaptive façade, biomimetics, biodesign, construction materials, sustainable architecture

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## **1. Introduction**

The relationship between nature, technology, and architecture is an ancient debate with many historical twists and turns; however, these past decades have brought unprecedentedly quick

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paradigm shifts. Biomimicry is a relatively new term, yet its connotations have been part of architecture for millennia, especially in form generation and imitating structural systems. While our interpretation for the earliest works is mostly conjecture, the written works relate the architectural styles of art nouveau, streamline design, anthropomorphism, zoomorphism, biomorphism, organic design, and biologically inspired design as precursors to biomimetics, biomimesis, or bionic [1]. While some designers and researchers interpret biomimicry as an all-encompassing approach to learn from nature (such as the biomimicry institute), others argue it should only be used to identify mimicking biological processes, and other phenomena should be called by different names. These include biophilia (love of nature) for taking inspiration from natural forms [2], biomimesis for imitation of natural models and systems, and geomimicry for utilizing geological processes instead of biological ones.

One of the recent innovation areas is material sciences, such as new ways of making old materials and innovation at nanoscales. Biomimicry processes tend to be either problem based, from design problem to biology, or solution based, from biology to design [3]. A newer term is biodesign; it encompasses mimicking biological processes; moreover it also includes integrating biological organisms as a part of the design or construction processes. Recent innovation areas include redesigning construction methods and material sciences by making use of biological materials. While there are few built examples, biodesign continues to evolve and utilizes both a problem-based approach and a solution-based approach simultaneously.

In this period of paradigm shifts, Benyus' definition of the role of architecture as creating environments inductive to human life [4] is also evolving. The debates on environmental impact and sustainability influence architecture through the world with new codes and measures; these are most visible on the topics of energy efficiency and environmental impact of buildings during and after construction. However, human-made environments and architectural systems are not sustainable since they make use of land, require resource inputs, and generate waste products. Therefore, architectural practices continue to search for more sustainable design concepts; some of the common concepts include passive, active, energy-efficient, zero energy, green, and intelligent. Yet all sustainable design concepts place an essential role to the building façade design since its place at the intersection between living spaces and natural environment makes it the skin of the building, where energy-air-water transition between indoors and outdoors occurs.

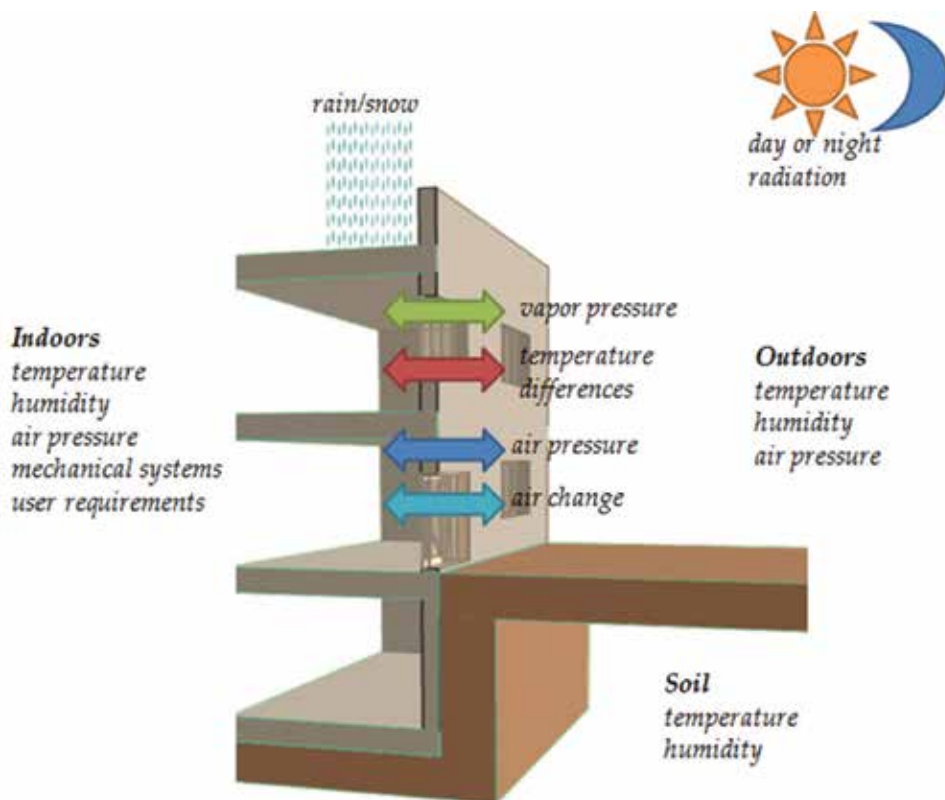
The main performance criteria of a sustainable façade include "energy requirements," "form and structure," and "sustainability considerations." Although all nature-inspired designs are not sustainable, this chapter argues that architects and engineers can employ biodesign principles for higher performing façades. In this context, this chapter aims to investigate the possibilities of biomimetics and biodesign methods in sustainability of constructional practices of the future, façades in particular. The scope is looking at design parameters, materials, and state of the art in building façades from a biomimetic and biodesign point of view. Although the number of materials and examples given in this study are limited in number, they put forward the given principles. This paper first discusses the design principles of sustainable façades, then explains related construction materials, and afterward investigates examples.

## 2. Design parameters for sustainable biomimetic façades

Façade is the exterior element of the building that separates the indoors and outdoors, yet another significant role of a façade is giving image to the building. Façades perform under the influence of climate conditions and affect the indoor living conditions; therefore the first criteria of a sustainable façade are usually defined as material and energy efficiency (**Figure 1**). Architects and engineers employ thermal, optical, air flow, and electrical mechanisms for higher performance in façades. Aksamija defines high-performance sustainable façades as exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants [5].

In this context, biomimetics and biodesign have helped to create façades for a long time; however, all designs that take nature into consideration are not sustainable. To create a sustainable façade, the design constraints should take into account the parameters for sustainable living models, for instance, how do organisms heat, cool, give shade, and control light?

A sustainable design problem would treat an organic skin as animated by natural phenomena, i.e., wind, light, rain, drought, snow, etc. In addition, it can also perform other functions



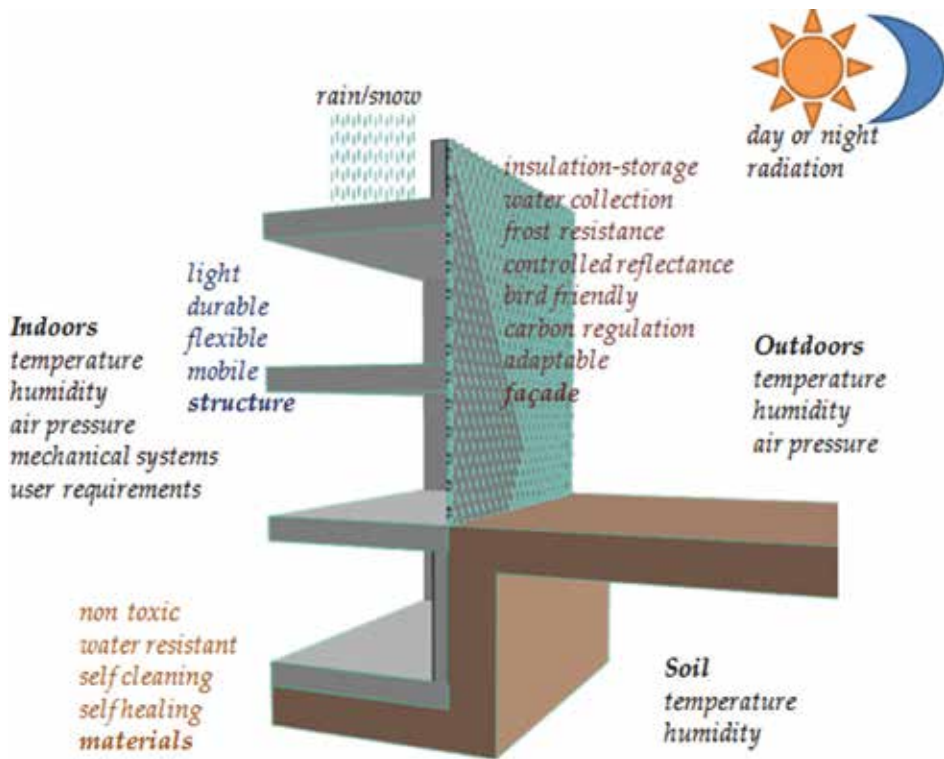
**Figure 1.** Design principles of a traditional facade, by TBT, 2017.

essential to life such as breathing, carbon capture, and water balance; for such functionality they usually have multiple layers. Loonen describes the underlying principles of bio-inspired façade design as adaptability, multi-ability, and evolvability [6]. **Figure 2** schematically represents the main design principles for a sustainable façade. Thus energy requirements, functional considerations, and structural efficiency should be integrated in a more sustainable façade.

**2.1. Energy requirements**

The most common design metric for sustainability of buildings is energy requirement to regulate the indoor environmental conditions. Most of the energy consumed in a building is necessary for heating/cooling requirements and is directly related to the façade design, since most of heat and light transfer between indoors and outdoors takes place through the façade. The regulation of time-dependent weather data such as solar irradiation, ambient temperature, sky temperature, wind speed, and relative humidity is necessary. From a sustainability point of view, these technologies can be classified under thermal comfort, visual comfort, and renewable energy production.

The parameters related to heat and energy transfer are solar radiation, wind, and climate. The utilization of a façade for thermal comfort changes according to the properties and thickness of the material layers in addition to the heat balance on the element’s surface due to both the properties of the materials (i.e., thermal absorption, emissivity, density, specific heat, and



**Figure 2.** Design principles of a sustainable facade, by TBT, 2017.



thermal conductivity). These are usually regulated with architectural technologies including solar orientation, insulation, and shading. In addition, there are a number of less common dynamic technologies such as thermal mass, dynamic insulation, radiative cooling, phase change, energy storage, natural ventilation, and energy generation.

TRIZ is a Russian acronym for theory of inventive problem solving, while BioTRIZ is a methodology that can interpret and transfer data from biology into technological procedures. Craig et al. used BioTRIZ to design a roof for a hot climate, Arabia [7]. The problem involves conventional roof design with high thermal insulation that would prohibit solar radiation and convection effects from warming the thermal mass of the roof yet at the same time restrict its radiative cooling. While many solutions were offered by the methodology, the researchers chose to replace the existing insulation with an open cell honeycomb that would stop convective warming yet at the same time allow long wave radiation to pass vertically. They estimate a reduction of surface temperature by an average of 4.5°C.

Visual comfort depends on the amount of necessary light and lack of glare. Levels of light transmission, transparency, translucency, color, and reflection effect interior-exterior light transmission and indoor lighting conditions. While glass systems that respond to light, electricity, and heat exist, the homeostatic façade system used by architecture firm Decker Yeadon mimics the muscle system and uses electrochemistry to lengthen and contract the dielectric elastomer to create a self-shading glass [8].

The façades can become generators of renewable energy. The primary energy source on earth is photosynthesis, which became the precursor for fossil fuels. Today photovoltaic technology biomimics plants to create artificial photosynthesis [9]. Some façades can be used to cultivate or act in mutual coordination with species such as algae that can grow and be harvested for oil, so they are suitable as a biodiesel, bioethanol, bio-hydrogen, or biomass production source (see Section 4.4). Yet these need not be living organisms and can be systems mimicking living organisms such as building integrated nano-wind turbines [10].

## 2.2. Form and structural efficiency

The most common type of biomimicry in architecture is copying surface morphology from nature. There are lots of buildings that take their shapes from nature, from bones to leaves and flowers to shells. Sometimes the analogy is only morphologic, as in the iconic Sydney Opera House's analogy with an orange shell, yet sometimes the appearance also serves a purpose. For instance, the roof of Esplanade Theaters in Singapore by DP Architects uses durian fruit as a model and their spikes as inspiration for sun shading and likewise has a secondary sun shading lattice; thus, it captures the sun, reduces its energy use, and reduces artificial lighting [11].

While most discourses on architecture emphasize that biological data will cause changes in architectural paradigms, most of the studies are focused on form generation [12]. Today, complex geometries can be defined by a set of rules for growth in parametric terms using computational methods. Gruber et al. propose a multistage design process that aim to address strategic decisions at the start of a project while facilitating exploration of architectural design. The stages of this process are identifying the features of the design; extracting feature genes; generating the new evolved and developed typology, i.e., phenotype; and altering genes to modify the phenotype [13].



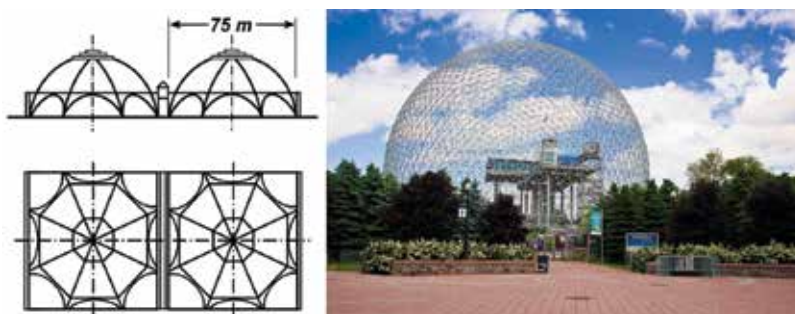
While utilization of evolutionary algorithms in parametric design is a widely discussed research topic, another aspect of digital technology in architecture is making entirely digital fabrication possible via CNC or 3D printing for these complex geometries. This would allow for material efficiency and ease of fabrication yet continue to be biomimetic. Yet minimal carbon footprint is only possible with an efficiently designed structure that is stable and durable and makes use of its environment to have minimal impact. Inspiration from biological processes and implementation of nature's principles allows for the design of façades in alignment with the flow of forces according to nature of the structure itself.

Through history, most of the structural systems were thus influenced from nature. From the cave houses to tensile structures, the prototypes of structural systems surround us through nature. Some of the earlier structural system classifications take these into account. The biomimetic approach looks at and sees insect mound in the masonry structures such as pyramids, shell structures in eggshells, tensile structures in spider webs, cell structures in honeycombs, and pneumatics in soap bubbles [14]. The first studies that emphasize that biomimicry is not only formal analogical but have to be an inspirational process from nature began in the early twentieth century and spread.

Some examples include Dischinger's reinforced concrete dome for shells (**Figure 3a**), Buckminster Fuller's revolutionary geodesic dome construction for space frame construction (**Figure 3b**), and Frei Otto's work on lightweight construction for tensile structures. In recent studies, the façade of One Ocean Pavilion by SOMA Architecture and Knippers Helbig Engineering for Yeosu Expo 2012 looks like fish gills from the outside, yet the hingeless structure of the lamellas that also regulate the light and air inside was inspired by the opening mechanism of the bird of paradise flower [15] (see Section 4.2). Thus bio-kinematics can be transferred to technical constructions to create ever-changing surfaces.

### 2.3. Sustainability considerations

Scientific research suggests that anthropogenic carbon emissions lie at the heart of global warming, yet nature uses carbon as a building element of living organisms. An essential issue of architectural processes is the utilization of optimum amount of resources and thus has lower ecological footprints. Moreover, nature also has no waste since output of one process serves as input for another. In addition, the chemical reactions in natural processes require neither high temperatures nor toxicity [4]. Another point is that while manmade environments mainly



**Figure 3.** Biomimetic structural examples; (left) reinforced concrete dome [16] and (right) geodesic dome [17].

rely on outside energy sources, the main energy source of nature is the sun and gravity. In this way, nature has various clues to offer humans for a more sustainable life. The façades also serve many considerations including air quality, water efficiency, carbon capture, use of nontoxic materials, low embodied energy, low material consumption, biological behavior, responsive, adaptable, breathing, and sensing.

Photosynthesizing or fog eating façades allow for carbon sequestration from the environment (see Section 4.3). While they create more air to breathe, they may also allow breathing by the planted greenery. In addition, greenery regulates flows of heat, air, water, and electricity to maximize energy efficiency. Besides thermal comfort, indoor air quality is directly associated with health and productivity issues in buildings [18]. The façade in Council House 2 by Mick Pierce in Melbourne makes use of a number of biomimetic principles to manage heating, lighting, air quality, and water inside the building. Every aspect of the building has been rethought so as to function as a tree with eco-tech architectural technologies. The façade is multilayered like the human skin; the outer skin (dermis) consists of stairs, ducts, balconies, sunscreens, and foliage for solar and glare control and creates a semi-enclosed microclimate [19].

Water is the source of life on Planet Earth, and it is the living medium for many organisms, yet in a building, the water considerations are twofold. First is the protection from water, and second is the efficient use of fresh water for resource conservation. Badarnah and Kadri propose the BioGen methodology for biomimetic design concept generation. It focuses on investigation of integrating a number of strategies to achieve improved solutions [20]. They use this methodology on the design problem for a water-harvesting façade in arid regions. First they map their exploration in a graph for four hierarchical levels: function, process, factors, and pinnacles that inhabit the region. Then they define pathways on the map, select from pinnacles, analyze, and classify selected pinnacles in order to reduce complexity. The dominant features in each category are identified and superposed with the design paths. The resulting preliminary design is based on the Thorny Devil (**Figure 4**), which is one of the many pinnacles in the system. The design includes a bumpy surface that attracts the water molecules, and grooves generated between the mounds that encourage capillary action into storage chambers. The water in the chambers is then transported through the wall and evaporated inside. They estimate that the wall would humidify the interior for one third of the year.



**Figure 4.** The thorny devil [21].

### 3. Biomimetic building materials and techniques for façade applications

Today, the building façade is no longer a cover to only protect the structure from the outside environment. The design of a façade aims to impart functional characteristics as well as an esthetic look; in addition, it considers extending the life of the building with more durable materials. Thus, a façade may be designed as an adaptive layer which has a great impact on the energy efficiency and thermal comfort of the whole building. With an interdisciplinary approach, stronger, functional, durable, and ecologically efficient building façades may be designed.

Bio-inspired manufacturing, either in micro-, nano-, or macro-level, manufacturing of materials or systems derived from biological self-organization methods, i.e., self-healing, self-cleaning, and self-assembly, are efficiently used for these purposes. Biological organisms themselves may be enforced to live and produce in a manmade environment, and their efficient characteristics are engineered; examples of those include fungi-producing thermal insulation materials for energy-efficient façades or algal photobioreceptors for energy generation.

The interdisciplinary approach for using microorganisms and/or their products may be termed as “microbial biotechnology” or as a more generic name “construction bioengineering.” Bio-inspired climate adaptive building skins that behave like a living organism may create an ecosystem that can provide a mutual relationship with the outdoor environment [22]. As an example of green walls, the biological materials such as greenery can be used as a material to cover a façade and to control temperature variations [23].

Either on organism, behavior, or ecosystem level, when inspiration comes from nature, it may reflect in various ways in building façades: designing a functional or esthetic form; producing a functional material for building the façade; adding a novel function, e.g., self-cleaning or energy saving; and constructing the façade with a new technique. Sometimes a biomimetic process may be used to produce the façade-making materials (**Figure 5**).

One may classify the biomimetic solutions for construction purposes by observing the examples available and researching the novel techniques that are still in the initial technology readiness levels. However, a deeper question arises, “why do we need biomimetic solutions for building façade applications?” Structural and functional necessities as well as rising importance on sustainability and energy efficiency divert scientists and engineers working on construction materials field to biomimetic solutions (**Figure 6**).

Regarding the necessities described above, there are many novel solutions based on interdisciplinary to transdisciplinary works. Some examples of façade-making construction materials and techniques are described below.

The high contact angle between the surface and the liquid-air interface of some plants, such as lotus, results in hydrophobic surfaces; those surfaces have self-cleaning ability as the water drops may slip easily carrying the contaminants away from the surface [24]. Gecko feet [25], pond skater [26], and shark skin [27] are other examples that human inspire for producing functional surfaces. These natural mechanisms were applied by construction industry to many products such as self-cleaning paints or clay roof tiles; in addition textile and automotive

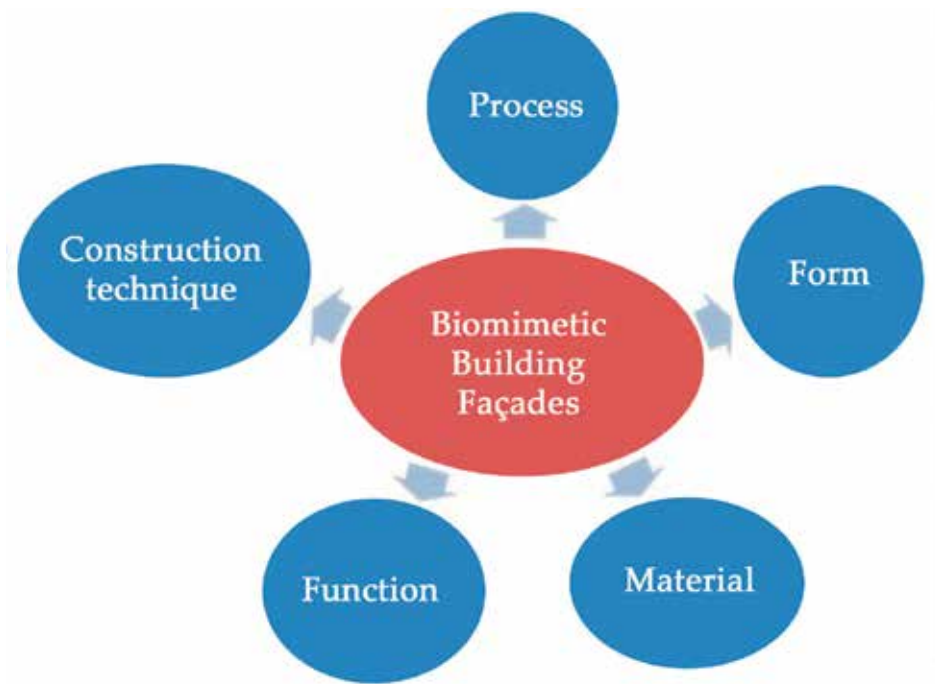


Figure 5. Biomimetic technologies for building facade design, by TBT, 2017.

Sustainable	Durable	Safe	Structural
Strong	Tough	Lightweight	
Adaptive		Self-shaping	
	Self-healing		
Energy Efficient			
Self-cleaning		Stimuli responsive	Functional
Photonic		Anti-reflecting	

Figure 6. Biomimetic solutions for construction materials used in facades, by TBT, 2017.

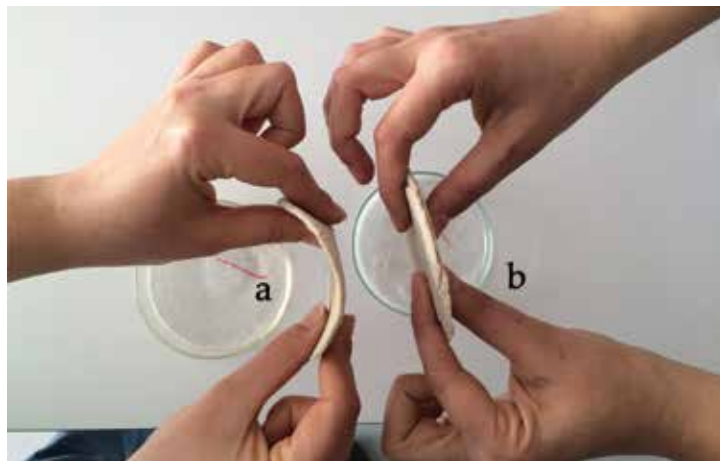
industry has produced similar solutions. Inspired from photosynthesis process, photocatalytic effects work in the combination of air humidity, UV radiation, oxygen, and nanoscale catalyst  $\text{TiO}_2$  being a basis for industrial self-cleaning paints and other industrial applications [28]. Having some commercial examples available, photocatalytic  $\text{TiO}_2$  nanoparticles are able to clean air of automobile-produced nitrogen oxides ( $\text{NO}_x$ ), providing them with extra functionality [29] (see Section 4.3).

Anti-reflectivity is an important functionality for surfaces that may be useful for energy-efficient façade applications. The eyes of the elephant hawk moth are coated with a regular pattern of conical nanoprotuberances, which significantly minimize light reflection. This ability improves night vision and is critical for moths to escape predators. Nanostructured moth-eye arrays are optically excellent for reducing reflections and used for applications such as glazing the skyscrapers and silicon solar cells [30, 31].

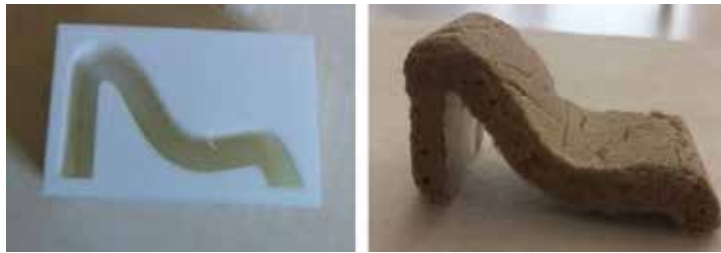
Inspired from the organisms living in arid climates, phase-changing materials store energy during melting and freezing. By using the thermal insulation materials for façade applications, interior spaces stay cool (or warm) for a longer period of time improving energy efficiency [32, 33].

Cultivation of living matter on façades is not a novel idea, and the green walls are a part of everyday architecture; however, when it comes to adding microalgae photobioreactor to the façade of a building, the benefits differentiate, and the process becomes more complex. Algae capture the energy by photosynthesis inside the open or closed systems that contain water, nutrients, and  $\text{CO}_2$ . Those systems can be integrated on the façade of a building through convenient designs that provide necessary sunlight for algae growth. Integrated photo-bioreactor solutions enable energy efficiency for both buildings and cities [34, 35].

The biological formation of minerals, i.e., biomineralization process, in particular the biocalcification, is used to form bio-binders, hardening sand to gain new forms, healing cracks in reinforced concrete buildings, soil stabilization and environmental processes, etc. It is possible to produce microbial (or bacterial) binders by microbial-induced calcium carbonate precipitation, thus producing novel materials for construction and enhancing their durability [36]. A commercial example of this is a technique patented by Dosier and labeled as BioMason™. The Biodesign Team Turkey (TBT) aimed to develop architectural design product that is in harmony with the nature and suitable to human health with partnership of bioengineering and architecture disciplines via directing bacterial calcification to form an architectural structure with the support of 3D printing technology of biodegradable poly-lactic acid (PLA). For this



**Figure 7.** Solidification trials on petri dishes ((a) without inoculum; (b) with inoculum), by TBT, 2017.

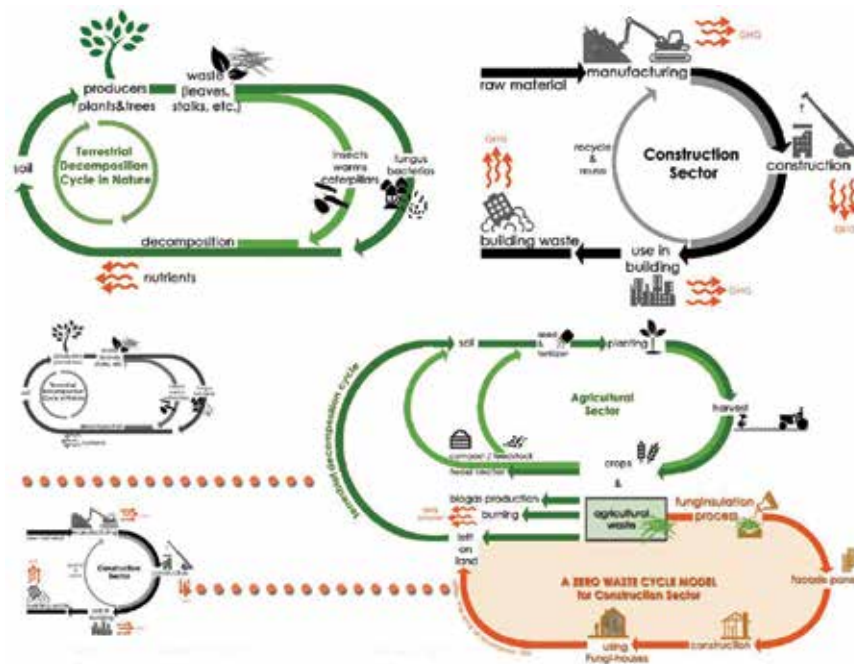


**Figure 8.** Prototype seating element: (left) 3D-printed design and (right) solidified urban unit, by TBT, 2017.

purpose, *Sporosarcina pasteurii* (*Bacillus pasteurii*) was chosen to use the urea mechanism to precipitate  $\text{CaCO}_3$ , thus hardening sand by utilizing urea (**Figure 7**).

After the successful solidification process in petri dishes, a unique life element was designed, and the mold was taken out from the 3D printer (**Figure 8** (left)). The mold was covered with sand, and then inoculum was added and evenly distributed throughout. The DSM 33 growth medium containing 100 mM  $\text{CaCl}_2$  was evenly distributed on the sand too and incubated for 1 week in a 30°C incubator. The lab-type prototype (**Figure 8** (right)) shows that real scale designs can be produced harmless, and environment-friendly life elements at large scales can be produced.

In addition, embedding the microbial agents in cement matrix by several methods, which may improve the microstructure of the material, furthermore, they may impart self-healing ability to such systems by bacterial biocalcium carbonate formation as a natural mechanism. Self-healing



**Figure 9.** Funginsulation architecture concept; (upper left) decomposition cycle in nature, (upper right) Lifecycle, and (down) funginsulation cycle, by TBT and Diploid, 2017.



is a mechanism of living organisms. Various methodologies such as usage of hollow fibers and pipettes resembling the veins in living organisms, incorporation of encapsulated agents, and implementation of expansive agents, mineral admixtures, and bacteria have been employed to tackle the vulnerability of cementitious materials to cracks [37] by a self-healing mechanism.

The ability to grow fungi by producing mycelium is the functionalized part of FungInsulation™ concept. A mycelium is a vegetative part of fungus, and it consists of branching mass named hyphae. Fungal mycelium can spread over soil and many other substrates by using the nutrients inside [38].

Rural Funginsulation Architecture concept by TBT and Diploid is a value-added solution to recycle agricultural waste to design and energy efficiently retrofit rural houses. A bio-inspired process is used to produce construction materials with superior thermal insulation property, and the solutions are tailor-designed for several rural areas having different agricultural waste types (**Figure 9**).

The abovementioned materials and techniques developed by biomimetic concept are examples of sustainable and functional solutions. Many others are under development, and they will provide more energy-efficient, durable, and functional solutions in the future. Thus, building skins with adaptive capabilities approaching to that of natural skins are on the way.

## 4. Contemporary biomimetic façade applications

According to Benyus' classification [4], biomimicry can mimic natural forms and natural processes. Designers can imitate the features of creatures or their behaviors. However, there are also cases of another level of biological inspiration, a bio-collaborative design that makes use of living organisms in the façade design. Below are some examples that make use of the aforementioned design principles and materials to generate various designs.

### 4.1. Experimental smartness

Media-TIC (1997–2007) is an office building designed by Enric Ruiz-Geli (from Cloud 9 architects) for Consorci de la Zona Franca and located in 22@ of Barcelona Poble Nou district, at the intersection of Carrer Roc Boronat and Carrer Sancho de Ávila. The 22@ is a science and technological district, which was converted from the old industrial area of the city, and is continuing to transform with many experimental high-tech buildings since 2000. In this environment, Media-tic building is named as “a kind of house of the Digital Community” and could be seen as a technological showcase that serves the purpose of being “green smart city” of Barcelona.

The building was designed exclusively using CAD/CAM technology. The design approach of Cloud 9 sanctifies the technology, and they regard Media-TIC as true representative of the digital age: “The theme of the Media-TIC building is how architecture creates a new balance with the digital use of energy... now we are undergoing the DIGITAL revolution. Between 1900-1950 the cathedrals of architecture were built: these were the factories. Factories whose technological and structural advances created work spaces. In the information era, architecture has to be a technological platform, in which bits, connectivity, new materials and nanotechnology are important.” They describe this design as “performative architecture” where the structure itself performs other functions [39].



This building has a hybrid program and proposes an information and communications technology center. The ground floor contains an open space and a communications hub open to the public, reception offices, and a restaurant. The building program also has an auditorium for 300 people on the first floor and offices, with open and flexible floor plans.

It can be said that Media-TIC building imitates nature's adaptability through its smart façades. The most apparent characteristic of this 38-m-high building is its adaptive architectural envelope inspired by breathing. This envelope includes "performative" elements on two of the four façades, which are made of the ethylene tetrafluoroethylene (ETFE) cladding within a net-like steel structure. ETFE was selected for its lightness, elasticity, geometrical flexibility, and thinness. The ETFE cladding surface also gives reference to the geometrical forms of atoms or elements with its concave and convex triangles. The Southeast and the Southwest façades are adaptive ETFE surfaces; their skin changes depending on the external conditions (**Figure 10**).

ETFE façades both filter out ultraviolet light and react to the changing weather conditions. On the southeast elevation, which would absorb 6 h of sunlight a day, 104 inflatable cushions are controlled by an independent computerized sensor. Each cushion contains three air chambers—a transparent outer layer, a middle layer, and third layer with a reverse pattern design. The air chambers between different layers not only slightly improve thermal insulation but also enable the control of solar radiation through a pneumatic system and a pressure sensor located in each cushion. The air inside each cushion is managed individually through a lighting sensor. It can also be manipulated and scheduled with an IP address [41]. When the sun's rays reach certain strength, air is pumped into the inner chamber and creates an opaque façade that protects the structure from the sun. When the middle and inner layers come together, they create, and the inflatable section only has one air chamber. This movement gives reference to orientation. The southwest façade consists of two ETFE sheets filled with nitrogen and oil coalescence to provide the necessary shading. This shading varies depending on the density of the air in order to obtain the desired solar transmittance [41].

The remaining façades would receive only 3 h of sunlight a day and use internal screen-type blinds for solar protection. In all, the project uses 2500 m<sup>2</sup> of ETFE cladding, achieving energy savings of 20%. It does not need cleaning because of the nonstick quality of the surface. It is proven to be compliant with international fire safety standards, and it does not contribute to the spread of flames or the production of smoke [41]. The building has additional sustainability goals such as a photovoltaic roof, which produces half of the



**Figure 10.** Media-TIC building: (left) exterior view and (right) inflatable cushions [40].

building's energy, and rainwater storage for use in the WCs. Accordingly, the building cut its emissions by 60% and gained a LEED gold certificate.

The building won World Building of the Year 2011 award in accordance with its values of 1–20% CO<sub>2</sub> reduction due to the use of district cooling, 2–10% CO<sub>2</sub> reduction due to its photovoltaic roof, 3–55% CO<sub>2</sub> reduction due to the dynamic ETFE sun filters, and 4–10% CO<sub>2</sub> reduction due to energy efficiency related to smart sensors. The building has another biomimetic approach indoors. Inspired by jellyfish, the interior paint absorbs energy from the sun all day and releases a green glow throughout the night. "It is a building that lights itself, but it does not light up the whole neighborhood" says Ruiz-Geli [39].

#### 4.2. Kinetic façade

One Ocean Pavilion (2010–2012) was designed by SOMA Architects for an open international architecture competition regarding Expo Yeosu 2012 in South Korea. The concept of the building is based on the Expo's theme, "The Living Ocean and Coast," and emphasizes the experience of the ocean: "as an endless surface and in an immersed perspective as depth." The building has two sides; one of them meets the coastline and creates a soft meandering edge. The opposite side embraces the ocean with vertical cones and its roof landscapes (Figure 11).

The building owes its main concept and popularity to its kinetic façade with fish-like characteristics: "(our architectural intention is) to produce a choreography and imagery out of the building's own layers, without displaying any further media content ...By involving real movement the kinetic façade aims to unify those usually isolated layers of architecture and media and define it as an interrelated and inseparable three-dimensional experience" [43].

A biomimetic approach was implemented for the kinetic façade on the main entrance façade of the building; it was developed with Knippers Helbig Engineers. The working mechanism of the façade was inspired by opening movement of the petal found in the "perch" of the bird of paradise flower (*Strelitzia reginae*) (Figure 12) [45], which is based on a torsional bending mechanism. Biomechanical investigations have established that the perch of the bird of paradise flower, which protects the stamen and ovary, can be released more than 3000 times with



Figure 11. One Ocean Pavilion bird's eye view [42].



**Figure 12.** Bird of paradise flower, by TBT, 2018.

no evidence of fatigue [15]. When the flower is pollinated by birds, the perch is bent downward and opened by torsional buckling [44].

The kinetic façade of One Ocean building has 108 fiberglass lamellas made of glass fiber-reinforced polymers (GFRP) that open and close via a servomotor and covers a length around 140 m with a height changing from 3 m to 13 m. Slightly curved lamellas are only 9 mm thick yet can reach 14 m of length. A local compression force at the top and the bottom leads to a controlled buckling and reversible elastic deformation inside the fins [15]. Each individual modular lamella is moved by actuators located on the upper and lower edges of the façade and is operated by solar panels located on the roof. The GFRP wings undergo lateral-torsional buckling, in order to deploy into a doubly curved shape. The high strength of the glass fibers is combined with a highly flexible epoxy resin in order to achieve a low bending stiffness and, at the same time, structural resistance to wind loads. Soma mentioned that the lamellas "... induce compression forces to create the complex elastic deformation. They reduce the distance between the two bearings and in this way induce a bending which results in a side rotation of the lamella" [46] (**Figure 13**).

Movement of the lamellas control light conditions in the foyer and the best practice area; in addition it creates animated patterns on the façade like ocean waves. These movements can also be likened to the gills of a fish [48].



**Figure 13.** The kinetic façade and closed lamellas [47].

### 4.3. Smog-eating façades

Photocatalytic  $\text{TiO}_2$  in the cement developed by Italcementi is known as smog-eating material for the last few years. Although it has been in use since 1995, the first patent had only a self-cleaning effect and was applied in many outstanding works, such as Misericordia Church in Rome or Cite de la Musique et des Beaux Arts, some tunnels or pavements, etc. “TX Active” technology, which was generated in 2006, added air cleaning property to the material [49]. The material captures air pollution when the façade comes into contact with light, then transforms the pollution to inert salts, and thus reduces smog levels in the environment. This new formulation was utilized in the two contemporary buildings, and their investigations are given as follows.

One of them is a façade design for Manuel Gea Gonzalez Hospital building in Mexico City, which is one of the most polluted megacities in the world. The original hospital building was constructed in 1942, and in 2013 a new building (named Torre de Especialidades) was added with a smog-eating façade [50]. The 2500 m<sup>2</sup> façade is designed by Berlin-based architecture firm Elegant Embellishments.  $\text{TiO}_2$  can act as a catalyst for chemical reactions when it is activated by sunlight. When UV rays hit the tiles, a reaction occurs, converting mono-nitrogen oxides (the substances that make smog smoky) into less harmful substances such as calcium nitrate and water, along with some  $\text{CO}_2$ . The  $\text{TiO}_2$  in the tiles does not wear; it can keep on doing photocatalysis indefinitely.

The tiles’ irregular and biomimetic pattern is a quasicrystalline or Penrose grid based on sponges and corals and was designed by Prosolve through Rhino (**Figure 14**). Prosolve’s modules are manufactured from an ABS-polycarbonate plastic sheet; it is vacuum-formed over aluminum tools, then cut, and coated by a robotic sprayer with layers of  $\text{TiO}_2$  and primers that adhere to the plastic substrate. The reliefs increase the absorption surface and reduce the



**Figure 14.** Façade of Torre de Especialidades [51].



speed of the wind, generating turbulences that better distribute the polluting particles over the surface of the cells. Since each piece of the puzzle has multiple reliefs, polluting particles can be captured from various directions [50]. The architects hope that the building can counteract the impact of air pollution and provide slightly fresher air into the hospital's immediate area. According to the developers, the façade will negate the effects of up to 1000 cars a day.

Expo 2015 Italian Pavilion was designed by an Italian architectural firm, Nemesi and Partners (**Figure 15**). The 13,000 m<sup>2</sup> building has six floors and presents Italy's past, present, and future through images, dynamic digital projections on mirrored walls, ceilings, and floors and accompanied by vibrant rhythms. The 9000 m<sup>2</sup> façade contains 900 biodynamic concrete panels. Around 80% of this air-purifying cement is made from recycled materials, such as scraps from Carrara marble. Italcementi tests have demonstrated that the photocatalytic cement can reduce NO<sub>x</sub> levels from 20 to 80%, depending on atmospheric conditions. According to researches, the reduction of NO<sub>x</sub> concentration calculated is around 45% in the area covered by the TX Active® blocks [49].

Nemesi and Partners wanted the building to act like a kind of urban jungle, not only esthetically but by also mimicking the role of trees in city landscapes—which naturally help purify the air. Inspired by nature, the final design resembles large stretched out tree branches which wrap themselves around the iconic building: "The overall concept of the architectural design of the Italian Pavilion is that of an urban forest in which the building, through its skin and its volumetric arrangement, takes on the features of an architectural landscape... The branching pattern of the external cladding of Palazzo Italia coherently interprets the theme of the tree of life, inserting it in the form of a petrified forest" [52].

#### 4.4. Cultivating algae

Algae are cellular organisms that have been the precursors to plants, and they can make photosynthesis more efficiently than many plant species. In this context, they can remove CO<sub>2</sub> from their environments and produce O<sub>2</sub>. Algae live in a hydrophilic environment and can be grown in photo-bioreactors on earth. The first application of photo-bioreactors in a building façade



**Figure 15.** Facade of the Italian Pavilion in Expo 2015, by TBT, 2015.



**Figure 16.** BIQ Apartment House: (left) exterior [53] and (right) closer view of panels [54].

is on BIQ apartment building (2013), designed by Splitterwerk and Graz and by engineering firm Arup in Hamburg, Germany. BIQ is a cubic, five-story building and is an abbreviation for “building with a Bio-Intelligent Quotient.” It was constructed as a part of the International Building Exhibition of 2013 (**Figure 16**). The algae façade serves as a buffer between the indoors and the outdoors and supplies both thermal heating and biomass for the building.

The 200 m<sup>2</sup> façade contains 129 photo-bioreactor panels with 2.5 × 0.7 m dimensions. They were assembled on a secondary structure in front of the house façade. Flat plate photo-bioreactor panels were used on the façade because of their high transformative efficiency to receive UV light. The algae are continuously supplied with liquid nutrients and CO<sub>2</sub> via a water circuit running through the façade. The light rays are absorbed by the façade and generate heat the same way a solar thermal unit does, which is then either used directly for hot water and heating or stored in the ground using boreholes [55].

When algae are ready to be harvested, they are transferred as a thick pulp to the technical room inside the building and fermented in a biogas plant. The performance of the algae façade elements was measured for 1 year. For this year, the biomass production at the façade was on average 15 g/day and was stored alongside the biogas production machine. It also produced 30 kWh/m<sup>2</sup> biomass and 150 kWh/m<sup>2</sup> heat energy. Thus the annual CO<sub>2</sub> emission of the building was reduced by 6 tons [55].

In addition, this façade has an important interactive surface for city and should be considered with its aesthetical quality like Jan Wurm (Arup) said: “As well as generating renewable energy and providing shade to keep the inside of the building cooler on sunny days, it also creates a visually interesting look that architects and building owners will like” [56].

Köktürk et al. have proposed a diamond-shaped flat plate photobioreactor façade system [57]. They have also designed a monitor and management system for their façade. The temperature is kept at 37–38°C, and the heat released from the system is used for hot water or for air conditioning with a heat exchanger. Accordingly, these buildings were not only inspired from nature but also embodied it as a component.

## 5. Conclusion

Despite all the advances in technology and environment-centered debates, the environmental footprint of the human race and buildings continues to increase. This is mainly because of increasing population and increase in comfort requirements. Nature creates sustainable environments and surrounds us with answers to most of the questions about sustainability since it has worked for millennia to perfect solutions. This thinking has permeated among some designers. They take inspiration and learn from nature on the road to become more sustainable and having less environmental impact. The most common approach is formal and functional biomimicry; in façades, some building elements and materials are even called biomimetic. The concept of biomimicry is in harmony with the concept of sustainability; however, there are many degrees of sustainability, and each and every biomimetic application is not always sustainable. The sustainability principles should be at the core of the design problem definition and its unique design constraints to reach a sustainable future.

This chapter has provided examples to biomimetic design approaches in the context of three main aspects in designing a sustainable façade; energy requirements, form, and structure; and sustainability considerations. Another way to make use of and learn from nature in design is biodesign, a way of bio-cooperation with natural elements. Biodesign is a relatively new term, yet the approach has been around for centuries as traditional elements such as green walls. While there are various conceptual studies, biodesign has very few built examples apart from its traditional interpretation. One of the limiting factors in utilizing biodesign is its big scope that requires a multidisciplinary approach with input from diverse disciplines that are not usually involved in the construction sector, such as biologists and bioengineers. Biodesign works go beyond biomimicry and bring an innovative way to look at and work with nature; therefore, their applications will probably become more widespread in façade designs of the future.

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