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# Energy and environmental performances in the buildings with sustainable and green architectures: A critical review

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**ABSTRACT**

Nature serves a valuable source of learning for humans, particularly inspiring architectural design. Architecture as an interdisciplinary field has been influenced by various natural science topics. Also, to respond to the growing environmental challenges, the use of nature's position in architecture and the building industry has received extensive attention. In this review paper, in the first stage, the concept of nature, the effect of nature forms on sustainability and its relationship with humans are examined and their reflection in nature-based architectures is expressed. In the second stage, the concept of designs and architectures inspired from nature and biology, design methods of these types of architecture and ways to achieve the goals of sustainable and green architectures have been thoroughly reviewed. In the third stage, we analyse the advantages and disadvantages of these designs and architectures, focusing on energy efficiency, well-being, thermal comfort, and characteristics of sustainable architecture. Finally, solutions are proposed to achieve energy reduction and increase thermal comfort in nature-based architectures.

## 1. Introduction

Today, human needs connection with nature and its complex geometric shapes [1-4]. The whole of nature, including inanimate and living organisms, moves in a sustainable ecosystem cycle over several billion years without harming the environment [5-7]. In the last 50 years, design and architecture have become a different stage and continue to evolve, trying to push their defined boundaries and interact with other disciplines [8-10]. While many topics have an undeniable impact on architecture, it is the science of biology that stimulates continuous research and innovation in many branches of architecture. In the current destruction of the environment and nature, it provided a good theoretical and practical framework for designers or architects, who were faced with the

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urgency of changing methods and re-prioritizing their goals [8, 11]. Over the past decade, there has been a growing interest in rediscovering nature in architectural design, and efforts to improve well-being and sustainability [12-17]. The methods studied in this review are nature-based and biologically inspired design methods.

Today, the demand for high amounts of energy in buildings cannot be avoided [18-22]. Excessive consumption of fossil fuels, especially in developing countries, poses complex challenges such as global warming, air pollution, and carbon distribution, which may limit human life due to obvious environmental consequences. Given these challenges, efforts are being made at various scales to reduce these destructive effects around the world. The use of renewable energy and passive design strategies as the main solution to reduce environmental burden have recently been considered by researchers [23-28]. Because people spend 90 percent of their time in buildings, space design creates challenges and opportunities for designers [29]. In the context of Covid-19, concerns about indoor environments and an immediate focus on creating spaces that promote emotional and physical health have increased [30-34]. One of the essential functions in the design of the built environment that has been considered by researchers is thermal comfort, which is defined as a sense of well-being of a person and mental conditions that explain satisfaction in a particular environment [35-40]. Achieving this environment is affected by air temperature and velocity, daylight, and relative humidity. Although there are numerous studies on thermal comfort in different climates to determine the comfort zone for residents, limited research has been done on strategies to achieve a comfortable indoor environment [18]. In the following text, the concept of nature, the effect of nature forms on sustainability and its relationship with humans is studied and its reflection in nature-based architectures is expressed. Also, the concept of designs and architectures inspired by nature and biology, design methods of these types of architectures and ways to achieve the goals of sustainable and green architectures is fully investigated. In general, in this review, we try to analyze the advantages and disadvantages of these designs and natural and biological architectures in terms of energy efficiency, well-being, thermal comfort and sustainable architectural features.

## 2. Background and Review

### *2.1 Nature*

Nature can be found biologically in living organisms such as humans, animals, and plants, as well as in topological features like mountains, seas, sand dunes, and hills [41-43]. Nature's form represents its physical aspect. An organism's physical shape enables it to behave in specific ways to achieve its life goals and self-sustaining process. This shape adapts to different functions and environments, allowing the living organism to behave appropriately based on living conditions and its surroundings. Despite the distinction of natural elements in variations environments, nature's form shares the common principles known as fractal geometry. As our comprehension of nature increases, architects strive to incorporate and reflect nature's deeper understanding into their designs [44-46].

Architects frequently find nature to be their most valuable source of inspiration. Throughout history, since the construction of shelter, housing, habitat, workplace or any kind of built environment, natural factors in this structure have always been an important and fundamental principle for them. Nature is the source of emotions, passion, and the scent of space and time [41, 47, 48]. Human is constantly imitating nature; He learned to make bricks from trees, was inspired by wildflowers to create the tops of the pillars and gave them sea waves to create plastering details and ornaments. The concept of nature and how to look at it throughout history has been one of the fundamental concepts in the interpretation of existence, science and art. Over the years, human has acquired new methods and tools and progressed in science, technology and production, at which time nature as the most important source of raw materials was exploited indiscriminately. As a result, with the lack of resources and pollution of ecosystems and the environment, the attention of various scientific communities turned to the issue of nature. Today, environmental preservation and achieving sustainable development is one of the fundamental issues of scientific societies around the world. In this regard, architectural design as a coordinator of man, environment and space in interaction with nature has adopted different approaches. Therefore, the study of architecture and nature seems necessary to obtain a proper definition of nature and the concept of sustainability architecture. Many architects believe that nature provides them with diverse solutions to construction challenges, enabling them to create buildings that behave in a self-sustaining process, thus embodying nature into architecture. Some architects show nature due to its aesthetics to create architecture focused on form (form-oriented). Other architects reveal nature according to its function to create innovative environmental, structural, functional and self-sustainable solutions [49-51].

### *2.1.1. The Evolution of The Relationship Between Architecture and Nature*

The relationship between nature and architecture has a long history that can be categorized in three periods: pre-modern, modern and post-modern. In the pre-modern period, more attention was paid to the origin of the universe, and therefore nature, meaning the origin, was expressed by architecture. During this period, many temples were built for gods and natural forces because human considered the movement of his world to be dependent on gods and supernatural forces. In this period, nature has two earthly and cosmic qualities, which are preceded by cosmic character and are considered as the most basic feature of ancient insights. The ancient Egyptians made the temples of the gods and the houses of that world stronger than the houses of this world. This type of architecture can be called architecture within nature, in other words, it is created inside nature. In the modern period, human views changed and caused the industrial revolution and the great advancement of science and technology. During this period, nature became known as the inexhaustible source of raw materials for the development of industry. Architecture in this period was reduced to the quantitative affairs of man and the physical standards of his life, and unlike pre-modern architecture, it was adapted only to human needs. However, it was not long before the environmental crisis swept through modern society. The architecture of this period can be called the dominant architecture of nature because the nature of all things was in the complete monopoly of human thought. In the postmodern period, the fusion of technology and nature appears to alleviate the crises of modern thought. In this period, nature, natural forces, ecosystem and the type of living relationship with the environment were considered and the architecture of the time was also influenced by this thinking. During this period, the concept of sustainability was born and developed in the scientific area in the world [52-56].

### *2.1.2. Interaction of Human, Nature and Architecture*

Nature and human addressed each other. Human civilization began with human's attempt to connect with and understand nature. Architecture has been created since the beginning of civilization because without it, civilization or culture could not have existed. The range of architecture developed from the most primitive form of cave dwelling to the most complex types of buildings. According to Ben Farmer, architecture is an art that cannot separate itself from the surrounding conditions [57]. The condition that must be considered is that each place has its own characteristics and requires a unique answer. Architecture has always been trying to be able to establish a close relationship with the concept of nature.

Nature cannot be attributed to a reductionist view that considers the object as independent and separate entities but must be considered in a holistic view that the object is composed of parts of a whole which has multiple interconnected, reciprocal and integrated functions. Nature is not an independent being but consists of parts of an integrated system that exist in an ecosystem [41], as shown in Figure 1.

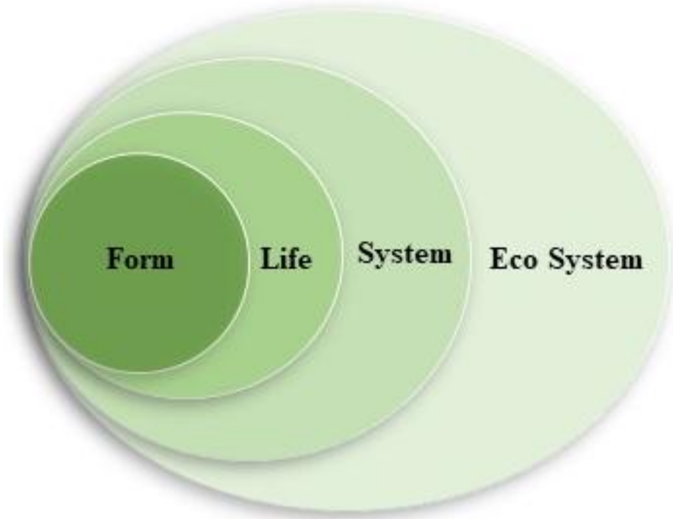


**Fig. 1.** The complexity of Nature as a system in an Eco-system

*2.2. Sustainable Architecture*

The three main cores for achieving an environmentally friendly architecture are: (1) efficient use of resources such as energy, water, land and other material resources, which includes the use, reuse, storage, recycling and collection of resources, (2) environmental protection, which includes the emission of low pollution and nature conservation, and (3) protect the health of residents and increase their productivity by increasing the internal environmental quality of the building, which includes the regulation and control of thermal comfort, lighting, acoustics, air quality and ventilation in the building [41, 58-60].

*2.3. Organic Architecture*
*2.3.1 Organic Architecture*

Organic architecture is a philosophy in architecture that promotes harmony between human habits and nature [61-63]. This is done in such a way that the design is so coordinated and related to its environment that the building, furniture and environment are part of a unified and related combination. In this architecture, it uses organic forms, forms of nature and living beings, which are related to natural processes. According to organic theory, all natural forms are dynamic. For instance, these forms can be the forces and pressures that are involved in the structure of an animal, such as the stretching of muscles and joints when the creature moves, and the growth and expansion pattern seen in the form of plants and oysters is an image of a living form. If an art wants to be expressive, it must be made organically; its components must be integrated in a dynamic and malleable system [64].

### *2.3.2. Pioneers of Organic Architecture*

The heyday of organic architecture can be seen in the first half of the twentieth century in the writings and designs of Frank Lloyd Wright [65]. In the early twentieth century, technology was expanding rapidly in Europe and America, and Wright did not oppose technology but did not accept it as a goal. According to his opinion, technology is a means to reach a higher architecture, which in his view is the same as organic architecture. Wright's theories in architecture, In the 1930s, Wright's principles of planning, taken from Wright's book on architecture and democracy [66], include lowering interior walls and creating an environment for airflow, light, and landscape to be reflected throughout. Also, his theories consist of harmonizing the building with the outside environment, free plan, showing the foundations as a short brick platform for the house to be placed on it, not using various materials, using new materials, giving logical proportions to all doors and windows, placing thermal installations inside the building (fire place in the centre of the building) and lighting installations and plumbing in the ossification of the building so that it is part of the building structure [67]. Sullivan believed in a way that was similar to the process of creation in nature [68]. He first coined the term of functional form which means that Sullivan saw the form functionality in the process of natural growth and movement. In the organic view, the artist had to create a composition that was parallel to nature and showed the process of life, growth and development [69, 70].

### *2.3.3. Principles of Organic Architecture*

Nature must be inside the building, components and materials as well. Organic architecture means homogeneity and integration of components in relation to the whole and the whole in relation to the components [71]. Also, the combination of form and function is essential in organic architecture. Moreover, respect for the natural environment is essential in which the form and the natural environment should be combined to create a complement. In the organic architecture, it is vital to use natural materials and use simple and straight lines [72-74].

### *2.3.4. Examples of Organic Architecture*

Several examples of organic architectures are summarized in Table 1. Here, several properties such as sustainability, energy performance, thermal comfort, and carbon footprints in these building are provided.

**Table 1**
Several examples of organic architectures.

| Photo | Project | Features | Description |
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|---|---|---|---|
|  | Fallingwater is a home created by architect Frank Lloyd Wright in 1939, located in the Laurel Highlands of southwest Pennsylvania. | **Sustainability:** | 1. Minimal interference in the natural environment ensures the preservation of ecological balance and biodiversity.<br>2. Combining the volume of the building with the natural environment so that each is complementary to the other.<br>3. Installing windows all over and removing the corners of the room.<br>4. Using natural environment materials such as rocks and plants, both inside and outside the building. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | While specific details about carbon footprint features are not provided, using natural environment materials such as rocks and plants, both inside and outside the building. minimizes the carbon footprint by reducing the need for extensive construction materials. |
| | | **Thermal comfort:** | NA |
| <br> | Taliesin West winter home and studio created by architect Frank Lloyd Wright's. Taliesin West Completed between 1937 – 1959, located in the desert Boulevard in Scottsdale, Arizona. | **Sustainability:** | 1. Unique architecture fully compatible with Arizona desert<br>2. The surface is patterned with abstract designs inspired by the natural realism found in the pattern of rattlesnakes, Gila monsters, chameleons, and the shapes of saguaro, cholla, and staghorn cacti.<br>3. The building consists of a series of interconnected spaces, linked by terraces, gardens, and pools.<br>4. Careful consideration is given to the arid desert climate.<br>5. The construction of the foundation and house used materials sourced locally, such as desert stone and redwood timber.<br>6. The house is designed to create a close, natural integration with the surrounding landscape. |
| | | **Energy efficiency:** | While specific details about energy efficient features are not provided, using low, horizontal planes to keep the house and studio close to the ground, may ensuring effective natural ventilation and providing shade and protection from the intense desert sun. |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
| | The Solomon R. Guggenheim Museum is an art museum designed by Frank Lloyd Wright. located in | **Sustainability:** | 1. Inspiration from nature.<br>2. Express the natural flexibility of organic forms in architectural design.<br>3. Geometric shapes convey specific human concepts, emotions, and feelings. For example, the circle represents infinity, the triangle signifies structural unity, the spiral |

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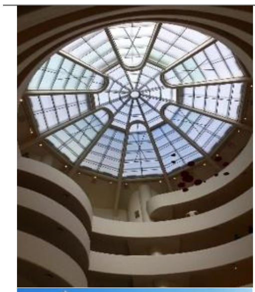
|   | Manhattan, New York City. | | symbolizes organic progress, and the square represents integrity. |
| | | **Energy efficiency:** | 1. Natural light was a significant factor in the design process.<br>2. The translucent canvas was utilized as a roof.<br>3. The roof was intentionally extended beyond the walls to block direct sunlight while permitting horizontal light to enter the room. |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|  | The Winslow House created by architect Frank Lloyd Wright- as a designed house. located in River Forest, Illinois. | **Sustainability:** | 1. The house is defined by a strong emphasis on simplicity and expertise in shaping and utilizing materials.<br>2. Nestled under a softly slanting roof and broad overhangs, the house presents itself as a symmetrical, solid structure, segmented into layers of cast stone, golden Roman brick, and a terracotta frieze adorned with sinuous Sullivan Esque patterns. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|   | The Ward W. Willits House is a building designed by architect Frank Lloyd Wright. Designed in 1901, located in the Chicago. | **Sustainability:** | 1. Integration architecture with the natural environment.<br>2. Its cross-shaped plan is formed around a fireplace that is in the heart of the building.<br>3. Building's two asymmetrical wings penetrate the park around the building like two open arms.<br>4. The use of natural materials. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|   | The Darwin D. Martin House Complex was designed by Frank Lloyd Wright and built between 1903 and 1905. | **Sustainability:** | 1. The House is a historic seaside cottage tucked beneath flourishing cypress trees, offering stunning vistas of the Pacific shoreline.<br>2. Prairie-style features include low-angled hip roofs with broad eaves, a prominent raised central section, rows of casement windows, and horizontal siding.<br>3. Single-story porches stretch out from either end of the house, running parallel to the lake, like the wings.<br>4. House covered in horizontal tongue-and-groove wood siding, a favorite of Wright for |

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|  | | | small cottages, the house was initially roofed with wooden shingles. |
| | | **Energy efficiency:** | While specific details about energy efficiency features are not provided, a spacious living room is warmed by a substantial Roman brick fireplace. (Initially, the house relied solely on its fireplaces for heating.) |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|   | The Robbie House is designed by Frank Lloyd Wright in the international style, built in 1910. Located in Illinois [75] | **Sustainability:** | 1. Robbie House best and last organic house. 2. The building has no ordinary facade, walls, ordinary external windows or entrance doors. 3. Using short walls and green space in the first floor. 4. Exterior walls covered with long and narrow red Roman bricks at the highest height have a kind of limestone covering. 5. The house, like a stronghold, protects the inhabitants from the noise of the street and shelters the entrance to its right. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|   | High Desert house was design by Kendrick Bangs Kellogg; the structure was completed in 1993. Located in Joshua National Park (Southern California), as an organic architecture. | **Sustainability:** | 1. The High Desert House consists of 26 standalone concrete columns resembling rib bones. 2. The columns fan out at the top, with one overlapping the next to create a layered, canopy-like roof. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|   | **Lotus House**, organic modern architect, was built by **Kendrick Bangs Kellogg** in 1978. Located on the rim of Pottery Canyon in La Jolla. | **Sustainability:** | 1. The house is built from Douglas fir beams that were steamed into curved shapes, creating an interior resembling a ribcage. 2. Floor-to-ceiling glass windows offer expansive views of the Pacific Ocean. 3. The living room is dominated by a massive, poured concrete hearth. 4. A sinuous design of undulating wood roof trusses, sculptural poured-form concrete and geometric tile. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |

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| <br> | The Onion House, designed by American architect Kendrick Bangs Kellogg and built in 1962-63. Located in Holualoa, Hawaii. | **Sustainability:** | 1. Exemplifying Organic Architecture, the arched roof panels resemble a shell or onion, while the lava rock walls evoke ancient Hawaiian temples, or heiau, found along the Kona coast.<br>2. The translucent roof panels, similar to onion skin, allow sunlight to filter into the house during the day and glow at night.<br>3. A 70-foot pool encircles the two main structures.<br>4. Lava rock walls form a high terrace overlooking the sea, where two arching domes are surrounded by the pool, terrace, and gardens.<br>5. Light filters through colorful stained-glass walls and translucent roof panels.<br>6. This site-specific architecture is well-suited to Kona's gentle climate, with trade winds buffered by Mount Hualalai and temperatures ranging between the 70s and 80s. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
| <br> | A holiday shell villa was designed by Kotaro Ide in 2008. The Villas is an ideal example of organic architecture. Located in Japan. | **Sustainability:** | 1. Well-coordinated with its surroundings and reflects nature in itself.<br>2. The Villa is in the heart of the forest stands as a sizable structure resembling a shell shape.<br>3. The shell-shaped construction features three-dimensional curved surfaces. The C-shaped section encircles a fir tree at the site's center, with a row of pine trees providing the primary view. The building's layout resembles the shape of the letter C. |
| | | **Energy efficiency:** | 1. A custom-designed floor heating system is installed to reduce the need for heat energy and avoid the emptying of draining excess water in cold climates.<br>2. The system seamlessly integrates into the architectural design.<br>3. All air and exhaust vents are positioned beneath the window frames, allowing air to flow outside through the terrace louvers.<br>4. Fixed windows are utilized to optimize natural ventilation, with air conditioning not installed in common areas.<br>5. Synthetic resin with vermiculite material is used for interior finishing to effectively prevent fires, absorb sound, and provide insulation against heat and moisture.<br>6. The heating and cooling systems demonstrate remarkable efficiency. |
| | | **Carbon footprint:** | NA |

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| | | **Thermal comfort:** | NA |
|  | Pearl Palace, a beautiful example of organic architecture, designed by William Wesley Peters in 1965. Located in Iran. | **Sustainability:** | 1. The main design of the building with a semi-transparent dome with an opening of 120 meters to each garden, beautiful fountains and a unique pool shone among the pleasant climates.<br>2. The circular shapes of this building are reminiscent of pearls, and in all the palaces of this circular shape, from the design of the dome, furniture, bathtub, chandelier to the design of small items have been used. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
| <br> | Seyhoun summer cottage was design by Houshang Seyhoun in 1974. Located in the village of Kaligon in the mountains north of Tehran, Iran. | **Sustainability:** | 1. The organic treatment and peaceful coexistence of this villa with the surrounding nature caused it to be included in the list of organic architectural works of Iran.<br>2. Even parts of the interior walls of this building are really mountain walls.<br>3. A small house with the most beautiful combination of architecture and nature, which is built in the heart of the mountain with the least changes. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |
|  | The Dafineh building was designed by the Frank Lloyd Wright in the 1950s. Located in Iran School of Architecture. | **Sustainability:** | In the construction of the building, metalworking along with fine concreting has been used with utmost precision and elegance. |
| | | **Energy efficiency:** | The windows around the building have an oval shape and natural light is provided in the interior. |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort:** | NA |

## *2.4. Eco-Tech Architecture*

Eco-tech is an architectural style [76-78], the buildings seamlessly blending into their natural surroundings, and function as integral components of the ecosystem and be included in the life cycle. The word Eco-tech is a combination of the words ecology and technology [79]. Ecology is a branch of biology that studies how organisms interact with their environment and other living things. Technology also means the techniques, processes, skills, and methods used to produce goods, services, or achieve goals such as scientific research. How to use technology in harmony with the natural environment is not the same in different types of buildings, in some important buildings and architectural indicators, the latest technical innovations are sometimes used. Also, some architects use natural materials to implement architecture and, in some cases, indigenous methods. Today, in Eco-tech architecture, using technology, it tries to make maximum employee of natural elements including sun, wind, ground water and plants to regulate the environmental conditions of the building [80]. Therefore, in this architectural approach, technology is positioned alongside and in harmony with nature rather than dominating it. This alignment allows for optimal utilization the most of environmental resources and provide user comfort [79]. Eco-tech architects refer to the building as the second shell. The first shell refers to the skin of the human body. In the works of Norman Foster and Renzo Piano, the second skin is as intelligently designed as the first skin. As human skin reacts to cold, heat, moisture, and airflow, using double-glazed windows, shutters, and removable thermal insulation such as sunlight, shade, airflow, and heat resistance during the day and night, and it is controlled by a computer system during the both warm and cool seasons throughout the year [79, 81-83].

### *2.4.1. Eco-tech Architecture and Its Relationship with Nature and Sustainability*

The use of natural forms in architectural design should be such that functional and aesthetic needs are combined [84]. The structure must obey the laws of nature and meet its requirements and respect nature. Eco-tech architecture is based on several basic points such as (1) quality orientation, (2) attention to the future, and (3) attention to the environment. Therefore, Eco-tech architecture does not adhere to a specific formal style; instead, it is inspired by transient conditions and immediate emotions while embodying profound concepts that intertwine human, nature, and architecture. Undoubtedly, the desired quality in this architecture is not provided without considering the nature, proper lighting of the spaces and air conditioning [82]. Since the sustainability of the building itself is considered as a phenomenon, so high quality construction and the use of materials with high sustainability should also be considered [53]. Achieving such a situation is done by using efficient management and applying the latest technologies. The important point that is considered in this type of architecture is that all the involved factors are related to each other and are considered as a single system [53]. Also, Eco-tech architecture aims to emphasize environmental considerations, focusing on reducing energy loss and dissipation, improving parameters that affect human health, utilizing materials that can be returned to the natural cycle, and minimizing the use of toxic substances [79].

### *2.4.2. Examples of Eco-Tech Architecture*

Several examples of Eco-tech architectures are summarized in Table 2. Here, several properties such as sustainability, energy performance, thermal comfort, and carbon footprints in these building are provided.

**Table 2**
Several examples of Eco-tech architectures.

| Photo | Project | Features | Description |
|---|---|---|---|
| | The Bahrain World Trade Center (BWTC) designed by Atkins, in 2008. Located in | **Sustainability:** | Incorporation of wind turbines in this project aligns with sustainability goals by harnessing renewable energy sources.<br>1. It's the world's pioneering skyscraper to incorporate wind turbines into its structure.<br>2. Connecting the two towers by three skybridges, each equipped with a 225-kW wind turbine, amounting to a combined wind power capacity of 675 kW. |

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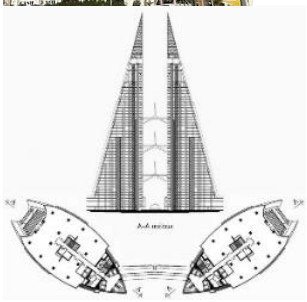
| <br> | Manama, Bahrain. | | 3. The sail-shaped structures flanking the towers are strategically shaped to channel wind through the gap, optimizing wind speed passing through the turbines.<br>4. The project has garnered numerous sustainability awards. |
| | | **Energy efficiency:** | By integrating wind turbines into the design, the project aims to increase energy efficiency and reduce reliance on conventional power sources.<br>The wind turbines are anticipated to supply 11% to 15% of the towers' total energy consumption, equating to roughly 1.1 to 1.3 gigawatt-hours per year. |
| | | **Carbon footprint:** | Utilizing wind power to generate electricity helps minimize the project's carbon footprint by reducing reliance on fossil fuels. |
| | | **Thermal comfort:** | While specific details about thermal comfort features are not provided, the sail-shaped structures are designed to channel wind through the gap, may enhancing thermal comfort within the building by promoting natural ventilation. |
|  | The Shanghai Tower was designed by Marshall Strabala and Jun Xia in 2015. Located in China. | **Sustainability:** | Harvesting rainwater for internal use, recycling wastewater, and utilizing geothermal energy sources contribute to the building's overall sustainability by reducing resource consumption and environmental impact.<br>1. The building's secondary transparent glass layer plays a pivotal role in its eco-friendly design.<br>2. Engineers devised systems to harvest rainwater for internal use and recycle a portion of the building's wastewater, reflecting its prioritization of sustainability.<br>3. Near the tower's apex, 270 vertical wind turbines were installed, projected to supply 10% of the building's electricity needs.<br>4. The tower has garnered sustainability awards and earned certification from the China Green Building Committee.<br>5. The building's heating and cooling systems are powered by geothermal energy sources. |
| | | **Energy efficiency:** | 1. The building's energy efficiency is bolstered by its innovative design features, including a second skin wrapping around the entire structure. This skin functions to moderate temperatures between inner and outer layers, optimizing energy conservation by trapping warmth in cooler months and dissipating heat during summer.<br>2. The installation of vertical wind turbines and the utilization of geothermal energy sources enhance the building's energy efficiency by harnessing renewable energy and reducing reliance on |

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| | | | conventional power sources and reducing dependence on traditional power grids. |
| | | **Carbon footprint:** | By incorporating renewable energy sources like wind and geothermal energy, the building reduces its reliance on fossil fuels, thereby minimizing its carbon footprint and environmental impact. |
| | | **Thermal comfort:** | While specific details about thermal comfort features are not provided, the building's thermal comfort is enhanced by design features such as a transparent glass skin and natural ventilation systems, which optimize daylight penetration and promote airflow.<br>Also, the double-layered insulating glass façade may reduce the need for indoor air conditioning by utilizing advanced reinforced glass with high temperature tolerance. |
|  | The Pixel Building was designed by Studio 505, and Grocon in 2010. Located in Melbourne, Australia. | **Sustainability:** | 1. According to Grocon "We believe that Pixel truly is the office of the future, and one of the most sustainable buildings in the world."<br>2. The building produces its own power and water with onsite wind turbines and a green roof that utilizes evapotranspiration of greywater and reducing reliance on traditional utilities.<br>3. The Pixel Building attained the highest rating ever awarded by the Green Building Council of Australia. |
| | | **Energy efficiency:** | 1. The rooftop hosts a garden alongside multiple solar panels and three wind turbines, harnessing renewable energy to power the building.<br>2. Smart windows automatically open during the night to release stored heat from the building while allowing fresh air to enter to optimize energy usage.<br>3. Building's toilet system reduces water consumption, enhancing overall energy efficiency.<br>4. The exterior of the building consists of randomly colored shards arranged in a pixelated pattern, strategically designed to optimize daylight penetration into the offices while minimizing glare and heat. Another notable feature is the building's rainwater harvesting system, enabling it to operate independently from the main water supply. |
| | | **Carbon footprint:** | 1. The Pixel is an office building that achieves complete carbon neutrality, mitigating its environmental impact.<br>2. Its construction involved the use of a specialized concrete blend that minimizes carbon emissions, reducing the building's carbon footprint. |

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| | | **Thermal comfort:** | 1. The building is equipped with a 100% fresh air-cooling system that operates using a gas-fired ammonia absorption chiller, ensuring comfortable indoor temperatures.<br>2. Smart windows automatically regulate temperature and airflow to optimize energy usage and enhance thermal comfort within the building. |
| <br> | The Learning Hub building was designed by Thomas Heatherwick in 2015. Located at Nanyang Technology University in Singapore. | **Sustainability:** | 1. It received the BCA Green Mark Platinum Award for sustainability from the Singaporean government.<br>2. It resembles a cluster of elongated bee hives.<br>3. The rooms are designed without corners to eliminate the typical classroom hierarchy, where the tutor is at the front and students face them.<br>4. The building is designed to be porous, with no single main entrance, it could facilitate natural airflow.<br>5. Plants and trees are incorporated on the roof and some circulation levels. Incorporating vegetation contributes to sustainability by improving air quality and supporting biodiversity. |
| | | **Energy efficiency:** | While specific details about energy efficiency features are not provided, the unique design and orientation of the building can enhance natural ventilation and lighting, reducing the need for artificial climate control and lighting systems. |
| | | **Carbon footprint:** | While specific details about carbon footprint features are not provided, the building is designed to be porous, with no single main entrance, it could facilitate natural airflow. |
| | | **Thermal comfort:** | While specific details about thermal comfort features are not provided, the open, corner-less design can promote better airflow and distribution of natural light, enhancing thermal comfort for occupants. |
| <br> | School of Art, Design and Media was desiged by CPG Consultants Pte Ltd in 2006. Located in Nanyang Technological University (NTU) in Singapore. | **Sustainability:** | 1. One of the key features of this building is its curved green roof.<br>2. The building is mainly composed of three interconnected blocks surrounding a sunken plaza, which is enveloped by a cascading pool and lush landscaping.<br>3. This architecture integrates seamlessly with the natural surrounding landscape.<br>4. The building includes energy and water-efficient features such as high-efficiency lighting equipped with motion and photo-cell sensors, retrofitted by an air-conditioning system, and a rainwater collection system with rain sensors and an irrigation system. The building reduces reliance on municipal water sources, promoting sustainable water management. |
| | | **Energy efficiency:** | Installing energy-efficient lighting with motion and photo-cell sensors minimizes unnecessary energy |

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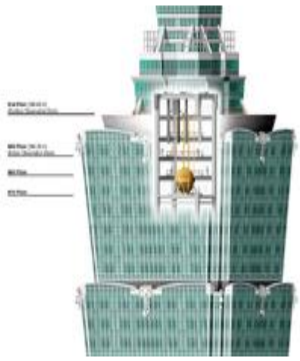
| | | | consumption by ensuring lights are only used when needed. |
| | | **Carbon footprint:** | While specific details about carbon footprint features are not provided, upgrading the air-conditioning system to be more energy-efficient reduces the building's carbon footprint by lowering energy consumption for cooling. |
| | | **Thermal comfort:** | While specific details about thermal comfort features are not provided, the use of motion and photo-cell sensors in lighting enhances thermal comfort by providing appropriate lighting levels based on occupancy and natural light availability. |
|   | Taipei 101, Taipei World Financial Center, was designed by C.Y. Lee & Partners in 2004. Located in Taipei, Taiwan. | **Sustainability:** | 1. Taipei 101 is renowned for its exceptional stability.<br>2. It achieved a Platinum rating in the LEED certification system, making it the tallest and largest green building globally. The Platinum rating reflects the building's commitment to sustainable design and operations.<br>3. The facade features green-tinted glass to resemble slender bamboo, eight pagoda-like tiers with eight floors each, and symbolic elements like the Ruyi and money box.<br>4. Its design includes unique tuned mass dampers to withstand earthquakes in the Pacific Ring of Fire and tropical storms in the region.<br>5. The double-paned and glazed blue-green glass curtain walls provide 50% heat and UV protection.<br>6. The building's recycled water system on the roof and facade fulfills 20 to 30% of its water needs. Utilizing recycled water reduces strain on freshwater resources, promoting sustainable water management. |
| | | **Energy efficiency:** | While specific details about energy efficiency features are not provided, the use of double-paned and glazed glass improves insulation, reducing the need for heating and cooling energy, thus enhancing energy efficiency. |
| | | **Carbon footprint:** | While specific details about carbon footprint features are not provided, its design incorporates tuned mass dampers to withstand earthquakes and tropical storms, reducing the need for frequent repairs and material replacements, thus lowering its carbon footprint, dampers enhance building resilience, reducing the environmental impact associated with maintenance and repairs. |
| | | **Thermal comfort:** | While specific details about thermal comfort features are not provided, the building's glass curtain walls may help regulate indoor temperatures. |
| | One Central Park was | **Sustainability:** | 1. This building received a 5-star Green Star award from the Green Building Council of Australia. |

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| <br> | designed by Foster and Partners, Ateliers Jean Nouvel and PTW Architects in 2013. Located in the Sydney, Australia. | | 2. Apartments were given an organic ambience by blending outdoor foliage and gardens with wooden interiors.<br>3. It has become the world's tallest vertical garden, A living tapestry of plants, flowers and vines stretching over 50 metres high.<br>4. The building's facade doubles as a living wall, featuring planter boxes with their irrigation system.<br>5. The façade of building acts as a living wall by incorporating planter boxes that required its own irrigation system.<br>6. Over 35,000 green wall plants, including 350 different species, were utilized for the green walls alone. Incorporating a vast array of plant species enhances biodiversity and promotes ecosystem health, contributing to sustainable practices.<br>7. It houses the world's largest membrane bioreactor within its recycled water network.<br>8. This building utilizes a low carbon generation power plant and an internal water recycling facility. |
| | | **Energy efficiency:** | Daylight is automatically redirected from mirrors, reflecting light to areas like the pedestrian corridor, pool terrace, and communal spaces. Utilizing natural daylight reduces the need for artificial lighting, thereby conserving energy and enhancing energy efficiency.<br>Implementing a low carbon generation power plant reduces reliance on fossil fuels, thus lowering carbon emissions and promoting energy efficiency. |
| | | **Carbon footprint:** | By utilizing a low carbon generation power plant, the building minimizes its carbon footprint associated with energy consumption. |
| | | **Thermal comfort:** | While specific details about thermal comfort features are not provided, incorporating natural elements like foliage and gardens into interior spaces may enhances thermal comfort by providing a connection to nature and regulating indoor temperatures. |
|  | The Reichstag building was reconstructed by Norman Foster in 1999. Located in Berlin, Germany. | **Sustainability:** | 1. The cupola, accessible to the public, serves as a functional part of the building's sustainability plan by encouraging engagement with the building's design and function.<br>2. It used Photovoltaic solar cells with an area of 300 square meters on the roof of the building to provide electricity. Incorporating solar panels reduces reliance on non-renewable energy sources, contributing to sustainable energy practices.<br>3. Its uses of biogas renewable fuel to produce electricity without pollution, which prevents the emission of 94% of carbon dioxide emissions. Utilizing biogas as a renewable fuel source |

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| <br> | | reduces carbon emissions and promotes environmental sustainability.<br>4. Mirrored panels arranged in an inverted cone within the dome reflect daylight downward into the debating chamber. |
| | **Energy efficiency:** | 1. Skylights located at the cupola's base offer a direct view into the debating chamber, allowing visual connection with government activities. Incorporating skylights reduces the need for artificial lighting during the day, enhancing energy efficiency.<br>2. It uses smart windows for air conditioning. Smart windows optimize natural ventilation and reduce the need for mechanical cooling systems, improving energy efficiency.<br>3. It stores excess heat in different parts of the building in a natural tank that provides hot water for heating. Storing excess heat for hot water heating maintains comfortable indoor temperatures while minimizing energy consumption.<br>4. It stores cold water in the underground layers to provide cooling in summer. |
| | **Carbon footprint:** | 1. The use of solar cells reduces reliance on fossil fuels, thereby lowering carbon emissions and minimizing the building's carbon footprint.<br>2. Utilizing biogas as a renewable fuel source reduces carbon dioxide emissions, mitigating the building's carbon footprint. |
| | **Thermal comfort:** | 1. In summer, the natural ventilation is done through a glass dome, and in winter, the warm air that ascended from the hall to the space under the dome is recovered and reused.<br>2. An inverted cone of mirrored panels in the centre of the dome supports ventilation in the building, exhausting hot air through the top of the cupola. It uses natural lighting by incorporating different mirrors through using the sun light.<br>3. Employing natural ventilation and heat recovery systems ensures thermal comfort by regulating indoor temperatures effectively throughout the year. |

### *2.5. Bionic Architecture*
#### *2.5.1. Concept and History of Bionic Science*

Bionics is the science that studies the system of nature and is inspired by the various behaviors and relationships within it [85-88]. Given that nature today is the product of centuries of evolution, so it has provided the conditions for us to emulate this evolved process. Engineers can meet the basic needs of today and the future by imitating and combining nature with technical methods. The result of this combination is bionics, which is a combination of the words biology and technique [89, 90].

From the beginning, man has gone to nature to perform his activities and has achieved his goal by imitating it. So, the true history of this knowledge goes back to the beginning of human creation. “The root of all forms is found in nature” [90], this simple sentence expresses the opinion of Paolo Portoghesi, the famous modern theorist and architect, about bionics. The science became famous when about 700 biologists, physicists, engineers, mathematicians and psychologists attended an Air Force conference held in late summer 1960 in Dayton, Ohio. It was at this congress that Jack. Oh you. Steele, an officer in the US Air Force Aviation Regiment, first used the word bionic [91]. By presenting articles, he provided a very clear definition of bionics that can be fully aligned with the three basic principles of nature, namely, "pattern ability, regularity, and evolution" [92]. According to him, bionics is the science of systems that are based on living things, have the laws and characteristics of living systems and are similar to living things [93, 94].

### *2.5.2. Bionic Architecture*

Bionic architecture has been introduced as one of the leading sciences in today's world [95]. Bionic architecture is a science that deals with the technical inspiration of buildings from the various behaviors and connections of the living world and solves technical problems through biological means. Revitalizing the building is one of the tendencies of bionic architecture [96]. In a general view, the goals of bionic architecture [97] include (1) providing mobility, (2) complexity, (3)energy and metabolism, (4) perception and communication, and (5) control. The difference between organic architecture and bionic architecture is that in organic style, the form and color of elements in nature are used more, but in bionic architecture, the system and function of natural elements are used more [98]. For example, a spider web design is used to build a strong structure [86]. In bionic architecture, a natural place formed on land or rock is used [99, 100]. One of these natural places are caves. Cave architecture, which is usually an aspect of tomb architecture, has existed since ancient times, and the most prominent examples of this style of architecture are the catacombs of Rome and Naples and tombs in Lebanon. Stone churches in Armenia, huge residential caves in Gourmet, Turkey, and Matra in southern Italy are other examples of this style of architecture. Mud architecture can also be considered as one of the branches of bionic architecture. Ancient and historical cities such as Sanaa in Yemen (Figure 2(a)) or the mud buildings in Dali in Mali (Figure 2(b)) are examples of this style of architecture. Bionic architecture, from the hottest region in the world to the coldest region, has tried to be inspired by nature [101]. Inspiration can be clearly seen in the Amazon huts made of leaves and wood, the buildings of various African ethnic groups, and the huts of the Alaskan and Greenland native Eskimos [102].


**Fig. 2.** Some examples of bionic architectures, (a) left image: Aerial view of traditional gardens in the old city of Sana'a [103], Close-up of a traditional garden within a residential quarter [103], right image: Traditional architecture of houses in Zebid village, Yemen, on the Red Sea coast [103, 104], and (b) left image: Djenné, a historically and commercially significant city in central Mali, situated on the Niger Inland Delta at the crossroads of major West African trade routes [105], middle image: Djenné's Townscape, right image: The Great Mosque of Djenne, which sits in the middle of this Malian town, the mosque is a world-renowned architectural icon [105].

### *2.6. Biomorphic Architecture*

#### *2.6.1. Biomorphic Concept*

The term "biomorphic" comes from combining the words "bio" and "morphic", which means "life" and "form". In fact, morph means the study of the appearance and form of organs and structural features of living organisms, which includes various aspects of external appearance as well as the form and structure of internal organs [106, 107]. Consequently, biomorphic design is inspired by and modelled on the form and structure of living things to form objects that represent a living thing [108]. In fact, trying to give a unique feature to an inanimate object, using the forms and structures of the natural systems, is one of the main features of this design [109, 110].

#### *2.6.2 Principles of Biomorphic Design*

Biomorphic design has three principles, (1) form, (2) materials and structures, and (3) principles of sustainability. Biomorphic architecture has specific shapes, structures, and visual systems that resemble natural systems, and biomorphic design uses local materials and sustainability to minimize sustainability problems in global architecture [111, 112].

##### *2.6.2.1. Form*

An important principle in biomorphic design is form [113]. Form creates a sense of closeness to nature in the users and in addition to the association of living beings, it also meets the needs of the users by coordinating between beauty and function [114]. Also, biomorphic design reflects the form, structure, and color of elements and proportions in nature and visually represents a form of life [111]. Typically, biomorphic design begins with inspiration from the living systems and design of a product.

Also, the inspiration of a form from nature leads to the creation of pleasure in the user, revealing creative abilities in natural forms, arousing the user's excitement, deep emotional reactions. From another point of view, these forms are full of symbolic elements and signs of identity which opens another window in the connection between the user and biomorphic products [115].

*2.6.2.2. Materials and Structures*

The architectural form and style are closely linked to the building's structure and materials. In biomorphic design, the choice of materials and structures is connected to the fundamental concept of natural life. This approach allows for the implementation of innovative structures and materials to create biomorphic architecture. Both the interior and exterior of the building can feature organic-shaped structures, which mimic the structures that exist in nature. Additionally, biomorphic architecture tends to use native materials and lightweight elements like membranes and other materials to support curved forms [111].

*2.6.2.3. Sustainability*

Biomorphic architecture is an architecture that considers ecological nature as well as green architecture [116, 117]. Biomorphic architecture can bring the benefits of energy efficiency, which is the concept of environmental responsibility [118]. Biomorphic architecture needs to prioritize ecological considerations to achieve environmentally friendly and highly sustainable designs [106].

*2.6.3. Biomorphic Design Features*

Important features of biomorphic design [119, 120] are as follows:

i. Simulation of the appearance of living structures from the point of view of form
ii. Development of form and harmony
iii. Focus on dynamics and movement in formatting
iv. Summarizing and sterilizing natural forms, in order to achieve pure and expressive forms
v. Intuitive perception of the mental feature of nature based on the needs, geometry and structure of the system.
vi. Achieve specific concepts of nature
vii. Strong communication with the user and response to all his senses
viii. Coordination between beauty and performance, in order to meet the needs of the audience

*2.6.3.1. Material Connection with Nature*

The relationship between material and nature in biomorphic architecture is characterized by different physiological responses to different types of natural materials and their color spectrum [121]. For example, green color indicates behavioral cognition characteristics. Also, biomorphic architecture uses natural materials or their derivatives, which leads to cognitive function, reduced energy consumption and carbon footprints [75, 122]. For example, the use of plant fibers such as long bamboo fibers in cementitious materials leads to greater strength, reduced production costs and greater compatibility with nature. The Figure 3 shows the grandchildren of the use of natural materials in biomorphic architecture [123, 124].

**Fig. 3.** At the top, the sustainable House in Romania utilizes natural materials for its facades [125]. Below, the residence in Vahrn, Italy by Architect Norbert Dalsass incorporates natural materials to blend harmoniously with the surrounding environment [75].

### *2.6.3.2. Complexity and Order*

Biomorphic forms have an order and complexity that represent living and non-living elements in nature. These forms are visually and perceptually pleasing and allow users to connect with nature, feel comfortable, think and be attractive. Also, this connection with nature reduces stress and increases concentration [126]. A space that presents information in a complex manner is deemed appealing to the human mind. This feature acts as a regulator between feeling tired and bored. Rubinowicz (2000) [127], discusses on fundamental role of chaos and geometric order in architecture and design, discussed how these elements are fundamental in urban structures and architecture. They naturally coexist and depend on each other. Geometric order is created through careful design and organized planning, while chaos is created when processes are self-organized. The Royal Ontario Museum of Libeskind in Canada and the Museum of Military History in Germany (Figure 4) are good examples of complexity and order forms [75, 122].

**Fig. 4.** At the top: The Royal Ontario Museum of Libeskind in Canada (Reference: left: [128], right: [129]). Down: Museum of Military History in Germany (Reference: left: [130], right: [129]).

### *2.6.3.3. Prospect*

Perspective is defined as a feature that provides an unrestricted, and open view of an area or large space. The idea of this feature is to provide residents with a sense of freedom, security and control over their immediate environment [121]. Hildebrand (1991), suggests that in building interiors or densely populated urban areas, perspective involves the ability to see one space through another [65]. One outstanding landscape example is the Kans Seeker Institute in California (Figure 5). The central courtyard creates the landscape by providing open, unlimited spaces, while enhancing residents' sense of security [131, 132].

**Fig. 5.** At the top: Salk Institute for Biological Studies by Architect Louis Isadore Kahn in Sandiego [133]. Down: California employs open space for the purpose of prospect [134].

### *2.6.3.4. Refuge*

According to Browning, et, (2014), state that "Refuge is a place for withdrawal, from environmental conditions or the main flow of activity, in which the individual is protected from behind and overhead". A space that provides the characteristic of a good refuge should increase the sense of security [121, 135]. Dosen and Ostwald (2013), explained that the landscape and refuge feature allows you to see all of your surroundings while being hidden and safe [136].

Villa Kogelhof (Figure 6) is an example of a landscape and refuge because the building is in a desert landscape with open and unobstructed views. This villa is built in two parts. One of those sections is underground, which guarantees asylum in an isolated environment. The other part lifts itself from the ground using minimalist supports and guarantees the view. The benefits of landscape and refuge patterns include reducing stress, boredom, fatigue and vulnerability [75, 122]

**Fig. 6.** Villa Kogelhof, Netherlands by Paul de Ruiter Architects exhibits the features of both prospect and refuge [137, 138].

### *2.6.3.5. Mystery, Temptation and Curiosity*

The mystery feature evokes the audience's sense by hiding visible information and placing hidden spaces and makes the person more inclined to explore in the environment [139-141]. Psychologists R. Kaplan and S. Kaplan [141] suggest that people primarily seek "understanding" and "exploring" in their environment, forming the basis of this pattern. The pattern of mystery can effectively enhance indoor and outdoor spaces such as corridors, entrances, squares and buffer spaces. Using long canopies and indirect entrances are two different methods to amplify the mysterious features of a building. The sensation of temptation conveys a more positive and enjoyable sense of exploration compared to mystery. Feeling tempted increases pleasure, curiosity and interest in learning more. The sense of mystery encourages further exploration into space for exploration, aiding in stress reduction and cognitive retrieval [142]. Techniques such as shading winding paths and translucent materials were used in traditional architecture to create a sense of temptation and curiosity (Figure 7) [75, 122, 143].

**Fig. 7**. (Left to right) Examples of enticement and mystery in hallway, inner courtyard and small cell. Bimaristan Al-Argoun, Aleppo, Syria [143-145].

### *2.6.3.6. Danger and fear*

Feelings of fear or danger are evoked when looking at a view that does not have a retaining wall or guide railing [146]. The feeling of danger can be the result of a reactionary situation that is created through the mechanism of relief and defense. Risk is a bold experience that delights the user and involves two contradictory feelings of fear and pleasure. The feeling of danger is characterized by the observation of a perfectly obvious danger, while a controlled risk creates an exciting sense of joy. As shown in Figure 8. A prime example of perceived danger is found in glass sky corridors, where users experience walking on a protective sidewalk [75, 122].

**Fig. 8.** Glass Skywalk at Tianmen Mountain in Zhangjiajie National Forest Park, China [75, 147, 148]

### 2.6.4. Examples of Biomorphic Architecture

Several examples of biomorphic architectures are summarized in Table 3. Here, several properties such as sustainability, energy performance, thermal comfort, and carbon footprints in these building are provided.

**Table 3**
Several examples of biomorphic architectures.

| Photo | Project | Features | Description |
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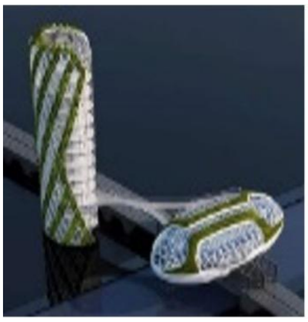
|   | The Anti-Smog building was design by Vincent Callebaut Architect in 2008. Located in Paris, France. | **Sustainability:** | 1. The Anti-Smog Building serves as an Innovation Centre for Sustainable Development, acting as a catalyst for cleaner air. This demonstrates the building's role in promoting sustainable development and improving air quality.<br>2. The TiO2 coating reduces airborne pollutants and contaminants and enhances air quality by breaking down pollutants, supporting sustainability. |
| | | **Energy efficiency:** | 1. Anti-Smog offers an engaging urban space powered by renewable energy, positively impacting the surrounding environment. The emphasis on renewable energy sources highlights the building's commitment to energy efficiency.<br>2. The exterior photovoltaic (PV) system generates on-site electrical energy and reduces the need for external power sources. |
| | | **Carbon footprint:** | 1. The project features the "Solar Drop," an elliptical structure positioned above unused railroad tracks. Utilizing previously unused space reduces the overall carbon footprint by repurposing land.<br>2. The "Wind Tower," another component of Anti-Smog, rises in a helical shape with a façade alternating between vegetation and embedded Vertical Axis Wind Turbines (VAWT) to capture urban winds. The integration of wind turbines and vegetation helps to lower the carbon footprint by producing clean energy and enhancing green spaces. |
| | | **Thermal comfort of users:** | NA |
|  | The Ascent at Roebling's Bridge is a residential building was designed by Daniel Libeskind in 2004 and was | **Sustainability:** | The Ascent at Roebling's Bridge uses blue-tinted glass and metal panels, which enhance its reflective quality and reduce the need for artificial lighting. This sustainable design approach minimizes energy consumption and integrates the building with its natural surroundings. |
| | | **Energy efficiency:** | While specific details about energy efficiency features are not provided, the building's design may emphasize open spaces and natural light, reducing the reliance on artificial lighting during the day and |

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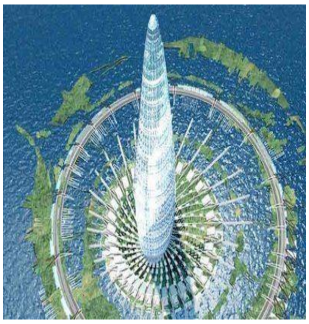
| | completed in March 2008. Located in Covington, Kentucky, United States. | | reduce energy consumption, making the building more energy efficient. |
| | | **Carbon footprint:** | While specific details about carbon footprint features are not provided, by employing high-end, energy-efficient materials and construction techniques, The Ascent may help reduce its overall carbon footprint. |
| | | **Thermal comfort of users:** | While specific details about thermal comfort features are not provided, the facade's blue-tinted glass and metal panels not only enhance aesthetics but also help regulate the building's internal temperature, contributing to thermal comfort. |
|  | The Bionic Tower was a visionary vertical city, an extremely large building designed for human habitation by Spanish architects Eloy Celaya, María Rosa Cervera and Javier Gómez. | **sustainability:** | 1. The Bionic Tower is proposed to be around 1,228 meters tall with 300 floors, capable of housing approximately 100,000 people.<br>2. The Bionic Tower is a conceptual project for an enormous vertical city designed to house a large population within a single, self-sustaining structure in terms of energy, water, and food, creating a sustainable living environment.<br>3. The design includes integrated green spaces and gardens, which would help with air purification, provide recreational areas, and contribute to the overall aesthetics and mental well-being of residents.<br>4. The tower would utilize various renewable energy sources, such as solar panels and wind turbines, to minimize its environmental footprint and ensure a sustainable energy supply. |
| | | **Energy efficiency:** | 1. Advanced building systems would be employed to optimize energy use, including smart grids, energy-efficient lighting, and HVAC systems.<br>2. The structure would incorporate natural ventilation techniques to reduce the need for mechanical cooling and heating, further improving energy efficiency. |
| | | **Carbon footprint:** | 1. While specific details about carbon footprint features are not provided, sustainable and recyclable materials would be prioritized in the construction of the Bionic Tower to reduce the embodied carbon footprint.<br>2. By concentrating a large population within a single building, the need for extensive transportation networks could be reduced, thereby lowering associated carbon emissions. |
| | | **Thermal comfort of users:** | 1. While specific details about thermal comfort features are not provided, the tower’s design would include climate control systems to ensure thermal comfort for its residents, adjusting to different weather conditions and optimizing indoor air quality.<br>2. High-performance insulation materials and techniques would be used to maintain |

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| | | | comfortable indoor temperatures while minimizing energy consumption. |
|  | City Hall was design by Norman Foster between July 2002 and December 2021 and completed in 2002. Located in Southward, London which served as the headquarters of the Greater London Authority (GLA). | **sustainability:** | 1. The design includes natural ventilation and the planned installation of photovoltaic cells by the London Climate Change Agency in 2006 to enhance environmental performance.<br>2. The incorporation of photovoltaic cells and natural ventilation demonstrates a commitment to sustainable practices. |
| | | **Energy efficiency:** | The unique bulbous shape reduces solar gain, helping to keep the building cool, although the extensive use of glass in the double facade can lead to higher energy consumption. However, the extensive use of glass can increase energy demands for heating and cooling, potentially offsetting some efficiency gains. |
| | | **Carbon footprint:** | The addition of photovoltaic cells to generate renewable energy. By producing its own electricity from solar power, the building reduces its carbon emissions associated with energy consumption. |
| | | **Thermal comfort of users:** | While specific details about thermal comfort features are not provided, the natural ventilation system and the design to control solar gain. |
|  | The National Space Centre is a museum and educational resource that was designed by Nicholas Grimshaw and completed in 2001. located on the north side of the city in Belgrave, Leicester, England. | **sustainability:** | 1. The geodesic dome at the top of the planetarium's roof is the highest point of its spiraling design. It punctures through the concrete roof and contrasts with the tall vertical tower.<br>2. The geodesic dome and solar cells contribute to sustainability by utilizing renewable energy sources and maximizing energy efficiency. |
| | | **Energy efficiency:** | The tower's design considerations, including insulation, solar protection, and energy generation by solar cells, aim to minimize energy consumption, maximize efficiency, and contribute to improved sustainability. Additionally, it addresses issues such as heat loss/gain, wind chill factors, skin reflectivity, rain screen, and weather protection. |
| | | **Carbon footprint:** | By utilizing renewable energy sources and implementing energy-efficient design strategies, the building aims to minimize its carbon footprint and environmental impact. |
| | | **Thermal comfort of users:** | While specific details about thermal comfort features are not provided, the tower's design addresses factors like insulation and weather protection to may enhance thermal comfort and ensure a pleasant indoor environment for occupants. |
| | Turning Torso is a neo-futurist residential | **sustainability:** | 1. Turning Torso is based on the form of a twisting human being.<br>2. Turning Torso's recognition for pioneering sustainable design, along with its use of |

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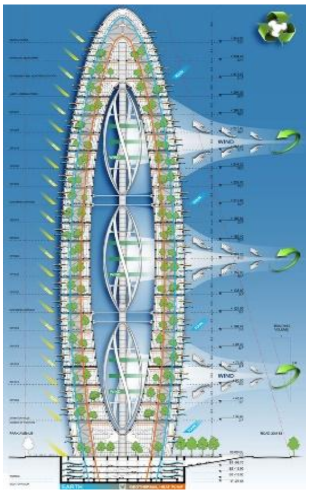
|  | skyscraper was designed by Santiago Calatrava and officially opened in 2005. Located in Sweden. | | renewable energy sources and waste-to-energy technology, demonstrates its commitment to sustainability. |
| | | **Energy efficiency:** | 1. Turning Torso's use of 100% renewable energy sources such as hydro, solar, wind, and geothermal energy, the building reduces its reliance on non-renewable energy improves energy efficiency and reduces its carbon footprint.<br>2. The building includes an organic waste disposal unit, which converts all waste material into energy. |
| | | **Carbon footprint:** | While specific details about carbon footprint, the building's reliance on renewable energy and waste-to-energy technology may help minimize carbon emissions associated with energy consumption and waste disposal. |
| | | **Thermal comfort of users:** | While specific details about thermal comfort features are not provided, the building's innovative design and sustainable practices likely may contribute to maintaining comfortable indoor temperatures for occupants. |
| <br> | The Bionic Arch is a concept tower designed by Vincent Callebaut Architects. The tower is designed for the Taichung Gateway City, located in Taiwan. | **sustainability:** | 1. The design of the Bionic Arch prioritizes sustainable features such as green spaces and living facades. It achieves this by integrating a park, green land, vertical platforms, sky gardens, and energy-efficient systems. These elements align with sustainability principles and aim to minimize its environmental impact while enhancing biodiversity and promoting a greener urban environment.<br>2. The Bionic Arch sets proactive goals to address nine key areas, including green landscaping, water conservation, daily energy efficiency, carbon dioxide reduction, waste reduction, water resources management, wastewater and waste disposal improvements, biodiversity protection, and interior environment refinement. |
| | | **Energy efficiency:** | The Bionic Arch's reliance on bio, solar, and wind energy sources demonstrates its commitment to energy efficiency and reducing dependence on fossil fuels. |
| | | **Carbon footprint:** | With its self-sufficient energy system and zero CO2 emissions, the Bionic Arch aims to significantly reduce its carbon footprint, aligning with government policies on energy saving and carbon emission reduction. |
| | | **Thermal comfort of users:** | While specific details about thermal comfort features are not provided, the incorporation of green spaces and living facades may contribute to creating a comfortable microclimate within the building. |
| | The Selfridges | **sustainability:** | 1. The Selfridges Building incorporates innovative design techniques to promote sustainability, such |

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|   | Building designed by the architecture firm Future Systems and completed in 2003. The building is a part of the Bullring Shopping Centre and houses Selfridges Department Store, located in Birmingham, England. | | as the use of an outer coating in its organic form made from 15,000 anodized aluminum discs.<br>2. The building's structural frame supports the free-form façade and enables the creation of spacious, column-free retail areas with ample vertical clearance.<br>3. Its curving lines form an irregular silhouette, evoking a sense of mystery and wandering within the urban landscape of Birmingham. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort of users:** | NA |
|  | Denver International Airport is an international airport designed by Fentress Bradburn and opened in 1995. Located in the Western United States. | **sustainability:** | The catenary steel cable system, similar to the Brooklyn Bridge design, supports the fabric roof. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | NA |
| | | **Thermal comfort of users:** | NA |
|   | Lotus building design by Studio 505, completed in 2013. Located in Jiangsu Province in China. | **sustainability:** | 1. Lotus Center and Park has become one of the most popular places of interest in Vojin with its stable contribution to the social and cultural life of the city, which is an important aspect of sustainability.<br>2. It is like a statue that comes out of the lake naturally and the visitor enters from under it. |
| | | **Energy efficiency:** | The project will operate more than 2,500 solar columns on its façade, which helps reduce reliance on non-renewable energy sources by harnessing solar energy for the building's operations. |
| | | **Carbon footprint:** | This project is designed to minimize energy consumption with more than 2,500 geothermal candles guided through the base of the artificial lake; the entire body of seawater and groundwater is used for cooling in summer and heating in winter. Utilizing geothermal energy and natural water bodies for temperature regulation reduces the building's carbon footprint by lowering the need for conventional |

| | | | |
|---|---|---|---|
| | | | heating and cooling systems that emit greenhouse gases. |
| | | **Thermal comfort of users:** | While specific details about thermal comfort features are not provided, this innovative use of natural resources could ensure efficient temperature control within the building, providing a comfortable indoor environment year-round. |
|   | Olympia stadium München is a stadium Designed by the German architect Günther Behnisch and the engineer Frei Otto, with the assistance of John Argyris at the end of June 1972. Located in Munich, Germany. | **sustainability:** | 1. This included large sweeping canopies of acrylic glass stabilized by steel cables that were used for the first time on a large scale. The stadium showcases advancements in sustainable architecture, providing durable and long-lasting structures.<br>2. Light, transparent roofs that are open and yet also afford shelter span across the gently landscaped Olympic Park incorporating the main sports facilities, including the Stadium, Arena, and Swimming Hall. |
| | | **Energy efficiency:** | NA |
| | | **Carbon footprint:** | While specific details about carbon footprint features are not provided, implementing durable materials like acrylic glass may reduce the need for frequent replacements, thereby lowering the carbon footprint associated with manufacturing and transportation. |
| | | **Thermal comfort of users:** | NA |

### *2.7. Biophilia Architecture*

#### *2.7.1. The Concept of Biophilia*

Biophilia was first used in the works of the German psychologist Fromm (1973) [149, 150] to describe the love of life as the passionate love of life and all that is alive. Thus, evolutionary dependence on nature forms the basis of biophilia for personal survival and fulfilment [151]. Since the 1990s, biophilia theory has shifted from its main focus on life or living things to exploring the relationship between humans and the natural environment. At the beginning of the 21st century, the concept of biophilia was developed and adapted in the field of architecture, drawing attention to the emotional aspect of human needs to interact with the natural environment in the building environment. Biophilic design was proposed to satisfy the passion for nature in architecture [152]. In summary, there are two main reasons for biophilic design: first, the desire for nature is widespread, and second, many nature-related design concepts have been criticized as formal strategies.

#### *2.7.2. Biophilic Design*

The goal of biophilic design is the active use of various elements in nature. In addition, biophilic design uses the features of various natural elements in the architectural environment to expose users to nature and coexist with them [153]. Thus, biophilic design is a sustainable design strategy that integrates users and nature [154]. Focusing on the positive effects of nature on users, biophilic design uses green walls, green roofs, indoor gardens, nature-friendly environments, water bodies, etc. in urban environments.

### *2.7.3. The Principles of Biophilic Design*

Biophilic design depends on the following basic elements (Figure 9): natural ventilation, natural light and organic forms and natural landscapes. These elements strengthen the connection between man and his immediate environment [155-157].

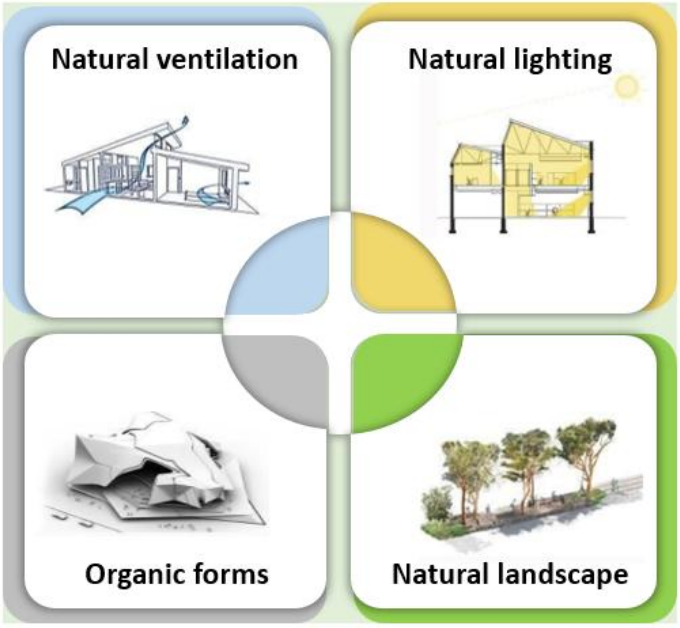



**Fig. 9.** The fundamental components of Biophilic Design [155].

#### *2.7.3.1. Origin of Biophilic Design*

Biophilic design is based on, but not limited to, the concept of biophilic. Many theories of environmental psychology show that man's need for nature is due to the instinctive sense of natural elements. Such theories explain the mechanism by which the physical and mental functions of contact with nature are created [30, 126, 135, 158]. These theories provide a theoretical basis for the development of biophilic design, which is briefly reviewed below.

#### *2.7.3.2. Habitat and Housing*

In evolutionary psychology, the emotional need for "nature" from the experience of habitat selection and housing is explained. It is argued that some natural landscapes or spaces were more conducive to the survival of our ancestors. Therefore, some of the identified features of these landscapes are also preferred in modern architectural spaces [159-161] and with the conscious arrangement of these natural features, attractive environments similar to nature can be created.

#### *2.7.3.3. Renovation*

Stress recovery theory shows that contact with natural features such as vegetation and water can produce a rapid and positive psychological response. Therefore, exposure to nature can reduce negative emotions and improve physiological stress and health problems [162, 163]. In comparison, the theory of restoring attention shows that excessive consumption of human attention by cognitive tasks leads to brain fatigue and psychological stress, and since we do not need to spend a lot of energy interacting with nature, it can create opportunities [141, 142, 164].

### *2.7.3.4. Place*

Theory of place attachment examines emotional relationships with places and argues that people tend to stay in more familiar places [165]. This theory also shows that connecting to the natural environment by combining regional features such as geomorphology and landscape in buildings can create a sense of place and community [166]. Various theories support the emergence of biophilic design and show that human desire for nature is deeply rooted. In contrast to the positive attachments of biophilia, some natural events such as fear of snakes, spiders, deep sea and altitude have negative psychological effects that are attributed to another feeling of bio phobia [162, 167]. Therefore, it is necessary to identify what kind of nature in architecture can create positive connections.

### *2.7.4. Biophilic Design Strategy*

To date, various design strategies, methods, priorities, and considerations have been used in biophilic design [143]. Their summary is shown in Figure 10, and the elements used in biophilic design are discussed below.

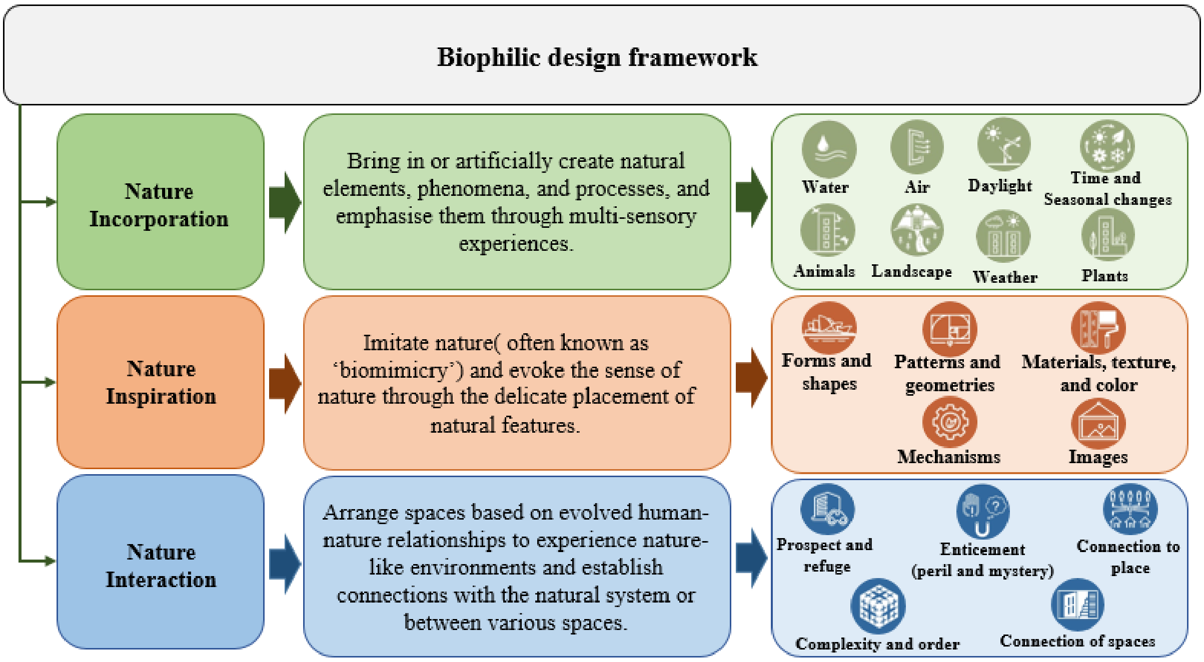



**Fig. 10.** Biophilic design framework: three design strategies and key elements.

### *2.7.4.1. Visual Connection with Nature*

Visual connection with nature is considered as one of the most important aspects of biophilic design. An example of this can be found in Figure 11, which was originally designed as a biophilic housing project in the Kasauli, hilly region of India. Each residential unit has unobstructed views of nature in order to regulate and maximize the performance of residents and increase their creativity. The most obvious cases in identifying design parameters in visual communication with nature include reducing stress through visual communication with natural elements [121, 168], giving priority to real natural elements over artificial or acquired aspects of nature [169], prioritizing to promote biodiversity, prioritize spaces for sports and recreation that are visually related to green spaces [170] and minimize exposure to nature for 5-20 minutes per day.

**Fig. 11**. Visual Connection with Nature at Myst, Kasauli by Tata Housing [143, 171].

### *2.7.4.2. Non-Visual Connection with Nature*

Non-visual connection with nature can be detected in the form of non-visual sensory receptors such as hearing, touch or movement, smell or taste. Figure 12 illustrates the non-visual connection with nature in which the sound created by the movement of water acts as a calming and restorative element for the inhabitants [11]. From the activity and response of the above sensory receptors, we can identify the design parameters as follows: small or momentary use of non-visual sensory stimuli [49], priority of natural sounds over urban sounds [49], use of natural sounds of birds, Winds and leaf eruptions to increase people's creativity [50][172].

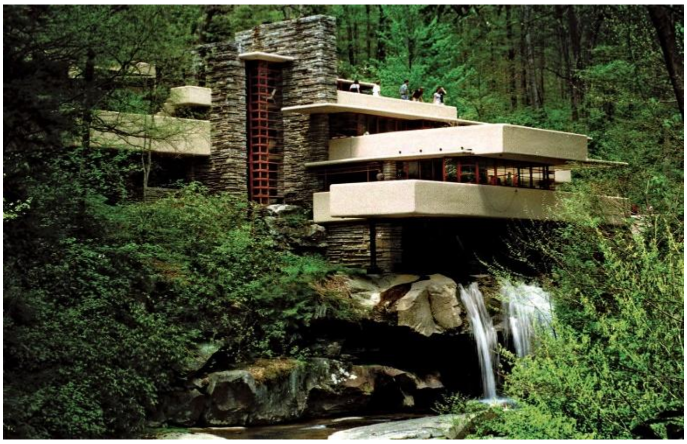


**Fig. 12.** The Falling water by Architect F.L. Wright in Pennsylvania [104].

### *2.7.4.3. Non-Rhythmic Sensory Stimuli*

Non-rhythmic sensory stimuli are random and transient connections with nature that reduce stress and improve productivity. These stimuli include clouds, shadows, sounds of nature and water. A space with effective non-rhythmic sensory stimuli acts as a refreshing environment [173]. Figure 13 shows the implementation of non-rhythmic sensory stimulus elements in the active designs of the Shimla Wildflower Hall and The Oberoi Amarvillas, Agra.

**Fig. 13.** Non-rhythmic sensory stimuli. At the top, clouds, shadows, and reflections are integrated into the built environment at Shimla Wildflower Hall, and below, the same features are observed at the Oberoi Amavillas in Agra [152].

### *2.7.4.4. Thermal Changes and Air Flow*

The role of ventilation and thermal comfort in the index of human habitat satisfaction is very vital. Airflow, thermal variability and natural ventilation are some of the key factors that provide thermal comfort for building occupants. Design parameters for a balanced thermal environment and air flow include maintaining vegetation between buildings, maintaining a small amount of water to induce evaporative cooling, using green roofs and green walls to reduce heat and maintaining fresh air flow, use building materials with low thermal diffusivity to prevent overheating in summer and excessive cold in winter [75].

### *2.7.4.5. Presence of Water*

The presence of water in biophilic architecture is considered as a restorative environment both visually and aurally [37, 49]. The gardens of St. Fiachara in Ireland (Figure 14), designed by Martin Hullinan, have restorative and recreational properties. Parameters of water use in biophilic design include perception of water as a pure element [63], priority to use multiple senses [49] and priority to natural water movements [44].

**Fig. 14.** St. Fiachra's Garden and it's located beside the Japanese Gardens on the grounds of the Irish National Stud at Tully, Kildare, Ireland. It was designed by Architect Martin Hallinan [75].

### *2.7.4.6. Light*

Light is related to human psychology and has different results for different types of light. Research shows that the presence of natural and clear light has a positive psychological effect on residents, enhances life, positive emotions and creativity [10]. Proper lighting of a space increases the accuracy and power of vision [57]. Design parameters for dynamic and scattered balanced lighting include balancing indoor and outdoor spaces through separation, creating a modified daylight mechanism that can change during the day to mimic the characteristics of natural light [65] and indirect exposure to light The environment is through holes to make the space appear larger [75, 122] (Figure 15).

**Fig. 15.** The top image features Suryagarh in Jaisalmer, India, which employs perforation, known locally as Jali work, to reduce the impact of direct light in a visually pleasing way [171]. In the middle is RAAS Jodhpur, a hotel in India [174]. At the bottom is the Church of Light, designed by Architect Tadao Ando in Japan, which utilizes light to enhance the emotional and spiritual atmosphere [171].

### *2.7.4.7. Connection with Natural Systems*

Browning, Ryan and Clancy in their book “14 Patterns of Biophilic Design”, described communication with natural systems as awareness of natural processes, especially seasonal and temporal changes in the characteristics of a healthy ecosystem. Any space that is well connected to natural systems creates a connection with a larger whole [121]. As shown in Figure 16, the Jacobite-style Viceregal Lodge was built by architect Irwin in 1888 as a summer resort for the then British Governor of India - Lord Dafarin in Shimla. The whole complex is designed in accordance with the natural systems of the area. Underground tanks were built under the gardens to store rainwater for all activities of the complex. Design parameters for quality communication with natural systems are collection, treatment and use of rainwater in landscape design [67] and provide visual access to natural systems [68].

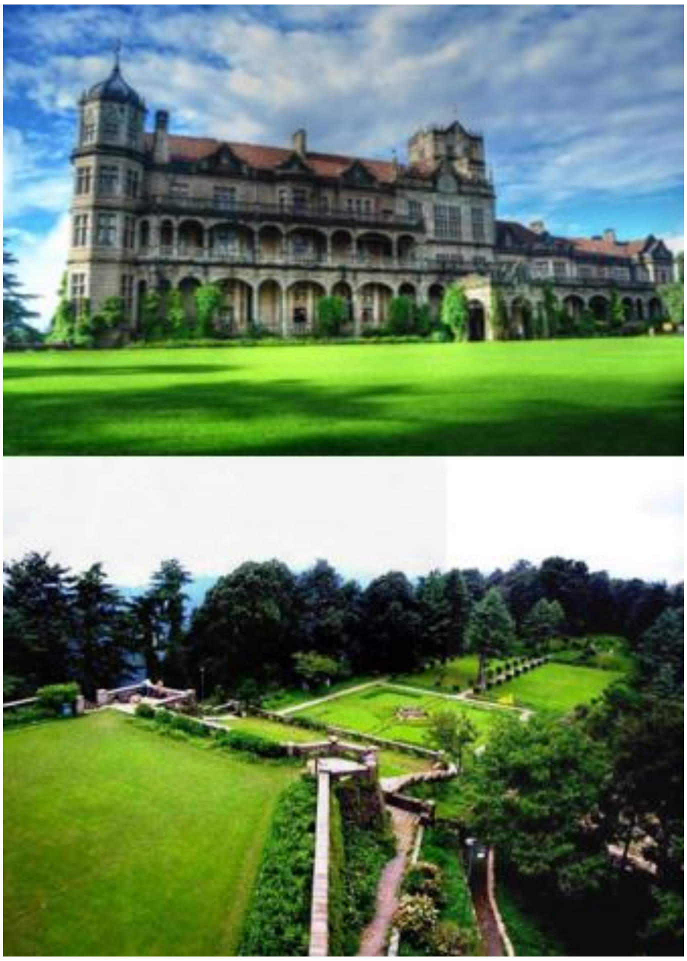


**Fig. 16.** The gardens and recreational areas of Viceregal Lodge are constructed over underground reservoirs [75].

Table 4 summarizes research findings on biophilic design patterns and biological responses [27]. Research findings on biological responses based on biophilic design patterns generally show positive effects on reducing stress, increasing cognitive skills and sensitivity, atmosphere and preference, increasing happiness, and increasing concentration [28].

**Table 4**
Research findings about biophilic design patterns and biological responses.

| **Biological Response** | | | | | |
|---|---|---|---|---|---|
| **Sensitivity, Atmosphere, and Preferences** | **Cognitive Skills** | **Stress Relief** | **Biophilic Design Pattern** | **Sensitivity, Atmosphere,** | **Cognitive Skills** |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | **and Preferences** | |
| **1** | Having a positive impact on the preferences for spatial | Increasing work engagement and concentration | Reducing blood pressure and slowing down heart rate | Visual Connection with Nature | Positive effect on spatial preferences | Increasing work engagement and concentration |
| **2** | Promoting mental health and psychological composure | Improving cognitive abilities in a positive way | Reducing systolic blood pressure and relieving stress | Non- Visual Connection with Nature | Supporting mental well-being and emotional balance | Positive effect on cognitive skills |
| **3** | Enhancing spatial preferences for view | Positive effect on Increasing concentration | Increasing comfort, happiness, and productivity | Dynamic and Diffuse Light | Improving spatial preferences for view | Positive effect on Increasing concentration |
| **4** | Changing the perception about environment and Promoting health | - | Relieving stress | Connection with Natural Systems | Altering how we see our surroundings and supporting good health | - |
| **5** | Boosting the preference towards viewing | - | - | Biophilic Forms and Patterns | Increasing reference for view | - |
| **6** | Promoting relaxed feeling | Lowering diastolic pressure | - | Material Connection with Nature | Promoting relaxed feeling | Lowering diastolic pressure |
| **7** | Increasing reference for view | - | Relieving psychological stress | Complexity and Order | Increasing reference for view | - |

### *2.7.5. Examples of Biophilic Architecture*

Table 5 summarizes the biophilic design strategies used in architecture and describes the types of elements in the proposed biophilic design framework. The positive and negative effects of these elements on the building are also discussed in the column.

**Table 5.**
Biophilic design framework: three design approaches and primary elements

| BDEs | Design Strategies | Strengths & Opportunities | Weakness & Threats | Example | Features | |
|---|---|---|---|---|---|---|
| **Water** | -Create water features like fountains, man-made wetlands, ponds, water walls, rainwater collectors, fish tanks, etc.<br>-Provide access to natural water bodies like waterfalls, rivers, streams, oceans, etc. | -Offered various ways to experience water with different sights, sounds, and textures. Increased the size of the water feature.<br>-Give preference to moving water rather than still water | - High-volume and large turbulence water that affects acoustic quality and humanity.<br>- Negative (biophilic) emotional responses (e.g. fear of deep water).<br>- Artificial water features may increase energy consumption. | Appel's Pizza Liberty Store, designed by Faster & Partners, bult in 2018. Located in Milan (Italy).<br><br> | **Sustainability:**<br>**Energy efficiency:**<br>**Carbon footprint:**<br>**Thermal comfort of users:** | Yes<br>NA<br>NA<br>Yes |
| **Air** | Increase natural ventilation using operable window, vents, narrower structure, airshaft, porches, clerestories, HVAC systems, etc. | - Enrich sensory variability and reduce boredom and negativity by imitating the subtle changes of natural air and ventilation.<br>- Broaden the acceptable range of thermal comfort for decrease energy demand. | - Natural ventilation may increase the circulation of population (e.g. PM2.5).<br>- Ventilation when outdoor humidity is high will bring excess moisture that increase the risk of mold contamination. | Mountain Restaurant & Bar, Zunyi (China), by ZJJZ Atelier, built in 2018.<br><br> | **Sustainability:**<br>**Energy efficiency:**<br>**Carbon footprint:**<br>**Thermal comfort of users:** | Yes<br>Yes<br>NA<br>Yes |
| **Daylight** | - Bring in natural light via glass walls, clerestories, skylights, atria, reflective colors/materials, etc.<br>- Mimic the spectral and ambient qualities of natural light. | - Dynamic lights and shadows forms transition between indoor and outdoor spaces.<br>- High-contrast lights bring attention and evoke a sense of sacredness<br>- Support productivity and boost retail sales | - Glares and spilling lights interfere with visual performance, and intense dynamics might be distracting<br>- Overheating and decreased building performance. | Institute du Monde Arabe, Paris (France), by Ateliers Jean Nouvel, bult in 1987.<br><br> | **Sustainability:**<br>**Energy efficiency:**<br>**Carbon footprint:**<br>**Thermal comfort of users:** | Yes<br>Yes<br>NA<br>NA |
| **Plants** | - Bring vegetation indoors by potting plants and | - Increase green space coverage, native plants | - Structural problem, excessive | Musee du Branly, Paris (France), by | **Sustainability:**<br>**Energy efficiency:** | Yes<br>Yes |

| | | | | | |
|---|---|---|---|---|---|
| | indoor green walls.<br>- Incorporate plants into buildings by using green roofs, green walls and facades, large atria with park-like setting, green pockets, etc. | ratio, and biodiversity.<br>- Improve shading/sheltering ability and reduce energy consumption.<br>- Restoration, stress reduction, productivity, and positive mood.<br>- Reduce air pollution and optimize air quality. | humidity, odors issues, etc.<br>- Highly artificial designs require intensive energy and maintenance | Patric Blanc, built in 2004.<br><br> | **Carbon footprint:** Yes<br>**Thermal comfort of users:** Yes |
| **Animals** | - Create spaces to accommodate animals, such as ponds, aquariums, etc.<br>- Build animal-friendly living areas to attract animals like nest boxes, gardens, green roofs/walls, etc. | - Increase biodiversity and enrich local species.<br>- Form an ecosystem with interconnected plants, soil, water, and geological features. | - Contact with some specify animals (e.g. snakes and spiders) or the sight of dead animals may cause negative (biophilic) emotions. | Mellor Primary School, Stockport (UK), by Sarah Wiggiesworth Architects, bult in 2015.<br><br> | **Sustainability:** Yes<br>**Energy efficiency:** NA<br>**Carbon footprint:** NA<br>**Thermal comfort of users:** NA |
| **Landscape** | - Build landscape in the sites such as wetlands, grasslands, prairies, forests, etc.<br>- Create interior landscape in atria, courtyards, entry areas, hallways, etc.<br>- Provide window views of natural landscapes. | - Enhance coherent and ecologically connected.<br>- Optimize the natural landscapes and minimize management requirements. | - Contrived superficial decorations, isolated, exotic plant configurations.<br>- Lake of participation and immersion.<br>- Lake of shelter and inappropriate distance and height to view the landscape. | Chichu Art Museum, Naoshima island (Japan), by Tadao Ando, built in 2004.<br> | **Sustainability:** Yes<br>**Energy efficiency:** NA<br>**Carbon footprint:** NA<br>**Thermal comfort of users:** NA |
| **Weather** | - Enhance exposure to weather and awareness of meteorological conditions through operable windows, porches, | _ | - Extreme weather conditions and climate change are not beneficial to human health and comfort | Sun Rain Rooms, London (UK), by Tonkin Liu Architects, bult in 2017. | **Sustainability:** Yes<br>**Energy efficiency:** Yes<br>**Carbon footprint:** NA<br>**Thermal comfort of users:** Yes |

| | | | | | | |
|---|---|---|---|---|---|---|
| | balconies, terraces, courtyard, transparent roofs, rainwater collectors and spouts, etc. | | |  | | |
| **Time and Seasonal Changes** | - Present the views of the building façade and appearance that change after long-term exposure to nature.<br>- Provide views of seasonal changes in plants. | _ | - Building envelopes may be damaged of become dilapidated over time.<br>- Perception of seasonal changes depends on individual preferences. | Bosco Verticable, Milan (Italy), by Stefano Beori Architects, bult in 2014.<br> | **Sustainability:** | Yes |
| | | | | | **Energy efficiency:** | NA |
| | | | | | **Carbon footprint:** | NA |
| | | | | | **Thermal comfort of users:** | NA |
| **Forms and shapes** | - Imitate the contours and motifs of organisms in building forms, structural systems, components, and interior spaces. | _ | - Overuse and repetition of forms and shapes can cause visual boredom | Metropol Parasol, Seville (Spain), by J. Mayer H. Architects, bult in 2011.<br> | **Sustainability:** | NA |
| | | | | | **Energy efficiency:** | NA |
| | | | | | **Carbon footprint:** | NA |
| | | | | | **Thermal comfort of users:** | NA |

*2.8. Biomimetic Architecture*

*2.8.1. Biomimetic Concept*

Biomimetic refers to the structure, principles, and mechanisms of living things and biomaterials in nature [175] and refers to a design approach that mimics the models, systems, and elements of nature to solve complex human problems. This term was first coined by Janine Benyus, author and naturalist from Montana, USA, as a "conscious imitation of the genius of nature". Julian Vincent defines biomimetic as "the abstract design of good design from nature" [176] and extended this definition to three levels of imitation. The first level is the imitation of the natural form. This type of imitation is to copy the morphological features of a living thing such as its visual shape, components, materials or appearance. The second level is the imitation of natural processes. This level is for reproducing the processes of a biological organism in its environment. The third level is the imitation of natural ecosystems. This set of processes is more complex than the previous two levels. Imitation of an ecosystem requires a larger picture of how a biological organism affects its environment.

### *2.8.2. Biomimetic Architecture*

There are many examples in architecture that have been influenced by nature. Structures such as tree branches, flower parables, grid configurations, etc. have inspired architectural design since time immemorial. This inspiration can be seen in two ways. (1) to reproduce form, (2) or to transfer the process of emergence of a living thing (such as matter, form, structure, etc.) to design. The first is merely a formulation concern and does not refer to a functional or ecological approach. The second is a different approach that offers observation and understanding of performance and harmony within nature. Many fields of science, including architecture, used Biomimetic. Biomimetic architecture is a sustainable design approach that mimics models, natural systems, and processes them in the built environment [177-183]. Figure 17 show an example of biomimetic architecture.

**Fig. 17.** TWA Terminal Building was designed by Calatrava and Eero Saarinen's and was opened in 1962, New York, USA (Reference: Wikipedia Commons).

Zari. M proposed a framework for understanding the levels of biomimetic science in architecture as follows (Figure 18) [178, 179]. Also, the Zari. M [184] approach was applied to an application and the subsets of each level are given in the Table 6.

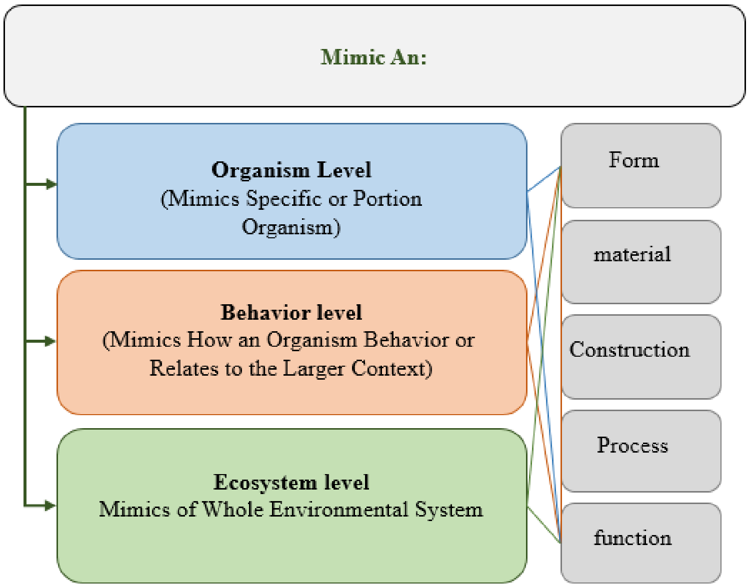



**Fig. 18.** Levels and dimensions of the biomimetic architecture.

**Table 6**
Framework for the application of biomimetic architecture [184].

| **Level of Biomimicry** | | **Example – A building designed to imitate a termite** |
|---|---|---|
| **Organism Level (Mimicry of a specific organism)** | Form | The structure resembles a termite. |
| | Material | The building is constructed using a material that imitates the exoskeleton or skin of a termite, such as a termite-like material. |
| | Construction | The building is constructed using a process similar to that of termites, which involves multiple growth cycles, for instance. |
| | Process | The building operates akin to an individual termite, efficiently producing hydrogen through meta-genomics, for instance. |
| | Function | The building functions similarly to a termite on a larger scale; for instance, it recycles cellulose waste and generates soil. |
| **Behavior level (Mimicry of how an organism behavior or relates to its larger context)** | Material | The building appears as though it was constructed by a termite; for instance, it resembles a replica of a termite mound. |
| | Construction | The building is constructed using the same material that termites use, such as digested fine soil as the primary material, for instance. |
| | Process | The building is constructed following similar methods as a termite would, such as piling earth in specific places at specific times, for instance. |
| | Function | The building operates similarly to a termite mound by carefully considering orientation, shape, material selection, and natural ventilation, for instance, or it mimics the cooperative behavior of termites. |
| | Material | The building functions similarly to how it would if made by termites; internal conditions are regulated to be optimal and thermally stable, for example. It may also operate similarly to a termite mound in a larger context. |
| **Ecosystem level (Mimicry of an ecosystem)** | Material | The building resembles an ecosystem, akin to where a termite would reside. |
| | Construction | The building is constructed using the same type of material found in a termite ecosystem, utilizing naturally occurring common compounds and water as the primary chemical medium, for instance. |
| | Process | The building is put together following the same principles as a termite ecosystem, employing the concept of succession and increasing complexity over time, for instance. |
| | Function | The building operates similarly to a termite, capturing and converting energy from the sun, and storing water, for instance. |

| | |
|---|---|
| Material | The building functions similarly to a termite ecosystem and is integrated into a complex system by leveraging relationships between processes. It participates in cycles such as the hydrological, carbon, and nitrogen cycles, akin to an ecosystem, for instance. |

### *2.8.2.1. Organism Level*

The first level, or organism, mimics a particular organism or part of a living organism. In short, imitation is a physical feature of a living thing. An example of this is the design of the International Waterloo Terminal by Nicolas Grimshaw & Partners, based on the imitation of the form (Figure 19). Due to its high opening, the terminal must respond to significant pressure changes as the train enters and leaves. For this reason, glass plates such as the Pangolin scale have been arranged to adapt to the imposed air pressure [8, 184].

**Fig. 19**. Waterloo International Terminal features glass panels that imitate the outer shell or scales of a pangolin [8].

### *2.8.2.2. Behavior Level*

Behavior imitation is to discover and understand how a living thing communicates and behaves in its environment. Understanding this level is possible by observing how a living thing tends to act in its environmental capacity and in the range of energy and availability of materials [5, 181, 184].Termites are the most common example to illustrate this level. As shown in Table 1, termites build their nests at the behavioral level to protect and stabilize the fungi at 30 ° C despite the 21 ° C temperature range, where they store the fungi produced. That's why termites build a 13-centimeter-high ventilation duct that ventilates hot air outside and cold air inside (Figure 20). Eastgate Business and Office Center in Harare, Zimbabwe uses the same behavior to heat and cool Natural building uses.


**Fig. 20.** Implementing the design principles of termite mounds to achieve natural ventilation in the Eastgate Center [5, 8].

*2.8.2.3. Ecosystem Level*

The third level for the integration of biology and architecture is bio-design. At this level, bio-design encompasses biological processes. This level of biomimetic aims to create a complete ecosystem that combines the other two levels to achieve a sustainable environment. This means a deep understanding of ecology and the regenerative processes of nature. This level may start on a small scale and lead to a larger scale such as green cities or ecological cities. As shown in Figure 21. Zira Island, Baku, Azerbaijan is an example of this level. The project is inspired by the seven peaks of Azerbaijan that form the horizon, as shown in Figure 9. Also, this model uses natural energy sources such as sun, water and wind (Figure 20) [5, 177].

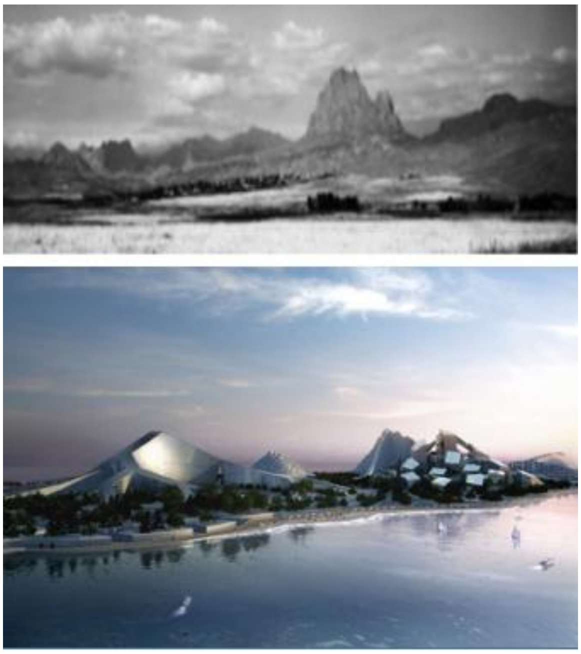


**Fig. 21.** At the top, there are the seven peaks of Azerbaijan, which create the skyline view of Baku, Azerbaijan. Below is the inspiration for the Zira Zero Island project in Baku, Azerbaijan [5].

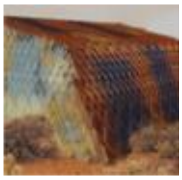
### *2.8.3. Examples of Biomimetic Architecture*

In international case studies, it was important to classify each case based on three biomimetic levels (organism, behavior, and ecosystem) and five features of each level. Several examples of biomimetic architecture with their levels and features are summarized in Table 7.

**Table 7**
Several examples of biomimetic architecture.

| Level/ Dimension | Organism | Behavior | Ecosystem | Case | Features | |
|---|---|---|---|---|---|---|
| Form (Building/envelop/skin) | Colored appearance | A changing color's skin | - | Šiauliai Arena is the largest arena in Šiauliai, Lithuania. It opened on July 25, 2007  | **Sustainability:** | **Yes** |
| Function | Visual | Adoption with surrounding environmental | - | | | |
| Process | Colorful appearance during sunny days | Changing color according to natural daylight | - | | **Energy efficiency:** | **NA** |
| Construction | - | - | - | | **Carbon footprint:** | **NA** |
| Material | Holographic glass | Holographic glass | - | | **Thermal comfort of users:** | **NA** |
| Form (Building/envelop/skin) Hexagonal shape unit | Multi colorful night appearance | Adoptive facade | Multi colorful night appearance | The Dubai Mixed-Use Towers, located adjacent to Burj Khalifa in | **Sustainability:** | **Yes** |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Function | - | Color visual at night | Temperature regulation and daylight control | | For night illumination (LED) and cooling | | Downtown Dubai, Dubai, United Arab Emirates.  | | |
| Process | - | Illumination | Movable according to sun day | | Energy production | | | **Energy efficiency:** | **Yes** |
| Construction | | - | - | | Converting sunlight to energy | | | **Carbon footprint:** | **NA** |
| Material | | LED | Shading device | | Photovoltaic Nano cell | | | **Thermal comfort of users:** | **Yes** |
| Form (Building/envelop/skin) | Using Human sponge bone | Using organic shape and change transparency as chameleon | Changing in the outlook | | Integrated glazing panels | | Proposed Research, Manufacturing, and Therapy Facility for Advanced prosthetics, Boston, USA.  | **Sustainability:** | **Yes** |
| Function | To support the main design concept | Regulating and controlling internal temperature and producing energy | Provide natural ventilation when open and control heat loss when close | Energy production | Allowing natural ventilation | Rainfall catcher | | | |
| Process | - | Changing opacity of photovoltaic cell | Opening or closing | Transforming light to energy | Circulation passive air ventilation | Collect rainwater | | **Energy efficiency:** | **Yes** |
| Construction | An arterial structure | Fritted system | - | | Some panels are fixed and others operable | Casting in concrete | | **Carbon footprint:** | **NA** |
| Material | concrete | Integrated system including the fritted system and solar cell | Operable panel of the integrated glazing system | Solar cell integrated in the fritted system | Operable panel of the integrated system | channels | | **Thermal comfort of users:** | **Yes** |
| Form (Building/envelop/skin) | Colorful Quadrant shape appearance | | Colorful Quadrant shape appearance | | Integrated glazing panels | | S.C.I.E.S Project, Great | **Sustainability:** | **Yes** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Function | Visual appearance of lizard | Insulation layer in hot days and providing passive heating and cool nights | Proving natural ventilation when open and control heat loss when close | Energy production | Allowing natural ventilation | Basin Desert, Utah, USA  | | |
| Process | - | Moving on sun tracking grid | Opening/closing | Covering sunlight to energy | Opening/closing | | **Energy efficiency:** | **Yes** |
| Construction | Braced steel grid | Movable system | Movable system | | - | | **Carbon footprint:** | **NA** |
| Material | Phase change materials operable glass+ colored + photovoltaic solar cell | Phase change material | Integrated glazing from operable clear glazing and photovoltaic panels | Colored photovoltaics | Operable window | | **Thermal comfort of users:** | **Yes** |

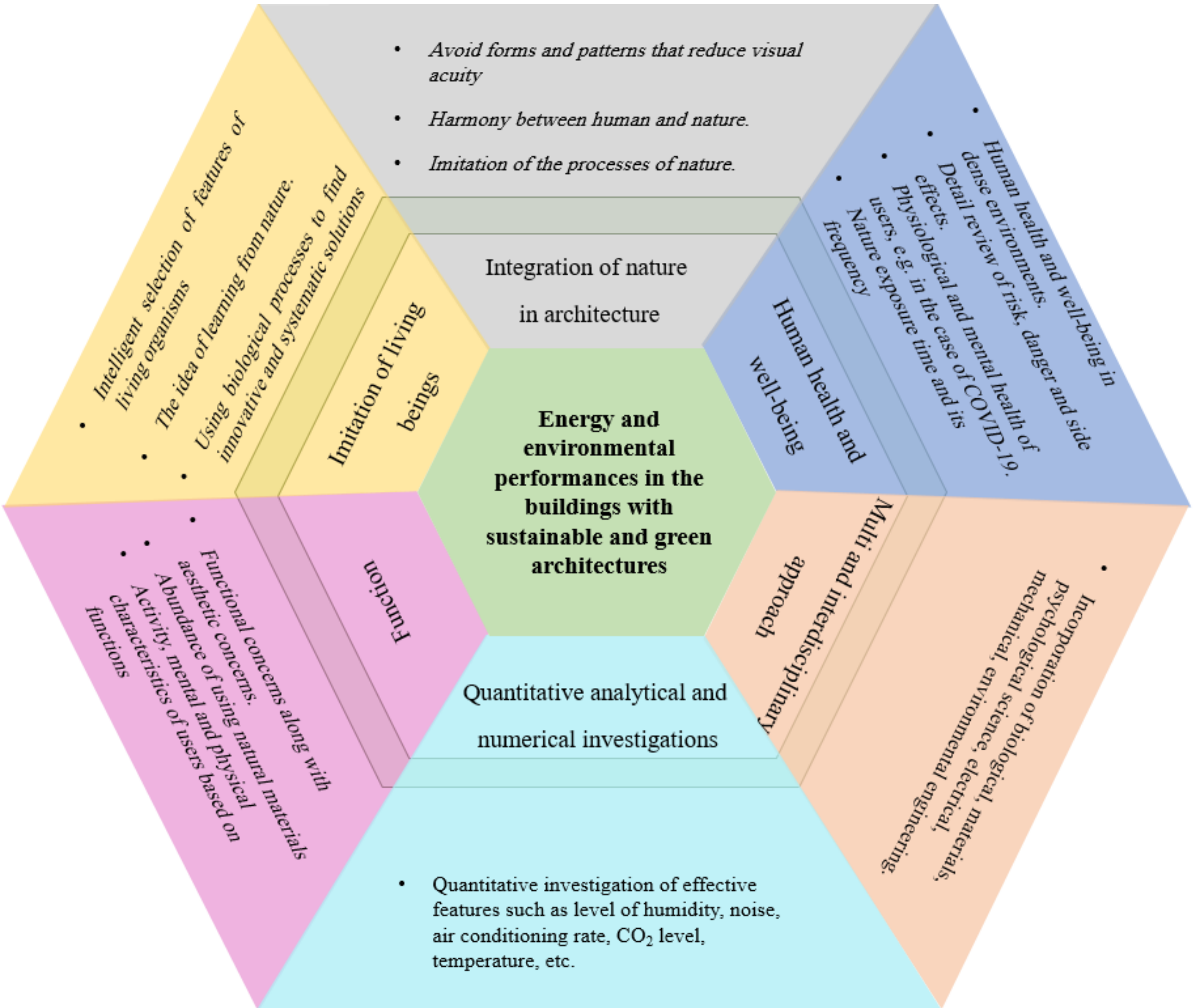



**Fig. 22.** The strategies for future research trend in the building with sustainable and green architectures.

## 3. Discussions and Conclusions

The use of nature in architecture is not a new approach and human has benefited from nature in the distant past and will do more and more in the future. In the field of architecture today, the way of thinking and acting towards nature must change and new approaches must be adopted to reduce destructive effects. Sustainable and environmentally friendly approaches to architecture have been a popular topic, but there is still much confusion in the building industry about how to make the most of these approaches. In this review article, in the first part, the concept of nature, the effect of nature forms on sustainability and its relationship with humans are examined and its reflection in nature-based architectures is expressed. In the second part, the concept of architecture inspired by nature and living organisms, their design methods and ways to achieve the goals of sustainable and green architecture were fully explored. In the third section, the advantages and disadvantages of these designs and architectures in terms of sustainable architectural features, energy efficiency, carbon footprint reduction and thermal comfort were analyzed.

Although all designs and buildings built with a nature-inspired architecture approach improve sustainability and energy efficiency, barely reduce energy consumption and carbon footprint to zero or nearly zero. Also, in the design of buildings, thermal comfort for users based on their physiological parameters and building functionality is rarely considered. Especially in the context of COVID-19, the high level of thermal comfort for people in the spaces where their activities take place has created a new wave of interest in personal thermal management. At present, the individual needs of thermal comfort, energy saving, sustainability, and low carbon footprints in buildings are strongly related to each other, and the realization of these criteria requires a precise and comprehensive compromise. In the following, future research paths to achieve these criteria in nature-based architectures are suggested:

### *3.1. Integration of Nature in Architecture*

Precise planning for harmony between human and nature. In order to achieve sustainable development, prosperity and energy efficiency in the world, natural design innovation in the construction sector must be considered with the rational use of intelligent technologies and exploring the new design process to be able to create a harmonious relationship between hman and nature.

Imitation of the processes of nature instead of imitation of the form of nature. Architects must extend nature beyond the principles of form or appearance in a building.

Combining, integrating and accompanying natural and biological design and architecture. To achieve rational, consistent, and efficient buildings, critical bio-design factors must be considered. Also, the further development of architectural themes such as topology, form, scale, composition, order and technology should be considered in future research.

Avoid forms and patterns that reduce visual acuity. Excessive use or repetition of patterns and forms, especially fractal patterns, should be avoided, and in designing buildings with such patterns, the context and its impact on the city and environment horizon should be considered.

### *3.2. Imitation of Living Beings*

Intelligent selection of features of living organisms along with physical features. To achieve greater impact on the built environment, increase energy efficiency and sustainable development, it is better to imitate living organisms in addition to physical appearance and use sustainable materials.

The idea of learning from nature instead of just imitating it. So having an integrated approach based on more than one capability or even more than one organism can work better.

Using biological processes to find innovative and systematic solutions. Inspired by the biological processes of living things such as camouflage, color change, reproduction, response to external and internal stimuli, proliferation and self-decoration, photosynthesis, inhalation and exhalation, movement, removal of waste, etc., architects and researchers can design more creatively.

### *3.3. Human Health and Well-Being*

Paying attention to human health and well-being along with the parameters of stability, energy, etc. in dense environments. Designs based on nature and livening beings as a part of human life is a good idea, but while dealing with built and very dense environments, the field of nature should be discussed in terms of human health and well-being.

Detail review of risk, danger and side effects. In these designs, risk, danger and side effects must be carefully considered, because it is a sensitive element for human psychology. Its user base must be well defined and precisely targeted in order to have a positive impact on the mental health of the population and its environment, and to develop nature-based solutions with common interests, especially for health promotion.

Paying attention to the physiological and mental health of users, especially in the case of COVID-19. In environments designed based on nature and living beings, by considering parameters such as maximum use of daylight and brightness, carefully placed windows for the exterior facade, appropriate variation in lighting levels, use of natural materials, bringing nature into the environment with plants, the use of green roofs and maximizing green space around buildings, maximize the restorative quality of the environment and users have less stress and can focus on their activities.

Consideration of nature exposure time and its frequency. The time spent by users and their frequent use of natural spaces in the building should be considered by designers. Excessive exposure to these environments, due to additional building materials, structural requirements, and maintenance budgets, not only does not improve the health and well-being of users but also wastes resources.

### *3.4. Function*

Pay attention to functional concerns along with aesthetic concerns. Designers and architects in these designs must consider different functional groups. Creating a high level of thermal comfort, saving energy, improving sustainability, reducing carbon footprint in buildings are important together and strongly depend on the type of the building functionality.

Abundance of using natural materials in a space based on buildings functionality. In design, there should be a preference for natural materials over synthetic materials because human sensory receptors can detect and sense differences between them. Also, the abundant use of natural materials in the built environments should be considered based on the building functionality.

Using the type of activity, mental and physical characteristics of users in a variety of building applications. Achieving buildings with minimal energy consumption and carbon footprint, an acceptable level of thermal comfort and health of users requires consideration of the type of activity, mental and physical characteristics of users and the performance and functionality of the building. For example, these features in hospitals where the distinct groups such as medical staff, patients and patients' family members are presents, in the offices where staff are sitting in a constant space and in residential buildings where activities are often dynamic are different and should be considered comprehensively.

### *3.5. Multi and interdisciplinary approach*

The use of multi or interdisciplinary approaches in these architectures are highly efficient and reduces costs and speeds up the design process. These types of architectures are closely related to various fields such as biological, materials, psychological science, electrical, mechanical, environmental engineering and it is recommended to use these disciplines more than ever in the early stages and during the design process.

### *3.6. Quantitative analytical and numerical investigations*

Designs based on nature and living beings are relatively new and lack quantitative studies. Quantitative investigation of effective features in these types of architectures can help specialists to obtain high performance design. Some of these features are level of humidity, noise, air conditioning rate, CO2 level, temperature, daylight, biodiversity level, available and visible green space area, type and quantity of natural materials, color and contrast, focal length in perspective, and fractal dimension in complexity. However, for some characteristics of environmental psychology such as sense of belonging, realization of personal identity and aesthetics requires both quantitative and qualitative investigations (Figure 22).

## Author Contributions

Conceptualization, F.S. and R.M.; Literature Review, F.S. and S.M.; methodology, F.S.; software, F.S.; validation, F.S., S.M. and R.M.; formal analysis, F.S.; investigation, F.S. and S.M.; writing—original draft preparation, F.S.; writing—review and editing, F.S and S.M.; visualization, F.S. and S.M.; supervision, R.M.; All authors have read and agreed to the published version of the manuscript.

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The data generated or analyses in this study are included within the manuscript. All data cited in this review are available from the sources referenced in the text.

## Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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