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Biomimetic Approach for Building Envelope Adaptation in Hot and Dry Regions

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Abstract: The term biomimicry comes from the Greek words "bios", meaning life, and "mimesis", meaning to imitate. Since the biomimetic approach has resulted in many successful examples over the years, a literature review shows how successfully biomimetic architecture could respond to mitigating climate change by examining the biomimicry approach for building envelope adaptation. To demonstrate the significance of biomimicry in fulfilling an adaptive building envelope, the paper will begin by explaining the biomimicry approach and building envelope adaptation methods. Additionally, it showcases some successful architectural examples that were able to enhance energy efficiency, highlighting how those examples were able to combat climate change through observing their adaptive strategies found in nature and the application of those strategies to buildings to enhance energy efficiency and contribute to resilience and sustainability. A hypothetical framework that follows the biomimetic principles for adaptive building envelope theories will also be proposed. The proposed framework will be applied to an office building in a hot and dry area, inspired by the adaptive strategies of cacti. Finally, to assess the efficiency of the suggested framework in achieving climate change mitigation, the paper will conclude by evaluating the outcomes through software simulation, measuring its potential in maintaining adaptive strategies within the building envelope, and how it affects the building's overall energy performance.

***Keywords*:** biomimicry, climate change, building envelope, adaptation

1. Introduction

With the climate changes that the world is facing, especially over the past three years, the vast urban growth, consumption, and emissions tend to rise rapidly, where buildings contribute 60 to 80% of the energy consumption and are responsible for 75% of the carbon emissions [1, 2]. A new path is needed to attain more resilient solutions and develop more sustainable strategies to reduce energy demands and mitigate carbon emissions.

The main question is: can the biomimetic approach to building envelopes be one of the methods to reduce and adapt to climate change?

Therefore, the main goal of this paper is to show the significant contribution that biomimetic building has made to the adaptation and mitigation of climate change and to raise awareness of the importance of biomimicry architecture in reducing the devastating effects of such a crisis. The necessity of incorporating the biomimetic approach and methods in

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building, as well as their impact on the environment, is also covered in the paper.

It is hoped that the biomimicry approach can foster sustainable green cities. Nature can serve as a platform where we can learn to reduce carbon dioxide emissions.

Accordingly, the paper will begin by addressing the biomimicry approach and show some examples of buildings that employed it to adapt to climate change, highlighting the natural domains they were inspired by, the challenges they resolved, and the outcomes that they attained in terms of energy efficiency. The paper will also propose a framework for the steps observed from studying the case studies. The same framework will then be applied to the façade of an office building in a hot and dry climate that resembles cactus plants, with software simulation used to compare the outcomes between the traditional or original façade and the biomimetic one.

Finally, the paper concludes and recommends the ability of biomimicry for building envelope adaptation and climate mitigation.

2. Biomimicry and building envelope adaptation

Building envelopes are like nature's skin, where they perform an almost similar function. To retain thermal comfort, they continue to act as a shield to keep the inside safe from the outside. They both experience similar challenges with the environment and create strategies to mitigate their impact and adapt to their surroundings. A variety of environmental variables impact both buildings and nature. These variables include temperature as well as wind, humidity, drought, precipitation, and others.

There are three main adaptive levels (morphological, behavioral, and physiological), as shown in Figure 1. For instance, morphological changes have to do with form, design, structure, etc. Cactus, for example, goes through physical change. Cacti can change their morphology to cope with harsh conditions by developing ribs, spines, and spherical shapes.

On the other hand, behavior-based adaptations are those that help an organism interact with its environment to survive. Finally, physiological adaptation is concerned with chemical and physiological processes, which constitute the third stage of adaptation to maintain equilibrium.

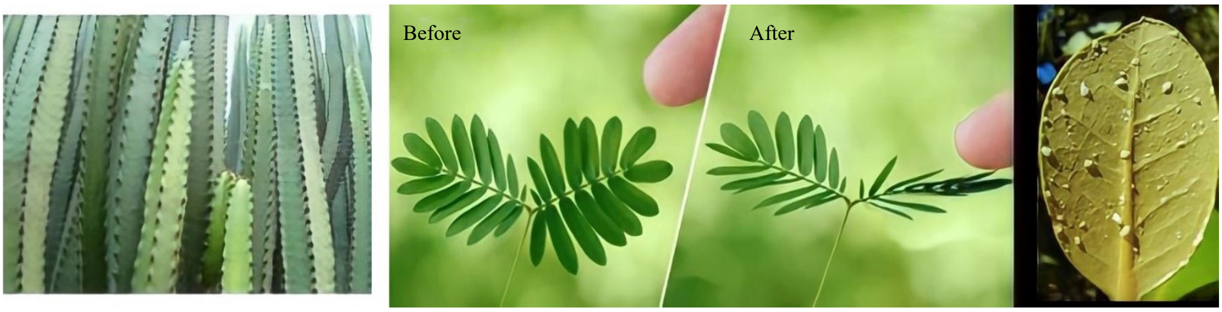

Figure 1. Examples of morphological, behavioral, and physiological adaptations

3. Biomimetic building envelope adaptation examples

What if we could mimic the way nature produces materials—for example, taking CO_2 from the air and turning it into biomass—like trees do?

In the architectural field, the building sector has the potential for climate change mitigation. Several examples apply the biomimetic approach.

Table 1 illustrates five of the most successful worldwide building examples that followed the biomimetic approach within the building envelope, structure, and form to fulfill energy efficiency, from Europe, Australia, Asia, and Africa. The following section summarizes the biomimetic approach within those buildings in terms of source of inspiration, biomimetic application, problem solving, and energy efficiency.

The Swiss Re-Gherkin Tower in London, United Kingdom [3, 4] draws inspiration from the Venus flower basket and utilizes pipes for heating in winter and cooling in summer. Allowing natural lighting contributed to energy savings of up to 50%, and the use of the same mechanism of the glass sponge to freshen the air and windows allowed natural lighting.

On the other hand, in Asia, the Esplanade Theatre in Singapore [5, 6], mimicking the durian plant skin in protecting its seeds, was able to allow sunlight penetration and radiate heat, thereby fulfilling energy reduction by 30% and providing 45% natural lighting.

Also, the National Aquatic Center in Beijing, China [7] was inspired by the structural system of the crystalline system of bubbles and the use of the ethylene tetrafluoroethylene (ETFE) material, which filters sunlight, is self-cleaning and durable, and achieves a 30% energy reduction while capturing solar energy. The project also achieved a 55% reduction in artificial lighting. Natural ventilation and the use of ETFE saved energy equivalent to covering the building with photovoltaic panels (PV) panels.

Inspired by the ventilation techniques of the termite mounds, the Eastgate Building in Harare, Zimbabwe [8] utilizes the outside air, which is either warmed or cooled by the building mass, depending on which is hotter. By fulfilling natural lighting and natural ventilation, the building used 35% less energy for temperature regulation compared to similar-sized buildings; the use of PV panels, water recycling, and waste management fulfilled 10% less of the energy used.

Finally, at Council House 2, Melbourne, Australia [9], as shown in Figure 2, the tree bark-inspired eastern façade is considered a second protective layer and consists of two overlapping layers of perforated metal with polycarbonate walling and fixed metal louvers. The building achieved energy savings of 82%, saved 65% of natural lighting and natural ventilation, and provided nearly 100% fresh air. The use of PV panels, resulted in a significant decrease of 72% in water consumption, together with the incorporation of waste recycling facilities that utilize recycled timber as a construction material.

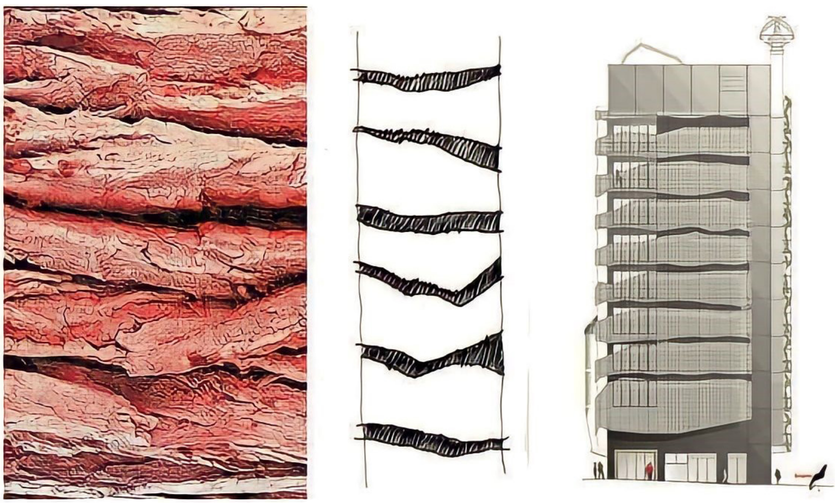

Figure 2. The tree bark that inspired the eastern façade [10]

The Council House 2 building in Melbourne was inspired by passive ventilation methods and temperature regulation observed in termite mounds. Termite mounds can maintain a constant temperature inside despite the significant temperature variations outside because cool wind is drawn into the base of the mound via channels and the 'coolth' is stored using wet soil. As the air warms, it flaws upward and out of the mound via vents, as shown in Figures 3 to 5.

Figure 3. Termite mound and physiology working process as an inspiration for Council House 2 building [10]

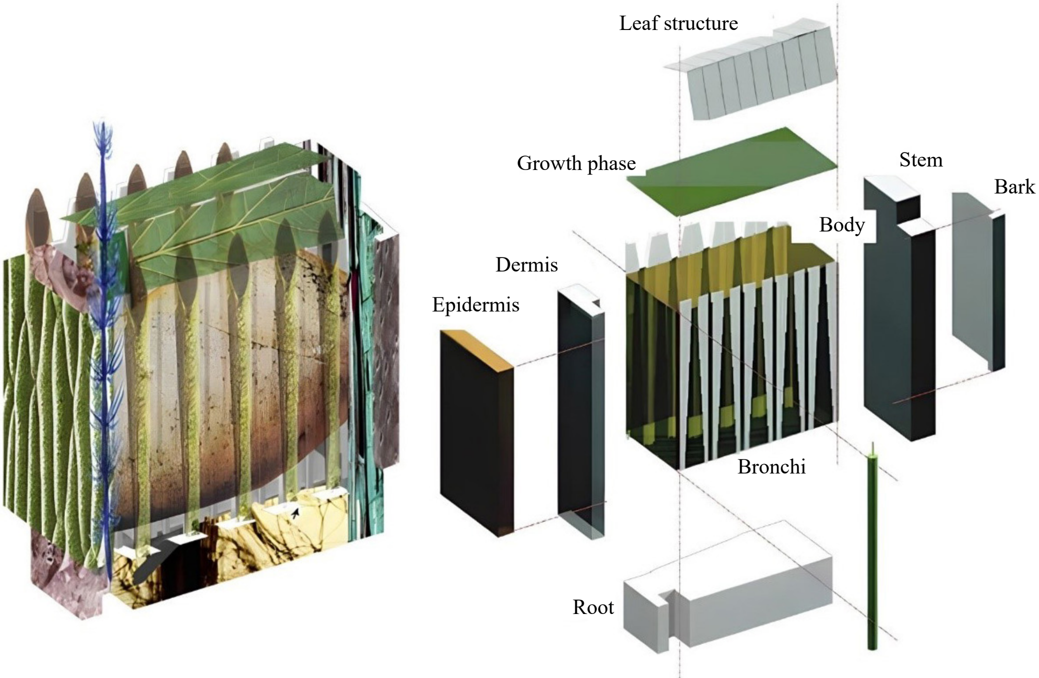

Figure 4. Natural analog concept sketching proposal for Council House 2 showing overlapping layers of the façade [11]

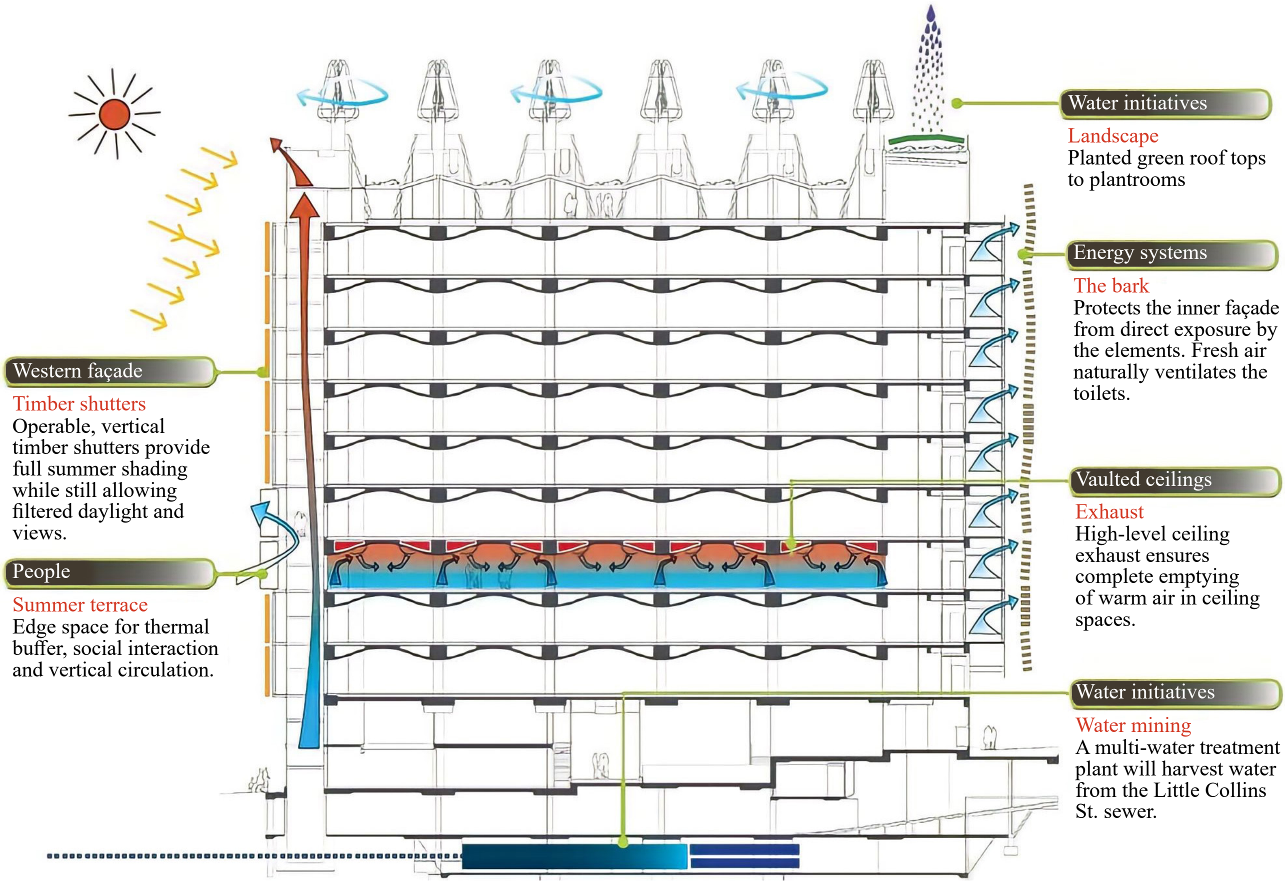

Figure 5. Illustration of the summer mode at the Council House 2 building [12]

The eastern façade of the building was created to function as a protective layer, housing the wet area and service core while also facilitating natural ventilation. Its design was inspired by tree bark, both for its visual appeal and its purpose in protecting trees.

The building resembled a living organism; its leaf-like design was intended to purify and filter air, as well as gather energy and release heat. To provide important gases, exhaust duct spaces were modeled like the bronchi of a tree. The concept was implemented on the north and south façades of the building, where it was transformed into functional air ducts. The root and stem concepts, which served as the basic core structure and arterial volume, provided a network for reticulated fluids and gases to manage heating, cooling, and ventilation within the building. These concepts were also used to inspire sewer mining for non-potable water.

The epidermis serves as the exterior skin of the structure, protecting it from the elements and regulating outdoor temperature.

Biomimicry was employed throughout the entire structure in various ways. The high thermal mass wavy vaulted ceiling is constructed of precast concrete, which accumulates additional heat during the day and releases it at night through purging. The lofty height of the exhaust ceiling ensures complete emptying of warm air in the ceiling space.

To support air movement, ventilation stacks were used on the building's northern and southern façades. Each floor received 100% of the outside air through vertical ducts that were connected to chilled ceiling panels, beams, and panels, and cold water was used to remove any excess heat from the building's interior air.

The building employs chilled beams, chilled ceiling panels, and evaporative cooling from the shower towers on the south façade to cool water and air.

Table 1. Biomimetic examples: The Waterloo International Terminal in London, United Kingdom; the Swiss Re-Gherkin Tower in London, United Kingdom; the Esplanade Theatre in Singapore; the National Aquatic Center in Beijing, China; the Council House 2, Melbourne, Australia; and the Eastgate Building in Harare, Zimbabwe

Location	Project		Biomimetic inspiration	Biomimetic application	Problem solved	Energy efficiency
Europe	Swiss Re-Gherkin Tower in London, United Kingdom [3, 4]		Venus flower basket	The use of pipes for heating in winter and cooling in summer. Allowing natural lighting.	Energy efficiency	Energy savings of up to 50% with the use of the same mechanism as the glass sponge to freshen the air. Windows allow natural lighting.
Asia	Esplanade Theatre in Singapore [5, 6]		Durian plant	Mimicking the durian plant skin to protect its seeds.	Sunlight penetration and radiating heat.	Energy reduction by 30%, providing 45% natural lighting.
Asia	National Aquatic Center in Beijing, China [7]		Honeycomb and bubbles	Inspired by the structural system of the crystalline system of bubbles.	The ETFE material filters sunlight, is self-cleaning, and is durable.	A 30% reduction in energy consumption was achieved through solar energy capture, and artificial lighting was reduced by 55%. Natural ventilation and the use of ETFE saved energy equivalent to covering the building with PV panels. Water recycling was implemented.
Africa	Eastgate Building in Harare, Zimbabwe [8]		Termite mounds	Inspired by the ventilation techniques of the termite mounds.	The outside air drawn to the building is either warmed or cooled by the building mass, depending on which is hotter.	Natural lighting and ventilation account for 35% of the energy needed for temperature regulation. Additionally, the use of PV panels, water recycling, and waste management results in a 10% reduction in energy consumption compared to similar-sized buildings.
Australia	Council House 2 in Melbourne, Australia [9]		The tree	The bark-inspired eastern façade, considered a second protective layer.	It consists of two overlapping layers of perforated metal with polycarbonate walling and fixed metal louvers.	Energy savings reached 82%, natural lighting was saved by 65%, natural ventilation was saved by 65%, and it provided nearly 100% of fresh air. The usage of PV panels resulted in a 72% reduction in water use, and waste recycling facilities were utilized, incorporating recycled timber as a building material.

3.1 *Case study analysis criteria*

The application of the complicated process of building envelope adaptation fulfills various purposes, including regulating heat, light, water, and airflow, depending on the environmental challenge that needs to be addressed. The adaptive level may involve morphological, behavioral, or physiological changes. Depending on the output to be addressed, such as heating or cooling, daylighting or shading, and the strategy for heat regulation, visual comfort, or indoor air quality, response capabilities vary—covering loss, gain, maintenance, or exchange. Moreover, the type of control, whether manual, intrinsic, or extrinsic, plays a role [13]. The mechanism can be mechanical, chemical, electrical, pneumatic, hydraulic, and others [14]. The action, involving phase change, form change, color change, folding, etc., is another consideration. The scale of application may encompass windows, walls, roofs, fenestrations, or the entire structure [15, 16]. Figure 6 summarizes the previous classifications.

Environmental challenges	• Light, heat, water, and air
Adaptive level	• Morphological, behavioral, and physiological
Input	• Solar radiation, perception, wind, and humidity
Output	• Cooling, heat release, absorption, shading, daylighting, and ventilation
Strategy	• Heat control, daylight control, and air quality control
Comfort goal	• Lose, gain, maintain, and exchange
Control type	• Exchange, intrinsic, and extrinsic
Mechanism	• Chemical, electrical, mechanical, penumatic, hydraulic, and fluid transport
Action	• Phase change, shape change, color change, transparency change, folding, sliding, rotating, pivoting, air flow, and water flow
Scale of application	• Windows, wall, roof, and fenestration

Figure 6. Classification of factors influencing building envelope adaptation [17]

The case studies in the previous section were further analyzed according to their level of fulfillment of the building envelope adaptation framework, as shown in Table 2.

Table 2. Case studies according to building envelope adaptation and biomimetic adaptation

		Swiss Re-Gherkin Tower	Esplanade Theater	National Aquatic Center	Eastgate Building	Council House 2
Environmental challenge	Light	✓	✓	✓	✓	✓
	Heat	✓	✓		✓	✓
	Water			✓	✓	✓
	Air	✓		✓	✓	✓
Adaptive level	Morphological	✓	✓	✓	✓	✓
	Behavioral				✓	✓
	Physiological			✓	✓	✓
Input	Solar radiation	✓	✓	✓	✓	✓
	Perception				✓	✓
	Wind	✓			✓	✓
	Humidity					✓
Output	Cooling			✓	✓	✓
	Heat release				✓	✓
	Absorption					
	Shading		✓	✓	✓	✓
	Daylighting	✓	✓	✓	✓	✓
	Ventilation				✓	✓
Strategy	Heat control	✓	✓	✓	✓	✓
	Visual comfort	✓	✓	✓	✓	✓
	Indoor air quality	✓		✓	✓	✓
Comfort goal	Lose	✓	✓	✓	✓	✓
	Gain	✓			✓	✓
	Maintain				✓	✓
	Exchange				✓	✓
Comtrol type	Extrinsic				✓	✓
	Intrinsic	✓	✓	✓	✓	✓
	Exchange					
Mechanism	Chemical			✓		
	Electrical					
	Mechanical				✓	✓
	Hydraulic				✓	✓
	Pneumatic			✓		
Action	Phase change or form change				✓	✓
	Color change					
Scale of application	Windows				✓	✓
	Walls			✓	✓	✓
	Fenestration				✓	
	Roof				✓	✓
	Whole building	✓	✓		✓	

From the previous examples, we could deduce the potential of biomimicry in architecture and its contribution to environmental and natural conservation. Also, those examples show awareness of the importance of the biomimetic approach on different levels. Some examples only applied to the organism level, but other examples were more successful in engaging the behavioral level. According to the previous analysis, Eastgate and Council House 2 appear to be the two buildings that best satisfy the majority of building envelope adaptation parameters.

4. Proposed case study

In Egypt, as far as the authors' knowledge, there are no buildings that applied the biomimetic approach; only on the conceptual stage, some architecture students followed this approach.

Most of the energy consumption in the building sector is associated with indoor air conditioning, cooling, and lighting. Therefore, the following case study is a conceptual case of an office building, trying to integrate the biomimetic approach on both the organism level and behavioral level to enhance the building's energy efficiency in terms of thermal comfort, sunlight hours, solar radiation, and glare.

4.1 *Inspiration*

Cactus plants, shown in Figure 7, are protected by spines against natural enemies. They can gather or direct water to the roots. They reduce temperature and water loss by reflecting sunshine, aiding in the evaporative cooling process. They also capture a layer of cold air next to the stem. Cacti have ribs and tubercles that enable them to grow and shrink in response to a water supply. After rainfall, the ribs allow water to drain to the roots while also shading the stem. Cacti's globular form gives them a larger volume and less surface area, which prevents water evaporation and increases water storage. Water does not evaporate as quickly in some cacti species because the water absorbed through the stem changes into a mucilaginous material.

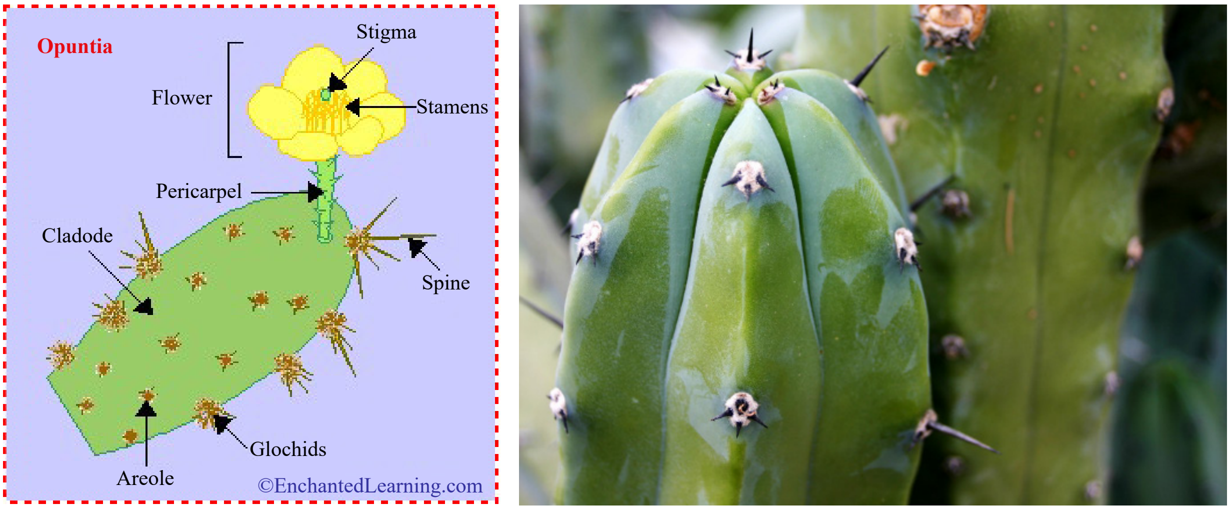

Figure 7. Cactus plant and its anatomy taken as inspiration [18]

4.2 *Translation process*

Following the same process as in the previous section, the cactus is an inspiration. It is a renowned model in hot-dry regions, drawing inspiration from its dynamic adaptation of stomatal opening and closing mechanisms on the behavioral level. Additionally, it features self-shading ribs and a globe configuration as morphological adaptations, along with cooling ribs as physiological adaptations.

Translating those adaptive features to the building envelope is demonstrated by creating a curved corrugated building envelope, as shown in Figure 8.

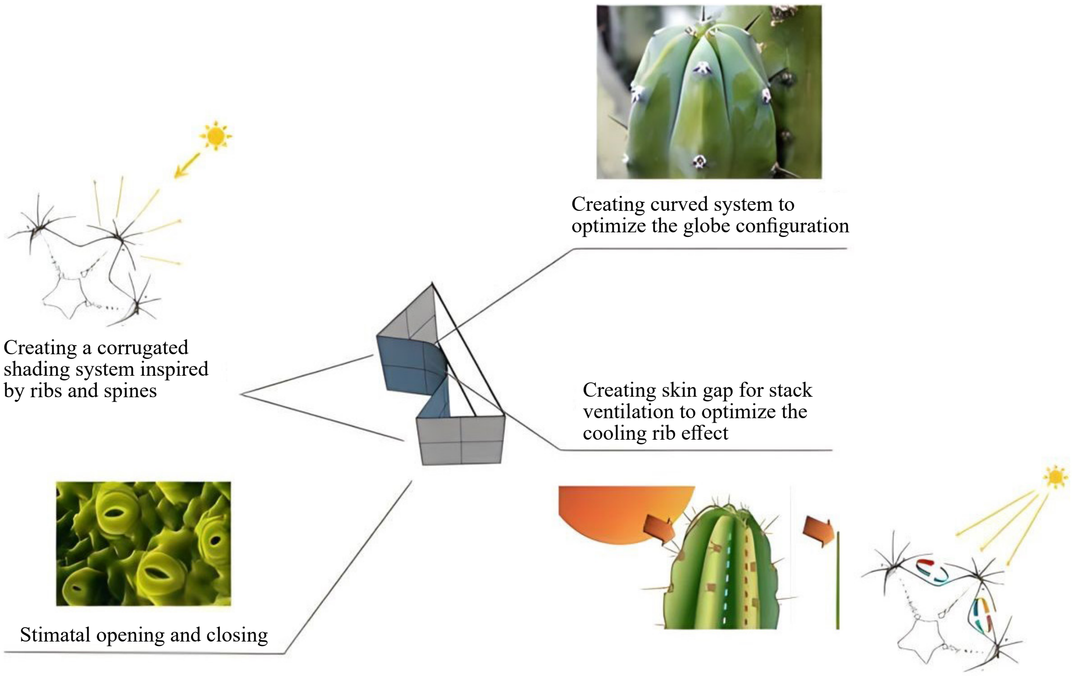

Figure 8. Building envelope component inspiration [17]

Duplicating the proposed component along the x-axis and y-axis to act as a folding component that can expand and contract, triggered by solar gains and temperature differences, provides a dynamic and responsive architectural solution.

The photochromic (PC) glazing with specifications—solar heat gain coefficient (SHGC) = 0.508, visible light transmittance (VLT) = 0.595, and thermal transmittance (U-value) = 1.786 W/m²K—alongside shape memory alloys for shades with SHGC = 0.396 and thermal transmittance (U-value) = 1.786 W/m²K were utilized. The angles vary from 10° fully closed to 60° fully opened. Building performance simulation is done on Rhino3D using the Grasshopper, Ladybug, and Honeybee plugins, as they are suitable for the conceptual phase. Figures 9 to 10 illustrate the folding component mechanism and its application on the façade.

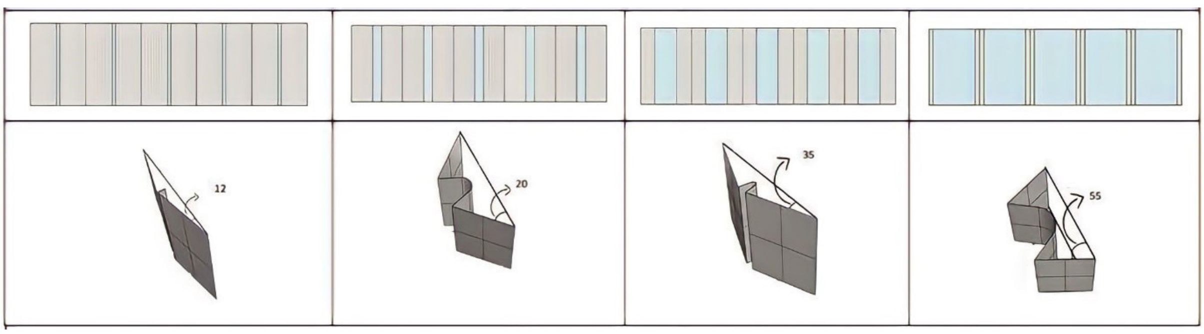

Figure 9. Module opening and closing mechanism from fully closed (left) to fully opened (right) [17]

Figure 10. Different façade configurations [17]

4.3 *Simulation process*

Environmental performance analysis for Cairo's four seasons is carried out. Building performance simulation is carried out on Rhino3D using the Grasshopper, Ladybug, and Honeybee plugins because it is appropriate for the conceptual stage.

4.4 *Results*

The limited adjustability of the standard shading system poses challenges in adapting to dynamic sun movements. However, as observed, the proposed biomimetic component demonstrates significant efficacy in accommodating variable sun angles and intensity throughout the year. Each portion and floor of the building respond uniquely, allowing repositioning as needed. It fulfills thermal comfort requirements, ensures sufficient solar radiation, and reduces glare with varying angles between 12 and 25 degrees in summer, 17 and 35 degrees in spring, 25 and 45 degrees in fall, and 27 and 55 degrees in winter. Figures 11 to 13 illustrate the resulting outcomes.

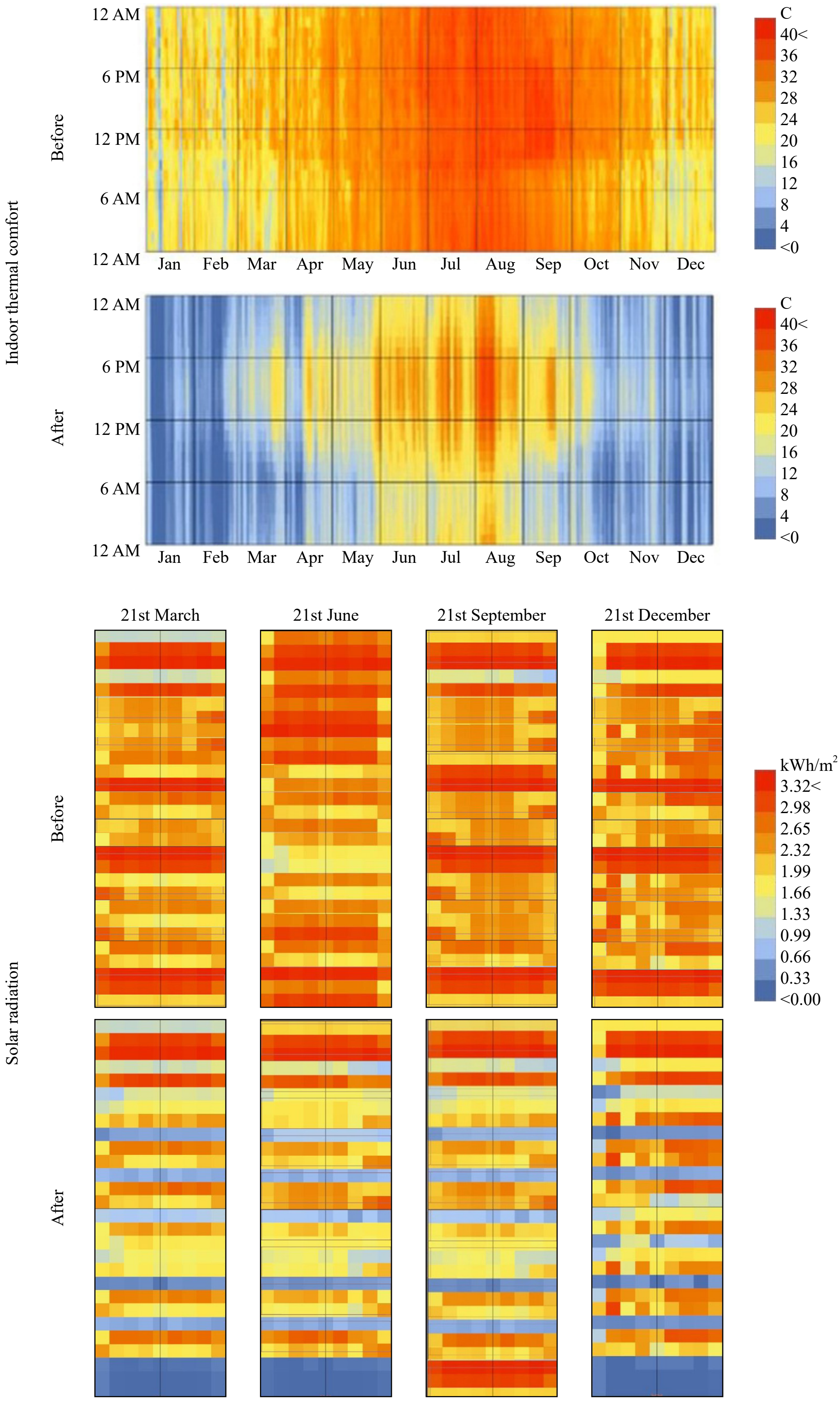

Figure 11. Solar radiation output [17]

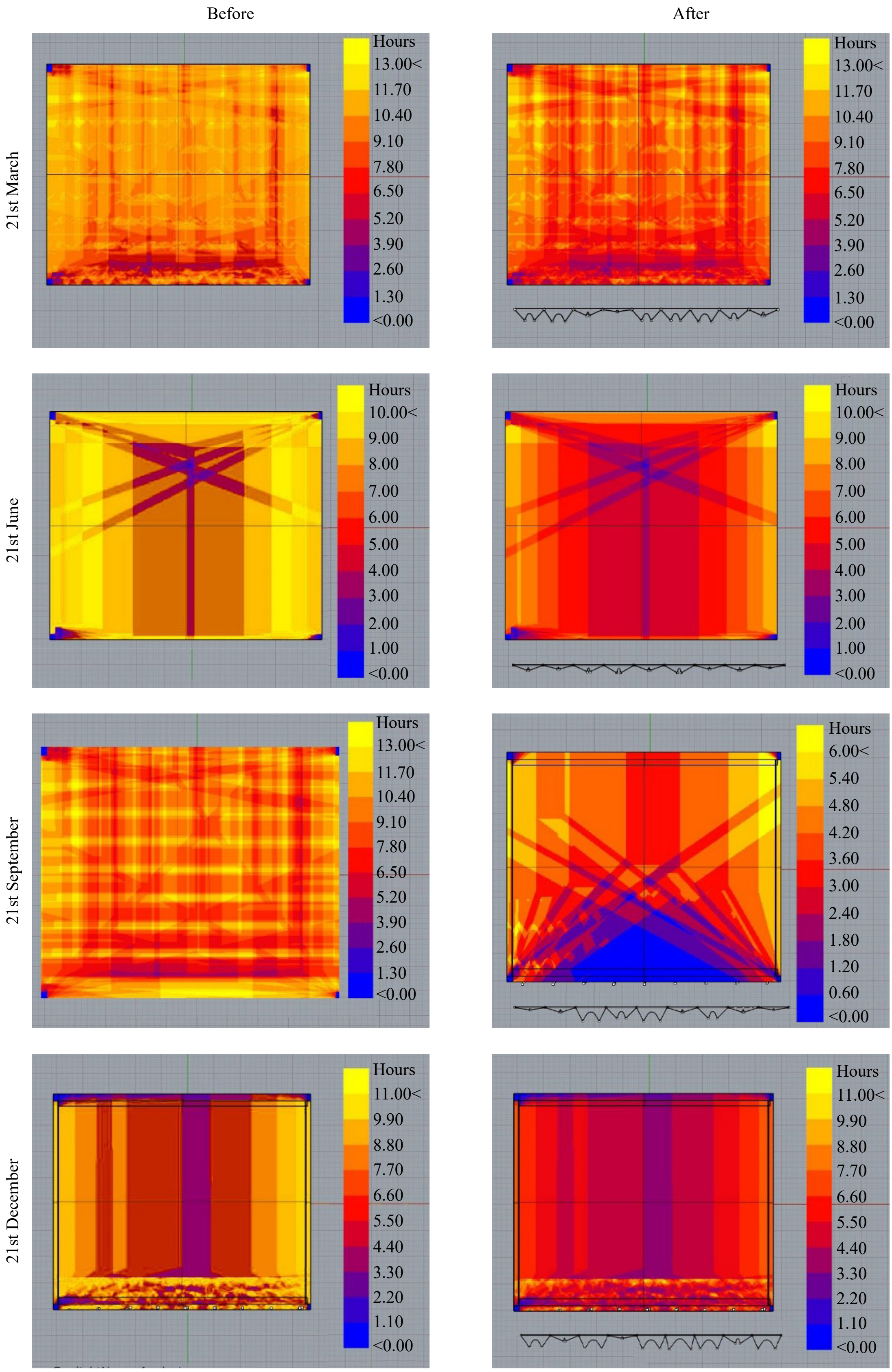

Figure 11. Sunlight hour comparison [17]

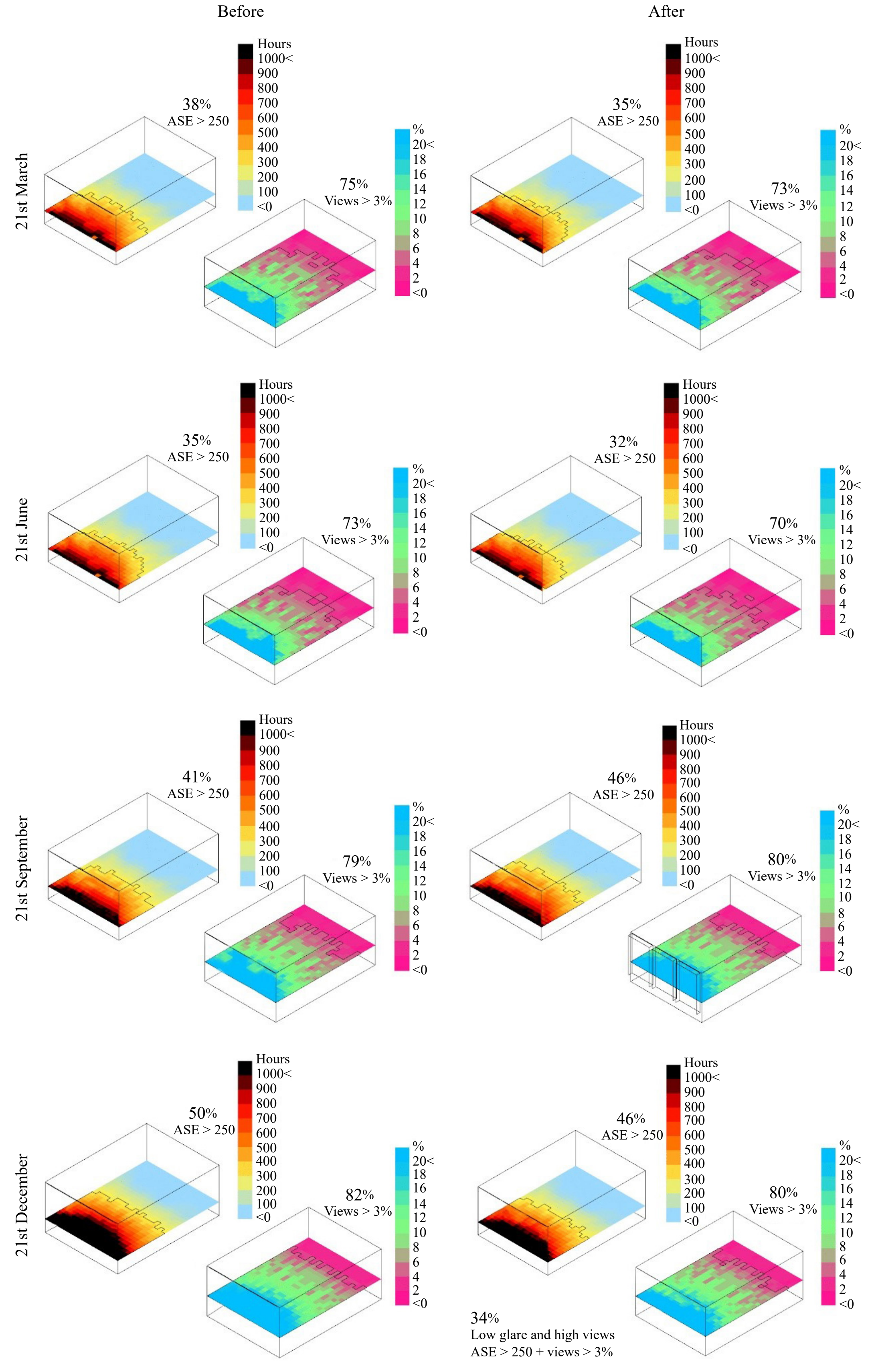

Figure 13. Glare and view comparison [17]

5. Conclusions

The climate change we are facing has evolved a new "normal" and changed the perception of the environment, prompting a re-thinking of innovative solutions. This involves addressing biomimicry goals such as resource efficiency, waste reduction, and fewer carbon emissions, along with the use of solar energy, among other strategies.

Resetting mindsets and embracing the biomimetic approach are crucial for developing innovative and adaptable solutions. This approach underscores the overlap between nature and architecture, emphasizing the numerous benefits of staying connected to nature.

Biomimicry emerges as a significant approach to attaining sustainability, valuing nature as a model, mentor, and measure. Drawing inspiration from nature is leading to new adaptive actions that address the challenges we are currently facing. The discussion on biomimetic architecture includes examples related to sustainability, energy efficiency, structural efficiency, waste and water management, light regulation, and natural ventilation. This analysis aims to highlight the integral link between the biomimetic approach, climate change, and the mitigation of greenhouse gas emissions.

The previous literature review discussing biomimicry and building envelope adaptation, case study analysis, and the practical case study could be summarized in Figure 14, which could act as a guide when adopting the biomimetic approach for producing an adaptable building envelope.

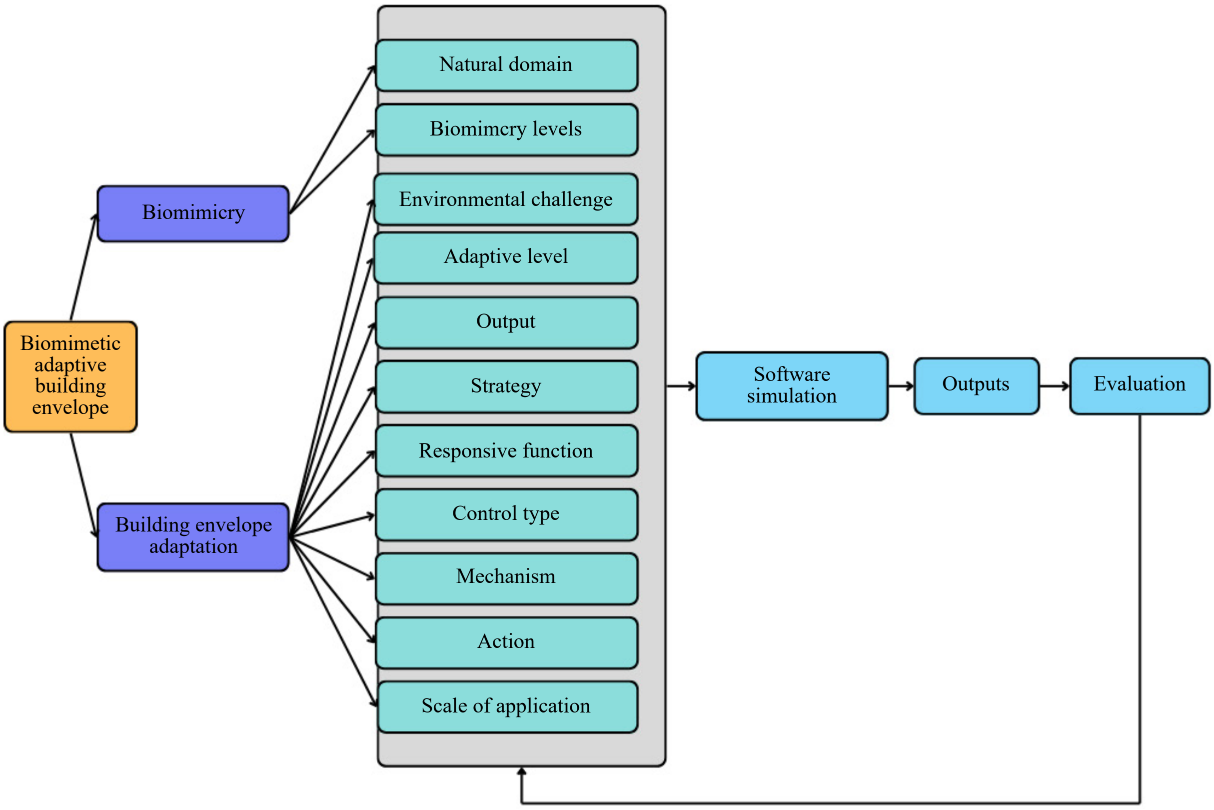

Figure 14. Summary of guidelines for the application of the biomimicry approach to building envelope adaptation

6. Recommendations

It is recommended to integrate the biomimetic approach in the early design stages, and the academic curriculum could contribute to the development of sustainable, environmentally friendly architecture. Further enhancements could be made to the proposed shading system. However, in this paper, the scope was conceptual and in the stage of idea generation. Also, by choosing other nature domains, different levels of adaptations, and different orientations, a possible extension could be proposed following the same approach.

Conflict of interest

The authors declare no conflicts of interest in any form.

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