Journal of Architectural Design, Engineering, and Science
Vol. 01, Issue 1, p. 29-39, June 2024

Criteria for Implementing Passive Strategies Utilizing a Biomimicry Approach in Vertical Housing Design

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Abstract

The issue of climate change and global warming has emerged as a significant concern confronting the world over the past decade. The substantial increase in temperatures observed during the last 10 years has led to a nearly threefold rise in sea levels compared to the period from 1901 to 1971. This escalation has precipitated natural calamities such as floods, landslides, extreme weather events, and alterations in rainfall intensity and patterns. Greenhouse gases, notably CO2, CH4, and N2O, generated by various energy-intensive activities, serve as primary drivers of global warming and climate change. Concurrently, buildings, including both residential and commercial structures, represent approximately 30-40% of global energy consumption and contribute over 30% of carbon emissions worldwide, particularly in urban settings. This surge in urbanization, particularly in major cities, not only escalates population density but also amplifies energy consumption. In tropical climates, energy usage in buildings predominantly caters to achieving thermal comfort, with air conditioning and lighting constituting significant portions of architectural design considerations. Strategies to address energy challenges in buildings range from enhancing energy efficiency to embracing renewable energy sources. It is imperative to undertake diverse initiatives to tackle these challenges without exacerbating environmental burdens that fuel climate change. Biomimicry, which involves emulating nature's designs and processes, offers a promising solution. Over the course of 3.8 billion years, millions of species have evolved and adapted to their environments, offering invaluable lessons on sustainability and resilience. By drawing inspiration from nature's solutions, humans can mitigate adverse impacts such as fossil fuel consumption and environmental pollution. Nature has perfected efficient systems and mechanisms to address myriad environmental challenges, including those posed by climate change. This research endeavors to explore various biomimicry approaches to enable buildings to harmonize with their surroundings and mitigate potential impacts through passive strategies in vertical residential designs tailored for tropical regions. Through the utilization of literature review methods and precedent studies, this research endeavors to formulate passive design criteria imbued with a biomimicry approach tailored for flat house design.

Keywords: Biomimicry, Passive Energy Strategy, Residential, Vertical Housing

1. Introduction

Climate change has emerged as a paramount global challenge, posing threats to the environment, public health, and economies worldwide (D'Agostino et al., 2022). Defined by Ekung et al. (2022), climate change denotes alterations in Earth's climate conditions stemming from variations in atmospheric elements attributable to human activities. The magnitude of climate change is influenced by factors such as greenhouse gas emissions, deforestation rates, and the ecosystem's response to climatic shifts. With projections indicating substantial changes in climate variables in the 21st century and the observed impacts of extreme weather events, adapting to climate change is poised to become an urgent imperative, particularly for urban areas in forthcoming decades (Carter et al., 2015).

Continued global warming is inevitable unless standards and policies, sanctioned by authorized bodies, are implemented and adhered to by influential industries (Y. Chen, 2015, cited in Imani (2020) Environmental considerations have progressively been integrated into development agendas, giving rise to the concept of 'sustainable development' (Lélé, 1991). As per Tolba (2013), sustainable development is interchangeably referred to in literature as "ecologically sustainable development" or "environmentally sound development".

Derived from various terminologies, the concept of ecologically sustainable design, commonly referred to as "ecologically sustainable design (ESD)," has emerged. ESD aims to foster energy-efficient buildings that enhance aesthetic appeal, comfort, and cost-effectiveness (GhaffarianHoseini, 2012). Despite the plethora of approaches towards achieving sustainability, such as the utilization of alternative building materials, integration of renewable energy sources, and implementation of recycling systems, experts underscore the paramount importance of energy efficiency within the built environment, particularly in buildings (Imani, 2020). Collectively, these approaches converge towards the shared objective of mitigating buildings' adverse environmental impacts, with a notable emphasis on enhancing their energy performance.

Conversely, the phenomenon of urbanization in major cities exacerbates population density, inevitably leading to heightened energy consumption. Castro-Alvarez et al. (2018) highlight that energy consumption per square meter tends to be higher in residential buildings compared to public or commercial counterparts, registering at 0.71 gigajoules per square meter. This underscores the considerable potential within the building sector for energy conservation efforts to curtail energy demand, particularly in urban environments (Shukla & Sharma, 2018).

The building sector is responsible for approximately 40% of global energy consumption and contributes over 30% of CO2 emissions (Pérez-Lombard et al., 2008). Within this sector, residential and commercial buildings collectively account for 20-40% of global energy usage, with nearly half of this energy consumption attributed to Heating, Ventilation, and Air Conditioning (HVAC) systems (Pérez-Lombard et al., 2008). As highlighted by Hassan & Al-Ashwal (2015), inadequately designed and operated buildings significantly compromise the thermal performance of their envelopes, leading to increased cooling and heating loads.

Poor passive thermal design exacerbates this issue, with energy consumption for HVAC systems, including heating, ventilation, and air conditioning, reaching approximately 68% (Hassan & Al-Ashwal, 2015). Consequently, energy-saving design strategies, encompassing both passive and active approaches, have been introduced to optimize energy usage in buildings and mitigate the impacts of climate change. Among these strategies, passive design has emerged as a particularly effective means of enhancing energy efficiency, fostering sustainable buildings, and reducing costs (Elaouzy & El Fadar, 2022).

Passive design entails architectural practices that leverage natural resources such as sunlight, wind, and solar paths to achieve thermal comfort, minimizing reliance on mechanical heating and cooling systems (Hassan & Al-Ashwal, 2015). At its core, passive design principles prioritize the utilization of available natural resources in the surrounding environment to attain indoor thermal comfort (Hassan & Ramli, 2010).

Nature serves as a significant source of inspiration, owing to the remarkable adaptability of biological systems to environmental conditions (Fecheyr-Lippens & Bhiwapurkar, 2017). Biological organisms employ diverse strategies to address challenges within their habitats, exemplified by the elaborate dwellings constructed by animals like termites and ants. Unlike human-built structures, these natural habitats seamlessly integrate with the surrounding ecosystem. Their intricate and complex construction enables them to effectively address environmental challenges such as ventilation, temperature regulation, structural integrity, escape routes, trapping mechanisms, specialized storage compartments (e.g., for food), and various other functionalities. Remarkably, these living organisms construct their habitats with minimal energy expenditure within their respective ecosystems.

Biomimicry presents a promising avenue for addressing these challenges. Over the course of 3.8 billion years, an estimated 10-30 million species have evolved and adapted, demonstrating solutions that align with human objectives while minimizing adverse impacts such as fossil fuel consumption and environmental pollution (Aanuoluwapo & Ohis, 2017). Nature has evolved efficient systems and processes to tackle various problems, including those related to climate.

This research endeavors to address several key issues pertaining to mitigating the impacts of climate change, emphasizing the need for design strategies that yield positive environmental outcomes. Specifically, the study aims to identify passive design elements conducive to energy conservation, particularly in the realms of natural lighting and ventilation within residential buildings, and to explore how principles of biomimicry can be integrated into passive design strategies to enhance these aspects.

The primary objective is to develop design criteria for flat housing units by leveraging passive design principles through a biomimicry lens as a means of conserving energy, with a specific focus on enhancing natural lighting and ventilation. Additionally, the biomimicry approach will be employed to address water management and promote the utilization of renewable energy sources.

2. Methodology

This research was conducted qualitatively in two stages through extensive literature review and analysis. The initial stage involved synthesizing a wide range of scholarly works to develop comprehensive design criteria, followed by a detailed examination of precedent studies. The literature review encompassed pertinent topics related to the implementation of passive design strategies and the integration of biomimicry principles in architectural design. Specifically, the review focused on apartment building typologies that have successfully incorporated various passive design strategies with a biomimicry approach. Through meticulous analysis of the literature and precedent studies, refined passive design criteria informed by biomimicry principles were identified and recommended for vertical housing applications. The methodological framework employed in this research is illustrated in Figure 1 below.

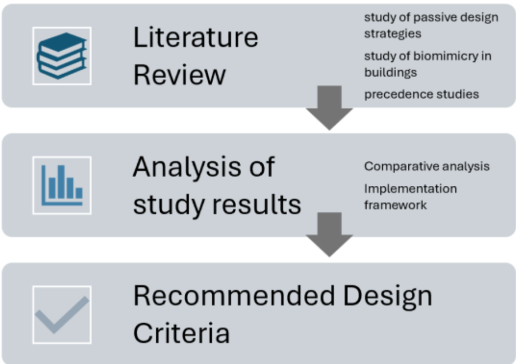

Figure 1. The methodological framework

3. Passive Design Strategy

Passive strategies encompass several key parameters that demand consideration (Gunawan, 2012; Loo et al., 2021). These parameters include building characteristics pivotal to the energy performance of buildings, notably building shape, building insulation (both material and thickness), window-to-wall ratio (WWR), and window glazing. Moreover, the building envelope assumes a critical role in ensuring thermal comfort and optimizing energy performance, particularly in high-rise buildings situated in tropical climates (Loo et al., 2021). As highlighted by Chen et al. (2020), elements such as building shape and orientation, in conjunction with building insulation (material and thickness), WWR, and window glazing, significantly influence energy performance. Similarly, the utilization of building envelopes to enhance thermal comfort and energy performance, particularly in high-rise buildings within tropical climates, is contingent upon factors such as the components of the roof, external walls, glazing, shading, as well as the orientation and configuration of the building (Aflaki et al., 2015).

To elucidate the underlying principles and objectives of passive design, a comparative analysis was conducted on definitions provided by seven authors. The comparisons revealed that the core principle of passive design entails leveraging climatic conditions, natural elements/energy, and environmental context within building features to furnish or sustain thermal comfort within the structure, as depicted in Table I.

TABLE I. COMPARISON OF DEFINITIONS OF PASSIVE DESIGN

Author	Principle			Purpose	
	Adapt to climate, natural elements, environmental context	*Minimizing reliance on mechanical equipment*	*Embracing an energy-saving and environmentally friendly approach*	*Ensuring comfort, within the building interior*	*Reduction of energy consumption and enhancement of energy efficiency*
Gunawan (2012)		✓		✓	✓
Altan et al. (2016)	✓	✓		✓	
Loo et al. (2021)	✓	✓	✓	✓	
A.Y. Freewan (2019)	✓			✓	✓
Oropeza-Perez & Østergaard (2018)	✓			✓	✓
Elaouzy & El Fadar (2022)	✓		✓	✓	✓
Juffle & Rahman (2023)	✓		✓	✓	✓

The comparative analysis of passive design definitions reveals that it is a design strategy leveraging natural elements and climatic conditions (e.g., sunlight, wind, water, land) to offer comfort, particularly thermal comfort, within indoor environments, while minimizing energy usage to reduce energy consumption in buildings.

From an analysis of ten recent literature pieces spanning the past decade, categories and sub-categories of passive design strategies were identified and summarized in Table II. Notably, in the category of window and fenestration characteristics (WWR, dimensions, area, placement position, shape, and opening configuration), unanimous agreement among authors underscores the significance of this strategy in passive design implementation. Similarly, the shadowing strategy category was identified in nine out of the ten literature sources, highlighting its importance.

Table II further illustrates a range of potential strategies through various subcategories, with natural ventilation exhibiting the most extensive array of sub-category strategies. The proliferation of research in this domain indicates the evolving and advancing nature of natural ventilation strategies, offering planners a multitude of alternatives to consider during the design process. Natural ventilation is widely regarded as a solution for low-energy buildings owing to its capacity for energy conservation, enhancement of human health, high durability, minimal noise, and low carbon dioxide emissions (Zhang et al., 2021).

These diverse categories and sub-categories are organized within the framework of strategy criteria depicted in Figure 2. This framework facilitates the implementation process by providing a structured approach for incorporating passive design strategies.

TABLE II. CATEGORIES AND SUBCATEGORIES OF PASSIVE DESIGN STRATEGIES

Categories	Sub-categories	Gunawan (2012)	Aflaki et al. (2012)	Altan et al. (2016)	Tataresta ghi et al. (2018)	A.Y. Freewan (2019)	Bhamare et al. (2019)	Loo et al. (2021)	Oluwatayo & Pirisola (2021)	HMNNC et al. (2023)
Orientation	Site orientation								✓	
	Building orientation	✓	✓	✓	✓			✓	✓	✓
Context and Microclimate	Type of buildings around the site	✓								
	Material in the context around the site	✓								
	Nature features around the site (vegetation, landscape, water features)	✓		✓	✓		✓			
	Landscape	✓		✓		✓	✓		✓	✓
	Water features within the site	✓		✓			✓			✓
Building Geometry	**Form and layout**	✓	✓	✓	✓			✓	✓	✓
	Dimension (thickness, length, height, area perimeter)	✓	✓	✓	✓			✓	✓	✓
	Interior space geometry							✓		
	Wall/partition layout							✓		
	Building corridors		✓		✓					
Material	Material, color, reflectivity of the building	✓		✓	✓			✓		✓
Daylighting		✓		✓	✓	✓		✓	✓	✓
Windows and Fenestration characteristics	**Windows and fenestration characteristics (WWR, dimension, areas, positioning, shape, and configurations of the opening)**	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Glazing type						✓	✓	✓	
Natural Ventilation	**Natural ventilation**	✓	✓	✓	✓	✓		✓		
	Cross ventilation	✓		✓				✓		
	Bernoulli's effect	✓				✓				
	Venturi effect	✓				✓				
	Stack effect	✓	✓	✓	✓	✓		✓		
	Wind tower/wind catcher					✓				
	Earth tunnel/ground coupling			✓	✓	✓				✓
	Thermal chimney									✓
	Trombe wall						✓			
	Night ventilation			✓			✓			
	Radiative cooling						✓			
	Evaporative cooling						✓			
	Radiant cooling						✓			
Building voids	Atria, courtyard	✓				✓		✓		✓
	Lightwell, airwell						✓	✓		✓
Building envelope	**Sun-shading device**	✓	✓	✓	✓	✓	✓	✓	✓	
	Self-shading building form					✓				
	Roof	✓						✓	✓	✓
	Walls, exterior façade, balconies	✓	✓					✓	✓	

Categories	Sub-categories	Gunawan (2012)	Aflaki et al. (2012)	Altan et al. (2016)	Tataresta ghi et al. (2018)	A.Y. Freewan (2019)	Bhamare et al. (2019)	Loo et al. (2021)	Oluwatayo & Pirisola (2021)	HMNNC et al. (2023)
	Thermal mass and insulation	✓		✓		✓	✓	✓	✓	✓
	PCM						✓			

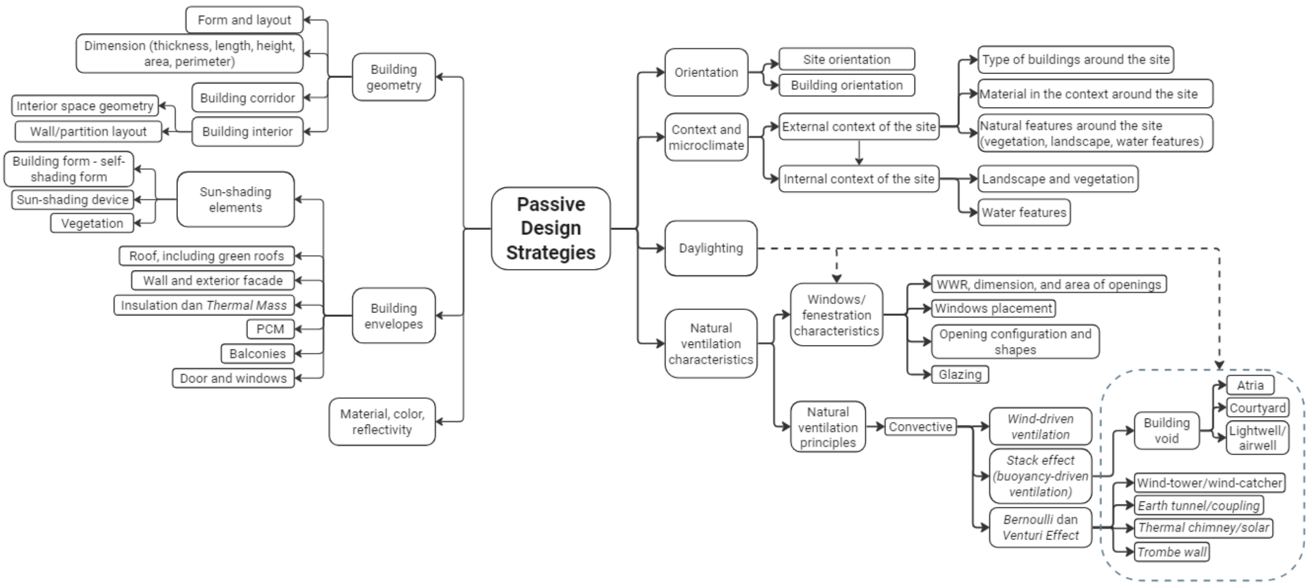

Figure 2. Passive design strategy criteria framework

4. Biomimicry Approach

Throughout history, nature has served as a profound wellspring of inspiration for architects seeking to conceptualize building shapes and embellishments (Pawlyn, 2016). Coined by Benyus (1997), biomimicry originates from Greek, comprising two constituent terms, "bios" denoting life and "mimesis" signifying imitation or mimicry. As elucidated by Pawlyn (2016), biomimetic design draws inspiration from the solutions to functional challenges that have been ingeniously resolved in biological systems. Biomimicry entails the emulation of organisms, their behaviors, or entire ecosystems, encompassing aspects such as form, material, construction methods, process strategies, or functions (Zari, 2010). Biological strategies inherent in living organisms serve as foundational elements for design innovation, holding the promise of contributing to sustainable architecture (Zari, 2015).

According to the Biomimicry Institute, biomimicry falls within the realm of bio-inspired design, representing an approach in design and engineering that draws upon biological science to address problems. It is important to note that not all designs inspired by biology can be classified as biomimicry. The Biomimicry Institute delineates distinctions between biomimicry, bio-morphism, and bio-utilization.

Bio-morphism, or bio-morphic design, entails visually resembling living elements from nature, often described as "looks like nature" design. This diverges from biomimicry, which primarily focuses on emulating the functionality of natural systems. While biomorphic designs may possess aesthetic appeal and draw on humanity's innate affinity for nature, they do not necessarily embody the functional attributes of the organisms they resemble. Research indicates that exposure to nature can positively impact human physical and psychological well-being, leading to improved health and happiness (Augeri, 2009). However, it's important to recognize that visual resemblance to nature is not indicative of biomimicry. Unlike bio-morphism, biomimicry prioritizes functional solutions over aesthetics, with a focus on leveraging biological designs and processes to address human challenges (Pawlyn, 2016).

In contrast to bio-morphism, bio-utilization involves the practical utilization of material elements or living organisms from nature for beneficial purposes in design or technology. Examples include planting vegetation around buildings to facilitate evaporative cooling or employing trees as furniture materials or living walls to enhance indoor air quality.

According to Benyus (1997), biomimicry serves three primary roles; nature as a model: Studying natural models and drawing inspiration from biological designs and processes to solve human problems. For instance, the development of solar cells inspired by the photosynthetic processes of leaves; nature as a benchmark: Using ecological standards to evaluate the effectiveness of an innovation; nature as a mentor: A perspective that emphasizes learning from and appreciating nature, not solely for what can be extracted from it, but for the lessons it can impart to humanity.

According to Zari (2007), biomimicry encompasses three levels that delineate the aspects of biological solutions available for emulation. These levels include the organism, behavior, and ecosystem levels. At the organism level of biomimicry, the emulation process focuses on a specific organism (either animal or plant) and may involve replicating either the entirety or a portion of the organism's characteristics.

Moving to the behavioral level of biomimicry, the emulation process shifts to the behaviors exhibited by organisms and seeks to translate how these behaviors manifest within a broader context. In ecosystem-level biomimicry, the emulation process extends to the entire ecosystem, encompassing the principles that underpin its functionality and operation.

Within each level of biomimicry, there exist five potential dimensions representing the types of mimicry applied to the design. These dimensions include the form (appearance), material composition, construction methodology, operational processes, and functional capabilities of the design. Zari (2007) conducted a comparative analysis, summarizing the differences between these types of biomimicry using the case example of a termite mound. Table III elucidates the various aspects imitated, ranging from the termites themselves and their behaviors to the broader ecosystem in which they reside.

TABLE III. FRAMEWORK TABLE OF BIOMIMICRY APPLICATIONS *

Level of biomimicry		Example: building that mimics termite mound
Organism level (mimicry of a specific organism)	Form	The building looks like a termite
	Material	The building is made from the same material as a termite, e.g.: termite exoskeleton or skin.
	Construction	The building is constructed in the same way as a termite, e.g.: it goes through multiple growth cycles of a termite.
	Process	The building works similarly to a termite, e.g.: termite produces hydrogen via meta-genomics.
	Function	The building functions similarly to a termite in a broader context, e.g.: it recycles cellulose waste and produces soil.
Behavior level (mimicry of an organism's behavior or interaction with its context)	Form	The building structure appears like it was constructed by termites, e.g.: a replica of termite mound
	Material	The building is made with the same materials that termites use, such as digested fine soil as the primary material.
	Construction	The building is constructed in the same way that a termite might build in, e.g.: piling earth in certain locations at certain times.
	Process	The building works in the same way as a termite mound would, e.g.: by careful orientation, shape, materials selection, and natural ventilation of termite buildings, or it emulates cooperative behavior of termites.
	Function	The building functions as it would if it's constructed by termites, e.g.: internal conditions are regulated to be optimal and thermally stable. It might also operate similarly to a termite mound.
Ecosystem level (mimicry of an organism's ecosystem)	Form	The building resembles an ecosystem - a termite would reside.
	Material	The building is made from the same kind of materials that a termite ecosystem is composed of, e.g.: water serves as the primary chemical medium and other naturally occurring common compounds.
	Construction	The building is constructed in the same way as a (termite) ecosystem, e.g.: using principles of succession and increasing complexity over time.
	Process	The building works in the same way as a (termite) ecosystem, e.g.: the structure gathers and transforms solar energy and stores water.
	Function	The building is able to function in the same way that a termite ecosystem would and contributes to a complex system by utilizing the relationships between processes. It's able to engage in the hydrological, carbon, nitrogen cycles etc. in a similar way to an ecosystem.

*(Adapted from Zari (2007))

The subsequent table illustrates instances of natural strategies and principles viable for adjusting and preserving internal temperature or heat levels in accordance with specific requirements, thereby anticipating external temperature conditions that do not align with the specifications outlined in Table IV.

TABLE IV. EXAMPLES OF NATURAL STRATEGIES AND PRINCIPLES IN DISSIPATING AND PREVENTING HEAT (COOLING MECHANISM)

Processes	**Factors**	Pinnacles
Function **Heat dissipation.** Occurs in environments where body temperature is higher than environmental temperature.		
Enhance convection) **Convection** is heat transfer method, where the heated fluid surrounding an object flows away from the object to transfer heat. Natural convection is fluid flow caused by differences in temperature/ pressure.	**Airflow** Because hot air has lower air density than cooler air in the atmosphere, it rises. The air cools down and loses energy as it rises, becoming denser before falling. As a result, a cycle that repeats itself produces wind.	**Elephant's ear** The flapping movement of elephant ears creates more airflow, which enhances convection to dissipate heat. Vibration is used to improve heat transmission, where perpendicular vibration to air flow is more efficient than parallel vibration to air flow.
		Zebra The alternating black and white stripes of the zebra have a cooling effect because of convective currents created on the surface. Temperature gradient causes heated air (near black stripes) to rise and subsequently displaced by cooler air (near white stripes), creating convective current. These currents can improve the airflow over the zebra's skin,

		which increases the rate of evaporation and causes cooling.
		Termite mound To provide better airflow, termites have constructed a network of chambers and tunnels within their mounds. The mound's design allows hot air to naturally rise to the top of the mound and be released, drawing in cooler air from the base of the mound and surrounding area. This continuous circulation of air keeps the temperature stable.
Enhance conduction The transmission of heat by direct particle collisions and kinetic energy transfer at the interface between two materials/matters	**Density**	**Substance density** Although conductivity rises with pressure, conduction in fluids (especially gases) is less intense than in solids. Conduction is dependent on three factors: (1) **material thickness**, the thicker the material, the lower the conduction; (2) **material density**, the denser the material, the higher the conduction; and (3) **surface area**, the larger the surface area, the higher the conduction
	Circulatory mechanism Release of heat (heat loss) by using blood circulation regulation. In endothermic living creatures, warm blood originating from the heart usually releases heat as it passes through areas near the skin.	**Blood vessels** Vasodilation is a mechanism used by endothermic living things (body heat derived from metabolism), such mammals and birds, to dissipate heat. By enlarging the blood vessels, this process increases blood flow to the skin and speeds up the body's release of heat into the surrounding air.
Emit radiation	**Surface/volume ratio** The amount of surface area exposed to radiation has an impact on heat loss. The amount of heat released is directly proportional to the heat released. The greater the surface area, the higher the heat released.	**Desert mammal** An example of a desert mammal is the kit fox (Vulpes Macrotis), has very large ears that are intended to increase the surface area for body cooling. Similar to the kit fox, jackrabbits also have very large ears with an extensive network of blood vessels, allowing for faster heat loss.
Evaporation Air moving over a moist surface causes evaporation, taking heat from the surface.	**Temperature** Increasing temperatures cause evaporation to occur	**Sweating in human skin** Human, horses, kangaroo, mammals.
		Panting dog, birds, and mammals where the rate of breathing is increased because of heat stress.
	Airflow rate	**Great egret bird with gular fluttering** Gular fluttering is a mechanism adopted by certain reptiles and bird species, used to increase the rate of evaporative cooling. In this process, the animal maintains its mouth open throughout this phase and uses vibration to improve air movement across moist vascular oral membranes; this increases evaporation and increases heat dissipation
Functions: **Heat prevention.** Occurs in warm environments with high radiation exposures.		
Minimize irradiation)	**Posture/ orientation)**	**Termite Mound** Termite mounds in Australia tend to be flattened and oriented north and south.
		Leaves Leaves have a certain slope for maximum or minimum exposure to sunlight.
	Morphology	**Elephant skin** Elephant skin has wrinkles to create a shaded area to prevent too much direct radiation exposure (lessen direct radiation exposure). It also provides sufficient area for holding moisture and evaporation as a cooling mechanism.
	Color	**Bright pigment** Materials with light colors and low density absorb less light than materials with dark colors, whether it's skin color or fur of birds of mammals.
	Reflectance	**Skink** The scale of skinks increases light reflection, thereby reducing heat load. **Encelia farinose** Fine hairs on leaves (including dead hairs), create silvery reflections when water is scarce and plants experience heat stress. These fine hairs reduce radiation exposure to leaves and lower surface temperature by several degrees.
	Surface/ volume ratio)	**Camel** The surface area of a camel's body is smaller than its volume. The smaller the body surface area, the smaller the body's exposure to radiation.
Minimize conduction	**Density**	**Fibers** The desert shrub, *Encelia farinose* has dense fine hairs on its leaves, thereby minimizing the absorption of solar radiation.

Sources: Badarnah (2015), Pawlyn (2016), AskNature.com

In addition to replicating shapes found in nature, careful consideration must be given to the manufacturing process. Nature inherently employs materials readily available in the environment and capable of self-construction. Furthermore, in the context of ecosystems, the biomimetic design process must encompass an evaluation of how the design functions within a specific environment, its ability to integrate with existing systems, and the potential impact it may exert *(Fecheyr-Lippens & Bhiwapurkar, 2017)*.

The key considerations in biomimetic design involve the design's responsiveness to environmental conditions (e.g., climatic variations), its integration with the surrounding environment, and its environmental impact.

Within the realm of architecture, the adoption of biomimicry principles in design has been demonstrated to enhance energy efficiency. By aligning with environmental conditions from inception, buildings designed using biomimicry principles can operate during their lifecycle with reduced energy requirements to adapt to thermal conditions, for example.

Several tangible instances of implementing biomimicry principles in architectural designs aimed at reducing energy consumption are delineated in the Tabel V.

Among the various categories, particularly the parameters of the building envelope, play a crucial role in both energy performance and building comfort. The building envelope constitutes a structural element that directly affects energy consumption for heating, cooling, and lighting purposes *(Jamei & Vrcelj, 2021)*. Consequently, the application of biomimicry in this thesis will be centered on enhancing building envelope elements.

TABLE V. EXAMPLES OF IMPLEMENTATION OF BIOMIMICRY IN ARCHITECTURAL DESIGN AND ITS ROLE IN REDUCING ENERGY

Building	**Biomimicry Inspiration**	**Strategies**	**Passive Design**	**Level of Biomimicry**	**Impact**
Eastgate Center, Harare, Zimbabwe	Termite mound	The center of the building structure is open, drawing hot air upward and pushing it through a duct resembling a chimney in the middle of termite mound.	• Building void • Natural ventilation (stack effect)	Behavior	Year-round temperature regulation without requiring support from an HVAC system. 35% less energy is used.
Council House 2, Melbourne, Australia	Termite mound	Utilizing ventilation strategies such as natural convection and ventilation stack in termite mounds.	• Natural ventilation *(stack effect)*	Behavior	Reduces energy consumption by up to 82%
Sinosteel International Plaza, Tianjin, China	Beehive	The window design resembles a honeycomb hexagon shape with 5 different sizes, positioned to respond to solar radiation in different configurations.	• Windows and fenestration characteristics • Orientation	Organism	Reduces energy consumption by up to 75%
Ministry of Municipal Affairs and Agriculture, Doha, Qatar	Cactus	Building uses shading devices that resemble cactus spines, controlling light and solar radiation. The shading devices can be opened or closed.	• Sun *shading device* • Building envelope	Ecosystem	Reduces energy consumption by up to 62%. Regulates temperature, heat loss, and heat gain.
Rafflesia House, Kuala Lumpur, Malaysia	Rafflesia flower	The concave and convex walls resemble Rafflesia flowers to regulate the air inside the building.	• Building Envelope	Organism	Zero waste energy building, using natural ventilation.

Source: processed from (Dash, 2018; Mohamed et al., 2019)

Numerous natural strategies are collected and scrutinized to see their suitability for the architectural object under study. The research object is a flat in a hot humid tropical climate. After careful consideration, cactus is selected as the natural object to be mimicked. Cactus is chosen because cactus is highly adaptable to a variety of temperatures. Cactus also responds well to excessive radiation exposure, which is a substantial concern in tropical regions. In addition, cactus can catch and store water, which is advantageous in tropical regions with a lot of rainfall.

As an illustrative example, Table VI delineates an analysis comparing cactus thermoregulation techniques with their application in passive design, with a specific focus on building envelopes. The predominant objective of these strategies is to effectively prevent and dissipate heat. By mitigating the cooling load of the building, these strategies are designed to have a discernible impact on the structure's energy consumption profile.

TABLE VI. BIOMIMICRY OF CACTUS IMPLEMENTATION IN PASSIVE DESIGN STRATEGIES

Strategies	Function	Process	Factors	Passive Design	Implementation
Cactus spines are denser at the top.	Heat prevention	Minimize conduction	Density	• Building envelope • Renewable energy	• Sun-shading, green areas are placed in areas exposed to solar radiation. • The roof acts as a catcher of solar radiation. Solar panels are placed on the roof.
Reflective cactus body	Heat prevention	Minimize irradiation	Reflectance	• Building envelope	• Light-colored building to reflect solar radiation (e.g. white)

The orientation of the cactus body minimizes the absorption of solar radiation. Cactus stomata tends to be larger and more abundant in shadowed areas	Heat prevention	Minimize irradiation	Posture/ orientation	• Building orientation • Daylighting	• Buildings are oriented towards north-south to minimize solar radiation exposure. • Windows/fenestration are oriented towards north and south. Windows are placed in the shaded area. • Openings facing west/east are shaded with sun-shading, the building façade itself, or vegetation.
Alternating cactus spines that create shading	Heat prevention	Minimize irradiation	Morphology	• Building envelope • Building form/geometry	• Buildings are divided into several structures to maximize the intake of natural ventilation and daylight. • The building is designed with an alternating pattern both in the layout and on the façade, using balconies to create shading.
Corrugated form of cactus that creates self-shading.	Heat prevention	Minimize irradiation	Morphology	• Building envelope • Building form/geometry	
The shading on the cactus body creates temperature differences to encourage convective airflow	Heat dissipation	Enhance convection	Airflow rate	• Windows/ fenestration characteristics • Natural ventilation	• The self-shading façade leads to variations in temperature between shaded and unshaded façade. Temperature differences can encourage convective airflow.
Cactus spines catch water to wet and cool the cactus evaporatively.	Heat dissipation	Evaporation	Airflow rate	• Building envelope • Building form/geometry	• Building envelopes, especially balconies, act as self-shading and rainwater catchers. • Green areas such as roof gardens serve function as rainwater catchment systems and evapotranspiration cooling using vegetation.

4. Conclusion

Climate change stands as an urgent concern impacting various aspects of human existence. The escalating levels of carbon emissions and greenhouse gases resulting from energy consumption, notably within the construction sector contributing up to 40% of global energy usage, serve as the fundamental drivers of climate change. Inefficient thermal performance in buildings, leading to increased cooling and heating demands, constitutes the primary catalyst for heightened energy consumption in architectural structures. Passive design strategies are employed as energy-saving measures to optimize energy utilization and mitigate the adverse effects of climate change. Introducing a biomimicry approach, which mimics natural processes, is crucial to prevent exacerbating the negative repercussions of climate change. The significance lies in the inherent adaptability of biological systems to environmental shifts over extended periods without detrimental effects. The integration of biomimicry into passive design methodologies has been pursued by numerous researchers, yielding notable benefits in energy efficiency.

Drawing upon the investigations of nine researchers, it was concluded that significant passive design strategies encompass orientation, contextual adaptation, microclimate considerations, building geometry, daylight utilization, natural ventilation, and building envelope optimization. The building envelope assumes significance due to its substantial influence on energy consumption.

Within a research context, the biomimicry approach to passive design, particularly in tropical climates, centers on heat and cooling management. This cooling mechanism comprises two functions: heat prevention and heat dissipation. Through a comparative analysis of various natural entities, factors and processes governing thermoregulation in natural objects are identified. These factors and processes subsequently serve as variables integrated into passive design methodologies.

Addressing the research objective concerning flats in tropical climates with high radiation exposure, the biomimicry approach emulates the attributes of the cactus plant, known for its adaptability to diverse weather conditions, resistance to solar radiation, and rainwater capture capabilities. This principle is then applied in passive design strategies such as optimizing the building envelope, architectural form and orientation, windows/fenestration characteristics, and natural ventilation. The emulation of the cactus principle, focusing on heat prevention and dissipation, serves as a building cooling mechanism while enhancing natural lighting and ventilation.

In conclusion, this paper primarily elucidates the process of studying and applying natural principles in heat regulation and integrating them into passive design methodologies.

Acknowledgements

This research constitutes a segment of a master's thesis within the architecture study program at the Bandung Institute of Technology. Gratitude is extended to all supervisors who have collectively contributed to the development of this paper.

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