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Enhancing Resilient Urban Infrastructure through Biomimicry: A Collaborative Approach among Architects and Engineers in Ghana

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Abstract

Urban infrastructure in Ghana faces increasing challenges due to rapid urbanization, climate change, and resource constraints. This research explores how biomimicry—a design approach inspired by nature—can enhance urban resilience by fostering a collaborative framework between architects and engineers. The study introduces the Biomimicry-Integrated Urban Resilience Model (BIURM), which provides a structured methodology for integrating biomimetic principles into urban planning and infrastructure development. Key focus areas include material selection and structural efficiency, passive cooling and energy optimization, and adaptive facades with water management systems. Through a critical review of case studies of biomimetic projects such as the Eden Project, One Ocean Pavilion, and Seawater Greenhouse, this study highlights the essential role of engineer-architect collaboration in bridging the gap between conceptual biomimetic design and technical feasibility. The findings emphasize the need for interdisciplinary research, policy support, and investment in biomimetic solutions to drive sustainable urban development in Ghana. The research concludes that by systematically applying biomimicry, cities can enhance resilience, reduce environmental impact, and create climate-responsive infrastructure tailored to local needs.

Keywords: Biomimicry, Resilient Infrastructure, Sustainable Cities, Architecture-Engineering Collaboration, Climate Adaptation.

1. Introduction

The rapid expansion of cities and the increasing challenges posed by climate change highlight the urgent need for resilient and sustainable infrastructure in Ghanaian cities (Mensah et al., 2021). According to Carter et al. (2015), conventional urban development strategies often fall short in addressing issues such as urban heat, inefficient resource management, and building safety regarding structural integrity in construction. Biomimicry— derived from the Greek words bios meaning life, and mimesis meaning imitation, an approach that takes inspiration from nature's time-tested strategies—offers a promising alternative by introducing sustainable design solutions that enhance energy efficiency, climate adaptation, water conservation, and structural resilience (Benyus, 1997; Pawlyn, 2019; Pedersen, 2020). Benyoucef & Razin (2018) defined biomimicry as a novel engineering approach inspired by nature, utilized for innovation across diverse fields such as engineering, transportation, and architecture. El-Zeiny (2012) highlighted the global interest among architects and engineers in biomimicry, seeing it as a source of inspiration for innovative solutions and a means of fostering a more sustainable built environment. Various strategies facilitate the different types of adaptation in nature, such as in Figure 1 according to Sommese et al., (2022)

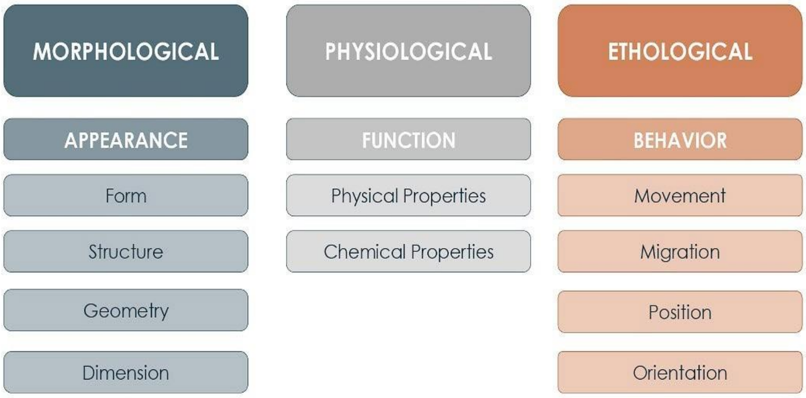

Figure 1. Levels of adaptation in nature and relevant examples (Source: Sommese et al., 2022)

Architecture, being an interdisciplinary field, draws influence from various aspects of natural, technological, and social sciences, with biology serving as a predominant source of inspiration. The framework of bio-inspired design has undergone significant evolution and diversification, largely propelled by advancements in computing technology, and its integration into architectural practices (Chayaamor-Heil et al., 2018; Benyoucef et al., 2018). Moreover, El-Zeiny (2012) emphasized that biomimicry extends beyond mere replication of natural elements or systems; it involves a thorough examination of organisms or ecosystems (Figure 2), followed by a deliberate application of underlying design principles extracted from nature.

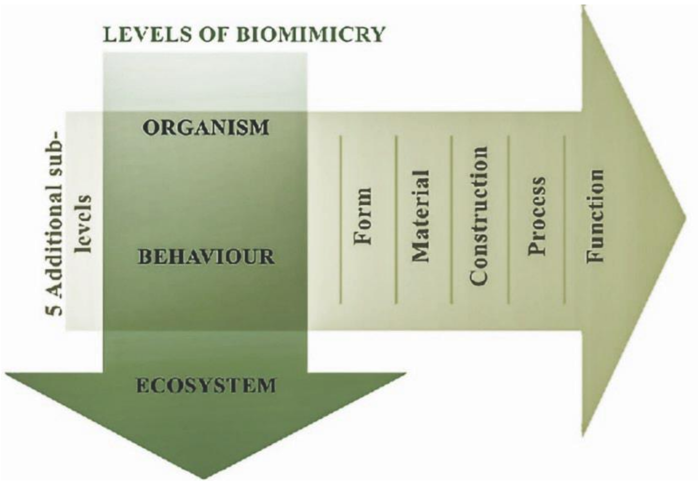

Figure 2. Levels of Biomimicry (Pedersen Zari, M. 2020)

Although biomimetic architecture and engineering have gained global recognition, their application in Ghana remains limited (Oguntona & Aigbavboa, 2024). As urban areas continue to grow, fostering collaboration between architects and engineers is essential for integrating biomimicry into infrastructure design, ensuring ecological responsiveness and structural efficiency (Benyousef & Razin, 2018). Research has shown that nature-inspired innovations—such as termite mound-inspired ventilation, honeycomb-structured load-bearing systems, and biomimetic water filtration—can significantly improve building performance and sustainability (El-Zeiny, 2012; Spaho, 2011). However, the effective implementation of biomimicry requires interdisciplinary cooperation, policy reinforcement, and investment in research to overcome obstacles such as material limitations, regulatory gaps, and a lack of technical expertise (Hayes et al., 2019).

This study employed a critical review methodology, examining biomimetic case studies, expert perspectives, and sustainable engineering solutions to explore how biomimicry can strengthen Ghana's urban infrastructure. By investigating the synergy between architecture and engineering in applying biomimetic principles, the research identified key strategies for improving urban resilience. The findings will contribute to policy recommendations and practical frameworks for incorporating biomimicry into Ghanaian city planning and infrastructure design, fostering innovative and resource-efficient urban development through the collaborative efforts of architects and engineers.

2. Materials and Methods: a critical review

This study employs a critical review methodology, systematically analysing literature, case studies, and expert perspectives (Sutton et al., 2019) to explore how architect-engineer collaboration can facilitate the integration of biomimicry in urban infrastructure. The methodological framework consists of four key phases: data collection, data screening, data analysis, and synthesis, with a particular focus on interdisciplinary collaboration in applying biomimetic principles to architecture and engineering as illustrated in Figure 3.

2.1 Phase 1: Data Collection

Data for this study was gathered from online academic databases such as Scopus and Google Scholar, alongside reports from educational institutions and industry publications. The research focused on biomimicry in urban resilience, particularly its application in architecture and engineering. A keyword-based search was conducted using terms like "biomimetic infrastructure," "adaptive architecture," "nature-inspired engineering," "biomimicry in urban planning," and "resilient biomimetic design." The selection process prioritized scientific journal articles, conference proceedings, case studies, and policy reports that highlight collaborative approaches between architects and engineers in applying biomimicry. Studies from various geographical locations were considered to provide a broader perspective on implementation challenges and opportunities. Given the study's emphasis on practical applications and interdisciplinary collaboration, the data collection focused on literature published between 2015 and the present, incorporating foundational works and recent advancements. This phase resulted in 50 relevant sources, forming the basis for further analysis.

2.2 Phase 2: Data Screening

The collected data underwent an initial screening process to refine the selection based on relevance to biomimicry in resilient urban infrastructure, architect-engineer collaboration and date of publication narrowing down reviewed materials to 12 outputs. Priority was given to studies and case examples that highlight joint design and engineering efforts in biomimetic urban solutions. Documents that focused solely on isolated architectural or engineering approaches without a collaborative dimension were excluded.

2.3 Phase 3: Data Analysis

The refined selection was categorized based on key themes, including:

- Interdisciplinary strategies for integrating biomimicry into urban planning
- Architectural design adaptations inspired by biological systems
- Engineering solutions for biomimetic material application and structural efficiency
- Collaborative methodologies between architects and engineers for optimizing biomimicry in infrastructure

Case studies were further analysed to assess the effectiveness of architect-engineer collaboration in implementing biomimetic features, such as self-cooling facades, lightweight structural frameworks, and water management systems inspired by natural ecosystems.

2.4 Phase 4: Synthesis

Findings from the critical review were synthesized to provide a framework for enhancing architect-engineer collaboration in the application of biomimicry to urban infrastructure. The study identified key factors necessary for effective interdisciplinary integration, including:

- Communication and knowledge-sharing mechanisms between architects and engineers
- Joint decision-making models for biomimetic design and construction
- Institutional support and policy recommendations to promote collaborative biomimicry initiatives

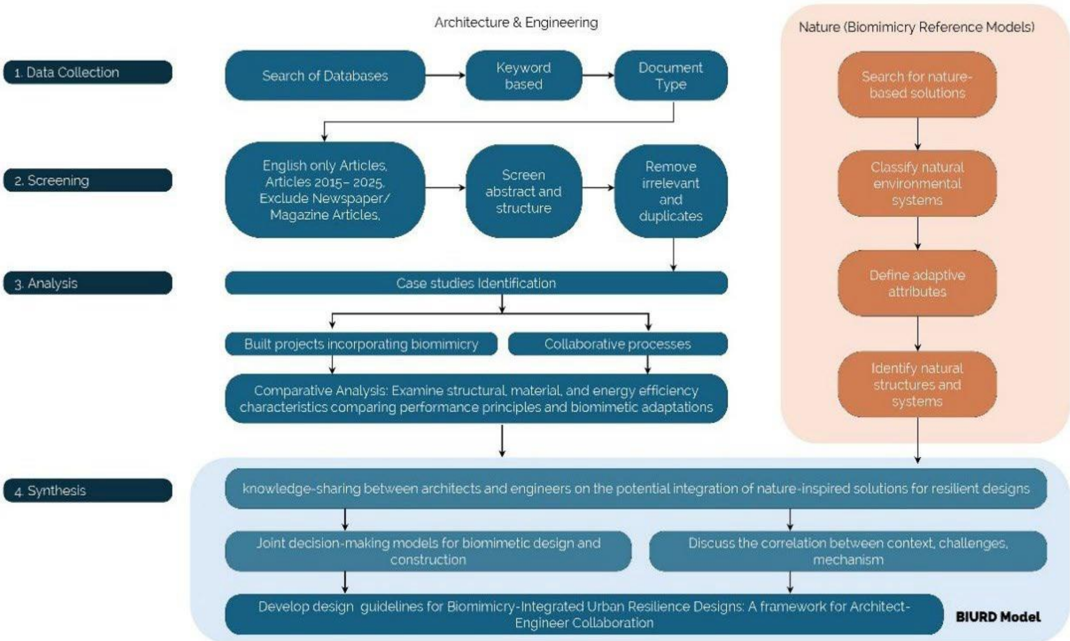

Figure 3. Methodological framework (Author's own construct)

The results of this study offer practical insights for fostering interdisciplinary partnerships in Ghana's urban development, highlighting how architects and engineers can work together to create a resilient, biomimicry-driven infrastructure that responds to environmental challenges while optimizing sustainability and efficiency. This methodology ensures a holistic evaluation of biomimicry's potential in urban resilience while emphasizing the critical role of collaborative innovation between architectural and engineering disciplines.

3 Results and Discussion

This section presents findings on how biomimicry enhances resilient urban infrastructure through architect-engineer collaboration. Insights were drawn from systematic reviews, case studies, and expert interviews, focusing on climate adaptation, energy efficiency, water management, and structural optimization. The discussion evaluates case study insights, expert perspectives, and the integration of biomimetic strategies into urban development. The Biomimicry-Integrated Urban Resilience Model (BIURM) is introduced as a framework for collaboration in Ghana's sustainable infrastructure. Key themes are analyzed, highlighting implications for urban resilience and the built environment while outlining future directions for biomimetic urban development.

3.1 Overview of Biomimetic Strategies in Urban Infrastructure

Findings from case studies and literature reviews highlight key biomimetic principles that contribute to sustainable and resilient urban infrastructure. These include structural efficiency modelled after trabecular bone structures, water management systems mimicking natural filtration processes, and self-repairing materials like bio-concrete (Pawlyn, 2019). These strategies enhance energy efficiency, material optimization, climate adaptability, and infrastructure longevity, making them essential for addressing urban challenges in Ghana. The table below summarizes the key biomimetic strategies, their natural inspirations, and their applications in urban design.

Table 1. Key Biomimetic Strategies and Their Functions in Urban Infrastructure

Biomimetic Strategy	Natural Inspiration	Application in Urban Infrastructure	Key Benefits
Passive Cooling Systems	Termite mounds	Ventilation systems, self- cooling facades	Reduces energy consumption by up to 90%
Lightweight Structural Efficiency	Honeycomb (beehives), Trabecular Bone	Modular buildings, load- bearing walls	Optimizes strength-to-weight ratio, reduces material use
Water Collection & Filtration	Namib Desert Beetle, Mangrove Roots	Rainwater harvesting facades, bio-filtration systems	Enhances urban water conservation and purification
Self-Shading & Adaptive Facades	Palm Fronds, Cactus Spines	Dynamic facades that adjust to sunlight intensity	Lowers solar heat gain, reduces cooling needs
Self-Healing Materials	Bacterial Calcite Precipitation, Bone Regeneration	Bio-concrete for crack repair in infrastructure	Increases longevity, reduces maintenance costs

Aerodynamic Urban Design	Bird	Wings, Fish Bodies	Streamlined building shapes, wind-responsive structures	Improves wind flow, reduces structural drag

3.2 Biomimetic Structural Systems for Urban Resilience: Nature as a Model

Architecture replicates the functions, shapes, and components found in nature to address challenges related to sustainability, efficiency, strength, durability, and other aspects according to Spaho (2011). Nature provides abundant examples of solutions to these challenges, developed over billions of years. These natural designs are intricately adapted to their surroundings and are optimized for energy and material efficiency as solutions to many of our design queries are likely embedded within the surrounding natural environment (Karana et al., 2019).

3.2.1 Nature's Forms

Biomimicry in architecture presents a promising avenue for sustainable and efficient design by imitating the forms, processes, and systems found in nature. It is essential in biomimetic architecture to comprehend the biological role models in building behaviour and ensure that the design effectively incorporates the mimicry of these biological role models, as emphasized by Spaho (2011) and Bhatia et al. (2018). Architecture that mimics natural forms underscores the extraction of structural properties inherent in these forms. Spaho (2011) continued to argue that natural structures have evolved over billions of years, demonstrating an unparalleled level of refinement through iterative processes and that present-day living structures embody nature's triumphs, with unsuccessful iterations fading into oblivion (Bhatia et al., 2018). These extant natural exemplars showcase a diverse array of resourceful materials and structural configurations capable of responding to various climatic and environmental pressures. These superior designs play a pivotal role in informing our architectural progress.

3.2.1.1 The Sea Urchin: Landesgartenschau Exhibition Hall

The sea urchin has served as a source of inspiration for both simplistic biomorphic designs and comprehensive biomimetic architecture. Its skeletal structure, known as a 'test,' comprises interlocking plates called 'ossicles,' as seen in the Figure 3b, each resembling a single calcite crystal. If solid, calcite would be weighty, but the ossicles possess a porous, lightweight, and rigid composition due to their sponge-like structure (Figure 4a), resulting in increased effective thickness.

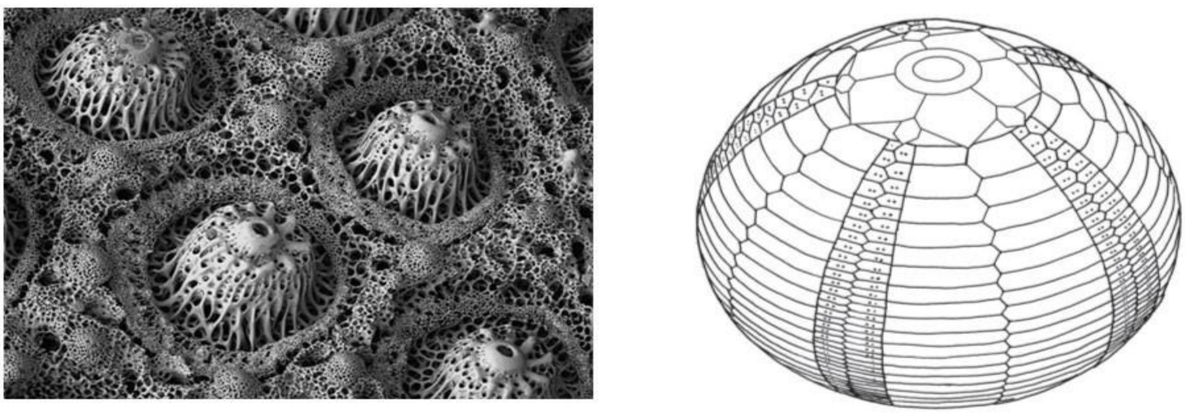

Figure 4. (a) A close-up image of a sea urchin skeleton showing its porous and lightweight structure,

(b) Structure of a sea urchin skeleton, which comprises interlocking plates. (Source: Pawlyn, 2019)
While the Doughnut House by Future Systems (Figure 4) drew visual cues from sea urchin skeletons, its functional structure differed significantly from that of the marine organism. In contrast, the Landesgartenschau Exhibition Hall at the University of Stuttgart in Germany (Figure 6) closely emulated the structure of a sea urchin, representing a pinnacle of biomimetic architecture research (Pawlyn, 2019).

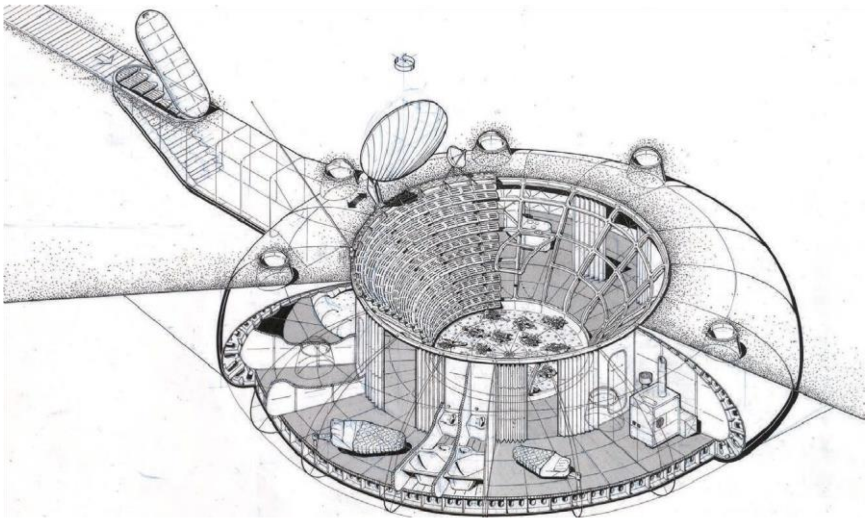

Figure 5. The Doughnut House by Future System – Biomorphic rather than Biomimetics (Source: Pawlyn, 2019)

This project, a collaboration between the Institute for Computational Design (ICD) led by Prof. Menges, the Institute of Building Structures & Structural Design (ITKE) led by Prof. Knippers, and the Institute of Engineering Geodesy (IIGS) led by Prof. Schwieger, drew inspiration from the interlocking ossicles of sea urchins. Constructed from 50 mm thick plywood panels intricately connected with precise finger joints, the building exemplifies the geometric complexity observed in natural biological structures (Pawlyn, 2019).

Figure 6. Landesgartenschau Exhibition Hall at the University of Stuttgart – Based on the Structure of a Sea Urchin Skeleton (Source: Pawlyn, 2019)
Computational design played a crucial role in resolving this complexity to achieve the optimal form, with each panel prefabricated robotically. Despite covering an area of 250 m2, the structure boasts a relative thinness akin to that of an eggshell.

3.2.2 Nature's Function

Architecture emulating natural functions underscores the extraction of specific or multiple functions from nature's instances, integrating them into architectural design. These functions are harnessed to address site-specific conditions, climate variations, energy usage, and other considerations, prioritizing environmental preservation and non-pollution. Functional biomimicry influences design choices concerning form, alignment, and material preference, shaping architectural solutions (Pawlyn, 2019; Spaho, 2011).

3.2.2.1 Soap Bubbles: The Eden Project

The Eden Project (Figure 7), envisioned by Grimshaw, exemplifies a project that extensively tapped into biological solutions across various stages of development, from initial site assessment to strategic shaping and detailed design. Initially conceived as the world's largest greenhouse, the project faced challenges due to the site's unstable nature, situated within an active China clay pit (Sanchez-Alvarez, 2022).

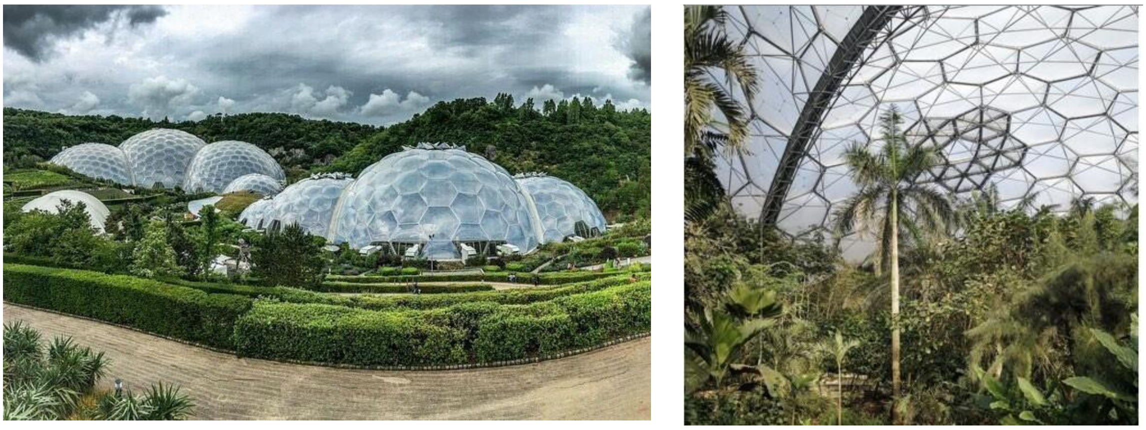

Figure 7. Image of the Edens Project in Cornwall, England Source: Mohamed, 2024)

To address uncertainties regarding the site's ultimate configuration, biomimicry played a pivotal role throughout the design process. Solar analysis identified the most advantageous areas for habitation, particularly the south-facing quarry walls, which could absorb and emit solar heat, thereby reducing the need for additional heating (Spaho, 2011). The irregular topography and uncertain ground levels rendered conventional rectilinear designs impractical. Inspired by the structure of soap bubbles, team member David Kirkland proposed a groundbreaking solution: a series of variably sized bubbles inspired by soap bubbles interconnected along a flexible line, mimicking the site's approximate topography (Figure 8).

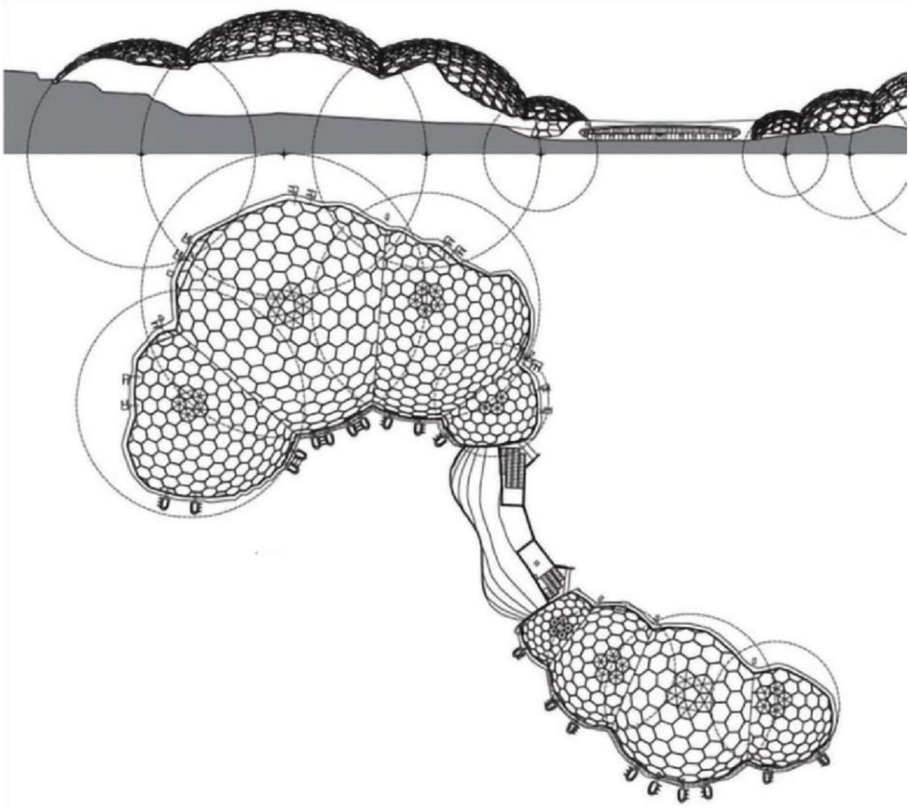

Figure 8. Schematic Site section and Plan of the Eden's Project (Spaho, 2011)

Subsequently, efforts focused on achieving optimal structural efficiency, drawing insights from natural examples ranging from carbon molecules and Radiolaria through to pollen grains (Figure 9).

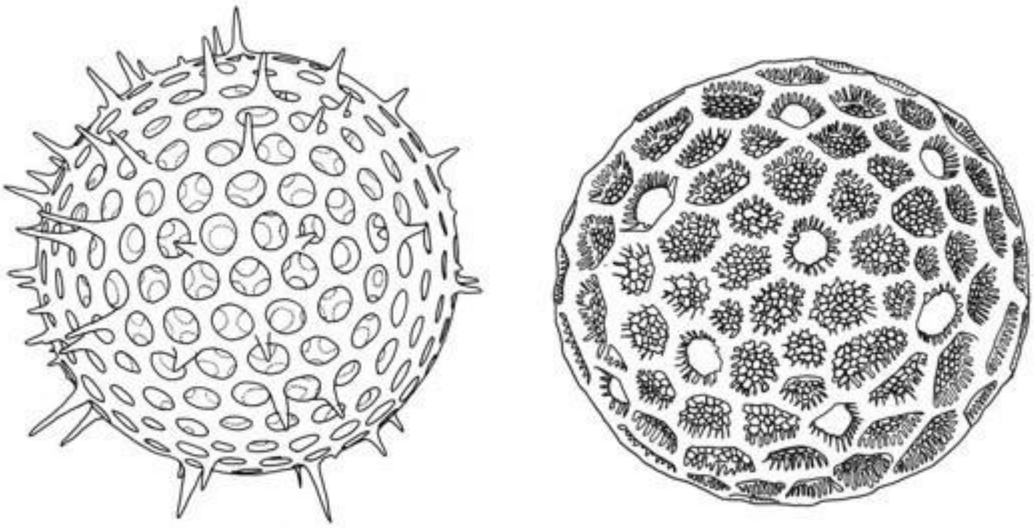

Figure 9. (a) Radiolarian structure (b) Pollen grain showing a geodesic structure (Source: Pawlyn, 2019)

This exploration led to the adoption of geodesic arrangements of pentagons and hexagons, pioneered by Richard Buckminster Fuller, renowned for his groundbreaking work in structural engineering. The design process commenced with conservative structural assumptions, which were subsequently refined through wind tunnel testing of scale models to ascertain wind loading (Pawlyn, 2019). \

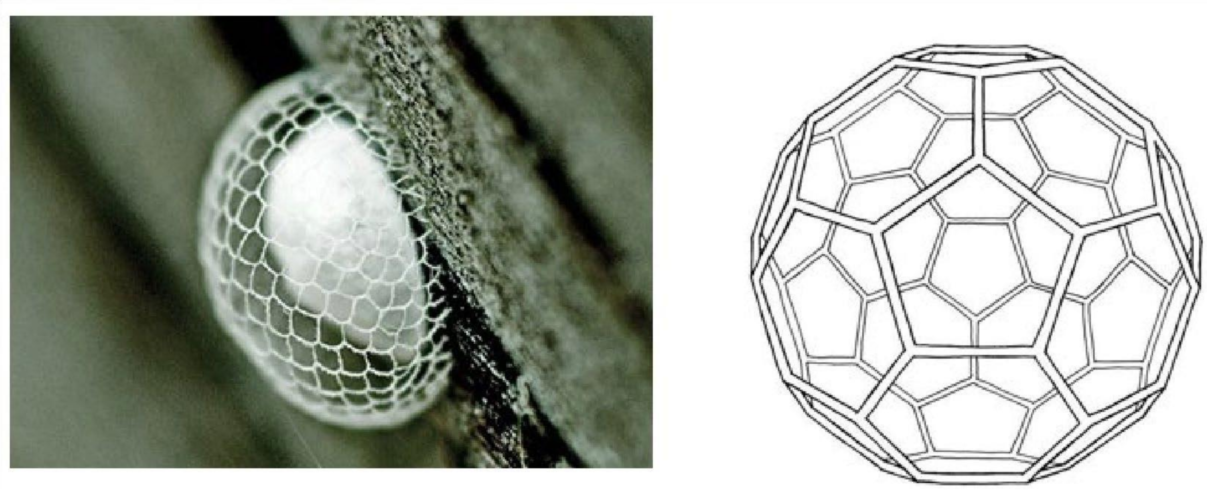

Figure 10. Protective enclosure formed by the Sisyridae sponge-fly (b) A carbon molecule known as a Buckminster Fullerene (Source: Pawlyn, 2019)

3.2.2.2Material Efficiency

A pivotal aspect of this refinement involved maximizing the size of hexagonal elements to enhance light penetration. Due to limitations posed by glass, both in terms of unit size and weight, alternative materials were explored, including ethylene tetrafluoroethylene (ETFE), a high-strength polymer (Figure 11).

Figure 11. ETFE pillows (Source: Source: Spaho, 2011)

ETFE, capable of being formed into lightweight cladding elements through welding and inflation, represented a departure from conventional rigid materials, drawing parallels with Buckminster Fuller's pioneering work on inflatable structures. ETFE offered significant advantages over glass, weighing only 1% as much and enabling the creation of larger "pillows" than standard glass sheets. Thorough material testing enabled the enclosure design to be tailored to site-specific conditions, resulting in a positive feedback loop of design innovation (Spaho, 2011).

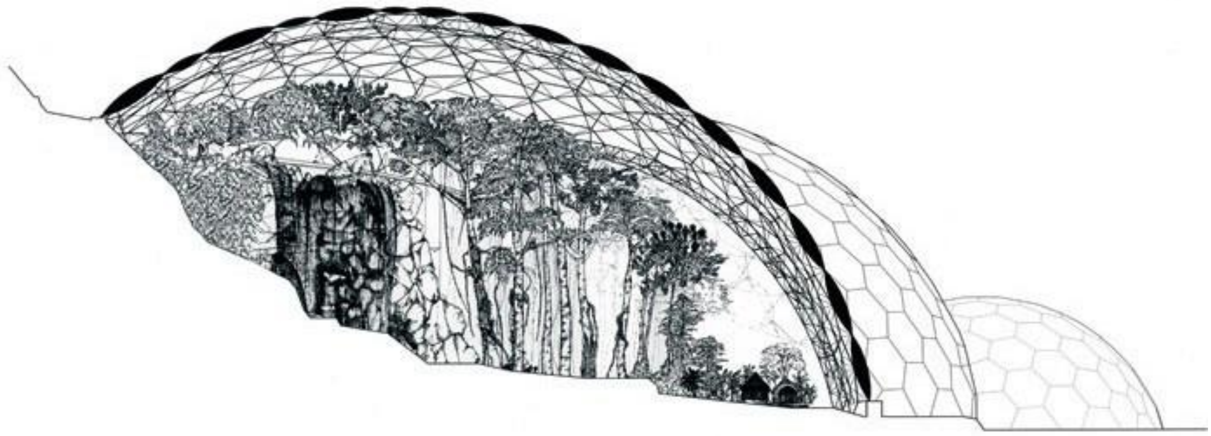

Figure 12. Cross section of Eden project (Spaho, 2011)

Achieving breakthroughs in material efficiency, such as larger pillows reducing steel usage, facilitated reductions in resource consumption and cost, yielding a scheme that utilized a fraction of conventional resources and incurred significantly lower construction expenses. Moreover, the biome's superstructure weight was less than the air it enclosed, reflecting a remarkable achievement in resource optimization. (Spaho, 2011). With advancements in materials technology and insights gleaned from biology, further strides in resource efficiency could be anticipated in future endeavours. For instance, emerging technologies like 3D printing hold promise for manufacturing steel tubes with optimized stress distribution, mirroring biological principles of material utilization.

Figure 13. Interior of the Humid Tropics Biome (Source: Mohamed, 2024)

Unlike historical precedents characterized by domineering architectural interventions, the biomimetic approach embraced by the Eden Project fostered a more harmonious relationship with the landscape. The biomes, accommodating the site's existing topography with minimal excavation, symbolize a more respectful coexistence between human activities and the natural environment (Spaho, 2011).

3.2.3Nature's Parts

Creating architectural designs inspired by nature involves identifying structural, formal, or functional characteristics from natural phenomena and incorporating them into building elements (Spaho, 2011). This process might involve completely replacing building skins and mechanical systems or adding an extra layer to existing structures. The primary goal is to elevate building performance, resulting in enhanced efficiency and harmonious integration with the surrounding environment.

3.2.3.1Bone: Canopy Structure

While bamboo exemplifies straightforward tubular structural engineering, bones offer a more intricate study. Bones often exhibit mechanisms for resolving asymmetrical forces. In Figure 13a, the stress lines in a femur are depicted, while Figure 14b. presents an X-ray image of the same bone.

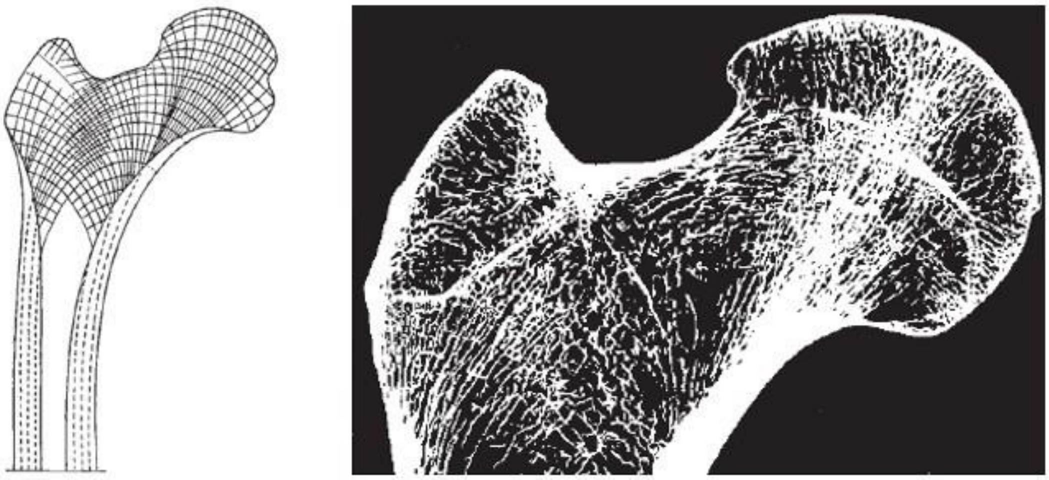

Figure 14. (a) Diagram showing the lines of stress passing through a bone+ (b) X-ray through a bone showing the arrangement of bony trabeculae (Source: Pawlyn, 2019)

Pawlyn (2019) highlights the precise correlation between the density of bone filaments and stress concentration, where areas experiencing high stress exhibit a proliferation of material, while voids are present elsewhere. D'Arcy Wentworth Thompson's seminal 1917 work "On Growth and Form" extensively documented such observations, noting, for instance, the similarity between a vulture's metacarpal (Figure 15) and a Warren truss, as Pawlyn (2019) stated. Vultures, subjected to intense selective pressure to achieve high strength with minimal weight, demonstrate remarkable adaptations

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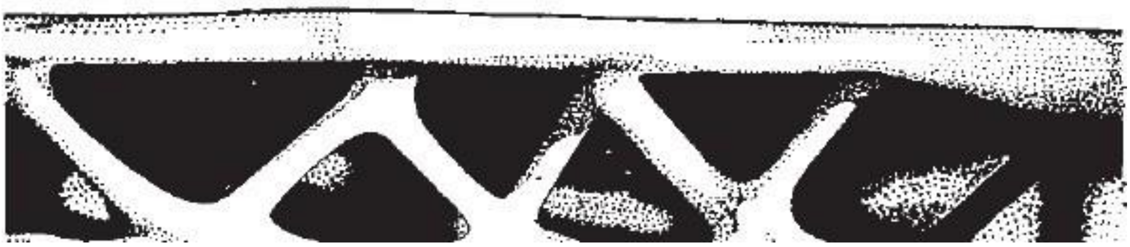


Figure 15. Vulture's metacarpal, which is effectively identical to a Warren truss (Source: Pawlyn, 2019)

Birds, overall, have evolved in response to weight-related selective pressures, with various species showcasing different interpretations of the principle "materials are expensive and shape is cheap." Avian skulls (Figure 16), such as those of crows and magpies, serve as engineering marvels, wherein the effective thickness of the skull is increased while reducing weight (Pawlyn, 2019).

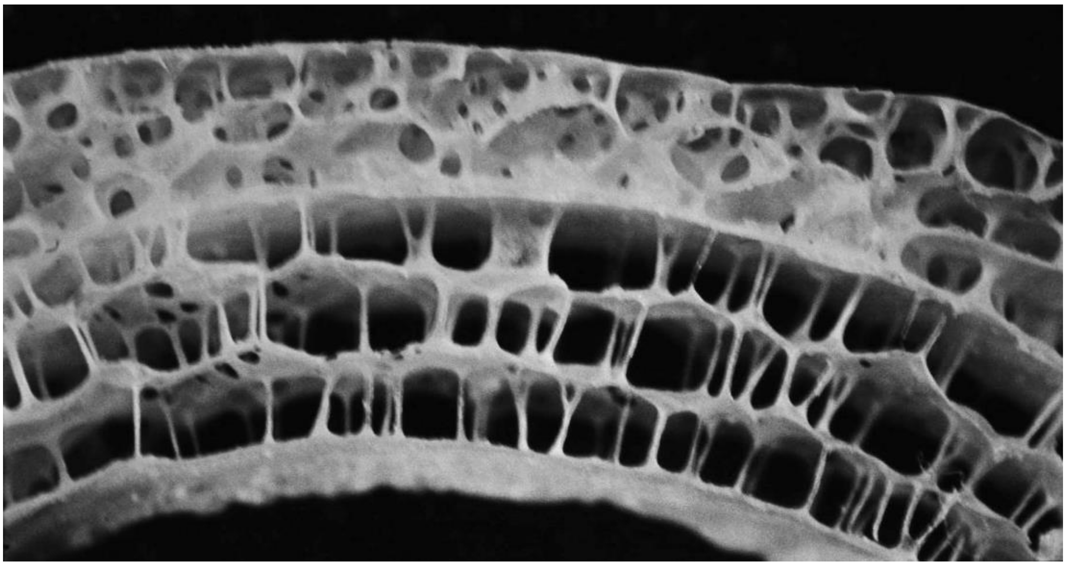


Figure 16. Section through the skull of a magpie showing thin domes of bone connected with struts and ties (Source: Pawlyn, 2019)

This structure resembles a space-frame, with two layers of structural members connected by struts and ties, further enhanced by adopting a dome shape for increased efficiency. Architect Andres Harris drew inspiration from this principle for a canopy structure, leveraging a comprehensive understanding of how bone tissue forms around pressurized cells, creating air voids between solid surfaces (Mohammed, 2019; Pawlyn, 2019). This insight suggests the possibility of constructing the canopy (Figure 17) in a manner akin to nature, utilizing a network of inflated void formers around which suitable materials could be cast.

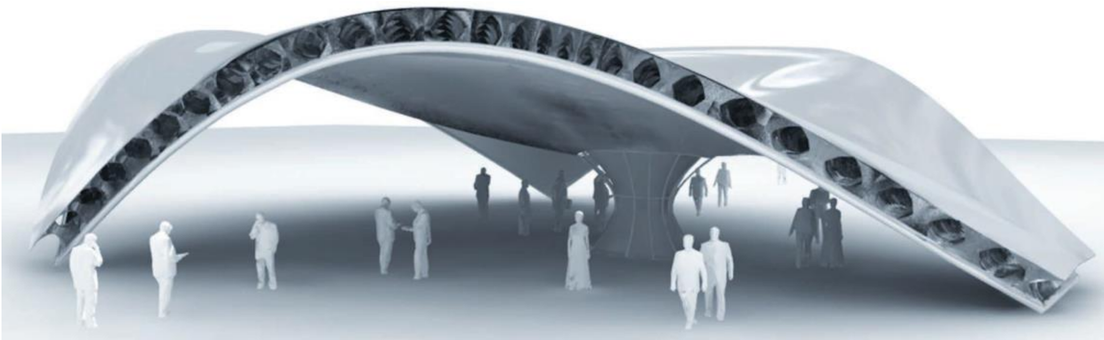


Figure 17. Canopy structure designed by architect Andres Harris, using the same structural principles as those found in bird skulls (Source: Pawlyn, 2019)

Skeletons have long captivated architects, ever since Thompson highlighted parallels between structures like the Forth Road Bridge and the form of dorsal vertebrae found in horses.

3.3 Use of the Right Materials

According to Pawlyn (2019), the concept of Cradle to Cradle emphasizes that merely being 'less harmful' does not equate to being 'beneficial'. For example, while efforts are made to reduce formaldehyde content or increase recycled materials in plastics, the goal should be to design products that are completely free of toxins and are fully recyclable (Pawlyn, 2019)

3.3.1 Concrete

Concrete is widely utilized globally, with an annual pouring volume of 15 billion tonnes expected to persist as less developed countries construct essential buildings and infrastructure. However, cement poses a challenge as it impedes complete reintegration into the technical cycle, leading to gradual downcycling of aggregates (Pawlyn, 2019). Yet, there are potential solutions, such as geo-polymer cements, pozzolanic cements, and naturally occurring cementitious compounds found in conglomerate rocks. Biomineralization sequesters an atom of carbon with every atom of calcium in the process of forming calcium carbonate (Figure 18). Cement production, by contrast, releases a molecule of carbon. Innovations spearheaded by Brent Constantz indicate progress towards mimicking the mineralization processes observed in corals and marine organisms, which absorb carbon during mineral formation.

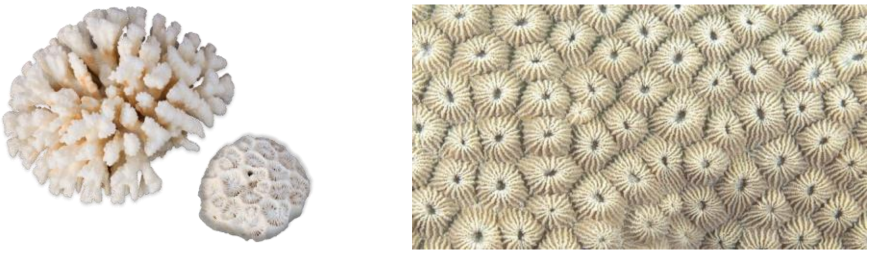


Figure 18. Biomineralisation as performed by corals and other marine organisms (Source: Pawlyn, 2019)

Constantz's work has focused on developing carbon-positive aggregates, offering promising prospects for quicker deployment and increased carbon sequestration. These innovations exemplify a growing field of 'drawdown technologies,' which could play a vital role in mitigating climate change by reducing and potentially reversing atmospheric carbon dioxide buildup.

3.3.2 Timber

Timber faces similar coating challenges to metals, with traditional finishes posing pollution risks upon disposal. Utilizing cellulose in 3D printing offers a groundbreaking approach to reimagining wood. In its conventional forms, timber is best chosen for its inherent weather resistance, such as oak, larch, and western red cedar, or by opting for products treated with non-toxic methods like Thermowood or Accoya. Example of the use of Accoya is the Exchange building (Figure 19) at Darling Square, New South Wales in Australia known as The Hive, by Kengo Kuma. Thermowood utilizes intense heat treatment to deter microbial decay, while Accoya achieves similar results through acetylation, using harmless acetic acid to stabilize moisture levels. These methods enable timber to reenter the biological cycle at the end of its lifespan (Pawlyn, 2019).

Figure 19. The use of Accoya on the façade of the Exchange building by Kengo Kuma (Source: Google.com)

3.3.3 Rammed Earth

Rammed earth, an ancient building material, has regained popularity due to its minimal environmental impact. Studying how animals use earth without modern tools offers insights (Pawlyn, 2019). For instance, the muddauber wasp adeptly compacts mud using thixotropy, reducing viscosity through vibration for efficient construction. Similarly, certain birds combine mud with plant fibers for enhanced strength, resembling reinforced concrete. Inspired by these natural processes, Italian company WASP inspired Trigonopsis, developed a clay-based 3D printer, Big Delta, capable of printing houses. For what is often regarded as a rather crude material, the results are striking (Figure 20).

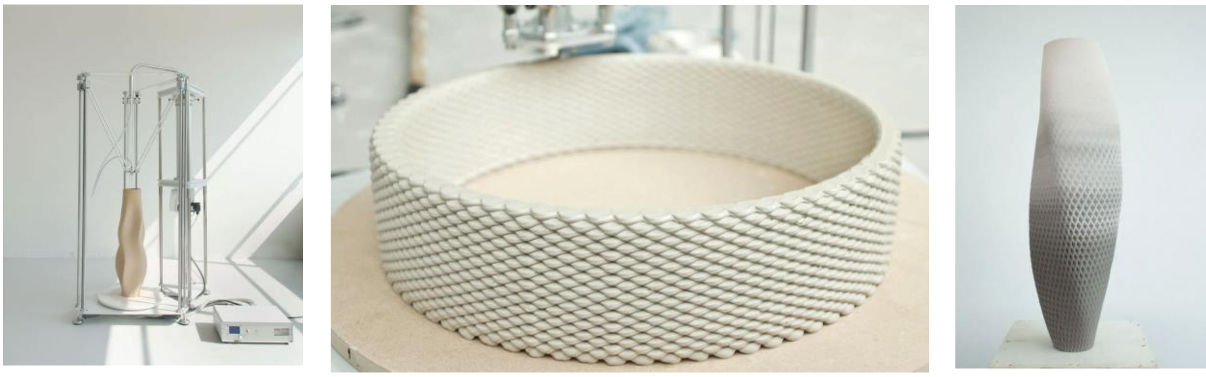


Figure 20. 3D-printed ceramic by Olivier van Herpt showing the beauty and precision (Source: Pawlyn, 2019)

This approach not only leverages local materials but also embodies the resourcefulness of natural builders. Embracing this biomimetic philosophy could revolutionize rural construction practices according to Pawlyn (2019).

3.4 Environmental and Energy Performance of Biomimetic Urban Systems

Nature has long served as a primary source of inspiration for architects and scientists alike, influencing the design of structures, building materials, environmental systems, and aesthetics (Mohammed et al., 2014). With billions of years of evolutionary refinement, nature offers a wealth of solutions to contemporary challenges in sustainable design, making it a natural source of learning (Nkandu & Alibaba, 2018). Biomimicry emerges as a compelling alternative in the quest for sustainable building design and technology, harnessing inspiration from nature to drive architectural innovation (Rao, 2014).

Biomimicry as a design approach can be broadly categorized into two groups: Firstly, identifying human needs or design problems and seeking solutions from organisms or ecosystems—a process termed as design looking to biology. Secondly, recognizing specific characteristics, behavioural patterns, or functions in organisms or ecosystems and translating them into human designs—referred to as biology influencing design (Mohammed et al., 2014). By imitating nature's functions, forms, and parts, architecture addresses various challenges such as sustainability, efficiency, strength, and durability (Spaho, 2011). Buildings increasingly integrate with nature, supporting natural processes rather than disrupting life-sustaining ecosystems—an approach crucial for reducing ecological footprints (Rao, 2014). Through biomimicry, architectural designs and engineering respond to site conditions, climate variations, energy demands, and other factors while minimizing environmental harm to develop resilient urban environments (Spaho, 2011).

3.4.1 Zero-Waste Systems: The Mobius Project

Natural systems operate in closed loops, where waste is non-existent, and everything serves as a nutrient. These regenerative ecosystems, powered by solar energy, offer valuable insights for reimagining our buildings and cities. Transitioning from linear resource use to closed-loop models stand as a crucial transformation that must achieve to create more sustainable buildings (Pawlyn, 2019).

The Mobius Project, developed by Exploration, integrates food, energy, water, and waste in synergistic cycles (Figure 21). Inspired by initiatives like the Tunweni Brewery and the Cardboard to Caviar Project, it features a restaurant, food production (fish, vegetables, mushrooms), waste management (anaerobic digestion), water treatment, and energy generation. By consolidating these cycles, outputs from one part of the system can serve as inputs for another, fostering efficiency. For instance, the building can process biodegradable waste using anaerobic digestion, with methane derived used for power and heat in the greenhouse.

Figure 21. The Mobius Project – a scheme that brings together cycles of food, energy, water and waste in synergistic ways (CGI by Filippo Privitali)

The restaurant minimizes waste by sourcing produce locally and utilizing food scraps for fish or compost. Surplus fertilizer aids in rehabilitating urban brownfield sites. Similarly to Graham Wiles' enhancements to the Cardboard to Caviar Project, the Mobius Project could refine further (Pawlyn, 2019). The project fosters community engagement and reconnects individuals with food while addressing urban sustainability challenges. Success relies on scaling elements economically and functionally, considering external factors like pollution and nutrient loss. Projects like the Mobius

Project offer opportunities to transition from linear to closed-loop systems, addressing urban sustainability holistically.

3.4.2 Water Management: The Seawater Greenhouse

Several projects have drawn inspiration from biological water harvesting methods, notably the Seawater Greenhouse (Figure 22). by Charlie Paton inspired by how the desert beetle harvests water in its environment

Figure 22. (a)The Seawater Greenhouse in Oman as it looked on completion Day (b)The Seawater Greenhouse one year later (Source: Pawlyn, 2019)

This innovative structure achieves significant irrigation savings by harnessing seawater evaporation driven by wind. At the front, evaporators create a cool, humid environment for crops, while at the back, a second evaporator raises air temperature and humidity (Pawlyn, 2019). Vertical polythene pipes act as condensation surfaces, resembling the beetle's shell, collecting water droplets for irrigation (Figure 23).

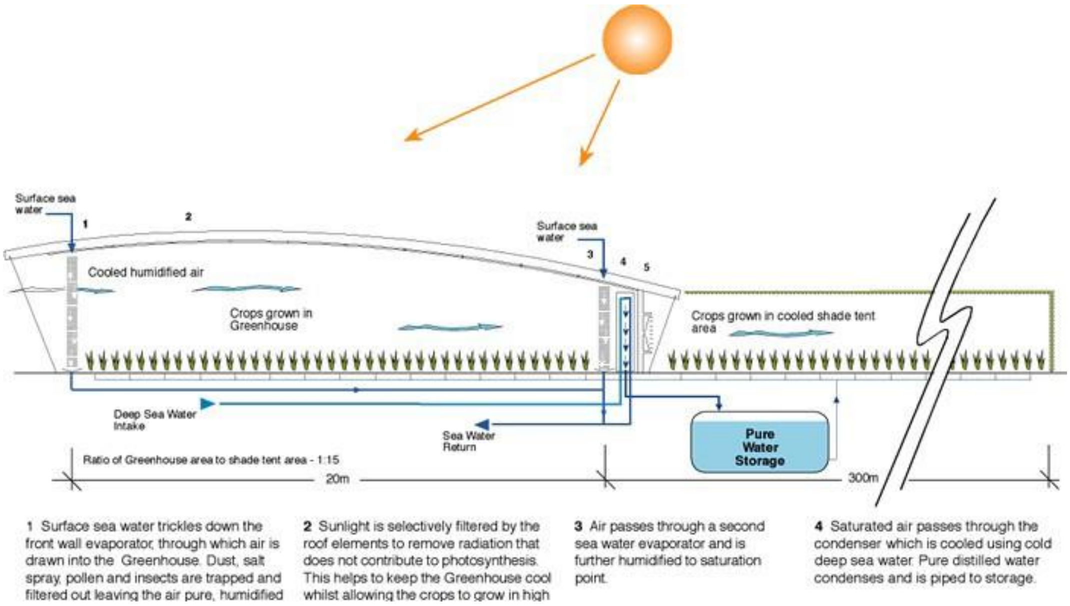
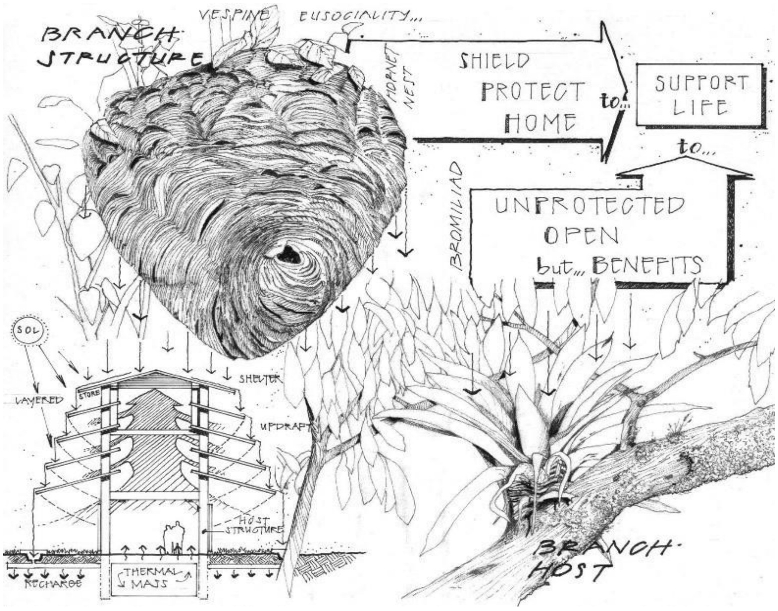


Figure 23. How the seawater greenhouse works (Source: Greenprophet.com).



This design effectively mimics and amplifies the beetle's water harvesting conditions, transforming saline water into fresh water using solar energy, wind, and minimal pumping. In many cases, innovative strategies for managing excess water offer numerous advantages, including reduced construction costs, minimized flood risk, enhanced biodiversity in water habitats, and groundwater replenishment. For construction in India's Lavasa region, known for its heavy rainfall of 11 meters annually, Biomimicry 3.8 and HOK architects embraced a holistic approach. They closely examined the local ecology and water flow patterns (Figure 24).

Figure 24. Sketch of the Lavasa project by architects HOK (Source: Pawlyn, 2016)

Inspired by this, the project aimed to maintain these natural cycles by emphasizing evaporation. This influenced the architectural design, resulting in cascading roof surfaces made of absorbent materials, unlike conventional structures (Pawlyn, 2019). These roofs maximize evaporation instead of efficiently channelling rainwater into gutters and downpipes. The stormwater management strategy extended to all urban surfaces to minimize runoff and promote groundwater recharge.

3.4.3 Thermal Control: One Ocean, Thematic Pavilion

The Plant Biomechanics Group at the University of Freiburg, known for their biomimetic innovations, developed the Flectofin shading system, inspired by the Bird of Paradise flower. This system, co-created with ITKE and the Institute for Textile Technologies, mimics the flower's motion to efficiently provide solar shading. By studying the flower's design, which features a perch that bends when birds land, activating petal movement to expose pollen, the group extracted the idea of a flap capable of a 90° rotation (Spaho, 2011). This characteristic is ideal for solar shading, offering unobtrusive views when not needed and full protection when required. After several prototypes, Flectofin was implemented as a large-scale shading system in soma's Thematic Pavilion at the 2012 Expo in Yeosu, South Korea (Figure 25) that uses thematic Pavilion by soma, using a kinematic facade inspired by early research on the Flectofin as a dynamic part of the facade that controls solar gain (Sommese et al., 2022).

Figure 25. Thematic Pavilion by soma, uses a kinematic façade (Source: Google.com)

3.4.4Energy Efficiency: Vertical-Axis Wind Turbines

Biomimicry has been utilized in designing various renewable energy technologies, resulting in comparable enhancements to those observed in building technologies. Biomimicry offers solutions to address the issue of excessive wind speed, which often necessitates the shutdown of less advanced wind turbines to prevent damage. Many leaves, for instance, adapt their orientation or roll up in high winds to minimize wind loading on trees (Pawlyn, 2019). Advanced wind turbines now incorporate computer-controlled systems to adjust blade angles, and future designs may include blades that flex under wind loading to reduce resistance and allow turbines to continue operating in strong winds. Inspired by palm trees that bend in hurricane-force winds, a team in the US aims to develop turbines with flexible blades, potentially reaching an impressive scale of 50 MW with 200 m long blades. Biomimetic research at the California Institute of Technology has shown that mimicking fish swimming in shoals (Figure 26) can significantly increase wind energy extraction.

Figure 26. (a) Shoaling fish swim in formations that optimize the use of eddy Currents (b) Scientists have applied the principles inn vertical wind turbines for a demonstrated substantial increase in energy generation (Source: Pawlyn, 2019)

3.4.4.1Crescent Dunes Solar Energy Project

Solar technologies have also benefited from biomimetic breakthroughs, such as lenses and mirror layouts inspired by sunflowers (Figure 27), leading to increased efficiency and reduced land requirements.

Figure 27. Concentrated solar power (CSP) mirrors laid out with phyllotactic geometry to optimize energy generation (Source: Pawlyn, 2019)

Future biomimetic applications may include self-cleaning surfaces and scratch-proof coatings for solar mirrors based on the sand skink's adaptation to sand. Artificial photosynthesis research holds promise for further advancements in solar technology. Biomimetic windows that mimic the efficiency of leaves or forests in processing sunlight across their surface area are becoming increasingly feasible (Pawlyn, 2019). The potential of clear solar-energy windows offers significant resource gains, akin to the potential impact of widely implementing biomimetic concrete. The table below provides a summary of notable biomimetic case studies studied, highlighting their natural inspirations, biomimetic strategies, and key impacts on urban resilience.

Table 2. Comparative Analysis of Biomimetic Case Studies and Their Contributions to Urban Resilience

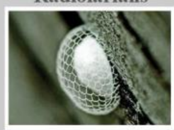
Case Study	Project Info	Biomimetic Object of Inspiration	Aspect Adopted	Biomimetic Strategy	Key Impact for Resilience
Eden Project 	**Location:** Cornwall, UK, **Year:** 2001 **Architect:** Grimshaw Architects **Use:** Greenhouse	**Sponge Bubbles, Radiolarians** 	Geodesic Dome Structures	Lightweight, self-supporting enclosures optimizing daylight use	Enhance daylight penetration, reduces heating demand
One Ocean Pavilion 	**Location:** Yeosu, South Korea, **Year:** 2012 **Architect:** Soma Lima **Use:** Exhibition	**Ocean-Wave Movements** 	Fluid Dynamics of Ocean Waves	Wave-inspired structure optimizing material use	Reduced construction waste, improved aerodynamics
Landesgartenschau Exhibition Hall 	**Location:** Stuttgart, Germany **Year:** 2014 **Architect:** ICD/ITKE/IIGS **Use:** Exhibition	**Sea Urchin Skeleton** 	Interlocking Shell Structure	Wooden shell structure with high load efficiency	Lightweight yet stable, reduces material use
Seawater Greenhouse 	**Location:** Various Arid Regions, Oman **Year:** 2004 **Architect:** Charlie Paton **Use:** Greenhouse	**Desert Beetle** 	Natural Desalination and Cooling	Passive desalination and evaporative cooling	Provides water-efficient agriculture in dry regions

Table 2 continued.

The Exchange Building 	**Location:** Stuttgart, Germany **Year:** 2001 **Architect:** Kengo Kuma **Use:** Mixed-Use	**Bird Nest** 	Bird nest pattern for shading	Modular facade allowing passive cooling and daylight optimization	Enhances natural ventilation, reduces energy demand
Crescent Dunes Solar Energy Project 	**Location:** Nevada, USA **Year:** 2015 **Architect:** **Use:** Solar Farm/Reserve	**Sunflower** 	Solar Tracking and Energy Storage	Heliostat mirrors follow the sun's movement to maximize solar energy capture	Provides 24/7 renewable energy, reduces carbon emissions

These case studies illustrate how biomimicry-based urban infrastructure can be climate-responsive, resource-efficient, and structurally adaptive, offering practical applications for Ghana's urban resilience strategy.

3.6 Architect-Engineer Collaboration in Biomimetic Design

Architects and engineers play distinct but complementary roles in the successful implementation of biomimetic urban infrastructure. While architects focus on the spatial, aesthetic, and environmental integration of biomimetic strategies, engineers ensure structural integrity, material feasibility, and efficiency. Their collaboration is crucial for translating biomimetic concepts into real-world applications that enhance urban resilience. In these selected biomimetic projects that were studied, engineers played a critical role in ensuring the functional efficiency and environmental adaptability of the designs. Their responsibilities included are summarised in the Table 3.

Table 3. Architect and Engineer Roles in Biomimetic Case Studies

Case Study	Biomimetic Strategy	Architect's Role	Engineer's Role
Eden Project (UK)	Geodesic dome structure for climate control	Designed lightweight, transparent domes to maximize daylight and create a controlled microclimate.	Engineered structural stability, optimized material efficiency, and developed climate control systems.
One Ocean Pavilion (South Korea)	Wave-inspired aerodynamic structure	Designed an undulating form for energy efficiency and structural optimization.	Engineered materials and wind flow systems to optimize aerodynamics and minimize material waste.

Landesgartenschau Exhibition Hall (Germany)	Lightweight interlocking shell structure	Designed biomimetic wooden shell inspired by sea urchins to maximize strength and adaptability.	Developed computational models to optimize load distribution and material efficiency.
Seawater Greenhouse (Various Arid Regions)	Passive destination for sustainable agriculture	Designed greenhouse layout to enhance natural cooling and humidity control.	Engineered passive desalination and heat transfer mechanisms to optimize crop production.
The Exchange Building (Japan, Kengo Kuma)	Modular honeycomb facade for passive cooling and daylight optimization	Developed a honeycomb-inspired facade for shading and ventilation.	Engineered a perforated skin system to regulate heat gain and airflow.
Crescent Dunes Solar Energy Project (USA)	Sunflower-inspired heliotropic solar tracking	Designed solar tower layout to optimize sunlight capture.	Engineered heliostat mirror tracking systems to maximize solar energy efficiency.

In these biomimetic projects, as seen from the Table engineers played a critical role in ensuring the structural integrity, functional efficiency, and environmental adaptability of the designs. They were responsible for material selection and structural efficiency, engineering lightweight biomimetic structures such as sea urchin-inspired wooden shells as seen in Landesgartenschau Exhibition Hall (Pawlyn, 2019) while designing self-supporting geodesic domes (Eden Project) to ensure load distribution, stability, and minimal material use (Spaho, 2011). Structurally, they optimized aerodynamic forms (One Ocean Pavilion) to reduce wind resistance and structural strain, while reinforcing solar tower frameworks (Crescent Dunes Solar Energy Project) to withstand dynamic loads and extreme environmental conditions. In terms of passive cooling and energy efficiency, they enhanced airflow and thermal regulation in wave-inspired structures (One Ocean Pavilion) and developed heliotropic solar tracking systems (Crescent Dunes Solar Energy Project) to maximize renewable energy absorption (Pawlyn, 2017; Sommese et al., 2022). Additionally, they contributed to adaptive facades and water management by developing self-shading mechanisms (The Exchange Building) that dynamically respond to sunlight intensity, and engineering passive desalination and evaporative cooling systems demonstrated in the Seawater Greenhouse case study for sustainable water use in arid regions (Pawlyn, 2019). This architect-engineer collaboration ensures that biomimetic urban infrastructure is not only aesthetically inspired by nature but also structurally sound, energy-efficient, climate- responsive, and resource-efficient, making cities more resilient and sustainable.

3.7 The Biomimicry-Integrated Urban Resilience Model (BIURM)

To systematically integrate biomimicry into urban resilience strategies, this study proposes the Biomimicry-Integrated Urban Resilience Model (BIURM). This model provides a structured approach to incorporating biomimetic principles into urban infrastructure through an interdisciplinary framework that guides design, material selection, and policy integration.

Key Components of BIURM:

1. **Biological Inspiration & Concept Development:** Architects and engineers collaborate to identify natural systems relevant to urban challenges.
2. **Parametric Modeling and Simulation:** Computational design tools simulate biomimetic forms, while engineering analyses assess structural and environmental performance.
3. **Material Selection & Prototyping:** Sustainable, nature-inspired materials are tested for feasibility and efficiency in construction.
4. **Performance Optimization:** Biomimetic designs undergo refinements based on energy efficiency, water conservation, and load distribution.
5. **Implementation & Policy Integration:** Urban planning authorities adopt biomimetic solutions, incorporating them into building codes and sustainability policies.

By following this framework, biomimicry can be effectively applied in Ghana's urban development, ensuring resilient, sustainable, and adaptive infrastructure.

3.7.1 Phases of the BIURM

This model fosters collaboration between architects and engineers in applying biomimetic principles to urban resilience. It integrates problem definition, biological research, and technology implementation into a structured workflow outlined below and summarised in Figure 28.

1. Problem Identification Phase (Architectural & Urban Context Analysis)

- **DEFINE**: Architects and urban planners identify urban resilience challenges (e.g., climate adaptation, water scarcity, energy efficiency).
- **COLLABORATION**: Engineers provide insights into structural constraints, material limitations, and feasibility.

2. Biological Research Phase (Nature-Inspired Strategy Development)

- **INVESTIGATE**: Architects and engineers analyse biological systems relevant to identified challenges.
    - Example: Termite mounds for passive cooling, mangroves for flood mitigation, or honeycomb structures for material efficiency.
- **SELECT**: The most viable biomimetic strategies are chosen based on scalability, functionality, and sustainability.

3. Design & Implementation Phase (Technology Transfer and Prototyping)

- **TRANSFER**: Engineering simulations and material testing validate biological inspirations.
    - Example: Computational fluid dynamics (CFD) for wind-responsive facades or finite element analysis (FEA) for load-bearing biomimetic structures.
- **CREATE**: Prototyping and integration of biomimetic materials and forms into urban infrastructure.
    - Example: Developing self-shading facades, bio-concrete structures, and adaptive

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drainage systems.

- **VALIDATE**: Engineers and architects assess performance through real-world simulations.
  - If ineffective, the model loops back to refinement stages.
  - If validated, the solution is adopted into urban development policies.

4. Policy Integration & Scalability Phase

- **GOVERNANCE**: Recommendations for incorporating biomimicry into **urban planning codes** and sustainability regulations.
- **SCALABILITY**: Assessment of how biomimetic solutions can be replicated in different climatic and urban contexts.

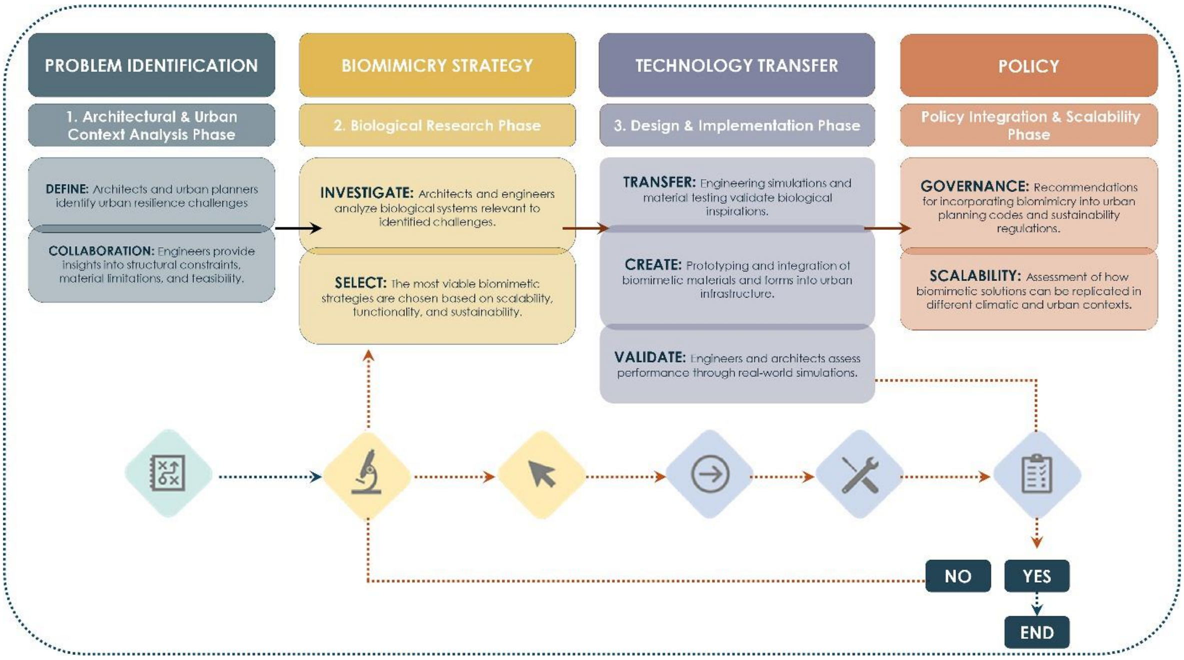

Figure 28. General scheme of the Biomimicry-Integrated Urban Resilience Model (BIURM)

This interdisciplinary model enhances urban resilience by systematically integrating biomimicry into Ghana's built environment, ensuring climate adaptation, energy efficiency, and sustainable growth.

3.7.1 Implications for Sustainable Urban Planning and Policy in Ghana

The adoption of biomimicry in Ghana's urban planning requires strong policy backing, interdisciplinary training, and investment in research. To fully integrate biomimetic principles into urban development, key policy recommendations include:

- **Incorporating Biomimicry in Building Codes:** Establishing standards that promote energy-efficient and climate-responsive infrastructure through biomimetic design.
- **Establishing Research and Training Hubs:** Encouraging universities and research institutions to develop cross-disciplinary programs in biomimetic architecture and engineering.
- **Public-Private Partnerships (PPPs):** Providing tax incentives and subsidies to private developers who implement biomimetic strategies in urban projects.
- **Climate Adaptation Strategies:** Integrating biomimetic urban resilience models into Ghana's National Urban Policy Framework (NUPF) to mitigate climate change impacts.

By aligning biomimicry with national sustainability goals, Ghana can enhance urban resilience, optimize resource efficiency, and improve environmental sustainability.

4 Conclusions

This study demonstrates that biomimicry offers a viable, sustainable approach to urban resilience, particularly in Ghana, where climate adaptation, water conservation, and material efficiency are critical concerns. Through architect-engineer collaboration, biomimetic principles such as passive cooling, adaptive shading, self-healing materials, and water-efficient systems can be effectively integrated into urban infrastructure.

The proposed Biomimicry-Integrated Urban Resilience Model (BIURM) provides a structured approach for implementing biomimicry in Ghana's urban planning, ensuring that nature-inspired innovations are systematically incorporated into building and policy frameworks. However, policy support, interdisciplinary training, and investment in research remain essential for mainstreaming biomimetic design. Future studies should explore the scalability, cost-efficiency, and user adaptability of biomimetic solutions in urban development. By adopting nature-driven design strategies, Ghana can pave the way for a more resilient, adaptive, and sustainable built environment.

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6 Conflict of Interest Declarations

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, orin the decision to publish the results.

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