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REVIEW ARTICLE

Reviewing biomimicry design case studies as a solution to sustainable design

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Abstract
There have been many studies on bio-inspired research, where biomimicry capabilities facilitating sustainable designs are in dearth. For a sustainable design, it is necessary to consider water efficiency, zero waste, thermal environment, and energy supply. This paper investigates how biomimicry is adopted in the sustainable design of buildings. A thorough content analysis of eight case studies focused on the built environment and how biomimicry integrated with the design of a building was executed. The selection of cases study was based on the concept of biomimicry by taking inspiration from nature and applying them in the everyday built environment. Thus, the building designs are more ecologically sustainable than conventional ones, where biomimicry approaches and principles are adopted. The findings suggest that the design of a building can inspire society with new ecological morals, where understanding of biological morphogenesis can inspire design to resolve challenges and essentially help create a healthy environment. Biomimicry harnesses and replicates the principles found in nature to create a built environment that benefits people and other living creatures and safeguards biodiversity. Thus, adopting biomimicry in designing a building will help to develop a culture of active environmental design.

Keywords Biomimicry · Biomimicry level · Biomimicry approaches · Sustainable · Design method

Introduction

The Biomimicry Institute defines biomimicry as the science and art of emulating nature's best biological ideas, processes, and ecosystem, where it was used to solve human and environmental problems (Benyus and Schwan 2006). This research asserts that the built environment practice should embrace biomimicry method to determine the best techniques to make building designs part of the ecosystem rather than an outsider to the ecosystem, causing environmental imbalance. To comprehend such situation, relevant answers and new possibilities for built environments can be explored by understanding nature and mimics form, systems, materials, function, process, esthetics, and ecosystems. Hence, this paper aims to explore biomimicry implementation in the constructed environment by looking on the approaches of design looking biology and biology.

Influencing design There are basically two approaches to biomimicry that plays a part in the design process. Firstly, identifying human problems and looking into the solution on how other organisms or eco-systems can resolve this problem is termed Design looking to Biology. Secondly, Biology to Design whereby identifying a particular function or the behavior of an organism or ecosystem and then applying it to human design. (Dash 2018).

Meanwhile, the biology influencing design is biological knowledge that influences human design. The collaborative design process depends on people knowing relevant biological or ecological research rather than on determining human design problems. An example is the scientific analysis of the lotus flower emerging cleanly from swampy waters, which led to many design innovations as detailed by Baumeister (2007). There are three reasons that this particular approach

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was selected: (i) designers can conduct research on biomimicry solutions without having in-depth knowledge and understanding in the scientific field, or designers can collaborate with biologists where they have a better understanding in researching the organism, behavior, and ecosystem (McDonough, 2002); (ii) designers find it easier to mimic the shape or mechanical aspects of organisms than to mimic other aspects that involve chemical processes without the collaboration between designers and scientists (Zari 2016); and (iii) approach design looking to biology is the transition of the built environment from unsustainable design to a more efficient design to an effective paradigm (McDonough, 2002). To further support the argument that designers need to include the biomimicry approach in their design process, this research has prepared a comparative analysis, in chart form, of biomimicry level versus biomimicry dimension.

Problem statement

This research paper aims to explore the biomimicry implemented to the constructed environment. In this study, two approaches were used: the design looking biology and the biology influencing design, along with the flow methods to understand the process. The design looking biology is an approach where designers look to the living world for solutions, and requires designers to identify problems and biologists to then match these to organisms that have solved similar issues (Vincent et al., 2006). This approach is effectively led by designers identifying initial goals and parameters for the design. Meanwhile, the biology influencing design is biological knowledge that influences human design; the collaborative design process is initially dependent on people having knowledge of relevant biological or ecological research rather than on determined human design problems. An example is the scientific analysis of the lotus flower emerging clean from swampy waters, which led to many design innovations as detailed by Baumeister (2007). There are three reasons that this particular approach was selected: (i) designers can conduct research on biomimicry solutions without having in-depth knowledge and understanding in the scientific field or designers can collaborate with biologists where they have a better understanding in doing a research on the organism, behavior, and ecosystem (McDonough, 2002); (ii) designers find it easier to mimic the shape or mechanical aspects of organisms than to mimic other aspects that involve chemical processes without the collaboration between designers and scientists (Zari 2016); and (iii) approach design looking to biology is one way to start the transition of the built environment from unsustainable design to a more efficient design to an effective paradigm (McDonough, 2002). To further support the argument that designers need to include the biomimicry approach in their design process, this research has prepared a comparative analysis, in chart form, of biomimicry level versus biomimicry dimension. A comparison chart is a chart that draws a comparison between two or more items on different parameters. The parameters that were used in this study are biomimicry level, biomimicry approaches, and five dimensions of biomimicry. This research carried out eight case studies that successfully blended architectural principles and biomimicry to make a remarkable environment: Beijing National Stadium, Jeongok Prehistory Museum, 30 St. Mary Axe also known as Gherkin Tower, Eastgate Center, Zira Island Master Plan, Lavasa Hill Station Project, Sahara Forest Project Qatar Tunisia and Jordan, The Eden Project.

Numerous studies are trying to attain sustainability through new designs and ideas, intelligent materials, and energy-saving technology. As biomimicry attempts have been made to establish worldwide sustainability standards, but not all genuinely sustainable architecture solutions have been produced, questions arise. To begin with, how is biomimicry implemented in the constructed environment? Second, why has biomimicry been chosen to solve human and environmental problems? The answer to these research questions will help to achieve the research aim.

Biomimicry research validates the ecosystem model and the species that coexist with the environment over time, and it addresses the most current and cutting-edge methods for achieving sustainability. Biomimicry provides a solution to a more regenerative built environment by serving as a source of inspiration for future new development (Benyus et al. 2009).

Literature review

What is biomimicry

Biomimicry term is made up of two words where bio that means life and mimicry or mimesis means imitating. To produce a sustainable design by using biomimicry, this requires studies related to nature by emulating natural forms processes, and ecosystems (Othmani et al. 2021). In biomimicry, most of the design are using shape or form of the organisms, and according to Mirniazmandan and Rahimianzarif (2017), using organic materials and natural processes is a new paradigm of sustainable. The designers were able to deepen their knowledge of biomimicry by inspired the nature into a design (Othmani et al. 2021).

Biomimicry as a vehicle for sustainability

The truth is, natural organisms have managed to do everything we want to do without guzzling fossil fuels, polluting the planet or mortgaging the future. - Janine Benyus

Sustainability is defined as the ability to meet one's needs without endangering one's ability to meet those needs in the future. Observing natural ecosystems reveals a sophisticated network of relationships between organisms, ensuring that nothing is wasted and that everything is recycled and reused. The waste of one organism is frequently a resource for the next. There is no sustainability problem when the pace of resource use does not exceed the rate of natural replenishment.

As organisms discover new methods to survive, they form relationships that keep the use and replenishment balance in check. Designers will be able to understand and design buildings that fit into the environment in the same way as humans fit into ecosystems when they replicate the organism by utilizing current resources and recycling waste that can be reused in the future. Benyus (2011) proposed nine criteria where the design will be tested to measure how well it succeeds at mimicking nature in her book titled *Biomimicry – Innovation Inspired by Nature* (Table 1).

The above nine criteria act as a guide when mimicking nature in design (Peters 2011).

These nine criteria will be guiding the designer in mimicking nature into the design. They may form the benchmark against which to test how sustainable a proposed design is and where possible suggest areas for improvement (Okeke et al. 2017).

Biomimicry approaches

Biomimicry relates modern ideas to nature by using nature as a source of design inspiration to solve human problems in a sustainable way. Figure 1 depicts how biomimicry tries to relate the constructed environment to the natural world by using nature as a model, a standard of measurement, and a mentor. This strategy is founded on the premise that when all designs look and mimic nature, will make this design accepted by nature (Benyus 1997).

Design looking to biology

Design looking to biology approach will guide the designers exploring the nature and looking for the solutions necessitates designers identifying challenges and biologists matching these two species that have solved similar problems (Fig. 2) (Mohd Ariffin and Farag Gad 2017). Designers effectively lead this technique by setting early design goals and parameters. Here is an example of such an approach:

This approach is one of the design principles that will lead to the integration of nature's strategy as the solution for any design challenge.

A bionic car inspired by boxfish

The prototype of bionic car designed by Daimler Chrysler is using this approach. This car has a large volume and small wheel base car. This design was inspired by boxfish (Ostracon Meleagris) (Reem Elsamadisy et al. 2019).

As a result, such a strategy does not necessarily address the fundamental reasons for a non-sustainable or even degenerative built environment. The bionic car (Fig. 3) illustrates the point. It uses less gasoline since the body is more aerodynamic due to the box fish imitating. It is also more economical because it mimics tree development patterns to determine the least amount of material required in the car's structure. On the other hand, the car is not a novel mode of transportation. Instead, minor enhancements to current technologies have been made without rethinking the car as a solution to personal transportation.

Designers are able to do research on biomimicry without having in-depth scientific grasp of biology or even collaboration with a scientist or ecologist, as long as they have access to available biological studies or can observe organisms or ecosystems (Rossin 2010). However, the translation of such biological knowledge to a human design context may remain limited due to a lack of

Table 1 Biomimicry principles

Criteria	Explanation
Whether it runs on sunlight	Is its primary source of energy passive?
Whether it uses only energy it needs	Does it consume only energy it needs to function?
Whether it fits form to function	Is the shape of the building derived from what it
Whether it recycles everything	How effectively does it handle waste?
Whether it rewards cooperation	How well does it relate with its surrounding environment?
Whether it banks on diversity	Is the design tailored to its environment or is it a one-size fits all type of building?
Whether it curbs excess from within	Is there a good economy of building material such that it only uses the amount of material it needs to function and is not overbuilt
Whether it taps the power of limits	Is it able to maintain the narrow range of values in which suitable for its inhabitants without need for supplementary devices like air conditioning heating system?
Whether it utilizes local enterprise	How well does it make use of local resources?

Fig. 1 Biomimicry principles

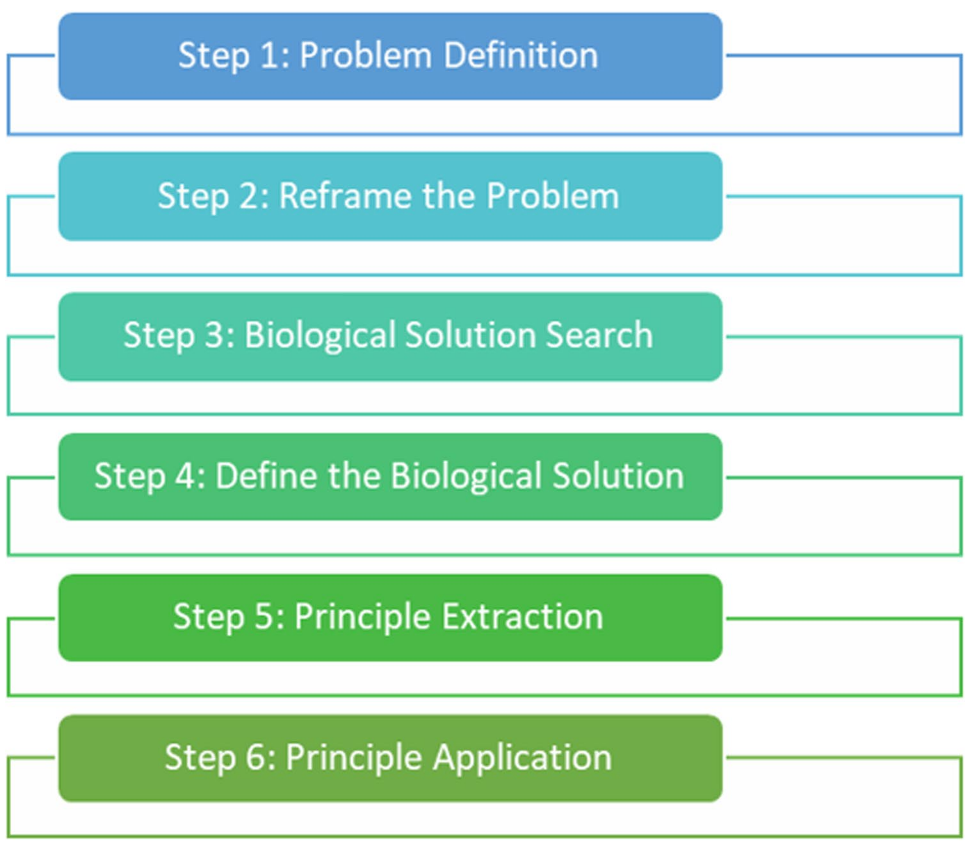


Fig. 2 Design looking to biology flow method

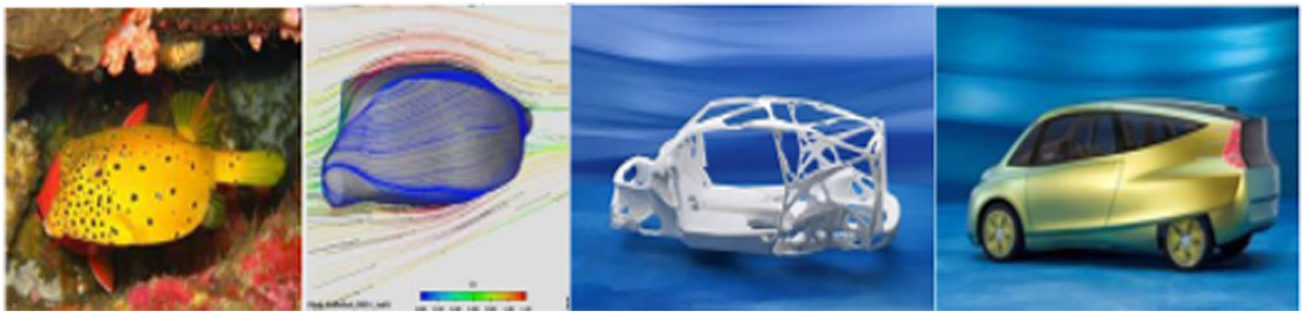


Fig. 3 Bionic car inspired by the box fish. Source: https://www.researchgate.net/figure/Lotusan-paint-inspired-from-lotus-flower-properties_fig5_343326109

scientific understanding. It is simple to duplicate organism forms and certain mechanical elements, but it is more complex than mimicking chemical processes because it will need collaboration with scientist. Despite these drawbacks, such an approach could be a starting point for transforming the built environment from an unsustainable to an efficient to an effective paradigm (Reem Elsamadisy et al. 2019).

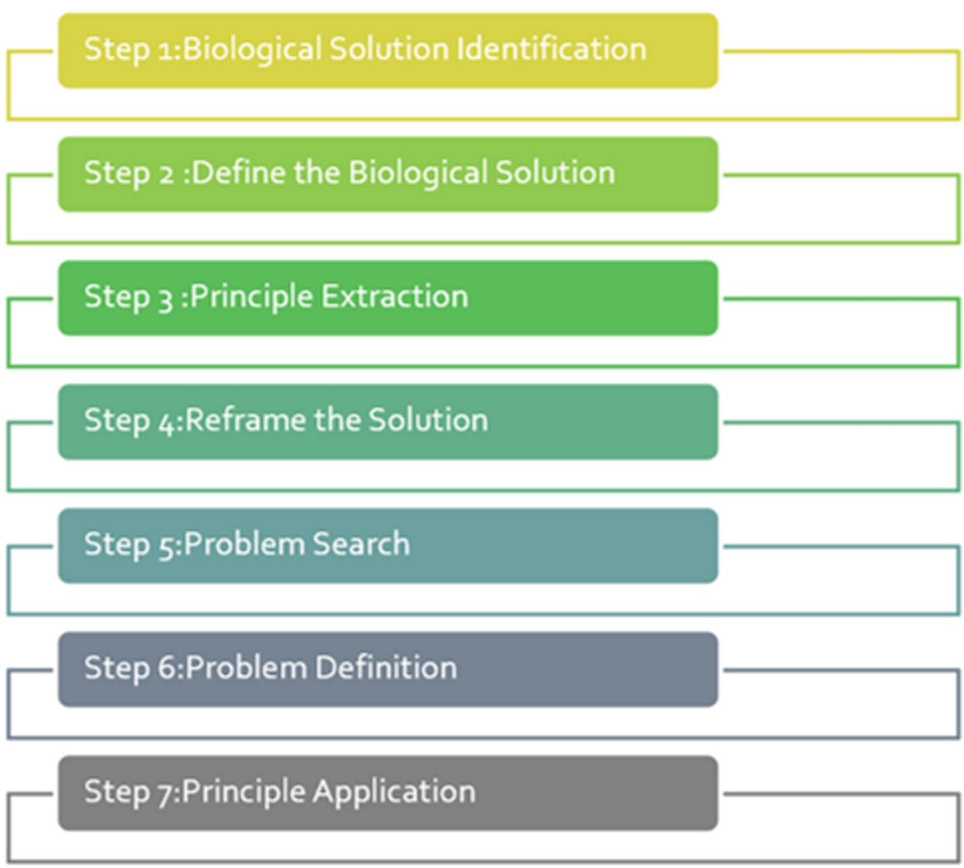
The Biomimicry Institute has referred to this design approach and explained it through the design flow as illustrated in Fig. 4.

Biology influencing the design

When biological knowledge influences human design, the collaborative design process is initially reliant on people who are familiar with relevant biological or ecological research rather than on predetermined human design challenges. Here is an example of such an approach:

In this case, the biological knowledge influences human design which is basically a collaborative design process mainly relying on the knowledge of relevant biological research (Fig. 4).

Fig. 4 Biology influencing design flow method



The constantly self-cleaning lotus

Despite the fact that the lotus plant (a white-water lily) grows in muddy lake and pond bottoms, its leaves are always clean. This is due to the fact that once a little particle of dust drops on this plant, it immediately waves the leaf, directing the dust particles to a specific location. Raindrops falling on the leaves are directed to the same spot, cleaning away the dirt. Researchers were inspired by this lotus feature to develop a new house paint (Hwang et al. 2015).

Researchers began working on how to make paints that, like lotus leaves, wash clean in the rain. As a result of this trial, the Lotusan brand of home paint was established by a German company called ISPO. The product was even sold with a 5-year assurance that it would stay clean without the use of detergents or sandblasting in Europe and Asia (Uchiyama et al. 2020).

An example is the scientific analysis of the lotus flower emerging clean from swampy waters, which led to many design innovations. The study of the lotus flower that was able to self-clean form dirts led to many design innovations including Sto' Lotusan paint which enables building walls self-cleaning (Wanieck et al. 2017) (as shown in Fig. 5).

With this approach to biomimicry design, there is the possibility for true shifts in the way humans design and what is focused on as a solution to a problem (Vincent et al., 2006). The disadvantage of this method from the standpoint of design is that biological research must be undertaken and then identified as relevant to a design context. As a result, biologists and ecologists must be able to assess the potential of their study in the development of fresh applications.

Biomimicry levels

According to Dash (2018), there are three levels of mimicking which are organism level, behavior level, and ecosystem level (Table 2). Organism level is a process of mimicking some part or whole part of an organism, while behavior level is mimicking the behavior or response of an organism to the context and ecosystem level is mimicking the function of the ecosystem (Shahda and Elmokadem 2018) To implement this, level must be based on the designer's design program and also to the existing context (Zari 2016).

There are five dimensions of mimic which are what it looks like (form), what it is made out of (material), how it is made (construction), what it is able to do (function), or how it works (process) (Mansour 2010).

Methodology

Defining case study

Carefully formulated research question(s), informed by the existing literature and a prior appreciation of the theoretical issues and setting(s), are all important in appropriately and succinctly defining the case. For this study, case studies were defined based on environmental issues and how the designers solve the problem by using biomimicry.

Selecting case studies

The decision on how to select the case(s) to study is a very important one that merits some reflection. In an intrinsic case study, the case is selected on its own merits. The case is selected not because it is representative of other cases, but because of its uniqueness, which is of genuine interest to the researchers. For this study, eight case studies were selected based on the concept the designers used in design and their approaches in achieving the sustainability of the design.

Assessing different design focuses

Case studies revealed that the design emphasized different biomimicry levels, depending on the design strategy employed. According to the findings, though based on a limited number of case studies, most of the design used organism level rather than behavior level and ecosystem level.

Exploring differences in the type of application

The next method addresses the type of application that the Biomimicry Institute suggests. The case study showed that all the designs use different biomimicry approaches either — design looking to the biology or biology—influencing the design. Another assessment is biomimicry level, and most of the designs are using organism level, and last, not least,

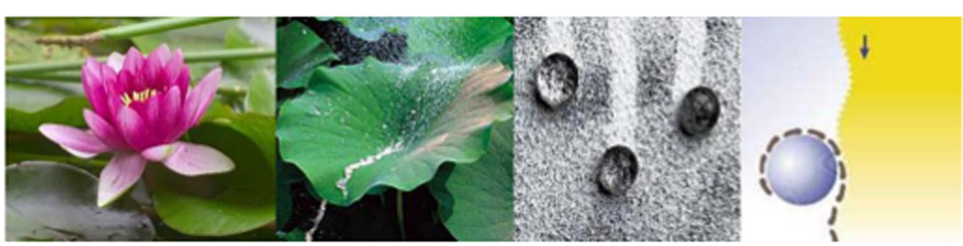


Fig. 5 Lotus inspired Lotusan paint. Source: https://www.researchgate.net/figure/Lotusan-paint-inspired-from-lotus-flower-properties_fig5_343326109

Table 2 Biomimicry level and dimension of mimicry

Dimension of mimicry	Organism level	Behavior level	Ecosystem level
Form	The building looks like a termite	The building looks like it was made by a termite; a replica of a mound	The building looks like an ecosystem (a termite would live in)
Material	The building is made from the same material as a termite: a material the mimics termites exoskeletons skin form example	The building is made by a termite; a replica of a mound The building is made from the same material as a termite build with: using digested fine soil as primary material for example	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as primary chemical medium for example.
Construction	The building is made in the same way as a termite; it goes through various growth cycles for example	The building is made in the same way that a termite would build i.e., piling earth in certain places at certain times for example	The building is assembled in the same way as a (termite) ecosystem: principles of succession and increasing complexity over time are used
Process	The building works in the same way as an individual termite; it produces hydrogen efficiently through metagenomics for example	The building works in the same way that a termite; by careful orientation, shape, material selection and natural ventilation for example or it mimics how termites work together	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and store water for example
Function	The building functions like a termite in a larger context; it recycles cellulose waste and create soil for example	The building functions in the same way it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example. It may also function in the same way that a termite mound does in a larger context	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationship between processes; it is able to participate in the hydrological, carbon and nitrogen cycles in a similar way to an ecosystem

for five dimensions of biomimicry, there are form, function, construction, process, and function.

Analyzing case studies using comparative analysis

A comparison chart is a chart that draws a comparison between two or more items on different parameters. The parameters that were used in this study are biomimicry level, biomimicry approaches, and five dimensions of biomimicry. This research explored eight case studies that successfully blended architectural principles and biomimicry to create a sustainable environment. The case studies are Beijing National Stadium, Jeongok Prehistory Museum, 30 St. Mary Axe also known as Gherkin Tower, Eastgate Center, Zira Island Master Plan, Lavasa Hill Station Project, Sahara Forest Project Qatar Tunisia and Jordan, and The Eden Project. The eight case studies were analyzed using comparative analysis by using biomimicry approaches (design looking to biology or biology influencing the design), biomimicry levels (organism level, behavior level, and ecosystem level), and five dimensions of biomimicry (form, material, construction, process, and function) (Fig. 6).

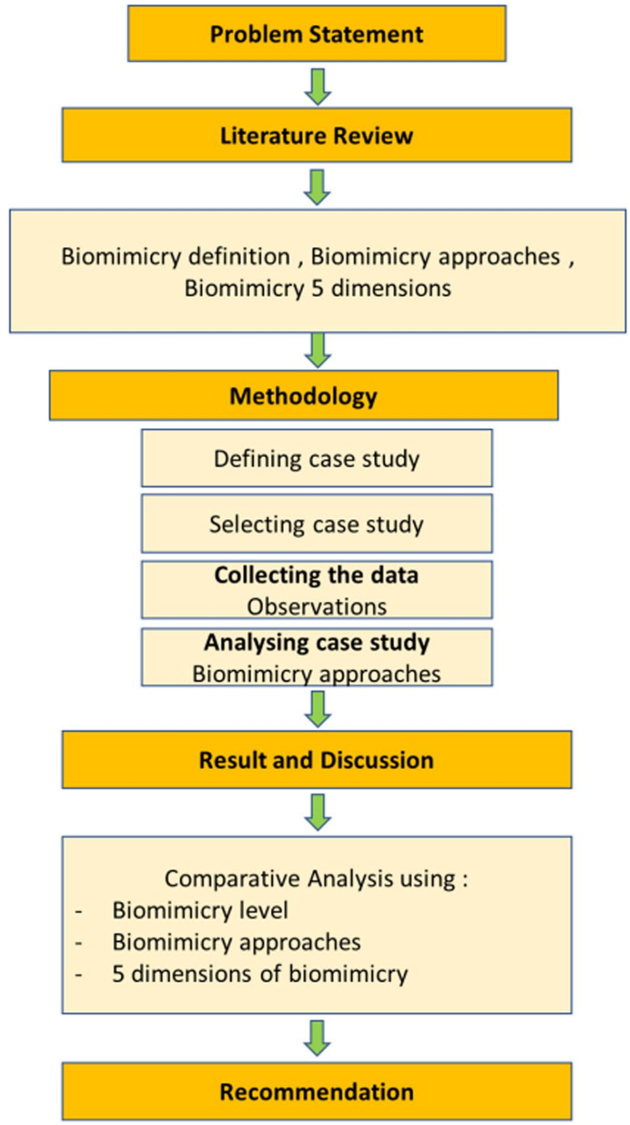


Fig. 6 Research method flow

Biomimicry approaches

All the case studies will be analyzed based on two biomimicry approaches as mentioned before in the "Literature review" section which are design looking to biology and biology influencing the design.

Design looking to biology

This method started by identifying the problem definition.

Step 1: Define a human problem in terms of required function(s) and constraints.
Step 2: Biologize the problem by reframing the human problem in biological terms.
Step 3: Apply search strategies in the biological world to find sources that solve the "biologized" problem.
Step 4: Understand how the biological sources solve the "biologized' problem.
Step 5: Identify solution-neutral behaviors and principles used by the biological source.
Step 6: Apply the behaviors and principles to solve the original human problem.

Biology influencing the design

Step 1: Identify a biological source that has solved a challenging problem.
Step 2: Understand how the biological source solves the "biologized" problem.
Step 3: Identify solution-neutral behaviors and principles used by the biological source.
Step 4: "Humanize" the solution in terms relevant to meeting human goals.
Step 5: Find salient human problems that match the "humanized" solution, select one, and define constraints.
Step 6: Apply the principles to solve the "humanized" problem.

Result

Case studies

From the case studies that are using nature as a source of inspiration for the design and levels of imitating nature, each level of biomimicry can imitate nature and solve significant environment problems, for example:

Case study: the organism level—nature is the inspiration for the formation

Beijing National Stadium Inspired by: Bird's nest

Design problem: Need a large span for stadium design without any obstruction for column in the middle of the stadium.

Biomimicry solution: Roof, wall, and staircase of this stadium are integrated into the spatial grid-like formation where the steel trusses were assembled overlapping each other and the space in between the gaps was filled with translucent membrane.

Jeongok Prehistory Museum Inspired by: Snake scales

Design problem: Undulating of landform causes difficult to construct the building on site.

Biomimicry solution: The exterior mimics the texture of snake scale.

Project features: The mirror-like stainless steel makes it possible to reflect solar heat rays on sunny days and perforations of outer skins and the steel grating floor of maintenance walkways allow ventilation of hot air by winds and convection effects inside the internal spaces.

St Mary Axe a.k.a Gherkin Tower Inspired by: Venus flower basket sponge

Design problem: Need lateral support into one, making the building to be stiff, efficient, and lighter than a traditional high-rise.

Biomimicry solution: This sponge sits in an underwater environment with strong water currents and its lattice-like exoskeleton and round shape help disperse those stresses in various directions and its round shape reduces forces due to strong water currents.

Project features: The round shape of the building reduces wind deflections and creates the external pressure differentials that drive the natural ventilation system. Air can flow around the building more smoothly compared to the rectilinear shape of a traditional office tower. A lattice-like, diagonally braced structure around the exterior allows for an open floor plan without interior columns. The openness also provides a large amount of natural light penetration.

Case study: the behavior level—mimicry of how an organism behaves

Eastgate Centre, Zimbabwe Inspired by: Termite's mound

Design problem: Hot temperature causes using air conditioning.

Biomimicry solution: To reduce the possible costs of maintaining the building's internal temperature, researchers looked to African termite self-cooling mounds. There is no air conditioning or heating in the building.

Project features: Passively cooled, Eastgate uses only 10% of the energy needed by a similar conventionally cooled building (Mick Pearce, 2003). When actively cooled, the center consumes 35% less energy to maintain the same temperature as a conventionally cooled building.

Case study: the ecosystem level

Zira Island Master Plan Inspired by: Mountains

Design problem: Inhabitable island

Biomimicry solution: Inspired by ecosystems that can produce vegetation and salination of water.

Project features: Zero energy resort and entertainment city design on the island

Lavasa, Hill Station Project Inspired by: Deciduous forest

Design problem: Lavasa surrounded by mountain has been deforested using slash and burn method. The occurrence of monsoon rains in the area causes soil erosion for 3 months each year. The original atmosphere of Lavasa was humid and had a deciduous forest before deforestation (Rossin 2010).

Biomimicry solution: Roofs that help re-release some of the monsoonal water back into the air as water vapor, pavement that allows water to permeate back into the ground, and building foundations that grip the hillsides like the roots of trees.

Project features: Six "ecosystem services" provided by the area's moist deciduous forest: water collection, solar gain, carbon sequestration, water filtration, evapotranspiration, and the cycling of nitrogen and phosphorus.

Sahara Forest Project Qatar, Tunisia and Jordan Inspired by: Namibian fog-basking beetle

Design problem: There is no fresh water for agriculture activity.

Biomimicry solution: Namibian fog-basking beetle, which has found its own way to evolve its own fresh water in a desert and to regulate its body temperature by accumulating heat by day and collecting the water droplets formed on its wings by the fog. The greenhouse design emulates this beetle to combat climate change in an arid climate (Michael Pawlyn, 2011).

Project features: Three core components drove the design of the greenhouse; the major one being a creating a saltwater-cooled greenhouse, concentrated solar power (CSP), and technologies for desert vegetation (An Oasis of Green Building. n.d).

The Eden Project (2001) in Cornwall, England Inspired by: Soap bubbles

Design problem: To maintain a tropical temperature and moisture level

Biomimicry solution: Soap bubbles inspired the forms of the biomes and cellular structures inspired the hexagonal frames. A biome is a natural occurring community of flora occupying a major habitat. The artificial biomes in the Eden project feature a humid tropic rainforest and Mediterranean biome (Michael Pawlyn 2011).

Project features: The use of inflated ethylene tetrafluoroethylene (ETFE), a material that is both light and strong (1% of the weight of double glazing), provides other benefits such as a lighter steel frame, letting in more sunlight and adding solar gain also, and it costs 1/3 less than the traditional glass solution. The final superstructure weighs less than the air it contains (Michael Pawlyn, 2015).

Discussion

From the study, the most widely used approach by designers is design looking at the biology rather than biology influencing the design. The designers identify the problem first and then find the appropriate biology to solve the problem of the environment for example case studies Beijing National Stadium, Jeongok Prehistory Museum, Gherkin Tower, and Eastgate Centre; this approach is easy to use because it does not require in-depth knowledge of biology, while the biology approach influencing the design is only used by three case studies which are Zira Island Master Plan, Lavasa, Hill Station Project, and Sahara Forest Project Qatar, Tunisia, and Jordan. These three case studies identify biology first and then find issues that can be applied using the designs that have been produced. This requires cooperation with biologists as well as engineers. In terms of levels, the designers managed to use different levels and did not focus on one level only. This shows that designers understand the level of mimicry and how it is applied to design. While in terms of achieving sustainability, most of the design succeeds in producing a sustainability design. This shows that biomimicry can be used as a method to achieve sustainability for a design. For five dimensions of biomimicry assessment, most of the designs follow the form of the nature because it is easy to mimic. For the material category, only Eastgate Centre followed mimic termite mound where the designers use brick to construct this building, while other case studies are using other materials (Table 3).

For construction category, case studies are mimics same with the nature forms, and for the process, the designs are using normal construction and did not follow the natural process to construct the building. Last category is function. All the designs successfully mimic the nature in designing the building and manage to achieve sustainability and solve nature problem.

Conclusions

Design that uses biomimicry is seen to achieve sustainability in this study. But its widespread use is still not widespread. This method should be widely introduced to designers based on what we can learn from nature rather than what we extract from it. By understanding how forms, organisms, behaviors, processes, and ecosystems face all the problems for billions of years, inspire from those abilities and apply them into design. By introducing this biomimicry, we will be able to increase the income of a sustainable design strategy integration with nature. As the biomimicry aims to copy nature in solving problems, the design will help in generating no waste and reduce the impacts to the surroundings. Biomimicry in design helps in sustainability as the research conducted in producing the solutions to one's problem is going with in-depth research and methods to create a sustainable design. By looking at the elements and systems of nature, in-depth can help designers in deriving the solutions to the design and planning issues. Biomimicry in design adds a sense of sustainability as well as creativity in which the added values from the design will last for a longer time than today's available designs. Therefore, designing with biomimicry in mind not only teaches the society the new ecological morals but also it can usefully inspire design that helps in creating a healthy environment and positively impacting the environment.

Recommendation

The findings of this study have contributed to the knowledge and understanding of biomimicry. Nevertheless, future research should continue to increase the understanding, exploration, and appreciation of the biomimicry concept. Future studies need to focus on components that are still lacking in the currently proposed biomimicry level design framework as well as adding details to it, especially those relating to its design components. Thus, it is recommended that future studies should focus on the following:

i. In-depth study needs to test the biomimicry framework effectiveness in actual design and implementation.

Table 3 The result of every case study in different categories / The summarized findings from different case studies including the comparison of biomimicry levels, approaches, and five different dimensions of biomimicry

No	Case study	Biomimicry level	Biomimicry approaches (DLTB/BITD)	Five dimensions of biomimicry				
				Form	Material	Construction	Process	Function
1	Beijing National Stadium	Organism level/ behavior level	Design looking to biology	The building looks like a bird's nest	The material is made from steel trusses and translucent membrane. The design of the materials mimics the bird's nest	The building is made the same way that a bird would build its nest, i.e., integrated into the spatial grid-like formation where the steel trusses were assembled overlapping each other and the space in between the gap was filled with translucent membrane	The building works in the same way as an individual bird nest, steel trusses as a wall mimics the branches and filled with translucent membrane mimics the plastic or paper to fill in the gap	The building functions like a bird's nest in a larger context
2	Jeongok Prehistory Museum	Organism level	Design looking to biology	The building looks like a snake	The material is made from a steel and mimics the texture of snake scale	The building is mimics the physical of snake i.e., the exterior mimics the texture of snake scale	-	The building only follows the form of a snake because of undulating landform and site context
3	30 St Mary Axe a.k.a Gherkin Tower	Organism level	Design looking to biology	The building looks like a Venus flower basket sponge	The material is made from a steel and glass mimics the shape of Venus flower basket sponge	The building mimics the shape of Venus flower basket sponge, i.e., lattice-like exoskeleton and round shape	The building works in the same way as a Venus flower basket sponge where the shape of the flower helps disperse those stresses in various directions	The building functions like a flower in a larger context where it helps disperse those stresses in various directions and its round shape reduces forces due to strong wind direction
4	Eastgate Centre, Zimbabwe	Behavior level	Design looking to biology	The building did not look like a termite's nest	The material is made from brick. Same like termites' mounds where it uses clay	-	The building works in the same way that a termite works: by careful material selection and natural ventilation	To reduce the possible costs of maintaining the building's internal temperature, researchers looked to African termite self-cooling mounds. There is no air conditioning or heating in the building
5	Zira Island Master Plan	Ecosystem level	Biology influencing the design	The design looks like an island and mountains	Variety of materials and mimics all the natures	The construction mimics the nature ecosystems	-	-

Table 3 (continued)

No	Case study	Biomimicry level	Biomimicry approaches (DLTB/BITD)	Five dimensions of biomimicry				
				Form	Material	Construction	Process	Function
6	Lavasa, Hill Station Project	Ecosystem level	Biology influencing the design	The design did not look like deciduous forest	There are no specific materials that used in this design	The design mimics the deciduous forest, i.e., tree roots	The design works in the same way that deciduous forest manages the flooding during monsoon season.	The design functions like a deciduous forest where it is able to manage flooding problems during monsoon season
7	Sahara Forest Project Qatar, Tunisia and Jordan	Ecosystem level	Biology influencing the design	The design did not look like Namibian fog-basking beetle	-	The design mimics on how Namibian fog-basking beetle collect the water droplets	The proposed technology combines saltwater-cooled greenhouses with solar power technologies, either directly using photovoltaic (PV) or indirectly using concentrated solar power (CSP) and technologies for desert revegetation	The pilot facility involved a purpose-built greenhouse. At one end of the greenhouse seawater is rundown a surface while fans blow desert air over it. The evaporation of the seawater results in cool and humid air within the greenhouse, thus lowering the temperature. The condensation of moist air, using pipes cooled with the seawater, results in a freshwater source for irrigation. The energy produced for the operation of the greenhouse is generated within a concentrated solar power plant within which solar energy is used to create steam and drive turbines

Table 3 (continued)

No	Case study	Biomimicry level	Biomimicry approaches (DLTB/BITD)	Five dimensions of biomimicry				
				Form	Material	Construction	Process	Function
8	The Eden Project (2001) in Cornwall, England	Ecosystem level	Design looking to biology	The building looks like a soap bubble	The material is made from inflated ethylene tetrafluoroethylene (ETFE) stronger than bubbles	The building mimics the shape of bubbles. The use of inflated ethylene tetrafluoroethylene (ETFE), a material that is both light and strong (1% of the weight of double glazing), provides other benefits such as a lighter steel frame, the final superstructure weighs less than the air it contains (Michael Pawlyn, 2015)	The building works in the same way as an individual soap bubble where it lets in more sunlight and adds solar gain also and it costs 1/3 less than the traditional glass solution	

This will further validate the framework and provide improvements.

ii. There is a need to assess user perceptions on various framework components as it is still new and untested against users' responses. Therefore, it would be helpful to conduct studies on user's preferences based on the proposed guidelines of the framework. Further study needs to be done on the needs and demands of users as well, which continuously change over time. These will contribute to improving the detailed aspects of the framework.

iii. Future research can also be done specifically on the biomimicry levels within the framework of the biomimicry concept specifically for academicians, and related professionals. Perhaps, a prototype or mock-up of the biomimicry design could be developed to test user responses in a more realistic setting.

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Data availability Social Science

Declarations

Ethics approval This is a review study. The researchers have confirmed that no ethical approval is required.

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