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Application of Biomimetic Strategies in Building Envelope Design for Water Harvesting

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Highlights

- This paper focuses on the knowledge of water harvesting in nature transferred to architecture.
- This paper aims to investigate and apply the water harvesting strategies of biological organisms.
- In this study a sustainable façade proposal inspired by living organisms is suggested.

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Abstract

Nature is a database that offers potential solutions to humanity's many problems with its countless living species and their developed adaptations. As in engineering, medicine, agriculture, etc., innovative approaches are sought in the discipline of architecture with the solution proposals offered by nature. Designers looking for creative solutions, especially in producing the most effective constructions with the most materials, providing energy efficiency in built environments, designing ecologically and harvesting water and developing methods that imitate and learn from nature. One of the main actors in the global agenda on climate change and the clean water problem is built environments. In this context, water harvesting methods to be developed through architectural design also emerge as one of the current research topics. In this paper, research has been conducted on how the water harvesting knowledge in nature can be integrated into architecture; A biomimetic shell proposal has been developed to provide atmospheric water gain. Firstly, the concept of biomimetics is clarified through a literature review and examples of water balance strategies of living things in nature are presented. Then, architectural examples inspired by these strategies are analyzed. The selected living organisms were analyzed in the field study section and a design concept that can harvest water on the building facade was developed based on the biological information obtained. Inspired by the water harvesting principles of cactus and *Bromeliaceae* plants, this design is presented as an alternative for water harvesting with different usage possibilities in built environments.

1. INTRODUCTION

Water is the root of all life, the place where life begins. It is crucial for humanity and the survival of all living things. A remarkable proportion, like 70% of the Earth's surface, is covered by water. But most of this water is found in the oceans, while only 2.5% is freshwater [1]. Water constantly moves in a cycle of evaporation, condensation, precipitation, surface and channel runoff, and subsurface flow, but it is also highly affected by global climate change. Nevertheless, it is increasingly threatened by growing populations, access to safe water, and pollution caused by human activities. The World Economic Forum ranked water crises as the most important global risk in relation to potential effects in its risk report published in 2015 [2]. The population living in water scarce areas increased from 2.1 billion to 2.5 billion between 2014 and 2024 and it is estimated to reach 2.7 billion people by 2030 [3]. As a consequence of the rapid depletion of water resources, sustainable use and production of water is becoming an important issue. Access to clean water is one of the Sustainable Development Goals (SDGs) and the goal is to ensure universal and equal access to safe and affordable drinking water for everyone by 2030 [4]. Water pollution is a significant problem facing the world today. Therefore, sustainable methods of water harvesting and water treatment are becoming increasingly important [5].

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Nature can evolve and transform in the most extreme environments, including Earth's driest or coldest places. Over millions of years, thousands of species have developed solutions to collect, transport, and conserve this vital fluid. Even in the driest regions, many species survive, efficiently transfer the water they collect from the air to the systems in their bodies, and store it with minimal loss. These creatures survive even in the most extreme conditions thanks to different methods. For instance, animals in arid habitats have evolved various mechanisms for obtaining water from rain, dew, thermally facilitated condensation on the shell/skin, fog or humid air overcome limited water supply [6]. Many organisms, such as insects and cacti, can survive in arid environments thanks to their surface structures that can collect fog. These surfaces have micro-nano structures that provide extremely minimal adhesion and allow water to be constantly collected and transported [7]. These species represent promising but undiscovered solutions for making atmospheric water available to communities around the worldwide.

Several studies have been conducted in different disciplines for nature-inspired water harvesting systems in recent years. [8] investigate the water collection behavior of bio-inspired fiber material inspired by spider webs. [9-10] emphasize various nature-inspired systems such as spider webs for fog collection. [11] designed and fabricated a cactus-inspired fog collector. [12] compared biomimetic fog-collecting surfaces with other fog-collecting surfaces and found that the biomimetic surface is more efficient. [13] described the steps to create a nature-inspired design. Design concepts were developed inspired by the water harvesting principles of various creatures such as the Namibian desert beetle, Molok lizard, Stoma, human skin, and glass plants. [14] focused on the current state of biology-inspired material technologies while focusing on the water-collecting principles of various living organisms. On the other hand, [1] drew attention to the water problem, studied nature-inspired water collection, purification, and separation processes, and designed a cactus-inspired water collection system. [15] designed a fabric using the water collection principles of desert insects and spider webs. [16] Caldas et al (2018) investigated spider web-inspired mesh surfaces for water harvesting from the fog. [17] designed a desert insect-inspired fog collection surface to make progress in the area of biomedical and microfluidic devices and discussed its effectiveness through experiments. [18] discussed the latest developments in the field, including the production and applications of bio-inspired hydrophilic-hydrophobic materials inspired by desert insects. Inspired by biological microstructures, [19] fabricated functional surfaces containing high-density copper oxide nano-needles that collect water. [20] produced solutions with a biomimetic approach to enhance the productivity of the surfaces where water is captured from the fog and tested these solutions with experiments. [21] designed and created wettable surfaces inspired by the water-harvesting properties of desert insects and the *Nepenthes pitcher* plant. [22] examined architectural samples designed with biomimetic approaches to water harvesting and highlighted that effective methods can be developed for buildings by using biomimetic design techniques. [23] proposed a water harvesting system inspired by the cactus plant for building facades. [24] discussed recent advances in bio-inspired designs and biomimetic water harvesting structures inspired by desert-dwelling cactus, desert beetles, lizards, and snakes. [25] proposed a novel nature-inspired hybrid super hydrophilic/superhydrophobic aluminum surface water collector. [7] fabricated a desert beetles-inspired water harvesting system using 3D printers.

Unlike other studies, this study suggests an energy-efficient, sustainable façade design proposal inspired by the working principles of living organisms in humid climate zones. The question "How can different water harvesting strategies of living organisms be transferred to building envelope design?" motivated this study. A design was also realized with the hypothesis that "the adaptation strategies of living things to achieve water balance provide important data for building envelopes located in humid regions."

From this point of view, firstly, general information about biomimetics was presented in the research, then 3 animal and 3 plant examples were examined to reveal which water harvesting methods living things use in nature. The following section includes designs inspired by nature in water harvesting. In the field study, a façade inspired by cactus and *Bromeliaceae* plants was designed for water harvesting by adopting the problem-based design method defined by [26]. The study's findings significantly contribute to understanding water harvesting architecture and play an essential role in bridging the gap between theory and practice.

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

2.1. Biomimetic Approach

Human beings have observed nature in their struggle for survival over the years and have developed solutions to the challenging conditions they face by imitating the processes in nature, interpreting them according to the situation, and synthesizing their findings [27]. The physical properties or behaviors of all living or non-living formations in nature have influenced science and technology in every period, and research on nature has deepened with the developing technology. It has been a source of inspiration in many branches of science [28].

Various terms such as biomimetic, biomimicry, bionic, bioinspiration, and bio-informed are used to define the process of 'learning from nature', which is a significant emerging research area [29]. In the scientific literature, these diverse terms are considered as synonyms as in [30-33]. However, each concept has a different meaning. The term "biomimetic", one of the most frequently used concepts in the literature, is stated as a synthesis of the terms life (bios) and imitation (mimesis/mimic) [29]. The concept of "biomimetic" is the collaboration between biology, technology, and/or other disciplines to solve problems by analyzing biological systems, processes, and functions, their abstraction, translation into models, and the application of these models [34]. With an interdisciplinary approach, experts from diverse scientific fields, such as mathematics, chemistry, biology, physics, architecture, design, engineering, material sciences, etc. analyze biological knowledge and systematically transfer it to technical applications [35]. [36] described "biomimicry" as "a new discipline that studies nature's best ideas and imitates these designs and processes to solve human problems". According to [37], biomimicry is understanding the different physical properties of organisms in nature, their behavior, and how they work, and using them to produce innovative solutions in design. Biomimicry is a philosophy and interdisciplinary design approach that uses nature as a model to overcome the social, environmental, and economic challenges of sustainable development [34]. The emerging field of biomimicry deals with new technologies derived from bio-inspired engineering at the micro and macro scale [38]. "Bioinspiration" is an inventive approach based on observing biological systems. The term “bionic” is the technical discipline that aims to replicate, augment, or replace biological functions with electronic and mechanical equivalents [34]. The concept is defined as the science of systems containing certain functions copied from nature or representing features of natural systems [39].

In this study, the approach of being inspired by nature is discussed through biomimetics. The field of biomimetics, which uses the natural world as a source of inspiration and problem-solving, seeks an answer to a design problem while discovering the solutions used by nature. Looking for a solution to the problem in nature and its guidance leads to two basic approaches in the biomimetic design process: problem-based and solution-based. These two approaches are expressed in various definitions by different researchers.

In the problem-based design approach, defining a design problem is essential. How the identified problem is solved in nature is investigated and this natural solution is abstracted and used in design. The solution-based approach adapts a specific feature, behavior, or function in an organism or ecosystem to solve to a design problem [40]. In this process, biologists try to produce solutions by adapting biological features to a technology or design problem [41].

The problem-based design process is expressed in different terms such as; design looking to biology [40], problem-driven [26, 42, 43] biomimetics by analogy [44], Problem-Driven Biologically Inspired Design Process [26], a challenge to biology [45], problem-based [13], technology pull [34], from a problem to biology [39].

The solution-based design process is also expressed in different terms such as; solution-driven [26,42], solution-based [13,43], biomimetics by induction [44], biology to design [45], biology push [34]; from biology to an application [39].

These two approaches are applied with different process steps put forward by researchers. Zari (2007) summarizes the problem-based approach in 5 steps, the first step being the definition of the design problem, followed by the search for biological analogies, then abstraction, testing, analysis, feedback in the fourth step, and design in the last step. The solution-oriented process is summarized in 5 steps: the first step is biological research, then functional morphology and anatomy research, the third step is abstraction, then testing, analysis, feedback, and finally design [40]. Zari's steps are presented in Figure 1.

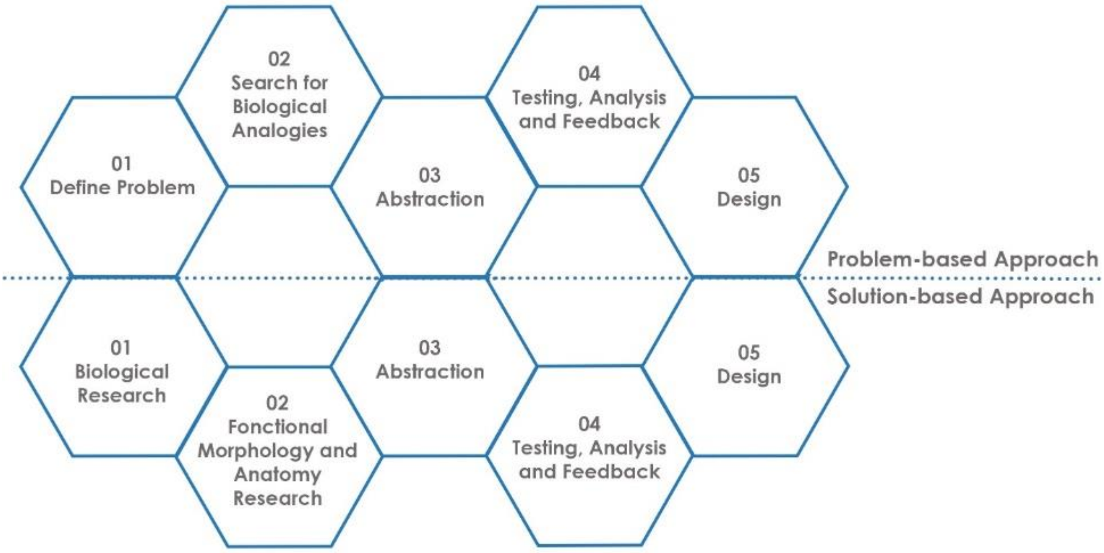


Figure 1. *Biomimetic design processes (adapted from [40] and created by the author)*

[26] identified 6 steps for the problem-based approach: defining the problem, reframing the problem, searching for a biological solution, defining the biological solution, principles extraction, and applying the principles. For the solution-based approach, five steps were identified: basic research by biologists, understanding the biological model, identifying principles in the biological model, abstracting biological principles, and developing technical applications.

In this study, a building shell/façade design was produced using the steps laid out by [26] using the "problem-based approach", which is one of the processes of the biomimicry approach.

2.2. Investigation of Living Organisms' Strategies to Maintain Water Balance

Water is an essential living resource vital for all life forms. Water needs and balance strategies vary among species adapted to different climatic and environmental conditions. Life forms in nature offer several vital lessons on water harvesting. In particular, species that survive in the world's driest regions have evolved the ability to passively collect water from fog and condensation of water vapor at night. These species have multiple transport mechanisms to retain or use the water they collect before it evaporates. Their ability to collect and transport water is based on unique chemical and structural properties in these species' bodies or internal structures. The knowledge gained from these natural processes makes it possible to design bio-inspired water collectors [46].

The water management strategies of natural organisms revolve mainly around four main functions: gain, transport, conservation, and loss. The water gain function is practiced by living organisms in water-limited regions. It is realized through the absorption of water particles in the air, such as fog or dew, through condensation or diffusion. Water transport is based on gravity, capillary action, or vascular arrangement in the leaf, while water conservation is ensured by decreasing the evaporation rate or controlling radiation exposure. Water loss is a strategy that occurs through mechanisms such as transpiration or evaporation [47]. By studying samples ranging from insects to cactus, it is considered that novel materials can be developed to help improve the productivity of existing water harvesting strategies and make the technique a feasible water source for communities worldwide [1].

There are countless examples of water balance strategies of living things in nature. Among these, the crustacean wharf roaches, tree frogs, and elephants can be exemplified in animals, while cactus, *Bromeliaceae* plants, and *Cotula fallax* can be considered in plants. For instance, the crustacean wharf roaches (*Ligia exotica)* passively collect water from wet surfaces and can transport it. It has a passive water transport system thanks to the open capillaries in its legs, which contain hair and paddle-like microstructures [46, 48, 49]. Like many frog species, the Australian green tree frog (*Litoria caerulea*) can collect water through the structure of its skin. When the frog stands in open environments, it cools down, then when it comes to moist and warm tree hollows, the moisture in the air condenses on the frog's cold skin due to the temperature difference between its skin and the environment. Dew drops on the skin fill the pores and are absorbed by the capillary networks in the skin [50-51]. The complex hexagonal-like network of cracks desert elephants' skin surfaces helps them retain water for a long time. This skin surface, which consists of micro-scale channels that can hold 5-10 times more water than a flat surface, prevents dehydration and allows for more extended thermal regulation [52]. The water harvesting strategies of these animals are shown in Figure 2.

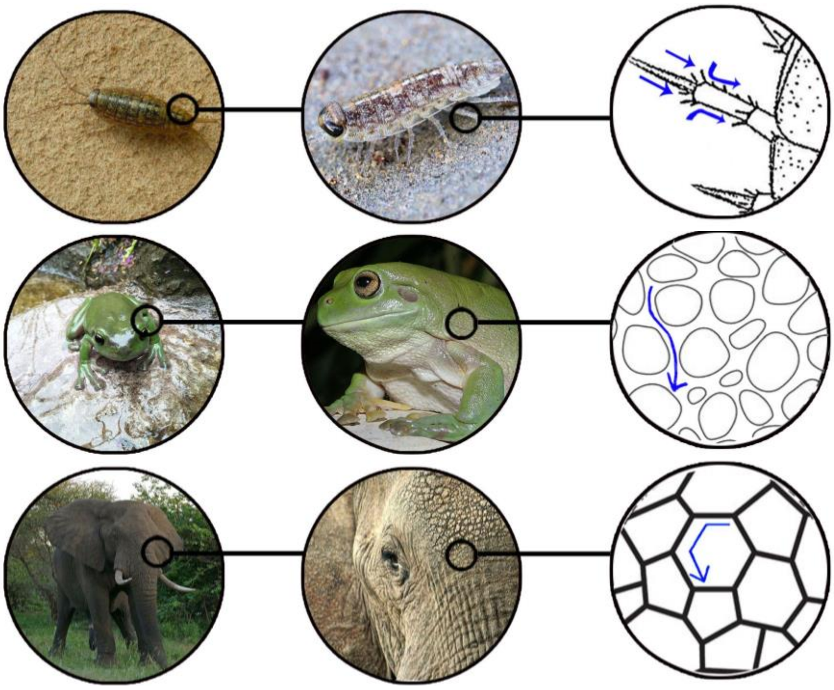


Figure 2. *Water management strategies of crustacean wharf roaches, tree frog and elephant*

When the plants that harvest water in the air are examined, the cactus plant draws attention with its thorny structure. The spines in cactus collect water from the air because of their conical structure. Water droplets are first collected at the tips of the spines and as they grow, they move towards the conical spine and are absorbed by the plant [53,54]. *Bromeliads* from the *Bromeliaceae* family are also critical water-harvesting plants. While collecting water through mound-like single-cell or multicellular structures consisting of epidermal tissues called trichomes in their leaves, they also prevent the absorption of the collected water by the leaves thanks to the wax-containing structure of the trichomes and transmit the water to the storage area of the plant with the help of the curved structure of the leaf [55]. *Cotula fallax*, which grows in South Africa, enables the collection and transmission of water droplets in 3D thanks to its leaves and the fine hairs covering them. The plant hairs wrap around the water droplets, allowing them to retain and grow more prominent, while the hydrophobic nature of the leaves allows water to be directed to the stem and then to the roots [1,56]. The water harvesting strategies of these plants are shown in Figure 3.

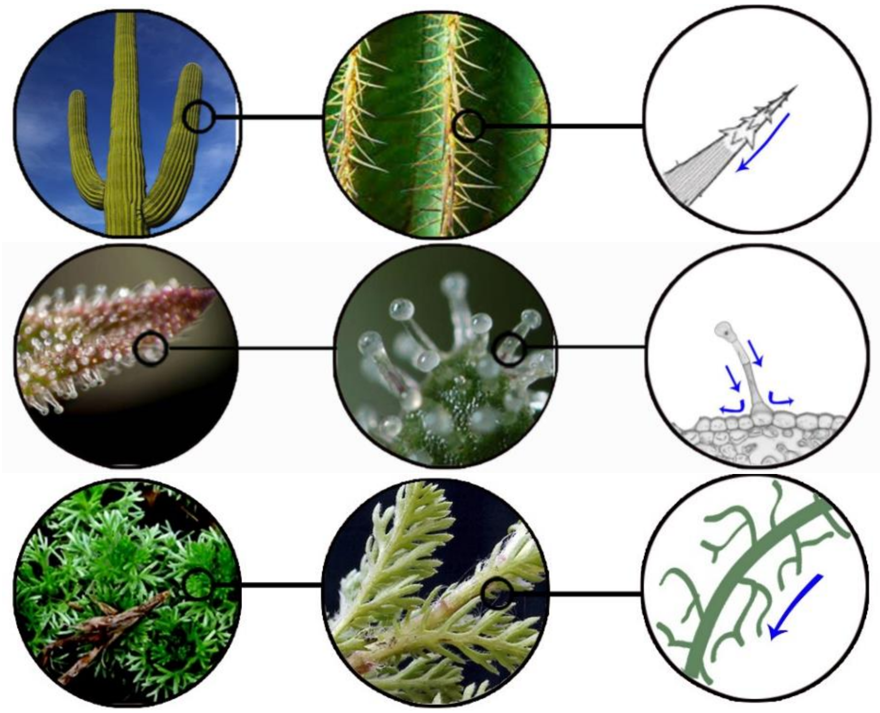
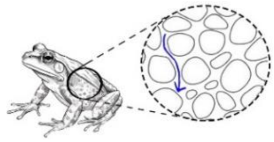
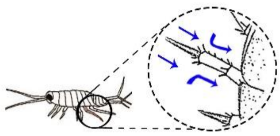
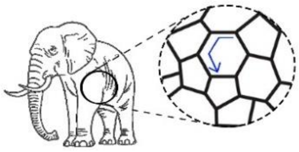
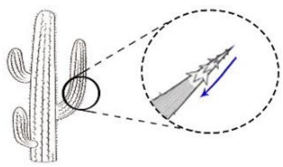
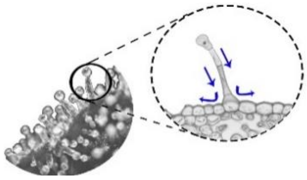
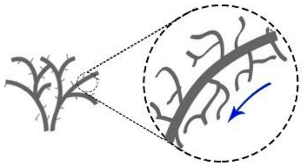


Figure 3. *Water harvesting strategies of Cactus, Bromeliaceae and Cotula fallax plants*

In ecosystems where direct access to water is limited, as in the examples, organisms have developed different water harvesting methods to obtain water and to transmit and conserve this water in balance. The water balance strategies of these organisms are summarized in Table 1.

Table 1. *Strategies of living organisms to maintain water balance*

Biological Phenomenon	**Strategy**													**Working principle**
	System		**Environment**				**Adaptation**			**Method**				
	Active	**Passive**	**Tropical**	**Terrestrial**	**Desert**	**Arctic**	**Morphological**	**Physiological**	**Behavioral**	**Water Protection**	**Water Gain**	**Water Transport**	**Water Storage**	
Tree Frog 														
	Drops of dew on the skin fill the pores here and are absorbed by the capillary networks in the skin.													
Crustacean wharf roaches 														
	It has a passive water transport system thanks to the open capillaries in its legs, which contain hair and paddle-like microstructures.													
Elephant 														
	The surface of elephant skin, composed of micro-scale canals, retains 5-10 times more water than a flat surface, preventing dehydration and enabling longer thermal regulation.													
Cactus 														
	The tips of the spines attract water droplets from the air, and the collected water droplets coalesce and move towards the base under the influence of place pressure caused by the conical form; the accumulated water is stored in the roots.													

Bromeliaceae 	The mound-like trichomes of epidermal tissues on the leaves harvest water from the air, their wax-containing structure prevents the collected water from being absorbed by the leaves and, with the help of the curved structure of the leaf, transmits the water to the storage area of the plant.	
Cotula fallax 	Plant hairs surround the water droplets, trapping them and making them more prominent, while the hydrophobic nature of the leaves allows water to be directed to the stem and then to the roots.	

2.3. Approaches in Which Biomimetic Strategies Are Used to Save Water in Buildings

Biomimetic water harvesting is a current topic in biomimetic research and is also very important for sustainable development goals. Under this title, the relationship between biomimetics and architecture is analyzed in detail, especially in the context of building shells. In this context, architectural shell projects inspired by the water harvesting strategies of natural organisms have been researched and analyzed in the literature. Some biomimetic architectural shell examples researched are at the concept design stage, some are at the prototype development stage and some have been successfully implemented.

2.3.1. Water harvesting surface

Inspired by the water harvesting strategies of various species, such as the Namibian desert beetle, molok lizard, CAM plants, and stoma, the research is a multi-layered building envelope design. The outermost layer of the façade mimics the hydrophilic and hydrophobic properties of the Namibian desert beetle's rugged dorsal shell, allowing water to be retained by this layer. The second layer, which mimics the capillary structure of the Molok lizard, is composed of micro-channels, which transport water by capillary action over the surface and direct it to the storage rooms. The final layer, adapted from the stoma and CAM plants, controls the opening and closing of the storage chambers with smart materials and passive elements that swell when saturated and shrink when dry. This system collects at night and is released indoors on dry or hot days to contribute to ambient humidity [13] (Figure 4).

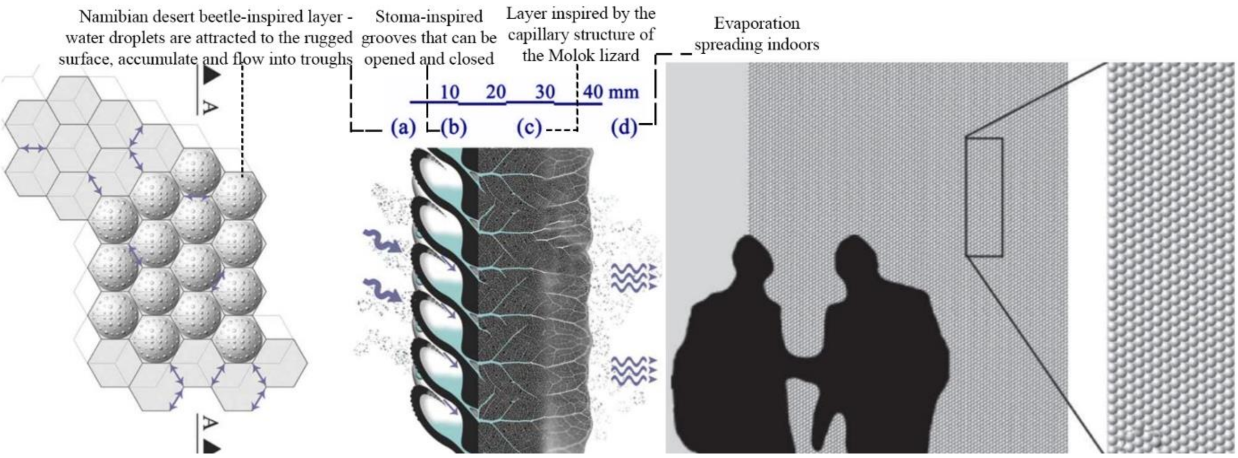


Figure 4. *The water-harvesting surface design [13]*

2.3.2. Aquaweb

Inspired by creatures such as spider webs, bee honeycombs, ice plants, and mycelium plants, AquaWeb, developed by Nexloop, is a modular product that can be integrated into architectural shells to effectively harvest, store, and transmit atmospheric water with a structure inspired by nature. Inspired by bee honeycombs, the design consists of hexagonal modules woven with a special mesh that mimics the fibers of spider webs to harvest atmospheric water from natural sources such as rain, fog and moisture. Once water is harvested with this unique mesh structure, it is collected in flexible compartments inspired by the pouches of ice flowers. The collected water is transported to various parts of the structure through pipes that mimic the water transport ability of mycelium plants. In 2019, as part of the Circular Economy pilot project, AquaWeb was integrated into a hydroponic container farm [57] (Figure 5).

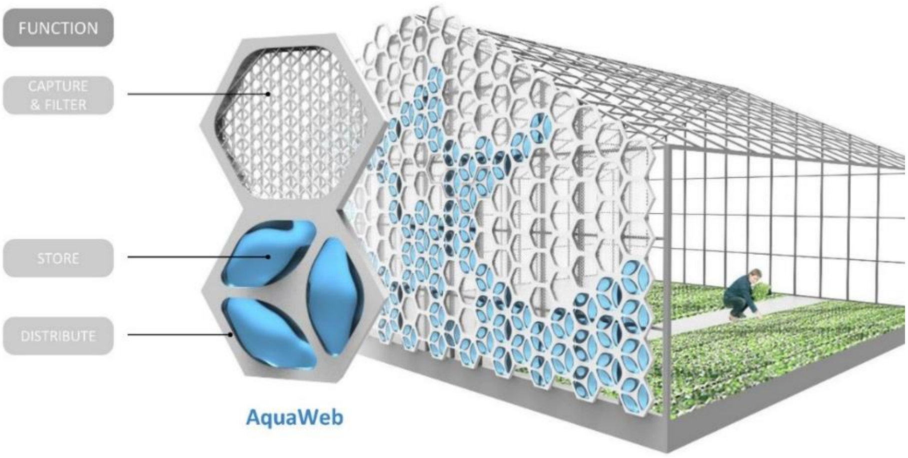


Figure 5. *Hexagonal greenhouse facade design that collects and stores water [57]*

2.3.3. Fog harvesting textile façade

Designed for the New European Bauhaus 2021 competition in the category of solutions for the co-evolution of the built environment and nature, the project is planned to be realized in Milan, Italy. The design focuses on mist harvesting, an alternative solution to face the water crisis. The idea of a passive, low-maintenance design to increase energy efficiency is based on the idea that water can be collected and transported on the web structures of spiders. The project is based on the results of 10 previous web tests to determine the characteristics of a suitable web for fog collection. The moist wind is intended to pass over the design and harvest the water. The harvested water flows down the sloping net to the collection channels. In this way, the project aims to fulfill the purpose of water harvesting [58] (Figure 6).

Figure 6. *Web system designed as a textile product that collects water from fog [58]*

2.3.4. Fog Catcher

Embracing the unique microclimate of West San Francisco, Fog Catcher offers a design for student housing that provides net positive energy without mechanical systems. The building is covered by a 'cloud-like' metal shroud that reflects natural winds, enveloping the student residences like a perforated, thin blanket. The design was developed in response to California's ongoing drought problems by applying the principles of biomimicry. Mimicking the dew collection mechanism of desert plants, the design consists of a transparent mesh that acts as a mist collector to collect mist condensation. Features of the mist collector include louvers that can be opened and closed at the users' discretion, allowing for privacy or sunlight control. The collected water is incorporated into a unique plumbing system and stored or used for toilets needs [59] (Figure 7).

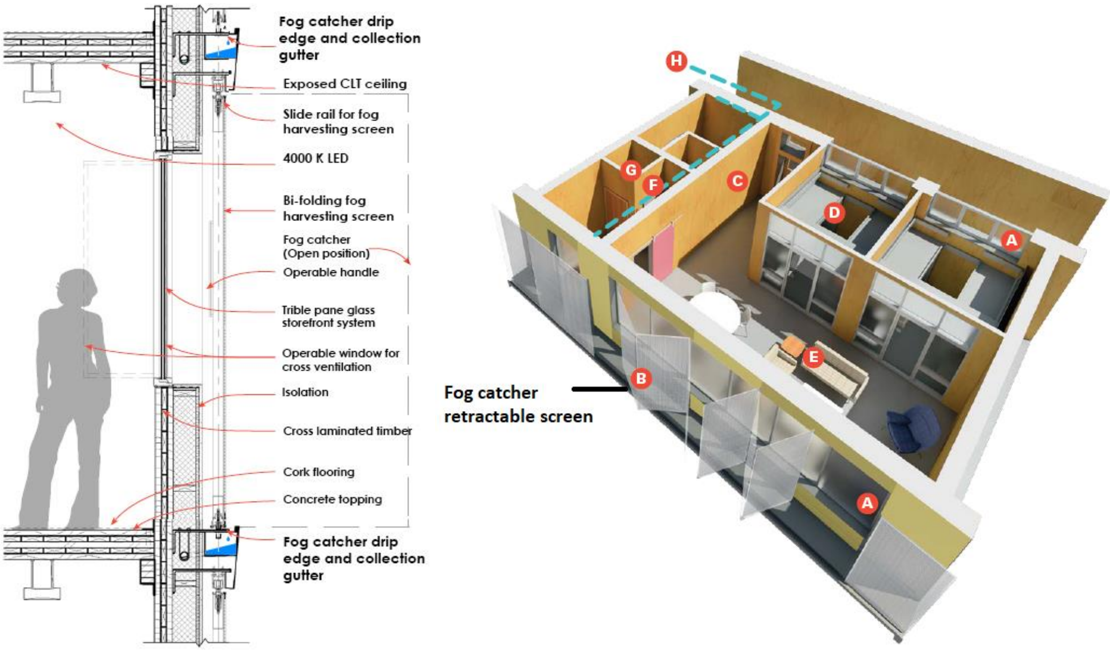


Figure 7. *Section and model of a retractable fog catcher screen [59]*

2.3.5. Water harvesting building envelope

The design focuses on the relationship between plant biological systems and architectural systems due to the ability of plants to adapt to water scarcity. The design is a water collector panel installed as part of the building façade and droplets are stored in a reservoir embedded under each panel. The water stored in each reservoir is directed through a pipe system to the primary storage. In this nature-inspired water harvesting system, it is proposed to use cone-like structures commonly found in plants to collect moisture. The Voronoi pattern, encountered in different forms in nature, is used in the channels where the collected water is transferred because it is effective in water transportation. Passive water transport with the Voronoi pattern is designed in a hydrophilic structure because it is more efficient on a hydrophilic surface than on a hydrophobic one. Since the surface tension of the hydrophobic surface is below the hydrophilic one, the surfaces of the cone-like structures are also considered hydrophobic [23] (Figure 8).

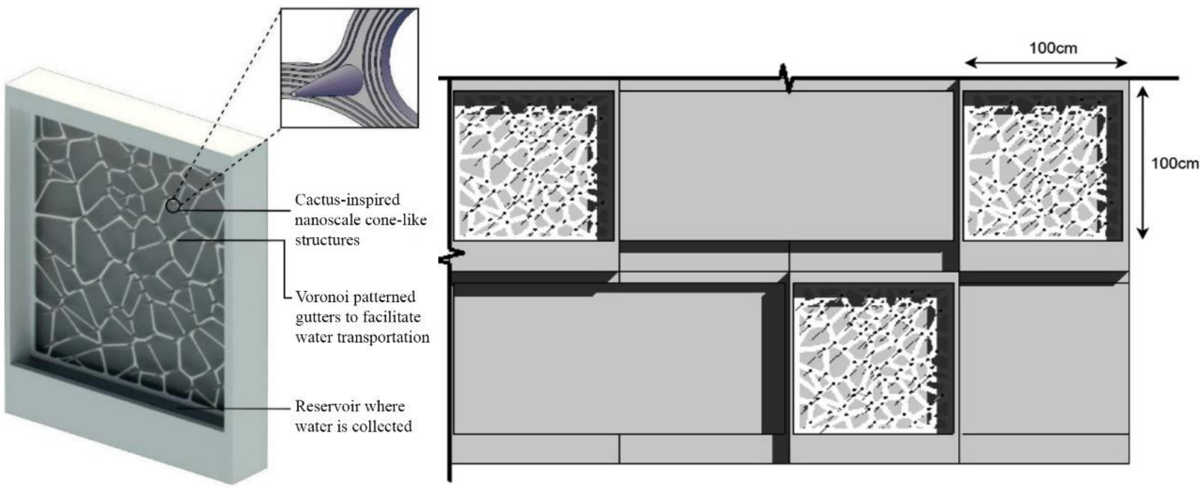


Figure 8. *Water harvesting facade panels inspired by plants [23]*

2.3.6. The Water Campus

The Water Campus in Leeuwarden, the Netherlands, which won third prize in a competition, was designed by Delft-based design studio DP6 on an area of 11,000 m2. The facade of the building, with a specialized function in water technology, is made entirely of a recycled transparent foil referencing water droplets. The facade can change the internal temperatures of the building, acting as both a cooling mechanism and a water buffering system that will direct rainwater to the surrounding water bodies. The water is conveyed through pipes to the droplet-shaped units, where it is stored [60] (Figure 9).

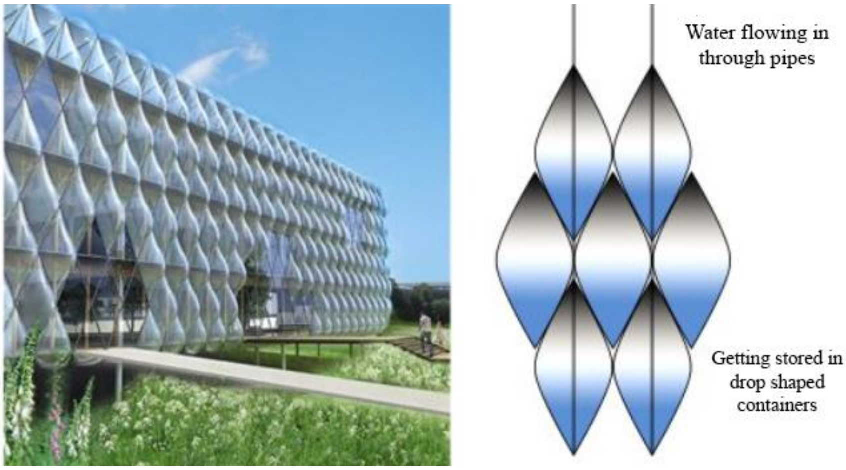
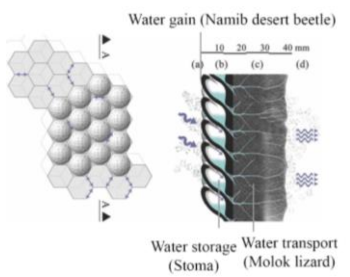
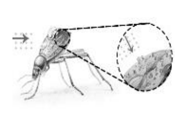
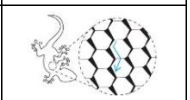
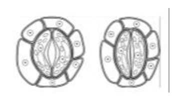
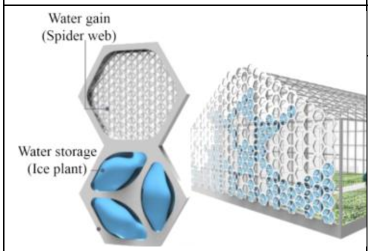
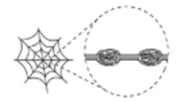
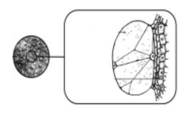
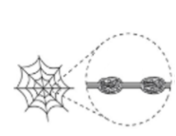
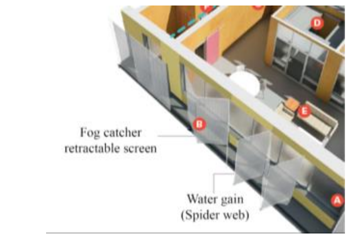
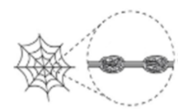
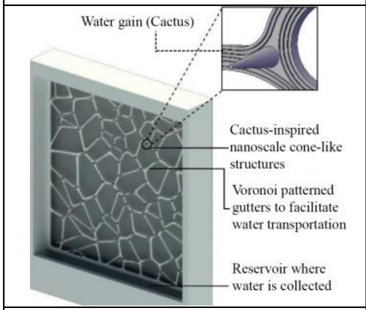
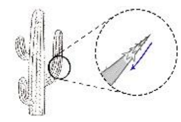
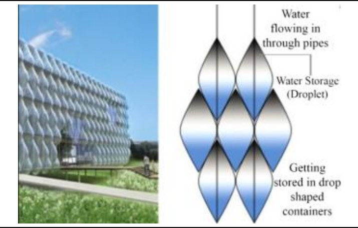


Figure 9. *Facade design in the form of water droplets inspired by droplets storing water [61]*

The examples mentioned so far are presented in Table 2, and they are evaluatied in the context of their features, such as water conservation, water gain, water transportation and water storage, and the knowledge gained from nature.

Table 2. *Architectural examples that use water harvesting strategies of species in façade designs*

<table>
<tr><th>Architectural Examples</th><th>Water Protection</th><th>Water Gain</th><th>Water Transport</th><th>Water Storage</th><th colspan="2">Organism and its inspired feature</th></tr>
<tr><td rowspan="3"></td><td></td><td></td><td></td><td></td><td>Namib beetle-hydrophilic-hydrophobic properties of the back</td><td></td></tr>
<tr><td colspan="4" rowspan="2">Water gain: The first layer is inspired by the hydrophilic and hydrophobic properties of the dorsal shell of the Namibian desert beetle,
Water transport: The final layer inspired by the capillary structure of the Molok lizard skin,
Water storage: An intermediate storage layer inspired by stoma that opens and closes.</td><td>Molok lizard-Capillary structure</td><td></td></tr>
<tr><td>Stoma-Openable and closable</td><td></td></tr>
<tr><td rowspan="2"></td><td></td><td></td><td></td><td></td><td>Spider web-Hydrophilic fiber structure</td><td></td></tr>
<tr><td colspan="4">Water protection: A mesh inspired by the hydrophilic structure of spider webs in hexagonal pieces like bee honeycombs,
Water storage: Water reservoirs inspired by the water bladders of the ice plant.</td><td>Ice plant - Water bladder</td><td></td></tr>
<tr><td rowspan="2"></td><td></td><td></td><td></td><td></td><td rowspan="2">Spider web-Hydrophilic fiber structure</td><td rowspan="2"></td></tr>
<tr><td colspan="4">Water gain: A fog-harvesting textile web inspired by the hydrophilic structure of spider webs</td></tr>
</table>

	Water gain: A fog catcher screen inspired by the hydrophilic structure of spider webs	Spider web-Hydrophilic fiber structure	
	Water gain: Façade panels inspired by the hydrophilic spines of cactus, Water transport: Voronoi patterned gutters	Cactus-Hydrophilic spines	
	Water storage: Facade in the form of water droplets inspired by droplets storing water	Droplet-Water storage	

3. MATERIAL AND METHOD

In humid climate zones, the humidity in the air can be a potential source for the water needs of buildings. In today's world where water scarcity is felt worldwide, nature will again be the source of solutions to this problem. The strategies of living creatures in nature to harvest moisture in the air can inspire for architectural water harvesting design.

In this context, as a solution to the water problem, a problem-based approach was adopted while being inspired by the working principles of living things in nature to harvest water in humid regions within the scope of the study. The study followed the problem-based process steps stated by [26]. First, the problem was defined and then the problem was placed in a biological framework. Then, the biological solution was searched and the biological solution was analyzed in detail. After obtaining the principle from the biological solution, this principle was transferred as an architectural façade solution in the last step. However, there was continuous feedback during this process. The steps of the process are presented in Figure 10.

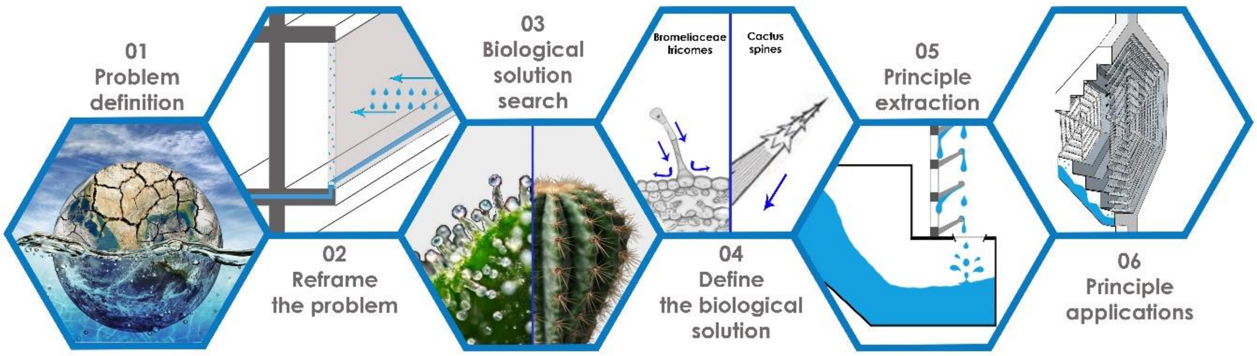


Figure 10. *Design process (created by the author following the problem-based process steps defined by [26])*

4. BIOMIMETIC BUILDING ENVELOPE DESIGN FOR HUMID CLIMATE ZONES

Focusing on harvesting water from the air in humid climates and using it for the needs of the building, the study adopts approaches inspired by nature. The double-walled design consists of a primary façade, which is the main shell of the building, and a secondary façade where water harvesting occurs. Water harvesting will be realized through water collector hexagonal panels installed as part of the secondary façade. In order not to obstruct the view of the interior of the building, the secondary façade is constructed with filled panels and hollow panels that harvest water. After the droplets are stored in a reservoir embedded in the hexagonal form of each panel, the water stored in each reservoir is directed to the main tank through a pipe system.

The study used the strategy of many species existing in nature as a design element. The hexagonal form used as a form by different species in nature was preferred for the main water-carrying structure. The hexagonal form is found in the honeycombs of bees and in the skin structures of animals such as Molok lizards and elephants that hold water in their skin. The shape of honeycombs is hexagonal because hexagons are the most suitable form to use a specific area most efficiently using the least material. Any space can be filled using hexagons without gaps and overlaps [62]. Since hexagons are composed of repeating triangles, the mosaic they create minimizes the waste of space or energy. In addition, the hexagonal skin of species that retain water in their skin makes them more suitable for retaining more water, as the hexagonal form gives a complete geometry without gaps. The use of the hexagonal form in living things is shown in Figure 11.

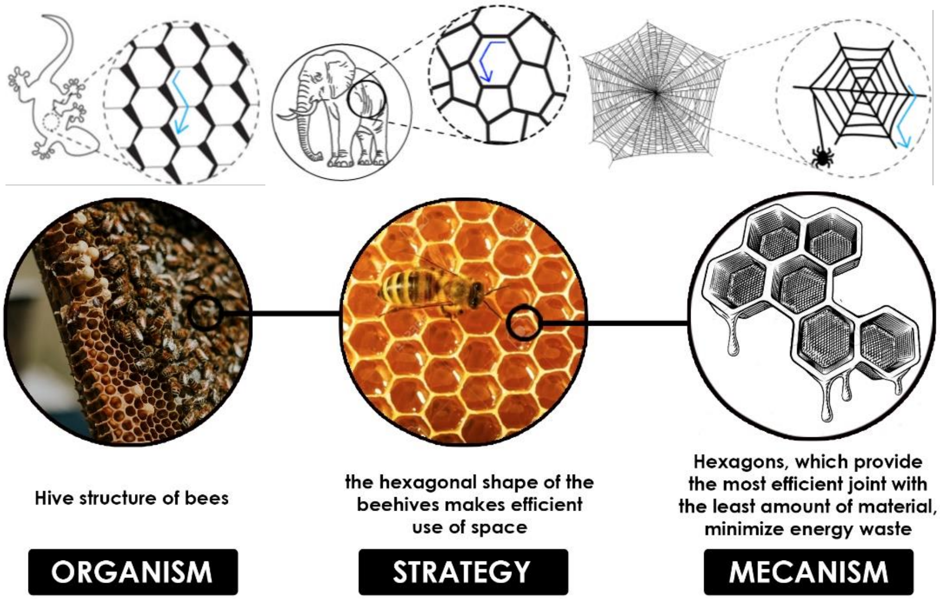


Figure 11. *Use of the hexagonal form in species for water transportation*

When the living things examined for water collection function are analyzed; when a generalization is made for the trichomes on the leaves of *Bromeliaceae* plants and the spines on cacti, it is possible to say that they have spines and similar morphology protruding from the surface and that this structure gives living things the ability to absorb water. When this principle is transferred to architecture, it is thought that systems that protrude from the facade in this way will benefit water collection. For this reason, the water collection system was inspired by the fact that the cactus collects water thanks to its spiny structure, and many plants such as *Bromeliaceae* harvest water from the air thanks to its trichome structure and then transfer it to storage areas without being absorbed through its waxy outer structure. The working principles of these inspired plants are summarized in Figure 12.

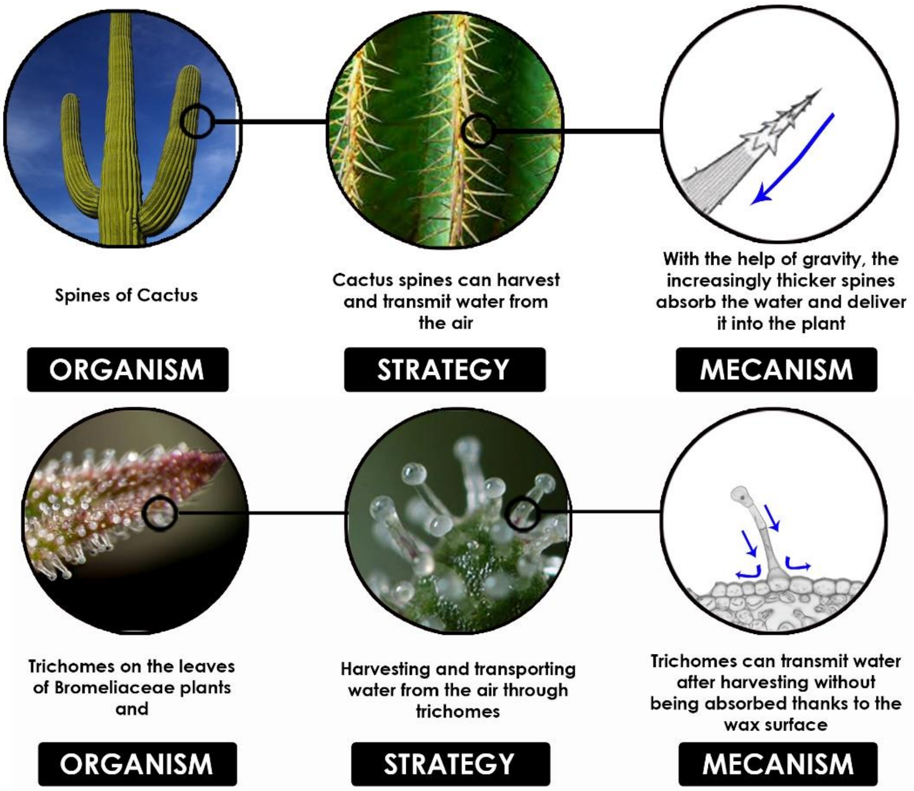


Figure 12. *Species inspired by water harvesting and their strategies against natural conditions*

A hydrophobic mesh inspired by the spider's web form that can easily carry water between the hexagonal panels was designed, and a hydrophilic structure inspired by the trichome that can harvest water was placed on this mesh and a water collection system was designed. A water collection network was designed on the front and back sides of the 35x35cm hexagonal units to collect water in both layers while providing air passage. The cross-section diagram in Figure 13 shows water’s the collection and flow direction of water thanks to nature-inspired hydrophilic and hydrophobic structures.

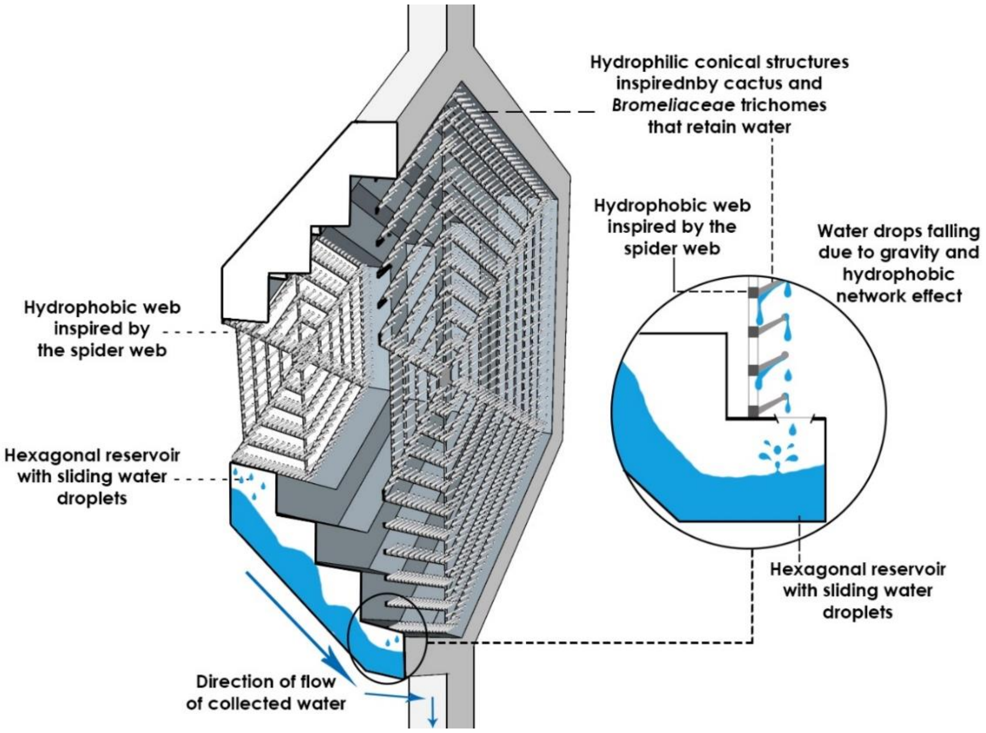


Figure 13. *Cross-sectional diagram of the designed hexagonal water collector panel*

The water collected in the hydrophilic cones inspired by cactus spines and *Bromeliaceae* trichomes is collected in the reservoirs on the front and back of the hexagonal panels through the hydrophobic mesh. The outer frame of all hexagonal panels along the façade has a water-bearing function, so the water accumulated in the reservoir slides through the hexagonal panels towards the main water collection channels of the building. Figure 14 depicts the water collection and flow in the hexagonal channels.

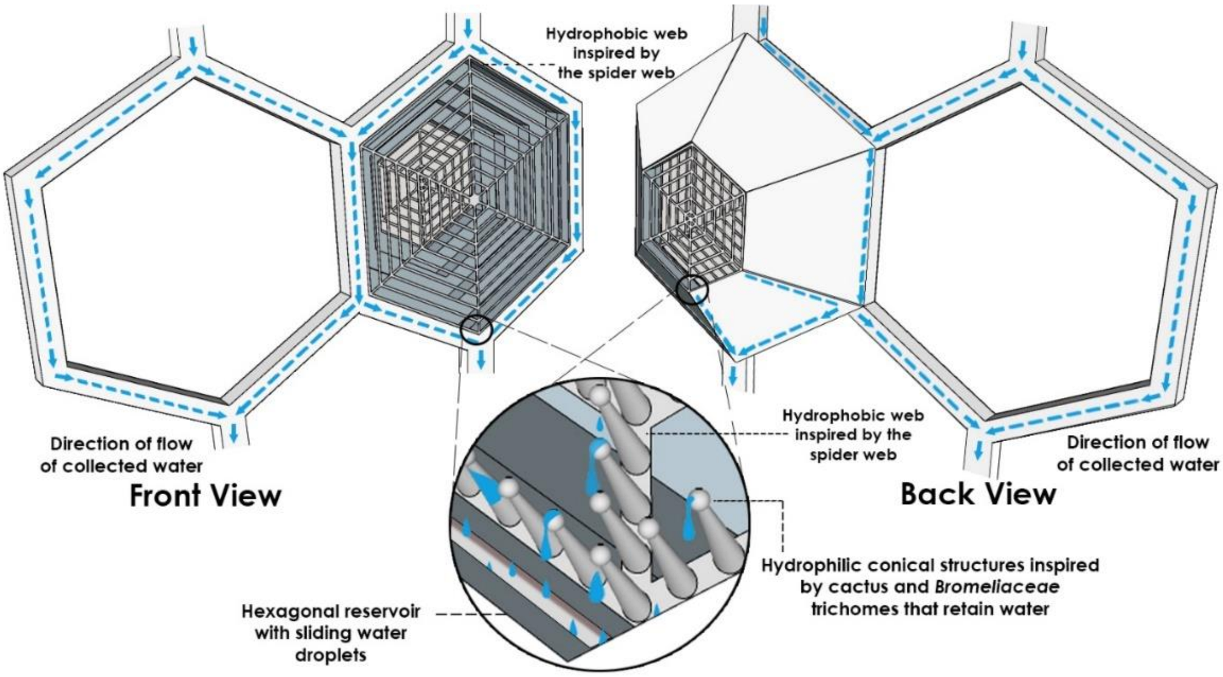


Figure 14. *Details of the designed hexagonal facade panels*

The design is a secondary façade that can be added to any building. In this way, the water collector panels on the facade are located 1.5 meters from the main primary facade and do not obstruct the main facade. The secondary façade water collector system is connected to the flooring with anchors. The sectional view of the facade is presented in Figure 15.

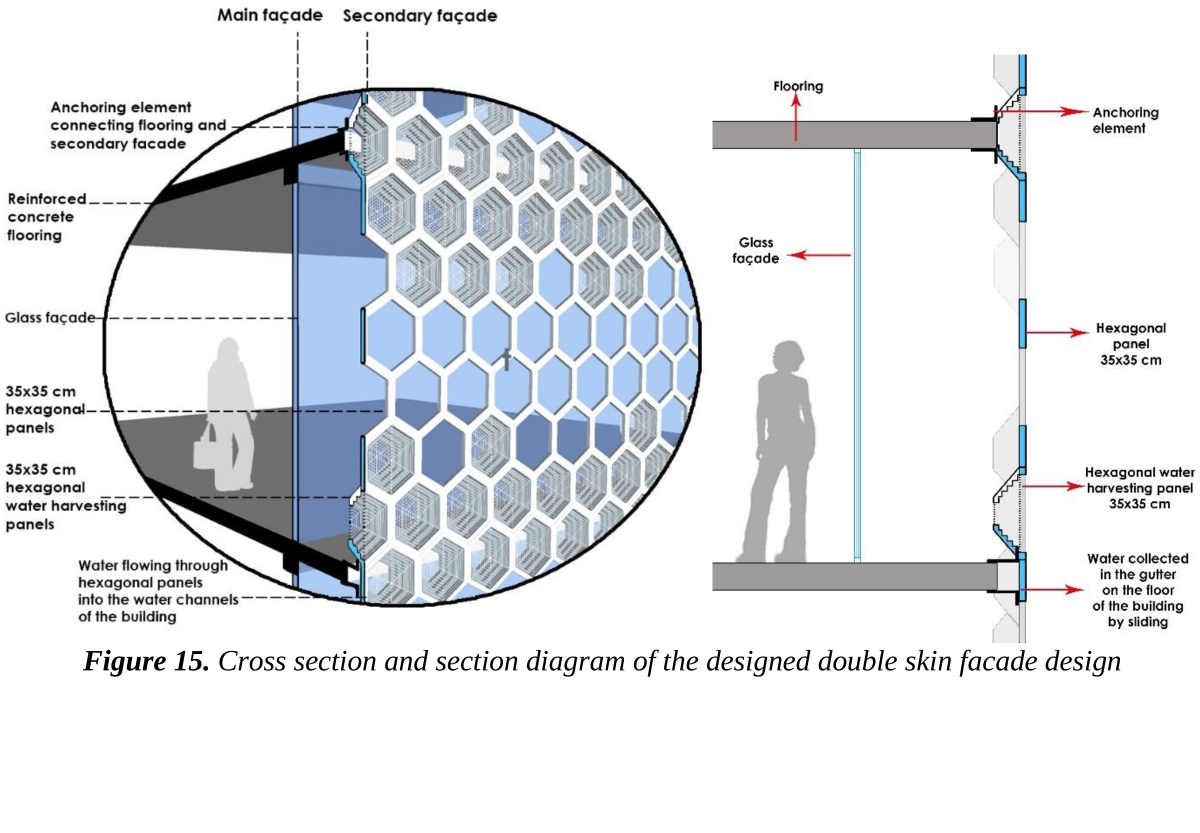


Figure 15. *Cross section and section diagram of the designed double skin facade design*

While the panels designed on the secondary facade are placed on the entire facade of the building, they are placed in such a way that they do not coincide with the eye level in order not to create any visual and light obstacles in the interior space and a rhythm is created on the facade. The use of the façade in an example two-storey building is modeled in Figure 16.

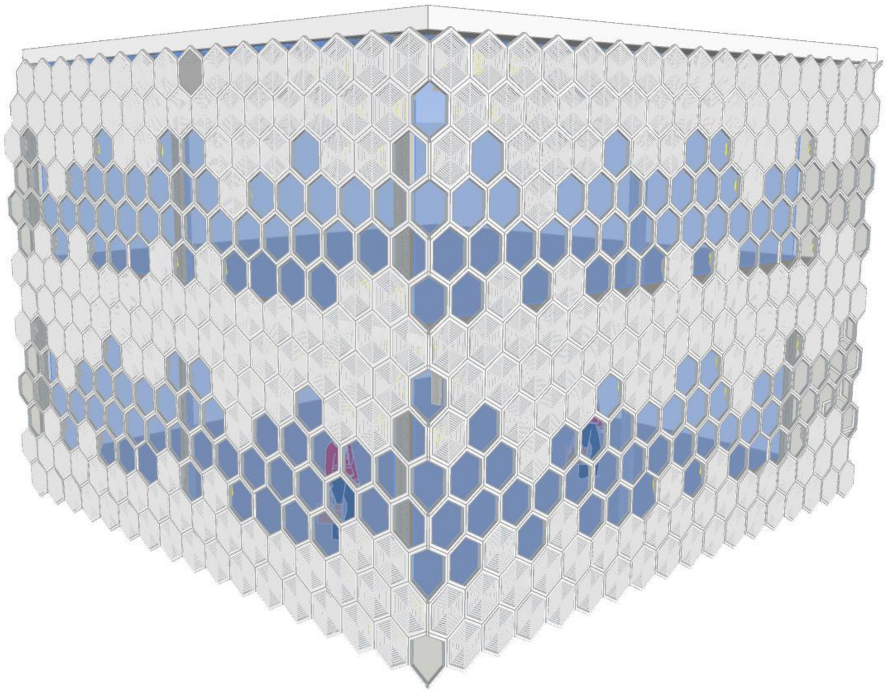


Figure 16. *Facade design inspired by nature*

As a result, the path from biological phenomena to water harvesting architectural shell design is presented in Figure 17. To summarize the research carried out in this context, cactus spines and *Bromeliaceae* trichomes provide information for water collection. In contrast beehives, spider webs, elephant, and lizard skins provide information for water transport due to their hexagonal forms.

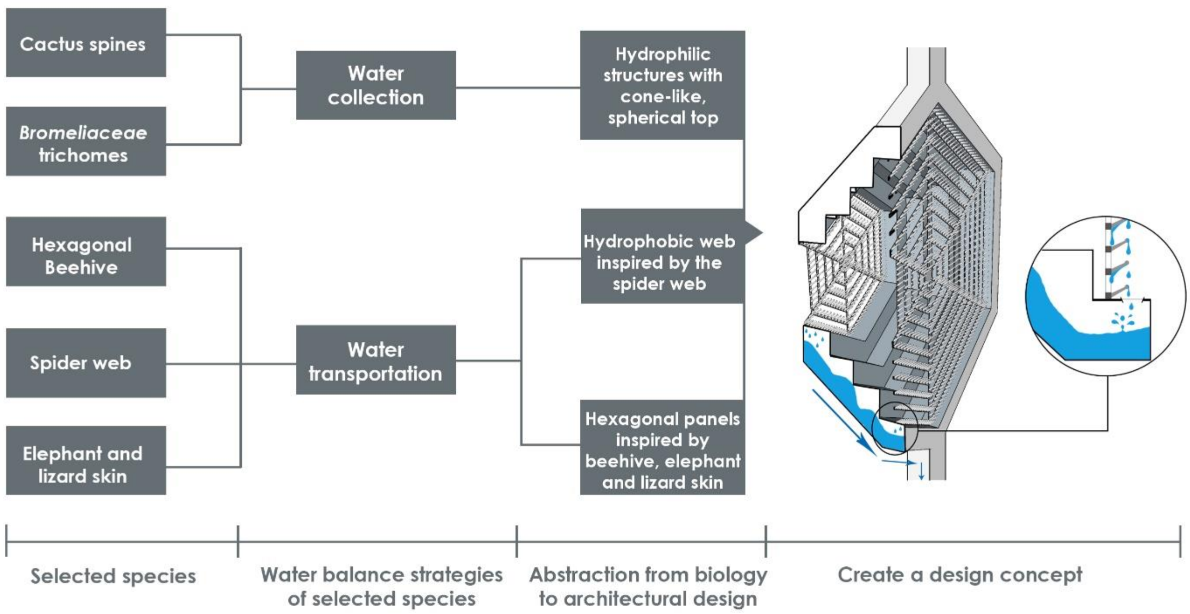


Figure 17. *A path from biological phenomena to water harvesting architectural shell design*

5. CONCLUSIONS

Among the most important of the various challenges that the world will likely face shortly is the water problem, as it is the primary source of life. Living creatures, which develop unique strategies to survive despite the various weather conditions they encounter in nature, provide a great potential that architecture, one of the most important actors of the construction and building sector, can take as an example to produce solutions to the water problem that the whole world has to face. This infinite resource offered by nature guides the way to reach sustainable solutions.

This paper aims to investigate and apply mechanisms that can inspire new solutions for constructing water management strategies for biological organisms. Therefore, firstly, living organisms with water collection strategies and their working systems are discussed. Then, examples of architectural projects designed with these methods are analyzed. Following the problem-based design method to produce a biomimetic design, the study determined the water harvesting problem as the main starting point and followed the path defined by Helms et al. (2009) step by step to reach the design [26]. The beehive form and the hexagon, the structure of the water-holding animals' skins, constitute the design's primary structure, and the collected water is transported through these hexagonal channels. Water is harvested passively through the mesh system inside the hexagonal panels inspired by *Bromeliaceae* trichomes and cactus spines and transferred to the channels embedded in the panels.

The research question, how can living organisms' different water harvesting strategies be transferred to building envelope design, is answered with modular hexagonal panels with a water harvesting mesh system inspired by *Bromeliaceae* and cactus plants on a secondary façade that can be attached to any building. Therefore, the study represents an alternative solution for today's water crisis and is essential for a more livable and sustainable built environment by saving water and energy.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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