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Sustainable Architecture Inspired by Camels: A Review

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Abstract

Natural systems provide frameworks that can enhance the efficiency of the architectural design process. Systematic observation and analysis of these systems enable architects to formulate innovative design strategies. The field of biomimetic architecture utilizes these principles to develop sustainable solutions for the built environment. This paper introduces the concept of biomimetic architecture, focusing on the camel as a model organism. It analyzes the adaptive features that enable camels to thrive in extreme conditions. The study also examines and categorizes architectural case studies that resemble camels according to established levels and dimensions of biomimicry. Furthermore, it evaluates the effectiveness of these approaches in reducing energy consumption and addressing climatic challenges in hot arid regions. The paper also shows that the camel, notably its nose cooling mechanism, has inspired several adaptive design solutions. Nevertheless, exclusive reliance on physical adaptations is limited. Greater benefits are achieved by integrating both behavioral and physical adaptations and by drawing from a diverse range of biological models. This comprehensive approach enhances building performance and environmental responsiveness. Based on these insights, the paper proposes a Camel-Biomimetic Framework to guide the development of sustainable buildings in hot arid climates.

Keywords: *Biomimicry, Biomimetic Architecture, Hot Arid Climate, Sustainability, Camel*

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1. Introduction

Over decades, all the natural beings, whether animated or unanimated, in addition to ecosystems, have successfully adapted to the surrounding environment. Each being has its unique form and behaviors that enable it to survive in different environmental conditions and fulfill its basic needs, such as food, water, shelter, and protection within its ecosystem. (Mazzoleni & Price, 2013)

This biodiversity assists scientists in exploring the topic of biomimicry science since it may provide further insights into various scientific domains, resulting in not only innovation solutions but also more sustainable outcomes. Biomimicry is defined as the study of mimicking how organisms, ecosystems, and their processes and tactics adapt to changing living conditions. Architecture is one of the practical fields that has been using biomimicry science. Biomimetic architecture is a sustainable design strategy that imitates nature models, systems, and processes to apply them to the built environment. (Maglic, 2012; Zari, 2012; Mazzoleni & Price, 2013)

1.1. Biomimetic Architecture

Biomimetic architecture is based on two approaches: biologically inspired design and biologically referenced design. The first approach acknowledges the existence of information before testing and transferring it to design applications, whereas the second approach identifies issues or requirements first, then looks for answers in nature. The

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second approach is more common than the first, but it requires a multi-specialty team. (Zari, 2007, 2012; Shahda et al., 2014)

Biomimetic architecture is divided into three levels (see Figure 1): the organism level, which mimics a specific organism or a portion of an organism; the behavior level, which mimics how organisms interact with one another and with their surroundings; and the ecosystem level, which mimics an entire environmental system. The three levels share five dimensions: form, function, method, construction, and materials. (Maglic, 2012; Zari, 2012)

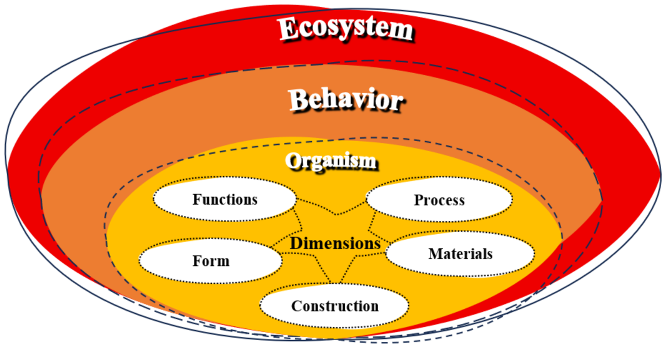

Figure 1: Levels and Dimensions of the Biomimetic Architecture Framework
Source: (Zari, 2012; Eid et al., 2021) Edited by: The Researcher

2. Camel

Camels are proverbial, especially in the 17th verse of Surah Al-Ghashiya, Holy Quran: "Will they not consider the camels as they were created?" It is regarded as a miraculous sign from Allah to ponder on how camels are born and how they survive in extreme environments. (*Holy Quran, Surah Al-Ghashiya (17)*, n.d.; Shahda et al., 2018) They served as both a key food source and a mode of transportation throughout Africa and Asia for many years. However, the reliance on camels grew as it was discovered that they flourished during the drought wave that ravaged Africa in the nineteenth century. They became suppliers of food, such as milk and meat, as well as clothing, such as wool, leather, and fibers. (Bornstein, 1990)

There are two camel species; 90% of camels worldwide are one-humped (Arabian), while 10% are two-humped (Bactrian). Bactrian camels live in cold and desert parts of Asia, whereas dromedary, Arabian, or one-humped camels live in hot, dry, and semi-arid regions of Africa and Asia, respectively. (Bornstein, 1990) Camels, particularly dromedary camels, have several excellent abilities that help them survive in their harsh habitat (Bornstein, 1990; Shahda et al., 2018), as do other animals, such as sheep and goats. (Bornstein, 1990; Shahda et al., 2018) They possess several adaptations for high temperatures, such as a light, smooth coat that reflects solar radiation and a large body that warms slowly and benefits from increased wind exposure due to their height. (Bornstein, 1990; Shahda et al., 2018)

The camel nose plays a key role in regulating respiratory air temperature. Its convoluted, moisturized turbinates provide a large surface area (about 1000 cm^2), allowing inhaled air to be cooled and humidified before reaching the lungs. (Clements-Croome, 2013) The nose also dehumidifies and cools exhaled air, conserving approximately 68% of the water used in humidification. (Clements-Croome, 2013; Shahda et al., 2018) Additionally, this air-cooling mechanism helps cool blood entering the brain through heat exchange. (Abdullah et al., 2019) Both nasal and brain cooling methods will be discussed in detail later.

Camels are well adapted to both hydrated and dehydrated conditions, with dehydration presenting greater challenges. They can survive without water for up to a month, though this depends on breed, climate, and age. During dehydration, camels reduce urine output, produce dry feces, and release heat at night to conserve water. When rehydrated, they can drink up to 30% of their body weight to restore reserves. (Bornstein, 1990)

3. Methodology

This research relied on an inductive theoretical approach through literature review. Initially, biomimetic architecture was defined, followed by an examination of camel adaptation strategies as a model organism in arid environments. Subsequently, architectural applications inspired by camels were then systematically reviewed, analyzed, and categorized using the Biomimetic Framework (see Figure 2).

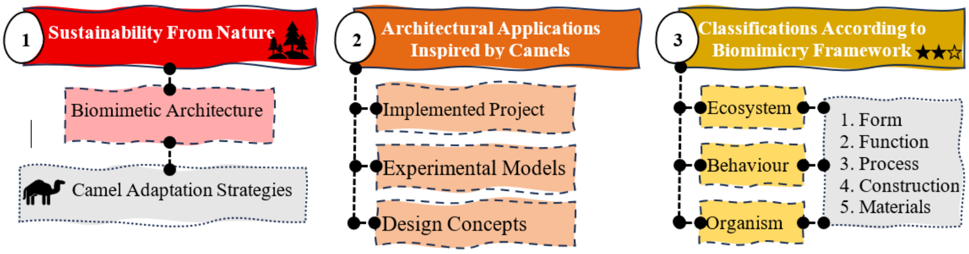

Figure 2: The research methodology Source: The Researcher

4. Case Studies

Camels serve as the inspiration for several case studies. Those cases might be categorized as implemented projects, experimental models, and design concepts. All the instances are gathered and analysed as follows:

4.1 Implemented Project

This section looks at camel-inspired innovations that have been executed. There are just two projects as follows:

4.1.1 Kilo Tent, Institute du Monde Arab

The Kilo tent is a performance venue designed by French architects Jean Nouvel and Architecture Studio Kilo (Mairs, 2014) and built in 1987 (see Figure 3). (Mairs, 2014) It was created in the outer plaza in front of the Institute du Monde Arab building in Paris, France, to host performances, as well as a café and store selling Moroccan-inspired items during the exhibition show. (Rosenfield, 2014) The tent was open to the public until January 25, 2015. (Grozdanic, 2014; Mairs, 2014)

The kilo tent is 500 rectangular square meters in size and is made up of nine woollen fabric peaks, which have been woven manually of random long strips of camel fur and goat wool by a female cooperative in the Sahara Desert (Grozdanic, 2014). The design concept aimed to merge the technological innovation showcased at the Contemporary Morocco Exhibition with a tribute to the nomadic traditions of southern Morocco. (Grozdanic, 2014; Mairs, 2014; Rosenfield, 2014; Massie, 2015)

(a)  (b) 

Figure 3: The Kilo Tent (a) in front of the institute du Monde Arab building, Paris, France fabricated of natural wool Source: (Rosenfield, 2014), (b) inside the tent Source: (Grozdanic, 2014; Rosenfield, 2014; Massie, 2015)

4.1.2 A Sustainable Bioinspired Cooling Unit

In camels, inhaled air is cooled within the nasal passages through the evaporation of mucus membranes lining the convoluted turbinates. (Clements-Croome, 2013) This process also cools the blood flowing to the brain as it passes through the cavernous sinus situated near the cooled turbinates. (Abdullah et al., 2019) That is what inspired *Abdullah et al.* to develop and test a sustainable cooling unit inspired by the camel unique thermoregulation system. (Abdullah et al., 2019)

Two cooling systems were designed, a wet and a dry system; both were simulated using Revit software. The wet cooling system mimicked the camel nasal turbinates using multi-rectangular clay rings. Clay is a traditional porous material used for cooling in Arab countries, and jute fibers are incorporated to hold sprayed water, simulating mucous membrane evaporation. The dry cooling system utilized a spiral of copper pipes to achieve dry cooling through convection, similar to how the cavernous sinuses cool blood flowing to the camel brain. These pipes can be integrated into room walls or ceilings and potentially incorporated into decorative elements like mashrabiya. (Abdullah et al., 2019)

To implement this cooling system, a building with an existing windcatcher is necessary. Entering hot air through the windcatcher evaporates water within the distribution system, then cools both the air and the water. This cooled water is then collected in a tank below. A solar-powered pump lifts this cold water to a series of copper pipes (the dry system). These pipes facilitate heat exchange with the room air through convection. Once the water and air inside the room reach the same temperature, the water is recirculated back to the distribution system, creating a continuous cooling cycle (see Figure 4). (Abdullah et al., 2019)

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A wind tower for wet cooling was constructed on a hotel roof in Yemen (see Figure 5). This 4.8-meter tower incorporates a wind catcher and four sections. The core of the cooling system lies within the second and third sections, where wet cooling units are housed. These units consist of sun-dried clay plates coated with jute fibers, facilitating evaporative cooling. Water is distributed over these plates and collected in a tank below. The implementation of a dry cooling system was deferred pending further research. (Abdullah et al., 2019)

This model was tested during 10 days in May, and the measurements were taken every twelve hours beginning at 9 a.m. The results showed that the wet cooling system reduces the temperature by 9.7 min. to 19.8°C max., and the humidity increases by approximately 40.5 percent min. to 70.6 percent max. compared to the outside. Based on the measurements, the bioinspired wet cooling system is an applicable and efficient cooling system that delivers thermal comfort to occupants in hot, dry, and semi-arid climates. (Abdullah et al., 2019)

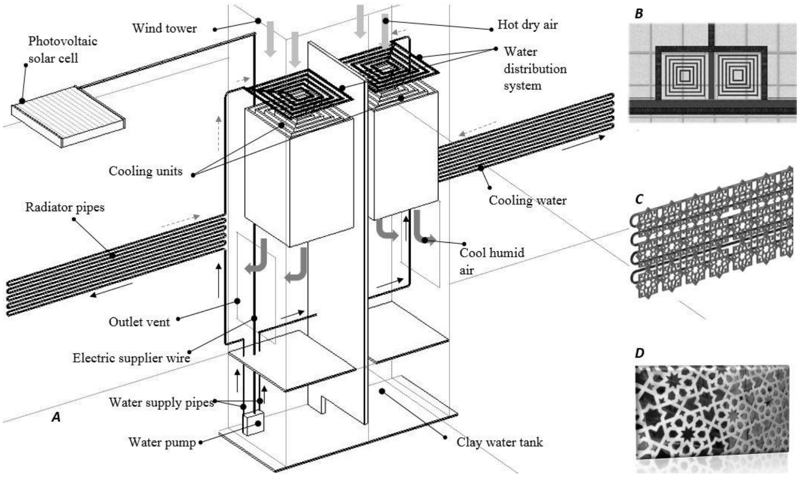


Figure 4: The proposed design of both cooling units simulated by Revit Source: (Abdullah et al., 2019)

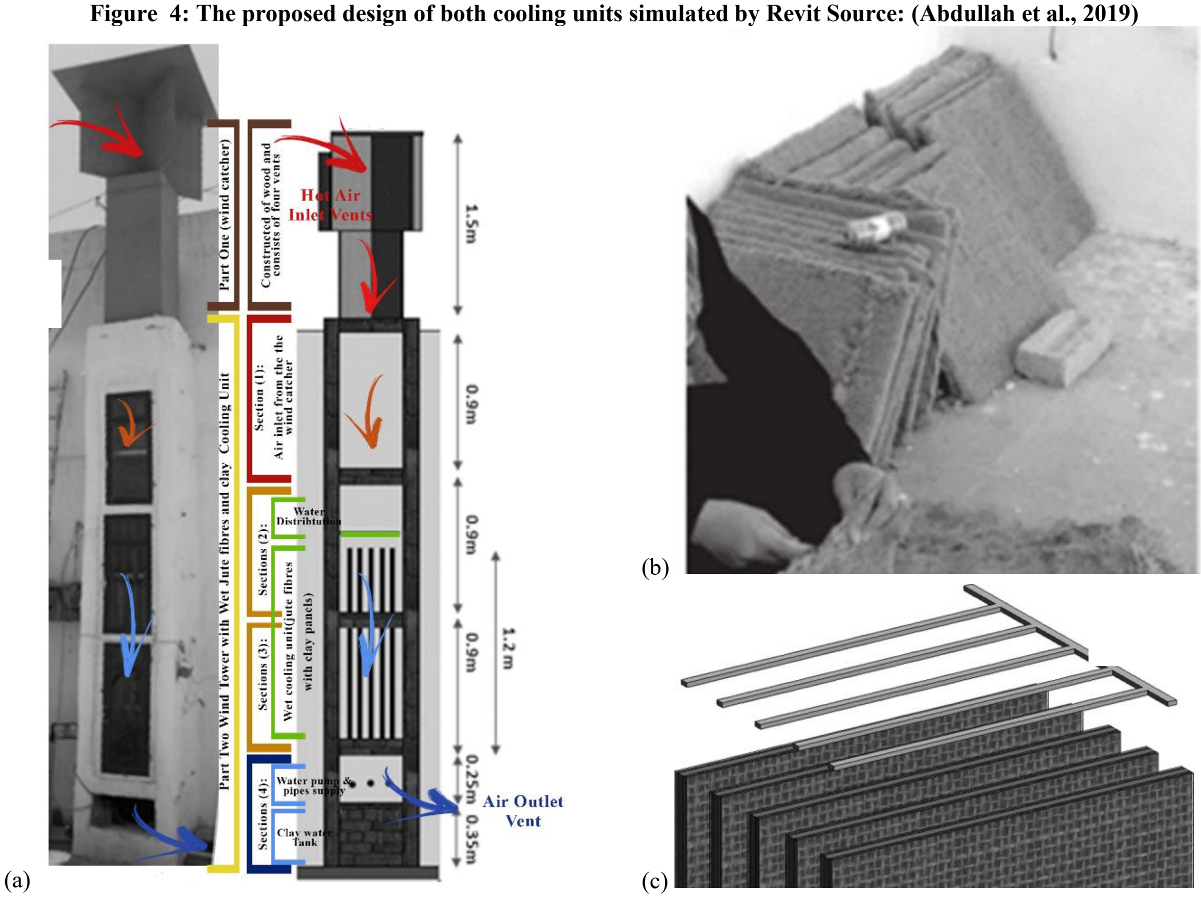


Figure 5: The wet cooling units inspired by camel nasal: (a) Wet cooling unit sections and cooling process, (b) clay panels covered with jute fibres, and (c) Water distribution system above clay and jute fibres panels Source: (Abdullah et al., 2019) Edited by: The Researcher

4.2 Experimental Models

This section covers the camel-inspired models that have been tested mathematically and/or experimentally. There are just two models as follows:

4.2.1 An Adaptive Breathing Skin

The breathing wall has two definitions: the wall ability to disperse water vapour to improve interior air quality and the wall capacity to convey air flow while absorbing air moisture to lower internal temperatures by cooling. (Elghawaby, 2010, 2012; Nour Eldin et al., 2016) According to the second definition, rather than the notion of inert facades, Elghawaby proposed an adaptable breathing skin for buildings in hot desert regions such as Sinai to improve natural ventilation, minimize the cooling energy consumption, and boost building sustainability. (Elghawaby, 2010, 2012)

To study this proposal, several biomimetic mechanisms, including cooling systems, heat dissipation, heat-gaining regulation, skin insulation, and water retention and loss reduction, were examined in diverse plants and animals. In addition to the behaviours of Sinai inhabitants (Bedouin), which allow them to avoid extreme heat environments, such as the traditional tents, there is also the dark, heavy clothing, which is made of both animal wool and other natural materials and can pass air flow, absorb moisture, and evaporate it for cooling. (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

The proposed skin consists of three layers (see Figure 6). The outside layer serves as a shade device to moderate solar radiation, in addition to moveable and openable vents that may be changed to control sunlight as needed. It may be made from moisture-absorbing natural materials like fabrics, clay, wood, or reeds. The middle layer is a network duct, which controls air flow entrances and sprays water for cooling. This layer is inspired by the sweat glands and air flow channels that exist in the human epidermis. An additional cooling strategy could be applied in this layer by convection with the Earth core or with any natural water resources, such as groundwater or seawater. (Elghawaby, 2010, 2012)

The last layer is the internal space vents, which is controlled by the user needs with a control system; furthermore, it may contain a condensed mechanism inspired by the vapour condensation process of the exhaled air in the camel nose to supply a potable water source. The researcher suggested that converting a traditional facade into thermal adaptive layers could be achieved either by applying traditional methods or new advanced technologies. (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

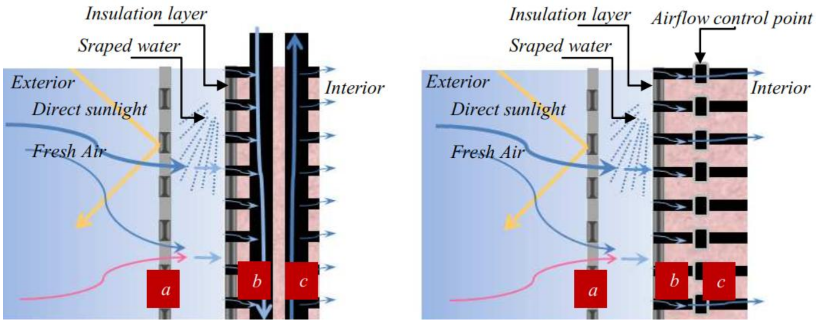


Figure 6: The notion of the adaptive Skin Layers, (a) the external layer, (b) the middle layer, (c) the internal layer Source: (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

In 2010, a field experiment was executed over two summer days in El-Qantara Sharq, North Sinai, Egypt, to examine the efficiency of the proposed design. Two models have been constructed: the first represents a traditional model constructed of solid traditional bricks and finished with cement, and the second represents the proposed design, constructed also with traditional bricks but with a network of vent ducts for ventilation and covered with textiles as a moisture absorption material (see Figure 7). (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

(a)  (b) 

Figure 7: The experimental test for the traditional and proposed design models while construction and after finishing: (a) the traditional solid bricks model, (b) the proposed breathing skin model Source: (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

In the absence of using evaporative cooling, the results indicated that the internal temperature degrees were less by 1.2 to 16.23% in the proposed design model than the traditional model, as well as the maximum temperature was less by 5.6 °C (see Figure 8). A mathematical test using aerodynamic modelling software was also used, and the findings revealed that a drop in temperature occurred in the proposed model by roughly 5 °C to 8 °C, which confirmed the prior results (see Figure 9). (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

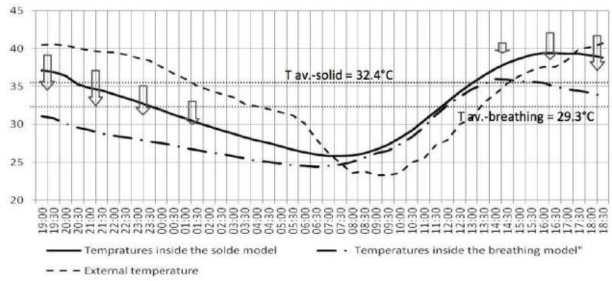


Figure 8: the temperature measurements in both traditional and proposed models Source: (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

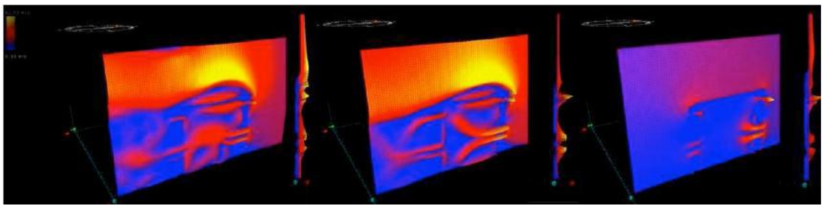
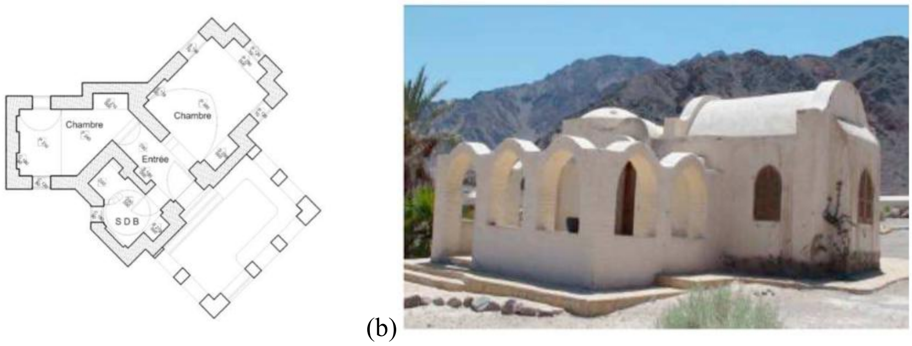


Figure 9: Airflow analysis of the proposed breathing skin model, simulating by Vaseri 2.5, Autodesk Source: (Elghawaby, 2010, 2012; Nour Eldin et al., 2016)

Elghawaby implemented a further step by applying the proposal in a constructed villa located in Sinai with local red brick walls for two days in July 2010 (see Figure 10). The external temperatures ranged from 27.5°C to 36.6°C, while the internal remained between 32.2°C and 34.0°C, respectively. By using an indirect geo-cooling system during the day and opening ventilation vents at night, the measurements indicated that implementing the proposal on the villa facades achieved a similar percentage of internal temperature reduction to that observed in the earlier experiment. If this decrease in temperature is not sufficient, the evaporative cooling strategy will be activated by water spraying on the external layer of the facades. The internal temperature was estimated to range from 24.6°C to 29.3°C. (Elghawaby, 2012)

Both experimental and mathematical simulation tests demonstrated the effectiveness of the proposed design in reducing internal temperature by 5°C to 8°C using natural cooling ventilation and achieving thermal comfort for the users; however, many issues, such as structural, environmental, economical, and aesthetical aspects, should be investigated. (Elghawaby, 2012; Nour Eldin et al., 2016)

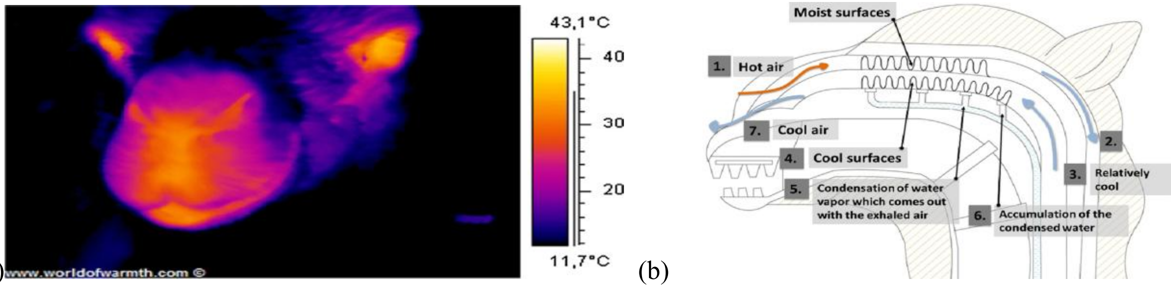


(a) (b)

Figure 10: The selected villa for applying breathing skin (a) ground floor plan and (b) 3D shot. Source: (Elghawaby, 2012)

4.2.2 An Innovative Strategy Inspired by Camel Nose for Desert Buildings

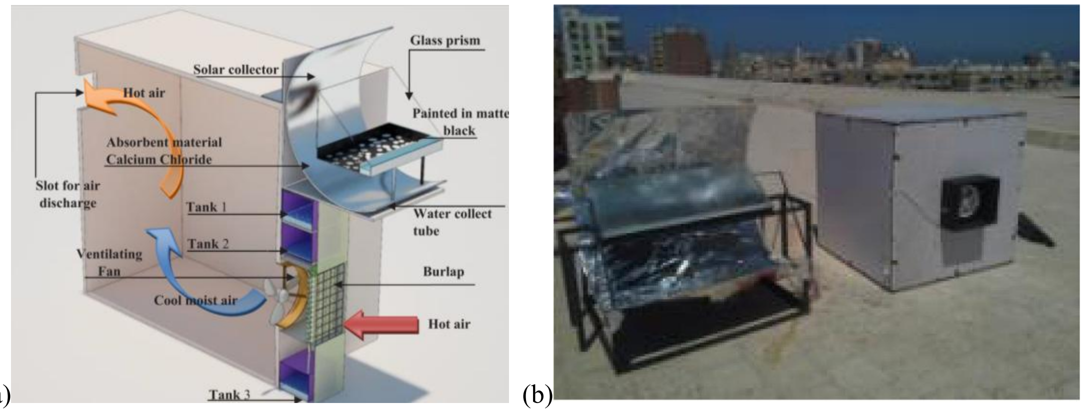
Shahda et al. developed a new design for cooling desert buildings based on the air-cooling mechanism found in camel nasals. The camel nasal comprises several tall and thin torsion pipes lined with mucous membranes known as turbinates. Air cooling happens during both the inhalation and exhalation processes. When the camel inhales dry-hot air, it enters the nasal tube, goes through the lengthy torsion pipes, and becomes cool and humidified because of the large surface area and mucous membrane evaporation, respectively. After that, the cooled air enters the lungs and remains within the usual temperature range of the body. The exhalation process is different somewhat; as the air returns to the turbinates and is further cooled, but this time it is dehumidified by absorbing previously lost moisture via humidification (see Figure 11). (Shahda et al., 2018)



(a) (b)

Figure 11: the camel nose (a) Temperature inside, and (b) cooling hot air in nasal Source: (Shahda et al., 2018)

The design Shahda et al. proposed is clarified as follows: Calcium chloride gas is used to absorb moisture at night. A heated metal surface coated in black matte and exposed to the sun is constructed on the south facade to maximize solar energy exposure and condense the absorbed moisture by heat evaporation. The condensed water is collected in a tank and attached to a perforated tube to moisturize many layers of burlap. This moisturized burlap is covered by a ventilation gap with a fan that pulls hot air through wet burlap and cools it before entering inside. To investigate this proposal, a cubic chamber was evaluated numerically and practically (see Figure 12). (Shahda et al., 2018)

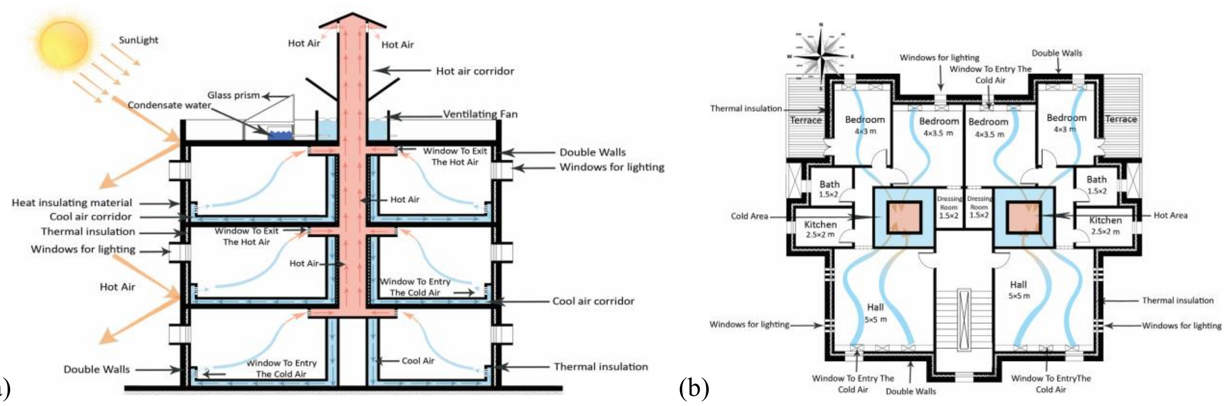


(a) (b)

Figure 12: Sectional 3D of the proposed strategy (a) tested mathematically and (b) Practically Source: (Shahda et al., 2018)

According to the numerical evaluation, a one-cubic-meter box has been constructed on the roof of the Faculty of Engineering building in Port Said, Egypt. The findings indicated that 1 cubic meter of air requires 1/6 liter of water for humidification and approximately 147.5 g of calcium chloride for condensing 1/6 liter of water. Environmental measurements revealed that the inside temperature dropped down by around 5 degrees from the external temperature at the peak hour, while the internal humidity increased by roughly 15 to 20 percent. (Shahda et al., 2018)

The proposed air-cooling technique is applied and simulated by using Ansys software on a selected model of a residential building in the desert. To apply this proposal, a double wall with thermal insulation material and an internal vacuum yard is required. The procedures of absorbing moisture, condensing it as water, and collecting it in tanks are situated on the building roof. The interior vacuum yard is divided into two zones to allow airflow by pressure differences. The center serves as a solar chimney for the hot air, while the region around it is a wind catcher with a fan on top that pulls air and then moisturizes it with the condensed water to spaces (see Figure 13). (Shahda et al., 2018)



(a) (b)

Figure 13: The architectural application of the proposed strategy; (a) section and (b) typical floor plan Source: (Shahda et al., 2018)

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4.3 Design Concepts

This section represents the design concepts inspired by camels that were not executed, tested, or simulated. There are two cases, as follows:

4.3.1 *Stoma Brick System*

Stoma brick is an evaporative cooling system developed for the building envelope in arid, dry areas (see Figure 14). The primary goal behind this system is to treat the building envelope as a medium rather than a barrier, allow many additional functions that provide thermal comfort in areas, and adapt to different humidity levels. To reach this goal, heating and cooling thermoregulation techniques of various organisms were studied and translated into four integrated principles. (Badarnah et al., 2010)

Those integrated principles are translated into four components: stoma brick, mono-brick, steel frame, and HEPA (see Figure 14). The first component, the stoma brick, is the primary component for the thermoregulation function and is made of three layers. The outer layer is a hairy structure material inspired by camel eyelashes to filter the air that goes through the envelope. (Badarnah et al., 2010; Arbabzadeh et al., 2020) Camels, particularly one-humped, have large eyes with thick layers of eyelashes and dense brows (Noor & El-bably, 2018; Akool et al., 2023), which is considered an eye adaptive and protective mechanism from strong solar radiation, blowing sand and dust, odd bodies, and small insects in desert regions (see Figure 15.a). (Soliman, 2015; Noor & El-bably, 2018; Akool et al., 2023)

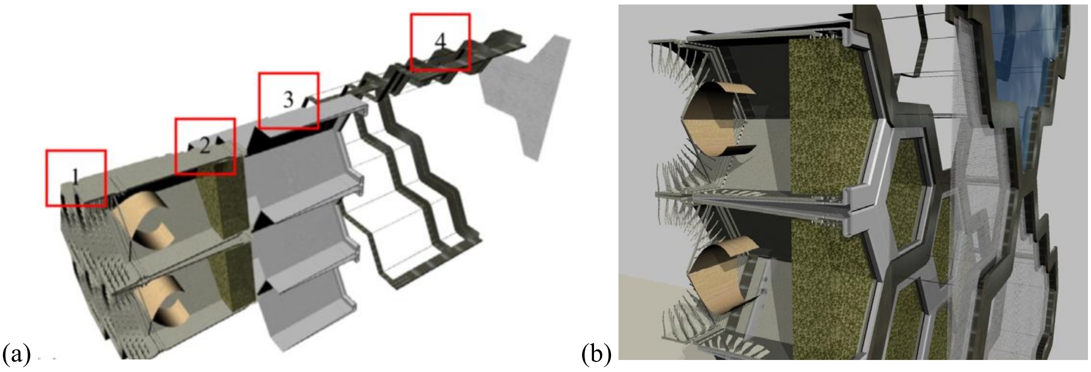


Figure 14: Stoma Brick System, *(*a) the four parts of the system separated, and (b) the four integrated parts as one system Source: (Badarnah et al., 2010)

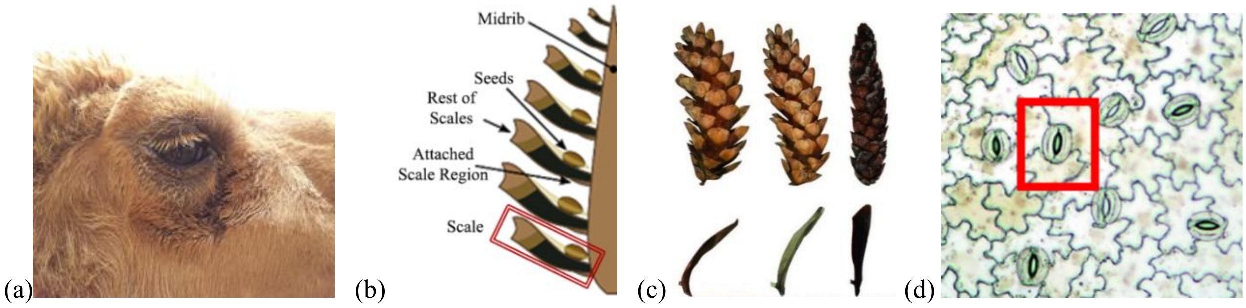
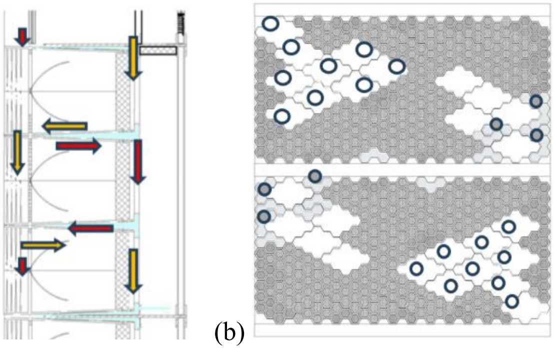


Figure 15: Inspired Organisms (a) A side view of the camel eye clarifies the dense eyebrow covered with long and heavy hairs. Source: (Akool et al., 2023), (b) Woody female strobilus cone while fertilization and red rectangle illustrate the absorption zone that is responsible for water absorption and deforming. Source: (Wheeler-Dubas, 2020) and (c) the pine cone in three different levels of humidity: open with 30% wet, semi-open with 80% wet, and enclosed while completely wet, respectively, from left to right. Source: (Eger et al., 2022), (d) The cell guards while opening stoma pores (highlighted with red dash line) for water evaporation. Source: (Crang et al., 2018b)

The second adjacent layer to the hairy one is a veneer closure inspired by pine cone deformation to allow closing and opening and be controlled based on humidity level. (Badarnah et al., 2010) The process of opening and closing the pine cone is complex and related to the shrinkage and expansion coefficients factor found in wood scales, which are associated with water absorption (see Figures 15.b & c). (Eger et al., 2022; Reyssat & Mahadevan, 2009)

The third layer of the stoma brick is a porous and spongy substance that retains moisture for subsequent evaporation inspired by plant stomas. (Badarnah et al., 2010) The epidermis of plant leaves, flowers, and stems contains cells known as guards, which play an important role in plant defence. When guard cells absorb water, they expand and flex, open a pore between the two cells, and form a hole on the leaf surface known as a "stoma" (see Figure 15.d). (Crang et al., 2018b, 2018a) Plant stoma serves as a dynamic barrier between the environment and the leaf intercellular air gaps. Both guard cells and stoma regulate gas exchange, including carbon dioxide and oxygen, as well as water evaporation between the leaf and its surrounding environment. (Crang et al., 2018a)

The second component is the mono brick, which incorporates water into an irrigation cycle to irrigate the stoma brick via perforations (see Figure 16). Figure 16.b shows two configurations of the SB based on its position on the envelope. (Badarnah et al., 2010) The irrigation cycle is inspired by the evaporation of human skin for heat transmission and cooling. Human skin is regarded as a medium that facilitates heat transport and exchange with the surrounding environment. (Badarnah et al., 2010) It differs from one another; nonetheless, it is 2 mm thick and comprises three layers: the epidermis, the dermis, and an intermediate fat layer (see Figure 17). The dermis is the thickest layer, which houses the vascular system, sweat glands, and thermoregulatory nerves. (Badarnah et al., 2010) Both vasoconstriction and vasodilation of the vascular system regulate the blood flow, which results in heat loss or gain, respectively. (Badarnah et al., 2010) If this method is insufficient, sweat glands act as an extra effective mechanism for latent heat loss by spreading moisture via skin pores. (Badarnah et al., 2010; Randall, 1946, 1947)



(a) (b)

Figure 16: Section in the stoma brick system illustrates (a) the mono brick layer with two irrigation cycles red and yellow, and (b) two different configurations of the SB three SB or nine SB Source: (Badarnah et al., 2010)

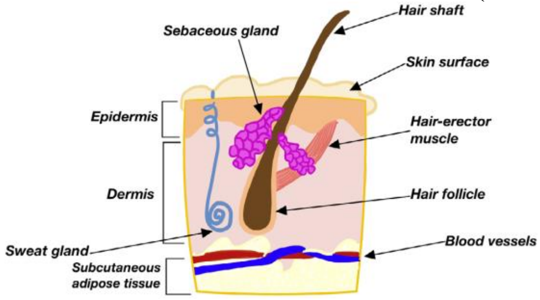


Figure 17: Skin layers composition and sweat glands Source: (Shamloul & Khachemoune, 2020)

The third component is the steel structural frame, which connects the entire system. (Badarnah et al., 2010) The last component might be a High Efficiency Particulate Air Filter (HEPA) *(USA Environmental Protection Agency, 2023)* or double acrylic glass providing natural light and visual interaction with the outside world. (Badarnah et al., 2010) It is proposed to humidify the hot air before it reaches the internal spaces.

In hot-humid conditions and thanks to the natural humidity, the veneer shutter deforms and opens to allow the air to pass through the spongy material and then to enter the internal spaces. In dry weather, the same process happens; however, the veneer shutter will be moisturized by the irrigation system. In cold and dry weather, the sponge acts as thermal insulation to reduce heat loss. Furthermore, additional blocks could be fastened to the ceiling to drive the heated and exhausted interior air out. (Badarnah et al., 2010)

4.3.2 *Phalanx Insulation System*

Phalanx is an innovative technology, which participated in the Biomimicry Global Design Challenge for 2019 (see Figure 18). It is a thermal insulation system made of sophisticated multilayered cladding for coastal building exteriors. It is innovated to passively cool internal temperatures by minimizing heat absorption, resulting in lower HVAC loads and mitigating building footprint. (Askeland, 2018; Insulation Grid Inspired by Camels, Ants, Termites, and Wheat Phalanx Insulation, 2019)

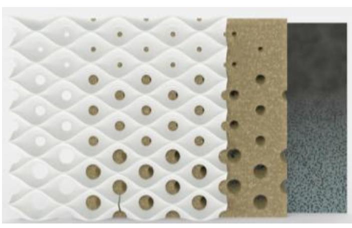


Figure 18: Phalanx Insulation System consists of three layers starting from the left: the shade layer, the air movement layer, and the capillary cooling layer. Source: (*ECO Group IIT Roorkee: Phalanx-Insulation*, 2021)

The Phalanx system was designed to minimize the heat island effect by dropping the amount of heat that buildings absorb during the day (see Figure 19). It consists of three layers, each inspired by nature. The first layer, or first barrier, is a wavy reflective layer inspired by the wavy surface of Echinocereus cactus plants, which provides a self-shaded surface and reduces heat absorption. It is also inspired by the reflectivity capability of the Saharan silver ant, which can reflect sunlight roughly 10 times more than regular ants through a very thin translucent covering on its back (see Figure 20). (Askeland, 2018; Insulation Grid Inspired by Camels, Ants, Termites, and Wheat Phalanx Insulation, 2019)

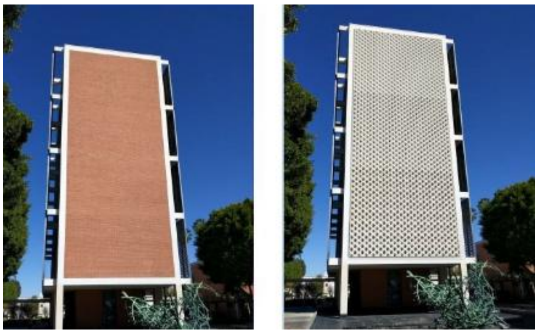
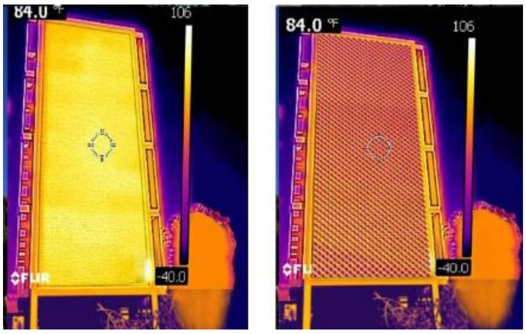
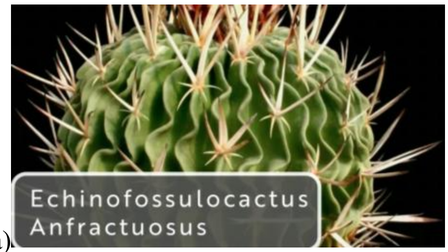
(a) 
(b) 

Figure 19: McIntosh Humanities Building, the women, gender and sexuality department, California University State, Long Beach, Ca, USA (a) Proposed Phalanx on the building, (b) Simulation of thermal absorption of Phalanx system Source: (Askeland, 2018)

(a) 

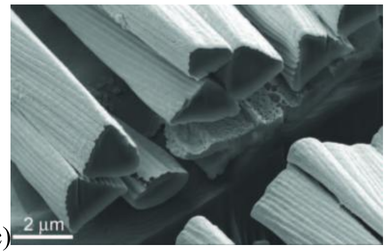
(b) 
(c) 

Figure 20: The first layer of Phalanx system, which is inspired by (a) The Echinofossulcactus plant, with its wavy surface, inspired for the first layer to cool its core by shading and (b) the Saharan Silver ant on the left figure. Source: *(Askeland, 2018)*, (c) its back covered with thin triangular transparent hairs reflects the sunlight (a cross section of the back hair). Source: (Nan Shi et al., 2015)

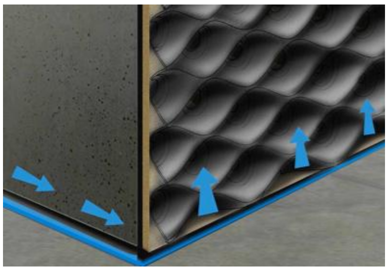
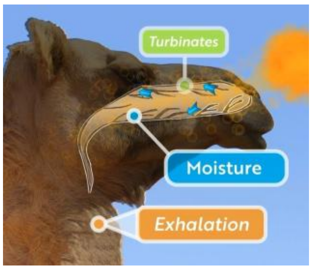
Both the first and second layers include many shafts that decrease in size as they are lifted higher. These shafts are inspired by the ventilation mechanism exits in termite nests, such as those in Africa. The termite nest is created of several shafts, some small and lateral, and others large and central. The ventilation mechanism operates by sucking air from the lateral shafts and pulling it into the central core, where hot air exits from the top (see Figure 21). (Askeland, 2016, 2018)

The last layer is quite unique: it is a combined system inspired by two organisms that collects wastewater, pulls it, and then releases it as a vapour to cool the surface (see Figure 22). The technique for collecting water is inspired by how a camel gathers moisture in its nose. The camel nasal allows air to move from the nostrils into the lungs via tiny structural bones within the nose known as turbinates. During the respiratory process, the moisture of the air stuck to thin walls, which increased in surface by turbulence. This part is made of fibrous material, which acts as a moisture condenser. (Askeland, 2016, 2018)

The second component, which releases and evaporates the water, is inspired by the wheat plant. When it heats up, the existing capillaries attract water and distribute it by tensions between the molecules as a vapour via the leaves to cool down. The cooling process spreads the collected wastewater through the capillary layer, where it is evaporated by the hot air used to cool the surface (see Figure 22). (Askeland, 2016, 2018)

(a) 
(b) 

Figure 21: The ventilation system inspired by the termite nest sucks the air through lateral (a) shafts as hot air and then pulls it to the central core and (b) where the air leaves from the top. Source: (Askeland, 2018)

(a)  (b) 

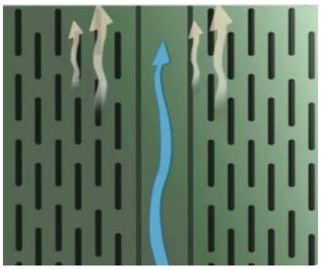
(c) 

Figure 22: The third layer of Phalanx system (a) a combined system that consists of (b) a water supply inspired by camel nasal and (c) a capillary system inspired by the Wheat plants cooling system by water evaporation through capillaries. Source: (Askeland, 2018)

5. Analysis and Discussion

After reviewing the case studies that were inspired by camels and categorizing them based on their current situation, which includes implemented projects, experimental models, and design concepts, it was important to classify each one according to biomimetic levels and dimensions mentioned previously in the methodology. Table I displays all the case studies analyses, along with their biomimetic levels and dimensions.

Based on the first category according to the current situation, the implemented projects are two projects. The design concept of the first project, “Kilo Tent,” is to coincide the technical innovation of the Morocco Exhibition with a nomadic traditional shelter of the Southern Moroccan residents. As a result, the designers inspire the traditional tent woven manually with natural camel hair and sheep goat (organism level). We also observed a camel hump look, which is classified as organism level.

In comparison to the previous project, “A Sustainable Bioinspired Cooling Unit” may be regarded as a comprehensive case. The convoluted passages in both mechanisms are inspired by the camel turbinates, cavernous sinus, and veins (organism level). However, the design is based on a behaviour level via the inhalation process of the hot air, which might also be classified as ecosystem level. In addition to enriching the third level by using solar cells to power the water pump, this will make the project more passive in temperature regulation and have a greater impact on the built environment.

The second category of case studies is experimental models, which includes two models. The first model, “An Adaptive Breathing Skin,” has undergone both mathematical and practical testing. The design concept is inspired by different thermal strategies as well as Bedouin habits. The inside layer of the breathing skin is designed to condense moisture from the inlet air to cool down, which is inspired by the camel nose capability of condensing moisture from exhaled air. The researcher follows both the organism and behaviour levels, as well as the ecosystem level, where natural hot air and moisture occur.

The second model, entitled "An Innovative Strategy Inspired by Camel Nose for Desert Buildings," is unique. We can sense the unity of the three levels incorporated into an architectural idea to provide a highly effective cooling system for desert buildings with limited water resources. In that case, the researcher attempted to imitate how the camel nose condenses moisture from respiratory air using calcium chloride gas, while the mucous membrane humidifies and cools the heated air using water-sprayed burlap. In addition to using solar energy as a natural resource for condensing the gathered moisture into water drops, it is based on the naturally moisturized air.

The last category of case studies involves design concepts. The initial design proposal, "Stoma Brick," combines many techniques found in many organisms, including camels, pine cone plants, stomas in plant guard cells, and human skin. In this scenario, the organism level is checked by filtering the incoming air using a hairy structure material inspired by camel eyelashes. As in prior cases, the design idea is based on the natural outside air (at the ecosystem level).

The final case, "Phalanx Insulation System," is identical to the prior. It is a hybrid of various organisms, including the cactus plant, the Saharan silver ant, the termite nest, the camel nose, and wheat plants. This system inner layer is inspired by how the accumulated moisture condensed when air passage halted through the camel nasal turbinates. This scenario validated the organism and behaviour levels by collecting precipitation and wastewater to moisturize and cool the incoming hot air via evaporation. As in all prior cases, the notion is based on natural hot air (ecosystem level).

Table i. Classification of the case studies according to biomimetic levels and dimensions. Source: The Researcher

Case	Levels / Dimensions	Organism	Behaviour	Ecosystem
Kilo Tent, Institute du	Form	Camel hump	-	-
	Function	-	-	-
	Process	-	-	-
	Construction	Woven manually to lock like natural coat	-	-
	Materials	Camel hair	-	-

A Sustainable Bioinspired Cooling Unit	**A. Wet Cooling Unit inspired by Camel Nasal**			
	Form	Wind catcher as nasal concha for pulling hot air	-	-
	Function	cooling the entered hot air	-	
	Process	A water distribution system for spraying water	cooling hot air as the inhalation process	Hot air as the respiratory air
	Construction	Rectangular rings to mimic big surface area of turbinates	-	-
	Materials	Porous natural clay with jute fibres plates as moisturized mucus membranes	-	-
	B. Dry Cooling Unit Inspired by Convection of The Brain Blood			
	Form	Spiral copper pipes such as cavernous sinus and veins	-	-
	Function	Big area in limited space to cool down the air temperature	-	-
	Process	The cooled water passes through internal spiral copper pipes to cool indoor temperature	Temperature regulation by convection	Solar energy for water pump battery
	Construction	Spiral circulation to lose heat	-	-
	Materials	Copper as a radiative material to exchange cool	-	-
An Adaptive Breathing Skin for	**Form**	-	-	-
	Function	Camel nasal	-	Natural ventilation
	Process	Dehumidification of the exhaled air	Exhalation process	Natural Dehumidification
	Construction	-	-	-
	Materials	Moisture-condensed technology/material	-	Natural moisture exists in natural air
An Innovative Strategy Inspired by Camel Nose for Desert	**Form**	Wind tower to pull air like nose	-	-
	Function	Cooling hot air as in inhalation process	-	-
	Process	Humidification hot air by spraying moisture	Pulling up and moisturizing the hot air	Hot air that evaporates moisture
	Construction	-	-	-
	Materials	Absorbing gas (calcium chloride) to collect moisture drops from the air by condensation to spray burlap and cool hot air such mucus membranes	-	Condensing moisture from natural air
Stoma Brick System	**Form**	Camels Eyelashes	-	-
	Function	Filter the air passes through	-	Filter natural air passes through
	Process	Prevent sands and dust	-	-
	Construction	Hanging smoothly	-	-
	Materials	Hairy structure materials	-	-
Phalanx Insulation System	**Form**	-	-	-
	Function	Cools down surfaces	-	-
	Process	Collecting moisture to cool surface temperature as camel gathers moisture in its nose	Heat islands near the surface due to high temperatures	Hot air
	Construction	-	-	-
	Materials	-	-	-

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In contrast, the six case studies inspired by camels, which included implemented, experimental, and conceptual phases, were examined in relation to environmental factors (see Table II). These projects, spanning external and cultural systems, demonstrate how camel biology and related models inform architectural design.

Camel adaptive strategies are implemented in projects such as the Kilo Tent and Cooling Unit. The cooling unit showed significant thermal improvements, with temperature drops of 9.7 to 19.8°C and humidity increments of 40.5 to 70.6%, supported by experimental tests and simulation tools. However, the Kilo Tent, although inspired by camels, does not have published performance data.

Experimental projects like the Adaptive Breathing Skin and Camel Nose Chamber show promising bio-responsive features, especially when using tools like aerodynamic and ANSYS modeling. These devices can cool up to 5 to 8°C, thanks to the camel ability to control nose moisture and its flexible skin.

Conceptual designs that draw from multiple models, including termites, plants, and camels, such as the Stoma Brick System and Phalanx Insulation System, challenge the boundaries of biomimetic innovation. However, these designs have not been tested, and there is currently no measurable performance data available.

Table ii. Comparison analysis of the case studies according to energy performance outputs, Source: The Researcher

Type	Function	Case Study	Energy Performance		Simulation Tool	Tested / Simulated	Country
			Temp. Reduction (°C)	Humidity Change (%)			
Implemented	Cultural	Kilo Tent (2014)	Not available	Not reported	None	No	Paris
	General	Cooling Unit (2019)	9.7 – 19.8	40.5 – 70.6 ↑	Revit	Yes (Field + Simulation)	Yemen
Experimental	Residential	Adaptive Breathing Skin (2016)	Up to 5.6 (field) 5–8 (sim)	Not reported	Vaseri	Yes (Field + Simulation)	North Sinai
	Residential	Camel Nose Chamber (2018)	~5.0	15 – 20 ↑	ANSYS	Yes (Field + Simulation)	Port Said
Conceptual	-	Stoma Brick System (2010)	Not available	Not available	None	No	Arid dry area
	Educational	Phalanx System (2019)	Not available	Not available	None	No	Coastal area/California

6. Conclusion

By incorporating biomimicry into architecture, unique and imaginative sustainable design solutions may be developed. These solutions minimize energy consumption in the built environment and mitigate the consequences of climate change. Along with tackling specific challenges such as heat islands, thermal control, and water shortages, particularly in hot arid regions, while reducing buildings footprint. Furthermore, all case studies demonstrate integration at the organism level, supported by behavioral and ecosystem levels.

The camel piqued the curiosity of numerous experts who seek more inventive and adaptable solutions for hot arid architecture. The bioinspired solutions by camels differ from one another, even though the camel is presented in all of them. Although few cases have been implemented and verified, which produced the intended outcomes, in addition, few bioinspired ideas have been presented. We also found that the camel nose cooling strategy was the major inspired feature in most cases.

Based on the analysed cases, we could conclude that relying solely on the physical characteristics of the camel could not be an adequate decision. Besides, mimicking the camel behaviour along with the physical characteristics could have a greater impact on both the occupants and the built environment. Furthermore, integration methodology based on more than one capability or even more than one organism is a complex multidisciplinary task but could achieve a better performance (see Figure 23).

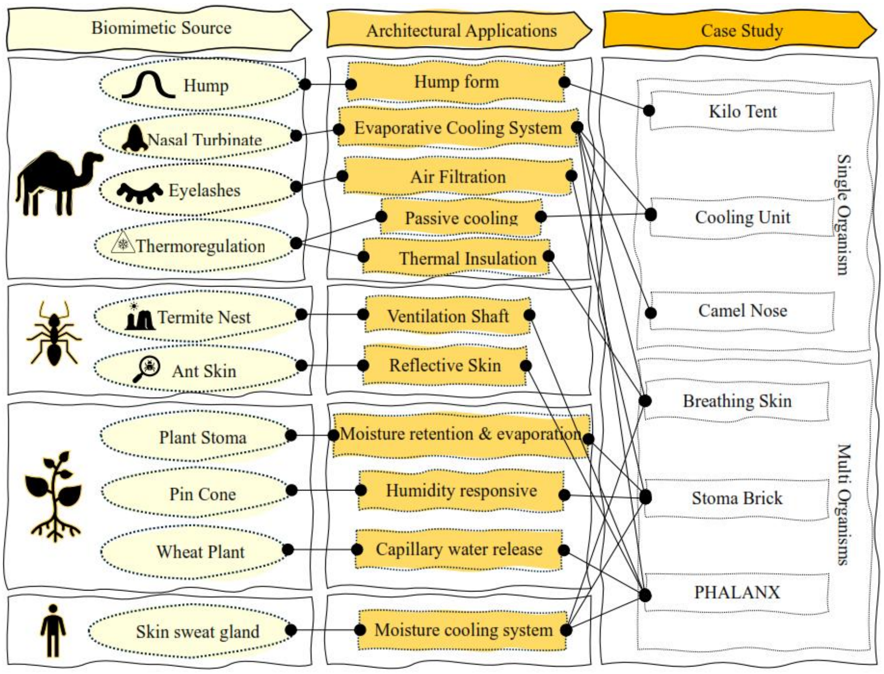

Figure 23: A graphic diagram summarizes the bioinspired sources with their architectural applications. Source: The Researcher

7. Recommendation

A "Camel-Biomimetic Framework" is suggested as a general guide for building design that integrates adaptive, passive, and environmentally responsive techniques stimulated by camel physiology and arid region ecology. This is based on the evaluation of the camel-stimulated architectural case studies (Cooling Unit, Adaptive Breathing Skin, Camel Nose Chamber, Stoma Brick System, and Phalanx Insulation System) (see Table III).

Key organic characteristics of camels are translated into sustainable construction techniques for hot arid climates. Layered envelopes with insulation and vapour management are inspired by the camel multilayered skin. Natural materials used in evaporative cooling systems are modeled after camel nasal turbinates, which manage moisture efficiently. The adaptive porosity of camel nostrils inspires breathable façades that react to environmental changes. Air-channeling systems in building envelopes are informed by the camel nasal passages, which use convection for inner air cooling.

The use of light-colored, reflective coatings to minimize solar gain is inspired by the camel light-reflective fur. Micro-textured surfaces that reduce heat absorption are based on the folds and textures of camel skin. Camel eyelashes and other protective features are referenced in architectural shading systems and filters. Finally, choosing responsive materials that adjust performance based on climate is guided by the adaptability of camel fur. Combined, these bioinspired strategies allow for climate-adaptive, energy-efficient design solutions.

Table iii. Camel-Inspired Framework: A General Design Guideline Source: The Researcher

Building Components	Camel-Bioinspired Features	Architectural Strategy
Multi-Layered Skin/Envelope	Camel thick skin and layered fur	Use multi layered facade systems with insulation materials, vapor barriers, and outer protective surfaces.
Humidity Regulation	Nasal turbinate moisture condensation and recycling	Integrate evaporative cooling (such as jute, clay, and textile membranes) for passive cooling.
Adaptive Permeability	Inhalation and exhalation processes and nostril shrinking	Design dynamic or breathable façades that regulate humidity/ air temperature (such as vents).
Internal Air Channels	A camel nasal pathway cool air before it reaches lungs	Design internal air pathways or chambers (like nose chamber) to pre-cool and humidify or dehumidify air.
Reflectivity + Coloration	Reflective light fur in sunlight	Apply light-colored, reflective coatings, or finishes to reduce heat gain.
Surface Texture + Geometry	Skin folds and fine textures to reduce radiation gain	Use micro-textures or geometric patterns on surfaces to control solar gain and reflectivity.
Shading and Filtering	Eyelashes and skin folds protect from sand and sun	Integrate filters, or screens for passive shading and air purification.
Material Responsiveness	Fur adjusts its insulation based on temperature	Use smart materials that react to temperature/humidity (like hydromorphic or shape-changing).

8. Future Research

A six-step methodology is proposed for implementing the camel-inspired architecture framework in hot, dry environments (see Figure 24). The first step is the contextual analysis, which identifies climate-related concerns. It is followed by the biological translation step, in which architectural elements such as shading or cooling are associated with camel characteristics such as humps, fur, or nostrils. The component development, the third step described in Table III, focuses on the design of the building outer envelope, or skin, that protect and insulate interior spaces. When selecting materials, options that mimic biological features are preferred, especially those that are locally accessible and sustainable. The preceding processes are then simulated and tested to determine thermal performance and airflow using software such as Revit or ANSYS. The last step in optimizing environmental performance is to integrate adaptive feedback systems. These are technologies that adjust building systems in response to real-time environmental changes, often known as refined improvements. Future research will assess the effectiveness and practical application of this process.

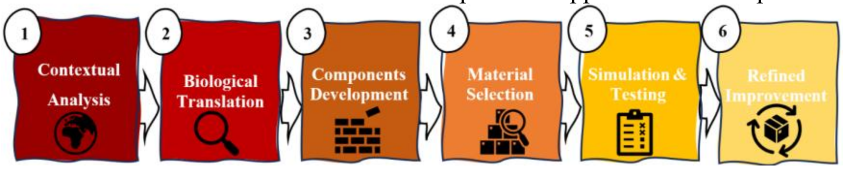

Figure 24: A Sex-Steps Process for implementing the camel-inspired architecture framework. Source: The Researcher

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT:

Yasmin M. Eid: Supervision, conceptualization, methodology, original draft preparation, and writing & editing. **Omnya S. Zekry:** Collecting data, formal analysis, and participating in the original draft preparation.

DECLARATION OF COMPETING INTEREST:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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