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COOLING STRATEGIES IN THE BIOLOGICAL SYSTEMS AND TERMITE MOUND: THE POTENTIAL OF EMULATING THEM TO SUSTAINABLE ARCHITECTURE AND BIONIC ENGINEERING

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ABSTRACT

Biomimicry, the science of emulating nature's strategies, has remarkably contributed to solving many of human problems in different fields. This paper studied the potential of interpreting some of the nature mechanisms to reduce or eliminate energy consumed for cooling purposes. It highlights three of most effective cooling and thermo-regulating strategies in extreme environments which are accomplished through morphological features. For the first two strategies, a comparative analysis of a mutual thermoregulatory mechanism was conducted for four different organisms. The third strategy listed four of the related hypotheses interpreted termite mound's mechanism of thermoregulation. The study concluded to draw the working principles of each strategy that can contribute to design eco-friendly and passive cooling systems for bionic engineering and architecture. It is assumed that applying thermoregulation strategies will lead to creative designs with significant energy saving.

Keywords: passive cooling, biomimicry, thermal comfort, sustainable architecture.

INTRODUCTION

In the building sector, a high percentage of the electrical energy is consumed to meet human thermal comfort requirements using Heating Ventilation and Air Conditioning systems (HVAC). For example, in Kuwait and the Gulf States, the HVAC systems "consume more than 70% of the installed capacity of power generating units" [1]. Similarly, in Australia, the non-residential buildings consume 70% of the total energy for air conditioning units [2]. Consequently, buildings are responsible for most of the total consumed energy over than the other sectors such as transportation and industry. Burning fossil fuels to generate electrical energy has contributed largely in destroying the ecological life and the climatic system in the earth causing natural disasters like global warming and ozone layer depletion. Furthermore, global warming has critical consequences such as ice melting in arctic which causes increase in the ocean level height [3] and widespread amphibian extinctions [4]. The emissions of the poisonous gases, such as SO2, NOX and CO2, resulted from burning fossil fuels are causing environmental pollution problems, acid rain and as a result death of vegetation [5]. Acidic rain and ozone layer depletion are the main causes for volcanoes rampage and heating of volatile-rich rocks [6]. Consequently, there is a serious change happen in the earth system and finding alternative air cooling mechanisms to the HVAC that can passively or energy-efficiently run will contribute to solve this challenge.

Biomimicry, the science of emulating nature techniques, has contributed to solve many of human challenges [7], [8], [9] including indoor air conditioning issues. A study by Abdullah *et al.* [10] showed that mimicking the thermoregulatory mechanisms in nature to novel air conditioning designs can contribute to a considerable energy saving. Therefore, this study highlighted some of the thermoregulation mechanisms in nature achieved by sort of form to be consciously emulated to passive cooling designs. Nevertheless, before dealing with the thermo-regulation mechanisms, heat transfer methods have to be discussed for a better understanding of energy exchange basics in each mechanism.

HEAT TRANSFER MECHANISMS

Heat is an energy which transfers by three means that are conduction, convection and radiation. Heat transfer by conduction occurs through the molecules movements from the more energetic part to the less energetic of a substance. Heat transfer by conduction can be calculated by Fourier's Law that is

$$q_{cond}^{n} = k\,\frac{T_1 - T_2}{L} \qquad (1)$$

Where, q_{cond} is heat transfer rate, *k is* thermal conductivity of the material, T_1 andT_2 the temperature of the two material surfaces, L is the thickness of the depth between these two surfaces.

Convection happens when a fluid or gas flow adjacent to a solid body with a higher temperature whereby the nearby molecules of the fluid become hotter and less dense making them float and be replaced by other molecules of the fluid. Therefore, buoyancy is the main motion vector in heat transfer by convection. There are two types of heat transfer by convection that are natural and induced or forced convection. Natural convection happens when wind passes nearby a wall, but the forced convection is caused by external forces like mechanical devices; e.g., fans, pumps, etc. This technique is used to run the cooling systems and the ventilation elements such

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as the chilling ceiling panels and wind tower in Middle East architecture. Simple heat transfer by convection can be calculated via Newton's law

$$Q_{conv} = h\,A\,(T_1 - T_2) \quad (2)$$

Where, Q_{conv} is heat transferred per unit time, h is the convective heat transfer coefficient, A area of the material, T_1 and T_2 are the temperature of both material surface and fluid, respectively.

Radiation is the heat emission from hot material to the surrounding through electromagnetic waves. The radiative heat loss can be described by *Stefan Boltzmann* law that is

$$Q_{rad} = \varepsilon\,\sigma\,A\,(T_1^4 - T_2^4) \quad (3)$$

Where Q_{rad} is heat emission, ε is material emissivity, $\sigma = 5.67\ (13)\times10^{-8}\ \mathrm{W\cdot m^{-2}\cdot K^{-4}}$, A is material area, T_1 and T_2 are the temperature of both the radiative material and the surroundings.

THERMOREGULATION IN NATURE

Regulation body temperature is an essential issue for the survival of biological systems and the integrity of their functions. Thermoregulation is the challenge of keeping the temperature of an organism and its brain within the acceptable ranges especially for the animals living in the extreme environment such as savannas and deserts. The two sources of heat gain for organisms in a hot region are the heat from the environment like sun radiation and the heat from metabolism [11]. Organism are exposed to the high temperatures and to stalking chase and predation by hunter of hungry animals producing high rate of metabolism heat [12]. Cheetahs run at speeds more than 100km hr^{-1} to pursue its prey, producing heat over 60 times than that at rest time [13]. This high temperature is fatal for the sensitive brain which operates within highly restricted temperature contexts [14]. To deal with the overheating challenge, organisms have a diversity of behavioral, physiological, and morphological thermoregulation mechanisms [11].

The adaptive behavioral mechanisms to reduce excess body heat varies from animal to another. Some animals seek shade on a microclimate area such as living in the underground burrows, others tend to do activities at night and some are resorting dormancy underground [15]. Small mammals have high body surface area to volume ratio resort to stay in burrows to avoid heat gain. Burrow is saturated microhabitats characterized by small range of temperature difference not like hot surface of the desert which fluctuates from 20°C at night to 70 °C at midday [16]. Moreover, mammals evaporatively cool their body by panting, licking [17], peeing, bathing and spreading saliva [14]. Furthermore, bees use evaporation mechanism to cool their nest by collecting water droplets and spread them in the hive [18]. To moderate body temperature, birds exhibit mobility behavior such as gular fluttering, wing fanning, in addition to orientate or posture their bodies in a perpendicular manner to the sun to minimize the exposed area to solar radiation [19]. A review of the behavioral strategies used by mammals to cope thermal challenges was conducted by Terrien *et al*. [20].

The physiological thermoregulatory mechanisms, homeothermy, are the physical or the chemical functions carry out by organism body to keep core body temperature constant as an adaptation to the temperature fluctuation in their environment. To cope their environment, organisms have varied reactions such as evaporation or controlling metabolism rate. This depends on the biochemical reaction rates [21], "enzyme activities, hormone expression, and cardiovascular functions" [22].

However, the morphological thermoregulation adaptation is the one achieved by some kind of form or structure to maintain body temperature within viable ranges of survival. Figure-1 listed some of the thermoregulation strategies in nature achieved through morphological features where three of them are extensively discussed in the next section.

The first thermoregulation strategy is through air circulation where excess heat is continually expelled by force convection through air movement and stack effect. This is achieved by the special structure of birds' nest that is full of ventilating holes [23] and the forced convection through panting in many of animals and birds to dissipate heat. However, the second thermoregulation strategy that is counter-current heat exchange is achieved through conduction to conserve heat in organisms living in an extreme environment especially the cold one. It is a crossover between the hot blood arteries coming from the body and the cold blood veins coming from the exposed organs to the coldness of the surrounding. When the hot blood of the arteries run in a close juxtaposition with the cold blood of the veins in opposite directions to each other, the heat is transferred from the arteries to the veins conserving a considerable amount of the body heat. This mechanism is found in the respiratory passages of the animals living in extreme environment [24], the tongue of the gray whale [25] and legs of arctic eider ducks [26]. This mechanism has been emulated to engineering and industry to recover heat energy such as indirect evaporative cooling systems [27].

As for reducing heat transfer, either heat loss from organism body or heat gain from the surrounding, insulation is the thermoregulation strategy used by many organisms to survive in extreme climates such as desert and arctic. It is achieved by some means such as fur, though using blubber and air layer are the most common. Blubber as an insulation strategy in marine mammals is characterized by low thermal conductivity preventing heat loss [28]. However, in the desert, snail protects its body from the hot surface of the desert which reaches up to 70°C [29] by placing its body in the upper part of snail shell which contact with the ground in a few points reducing heat transfer through conduction. As a result, a layer of still air occurs between snail and the hot ground creating "an insulating air cushion" without which animal will reach the lethal temperature [29; p. 389]. Moreover, to avoid the direct sun

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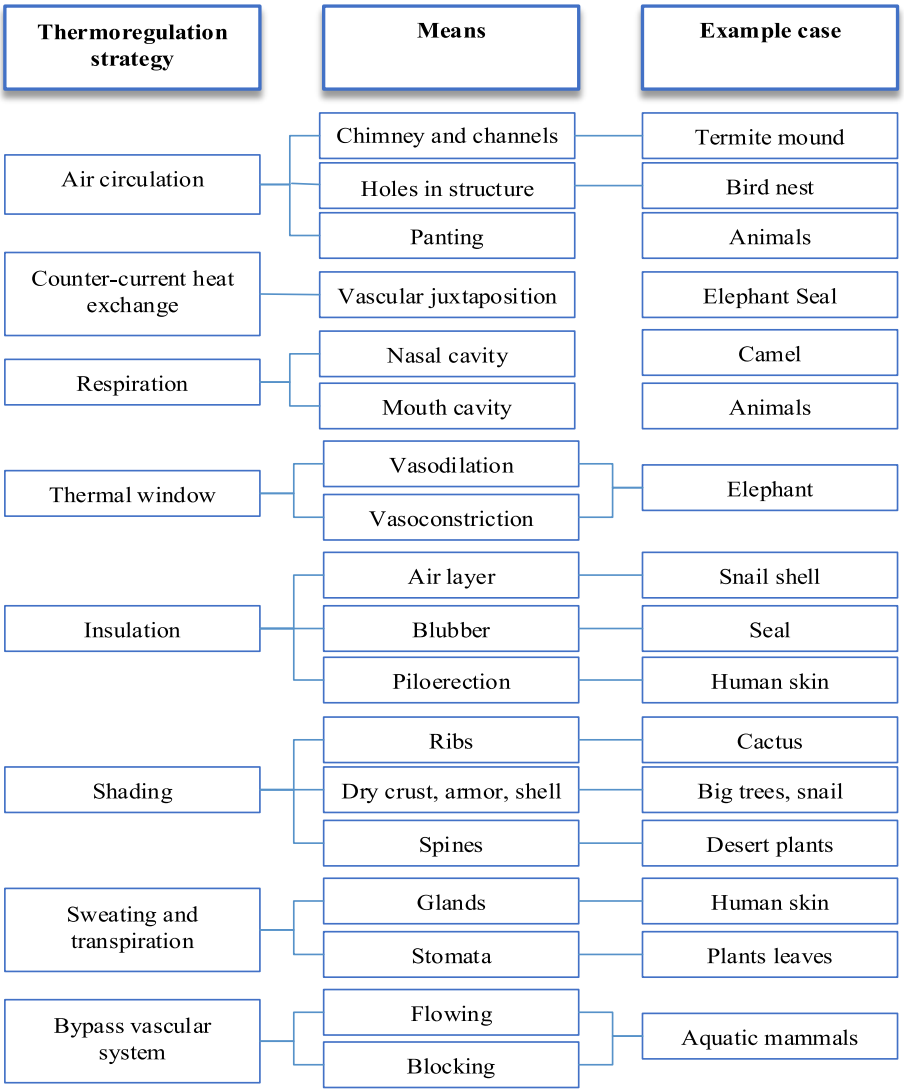

Figure-1. Some of the morphological thermoregulation strategies in nature.

which can generate the same heat as a single bar radiator over each square meter of a surface" [30], shading is the effectual strategy for reducing heat gain. Desert plants like cactus has ribs and spines which contributed to offering shading areas enabling them to survive in the harsh desert environment [31], [32].

Evaporative cooling through cutaneous surfaces such as perspiration and secretion is an effective way to avoid overheating in organisms which do not have insulation like fur. Sweat is secreted by many glands in the dermis layer and controlled by sensors. This cooling technique was the inspiring notion for the Bio Skin facade system of the Sony Research and Development Office in Tokyo which is consists of a network of porous ceramic that collect rainwater for cooling air in summer [33]. Furthermore, bypass system for blood vessels is a technique of controlling blood flow to the superficial layer of the skin. This system is mostly found in aquatic mammals which "permit a precise regulation of the amount of heat that reaches the skin surface and thus is lost to the environment" [34; p. 251]. So, when there is a need to dissipate excess heat of the body, the blood flows through this system to the superficial skin whereby heat is dissipated through convection. However, when the environment is cold, and an animal needs to conserve body heat, the blood is restricted by this system to flow through the internal blood vessels. Either as regards of the three thermoregulating strategies that are respiration through the nasal cavity, air circulation in the termite mound and thermal windows in some biological systems, a comparative study was conducted in the following section.

Comparative study of cooling mechanisms in some of the biological systems and termite mound

This study highlights three of the most common and effective cooling, thermo-regulating strategies in the extreme environments that are accomplished through the morphological features. Two comparative studies were conducted for four organisms under two cooling mechanisms that are cooling through (1) respiratory passages and (2) organisms' appendages. The third study reviewed four of the well-known hypotheses on

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interpreting the thermoregulation and ventilation mechanism in the termite mound. After that, the study extracted the key working principles of each mechanism from the perspective of (1) morphological features and (2) heat transfer methods.

Nasal heat exchange: Cooling through respiratory passages:

Evaporative cooling is the most cooling mechanism used by flora and fauna. It is more effective mechanism where air is hot and dry or unsaturated. This kind of environment creates an adequate difference in water vapor's concentration between ambient temperatures and wet surface. It takes different forms but all of them aim to dissipate overheating or hyperthermia in organisms' body through vapor cooling. It occurs through diffusion in the available surface for evaporation [35]. When water evaporates, the surface become cold. Accordingly, it cools the existing vascular net under skin which cools the rest of the body and brain due to blood circulation.

The main element of evaporative heat loss is water which has exceptional physical properties. It has high specific heat capacity means that it needs large amounts of heat energy, 4200 J/(kg °C), before changing the temperature of 1 kg of water by 1°C [36]. Therefore, when this strategy occurs in organism, water either in a form of sweat, mucus, or saliva absorbs great deal of ambient temperature heat to evaporate water causing cooling for the wetted area. Additionally, water has the property of conductivity transfer heat more easily than other liquid apart from mercury. To find out the specific heat capacity, this equation can be used

$$E = m \times c \times \theta \quad (4)$$

Where E is the energy transferred in joules, m is the mass of the substances in kg, c is the specific heat capacity in J / kg °C, and θ is the difference in temperatures in °C.

There are two types of evaporative cooling, (1) the active means which are the behavioral cooling like dipping and (2) the passive means that are physiological cooling such as sweating and the physio-morphological cooling e.g. the evaporative cooling by nasal turbinates. The case studies of cooling through respiratory passages are camel, reindeer, muskoxen, and giraffe. What connect them is the ability of regulating their brain temperature within a fluctuating environment. These mammals (artiodactyl) live in extreme environment and face big ranges of temperature changes either during the day or throughout the year [37], [38], [39]. However, in these environments, the temperature fluctuation is lethal for animals' brain which is only working within specific ranges 37°C-38°C [40]. Selective brain cooling is the mechanism used by these animals to cope with heat stress and keep brain's temperature within the safe range [41], [42].

The cooling process takes place in nasal cavity which contains turbinate covered by mucous membrane where there is a mesh of nasal veins [43]. As seen in Table-1, the four mammals have a common spiral-like nasal turbinate structure for thermoregulation. The spiral structure is simple in the animals living in a more moderate environment like a giraffe and it is more complicated for animals living in the extreme environment like reindeer and muskoxen. Hillenius [44], [45] suggested that complex structure of nasal turbinal is an attribute of mammalian respiratory functioning to decrease metabolic water and heat loss accompanying with the high ventilation rate. The spiral form compresses a structure of a large surface area within a small volume [46]. The large surface area of nasal mucosa and concha are responsible for directing, humidifying, thermo-regulating and filtering inhaled air [47], [48]. Nasal turbinates are elongated narrow bony structure and projected downwards. They have convoluted structures of thin cartilage and covered with a ciliated mucous membrane. The cartilage turbinates are padded by thin, highly vascularized mucosal lining [49] stretching along nasal cavity [50]. The turbinates take a streamlined form which has a lower resistance to air and makes it move smoothly without creating turbulent currents. The drag coefficient of streamlined body is 0.04 which is the lowest value among all forms. This form is like the body form of an aircraft, Shinkansen bullet train, which inspired from streamlined form in nature.

Selective brain cooling begins when an organism inhales air which passes through the wet surface of the turbinates making mucus evaporates. This cools turbinates surface which in turn cool the nasal veins in the mucosal lining. The effective heat and water exchange in nasal depends on the small transverse like the gap between turbinates and the large axial dimensions of the airways [51], [52]. It is found that the difference in temperature between blood in vessels and the mucosal lining is negligible and this indicates a high heat transfer between them through conduction [46]. Then, the cold blood moves through nasal and angular veins to the cavernous sinus located under the brain. The cavernous sinus works as a pond of a cool venous blood where it meets the warm arterial blood destined to the brain. The arteries split into a tiny network to reach "up to hundreds of small arteries, composing the rete mirabilia, which maximizes the heat exchange" through conduction [14; p.692]. By this mechanism, the arterial blood is pre-cooled before entering a brain. In hot seasons or when an animal is doing exercises, there is an active adaptation that increases cooling blood and its circulation rate. It is through the increment of the respiratory frequency rate that is the rate of breaths per minute [38], [53], [54], [55].

In extreme cold environment, this mechanism is used to recover heat and water lost through respiratory process by utilizing counter-current heat exchange in the nasal turbinates [56], [46]. So, when an animal inhales the cold dry air, the air become more humidified and warm by evaporation of turbinates mucous on nasal leaving them cold. However, when an animal exhales, the hot saturated air passes through these cold mucosal surfaces of turbinates recovering both heat and water before it is exhaled at a low temperature [57]. This strategy works in a better way when there is a need for heat conservation due to counter-current heat exchange for retia blood which

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guarantee a better chance of heat and water exchange in exhalation [50], [58], [59]. This strategy is similar to that one used in cooling towers where the vapor water is recovered by the special morphology of the drift eliminator in addition to being cooler than the water vapor.

Working principles of evaporative and conductive cooling in selective brain cooling strategy

The comparative study in Table-1 shows some mutual features used to regulate the brain temperature for the four selected organisms. These principles are responsible for thermoregulating the respiratory air and cooling brain temperature in extreme and during exercises. The working principles for the evaporative and conductive cooling strategy through respiratory passages are as follows:

- The respiratory passages constantly covered by mucus layers as wet surface.
- The respiratory passages are continuously exposed to the (exhale and inhale) air flow which enhances the process of evaporative cooling
- The more the contact surface area between the air and mucus layer, the more the heat and water exchange and recovery.
- The scroll-form of turbinate compresses a big surface area within smart, small frame and this structure is only found in these animals living in extreme environment either very cold or very hot for heat and water recovering.
- The complicated form of scroll-type turbinate structure slightly reduces air velocity.
- The peak efficiency of heat and water recovery by turbinates occur in the extreme weather, either cold or hot.
- The increase in air flow means increase in evaporation rate and as a result a better chance of both cooling and thermoregulation.
- Active adaptation such as panting is an assistant way to enhance force convection for cooling purposes.
- The thermal characteristics of the turbinate structural layers are featured by high conductivity.
- Heat transfers through evaporation, conduction, and convection.
- Vasodilation of vessels in mucosal lining is for heat loss and vasoconstriction and counter-current is for heat conservation.
- Splitting arteries into tiny networks significantly increases the contact surface area for heat exchange through conduction.

The derived principles from the cooling strategy in nasal might be helpful for developing designs which stands on evaporative (1) air cooling and (2) circulating fluid in power stations and factories. Examples of that, evaporative air conditioning system [60], [61]; gas turbinate pre-cooling [62]; poultry and livestock cooling or farm buildings [63]; preserving plant products [64]; greenhouse cooling [65], [66] and precooling of inlet air for dry coolers [67].

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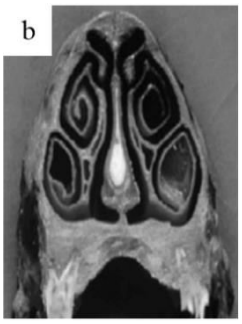
Table. Comparative study for the thermo-regulatory strategies by the respiratory passages in four organisms

Nasal cross-section	a  **Retrieved from Badawy and Elmadawy [52]**	b  **Retrieved from Casado Barroso [49]**	c  **Retrieved from Blix [68]**	d  **Retrieved from Langman [69]**
Thermal regulators	Camel nasal	Reindeer nasal	Muskoxen nasal	Giraffe
Environment	Desert	Arctic		Semi-arid savannah
heat loss in extreme through respiration	60 cal. h-1. Kg-l [53]	45% of the heat production [38]	Not studied yet (NS)	NS
Heat recovery in extreme	Only 6 cal. h-1. Kg-l is dissipated [53]	75% of exhaled air [73]	Assumed by [74], [75]	8% of the metabolic heat production [69]
Water recovery	70% [71] [70]	80% [73]	NS	58% [69]
Influential structural factors in nasal turbinates (passive adaptation)				
surface area	1000cm^2 [70]	772 cm^2 [49]	5363 cm^2 [49]	7500 cm^2 [77]
Midst air gap	1-2 mm [70]	1-3 mm [49]	Varies based on depth [49]	4mm [69]
Shape	scroll	scroll	scroll	scroll
Well vascularized mucus	yes	yes	yes	yes
watery lining (mucus)	yes	yes	yes	yes
(active adaptation)				
respiratory frequency breaths per minute	From 3 to 60 [53]	Up to 270 [42] [38]	reported [55]	From 6.5 to 13.4 [69]
Effecting environmental factor				
Air temperature	yes	yes	yes	yes
Air humidity H	yes	yes	yes	yes
Temperature (T)				
Ambient temperature	below freezing to 55 °C [43]	annual changes up to 80°C [38]		8.9-32.2°C [78]
Organism range T	35 °C - 41°C [72]	38.4-40.4 °C [76]	37.7–41.3°C[74]	37.3°C [69] 35.7-39.1 [77]
Vasodilation/ heat loss	33 < Ta < 45 °C [43]	During exercises [50]	NS	NS
Active adaptation	38°C < Ta [40]	35°C <Ta [56]	Reported in [55]	36 < Tb [77]

Radiative cooling: Thermal radiators

In nature, the different heat transfer modes, radiation, convection, conduction, and evaporation take mostly place at surface. This explains the large additional areas in some animals' appendages which are important for the balance of their bodies' temperature. In biology, these vasomotor appendages called thermal radiators, heat sink or thermal windows. Thermal radiator is a hot body which emits electromagnetic radiations to the cooler surrounding. In some areas in organism's body which are bare and has no cover fur, they work as thermal window. By using infrared camera, researchers discovered that animal emit heat when it is hotter than environment [79]. It is a way of heat exchange to regulate body temperature through balancing metabolic heat production. It is also an adjustment to control blood flow to the appendage by either vasodilation or vasoconstriction. Examples of the thermal radiators in nature are jackrabbit ears [80], elephant pinna [81], toucan bill [82], hornbill's bill [83], rat tail [84], goats horn [85], fiddler crabs claw, hot spots

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and radiators in animals like bat's wings [86] and seal's skin. This study covered four of the biggest radiators in nature that are jackrabbit ears, elephant pinna, toucan bill, and the average size radiator of hornbill's bill which called in this study appendages. The selection criteria of these cases is based on their efficiency of thermoregulating body temperature by either radiating excess heat or conserving body heat.

Jackrabbits live in a desert and elephants live in savanna where the temperature is greatly varied between summer and winter, daytime and night. It ranges from 50°C to below freezing [87], [88]. Additionally, in such hot arid climates, water is scarce and heat loss is achieved through none-evaporative mechanisms [83].To cope with these harsh environmental circumstances, these organisms lose excess heat gained either from metabolic energy through their big appendages like ears in jackrabbits and pinna in elephants [89],[81]. These appendages represent big part of the body surface area to reach up to 25% in jackrabbit [80] and up to 20% in elephant [87]. The large surface area to volume ratio of the jackrabbit ear and elephant pinna are loaded with an intensive network of vessels [90] which has tree-like morphological structure. Tree structure is the "principle of global maximization of performance in volume-to-point (or point-to- volume) flow" where it solves "the problem of minimizing the thermal resistance between an entire heat generation volume and one point" [91; p.4]. The fractal form of the branches growth maximizes the heat loss from one point to a large surface area which takes the full advantage of heat exchange. These appendages have thin, uninsulated skin like a membrane working as a thermal window. During doing activities, body temperature becomes hotter than air temperature, therefore, blood vessels expand and blood flows to fill veins, arteries, and small capillaries in the ear/pinna. This increases the contact surface of vessels with the air and guarantees a better chance of heat exchange and blood cooling through heat dissipation.

However, in birds, the differences in peak size is an adjustment to the environment temperature and humidity which is considered as a key adaptive appendage for body thermoregulation [92], [93], [94], [95]. It is also proposed that the variety in birds' beak size is an adjustment to water vapour pressure or humidity gradients [92]. Since toucans and hornbills live in a habitat where temperature and humidity are remarkably high and evaporative heat loss seems ineffective, the non-evaporative cooling mechanism is essential for surviving [83]. The uninsulated peaks of toucans and hornbills are responsible for balancing the high metabolic heat produced when feeding and flying. The well-vascularized, superficial vessels [96], [82], [83], [97] which intensively spread within the dermis of the peak is responsible for controlling body temperature achieved through modifying blood flow either through vasodilation to dissipate heat or by vasoconstriction to conserve it.

The mentioned appendages lose heat through radiation by exposing the vessels' surfaces to the surrounding air and through convection by increasing air flow through flapping [87], [81].These appendages not only dissipate heat but also conserve body heat at low ambient temperature and keep core body temperature constant by means of vasoconstriction and counter-current blood flow for heat exchange [98], [99], [87], [82].

Working principles of radiative cooling through organisms' appendages

The comparative study in Table 1 inferred some common features used to regulate the temperature of the four organisms and keep it constant despite the considerable difference in the temperature of their environment between cold and hot times:

- The more the exposed surface area of the organ, the more the heat loss where $H_{loss} \propto A$.
- Peak heat loss occurs when organ temperature is around 10°C more than the ambient temperature.
- Uninsulated, superficial and well-supplied parts are crucial factors to maximize heat loss.
- The morphological features of vessels aretree-like and branching which increase the exposed surface area for heat exchange.
- Wind is helpful to enhance convective heat loss; however, temperature gradient is the indispensable factor for achieving heat transfer.
- Active adaptation such as flapping and panting is an assistant way to enhance force convection for cooling purposes.
- Heat transfers through organisms' thermal radiators by radiation and convection.
- Organisms use vasodilation for heat loss and vasoconstriction for heat retention.
- Appendages are used both to dissipate heat and gain heat by exposing their surfaces as well as vessels to the direct sun radiation.

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Table-1. A Comparative study of the thermal window in four organisms.

Thermal radiators in the organisms	**Jackrabbit ears (1)**	**Elephant pinna (2)**	**Toucan bill (3)**	**Hornbill beak (4)**	**Notes**
Efficiency of excess heat loss	16 - 66 % and up to 161% of metabolic heat production [80]	Up to 100% of metabolic heat [87]	30 - 60% and up to 400% of resting heat production [82]	Up to 19.9% of heat loss [83]	Heat loss varies depending on time, region, temperature...etc.
Peak heat loss when T_b higher than T_a by	7°C -11.5°C	~ 16°C	Not stated	Ta within ~10°C below T_b [83]	T_b body temp. $T_{a\ ambient}$ temp.
Efficiency of heat gain	47-57% [80]	Not stated	Not stated	Not stated	When heat is needed
Effecting physical factors of appendage (passive adaptation)					
Large surface to volume ratio	19- 25 % of body surface [80]	20% of the body surface [87]	30 to 50% of body surface [82]	4.7%of body surface [83]	More exposed surface, more heat exchange
Shape	flat surface [100]	flat surface [102]	Big beak-like [105]	Big beak-like [83]	Enhance convection
Superficial and well vascularized (thin wall)	Yes	Yes	Yes	Yes	More vessels mean more heat loss
Vessels morphology	Branching	Branching	Branching	Branching & sensory	Such morphologies enhance heat loss
Weight	Yes	Yes	Not stated	Not stated	Weight affects heat production
Uninsulated appendage	Yes	Yes	Yes	Yes	Enhance convection
(active adaptation)					
Active adaptation	Flapping and panting	pinna flapping	Panting	panting	Enhance forced convection
Effecting environmental factor					
Air temperature	Yes	Yes	Yes	Yes	Enhance heat exchange
Wind speed	Yes	Yes	Yes	Yes	Enhance convection
Temperature (T)					
Ambient temperature	3°C to 50°C [101]	8 °C- 40 °C [103]	10 °C to 35°C [82]	15°C to 45°C [83]	Highly varied
Organism average T	37 °C - 40.5°C [89]	36.2 ± 0.49 °C [103]	~38° to 39°C [82]	~37° to 39°C	Almost constant
Period of Vasodilation for heat loss	24 < Ta < 40 °C [80]	15°C to 20 ≤ Ta [81]	16 < Ta < 25°C [82]	30.7 ≤Ta < 41.4°C [83]	Heat dissipation
Period of vasoconstriction	1.4°C<Ta < 24 °C 40 °C< Ta [80]	Ta ≤ 9 °C [81]	Ta < 16 °C [82]	15 °C ≥Ta < 30 °C [83]	Heat retention
Active adaptation	Ta ~38.7°C - 45.5°C [80]	21 < Ta [104]	18°C < Ta [82]	Ta = 37.4 ± 2.1°C [83]	Forced convection

As the purpose of this study is to emulate nature solutions, therefore, for dispelling heat from buildings, large additional areas specialized for this aim are required to achieve this goal such as chimney. These extra surface areas could be useful in cold times of the year to warm indoor air. These principles are helpful in developing the existed design of passive cooling architectural elements which is based on dissipating the excess heat through natural ventilation such as solar chimney, thermal chimney, and solar updraft tower. The similarity between solar or thermal chimney (Buoyancy driven natural ventilation; stack ventilation) and thermal radiators in nature is that their main function is dissipating heat. Their performance strategies depend mainly on the temperature differences between the inside and outside.

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Air cooling in termite mound by convection: Buoyancy

Termite mound architecture has been recommended by scientists to be a good bio-model for inspiring passive cooling mechanism for building [106], [107], [108], [109]. Architects can emulate the structural and technical system of the mound to sustainably control the thermal conditions in building within the thermal comfort range for human. What attracts scientists to study mound architecture is the constant temperature of 31°C, high humidity and the low CO2 concentrations in the nest; although, the environment temperature fluctuated largely up to 39°C between day and night [9], [110], [111]. To meet these requirements and keep the cultivated fungus and central nursery in a specific living condition, termites built uninhabited massive structure with a special design. Termite mounds consist of central shaft and many of peripheral air passages and porous surface. It can reach up to eight meters in height and they vary in shape which determined by the environment, the species and their function [112]. Termite mound in nature can range in form from plate-like elongated mounds, flat hillocks, cathedral mounds and dome-shaped mounds. Most of studies concentrated on the ventilation mechanisms in the cathedral-shaped termite mound [113], [114], [112]. The architecture of each kind differs from the others in the degree of walls' porosity, thickness, surface design and mound internal structure; some with open mound, others with closed mound. Site location and orientation are important factors considered by termites when building their mound.

Some of the well-known hypotheses on the thermoregulation and ventilation mechanism used in termite mound are the ones proposed by Lüscher [111], Korb & Linsenmair [114], Turner and Soar [109] and King *et al.* [106].

Martin Lüscher [111] is the first scientist to highlight the thermoregulatory functional role of the termite mound where the nest temperature is 30 °C and fluctuating throughout the day less than 3°C and annually only 1°C. He proposed an assumption on the thermoregulatory mechanism used on the mound that is the thermosiphon theory. According to Lüscher, there are two million termite inhabiting mound weighted 20 kg which need a significant amount of air to exchange gases. In closed mound, which has no clear outlets but porous surface, he suggested that due to the high metabolic rate produced by colony, which is approximately 100 watts, warm airrises through central shift driven by buoyant forces then it directed down to air channels inside the ridges where the respiratory gases, heat, and water vapor exchange. Due to the thermosiphon effect, the cooler air with high density is absorbed and forced downward to the mound providing nest with a fresh air. However, a better ventilation system is taking place in open-chimney mound which is generally characterized by growing vertically up creating an efficient structure for air flow circulation. The chance of a well ventilation is in the upper, large vent in the mound (chimney) where the exposure to wind velocity is higher than those openings in lower level. Due to this, air moves rapidly in the upper chimney outlet withdrawing the nest air to outside the mound through a Venturi effect, consequently, fresh air is drawn into the mound through the lower vents.

This mechanism was the core notion for the design of Harare's Eastgate Centre in Zimbabwe which save a considerable percent of the energy required for air conditioning. Turner and Soar [109] refer the success of the building design to the smart integration of some thermo-control mechanisms in different kinds of mounds within one effective functional building.

However, Korb and Linsenmair [114] contradict Lüscher hypothesis by measuring the temperature, CO2 concentrations, and air currents in and around two kinds of Macrotermes bellicosus mounds. They assumed that when the sun heats the thin walls of the ridges in the cathedral-shaped located in the savanna, the air in channels heat up causing a temperature gradient which increases the opportunity of gases exchanges with air by diffusion through the thin wall of ridges. Due to the stack effect, convective flows rise from peripheral air channels to the top of the mound passing through the central shaft and down to the nest. This mechanism is dubbed externally driven ventilation because temperature gradient is caused by ambient temperature. In agreement with Lurcher's thermosiphon hypothesis, internally driven ventilation in forest mound is induced by temperature gradients produced by the fungus and termite metabolism. However, the hypothesis of metabolic driven ventilation was invalidated by King *et al.* [106] who proven that there are same temperature gradients and flow pattern in both dead and alive one in daytime.

The authors refer the superiority of externally driven ventilation over internal one to three factors: (1) the higher temperature gradient caused higher diffusion rate, (2) the more exposed surface area, the more the gas exchange, (3) the more the air currents circulate, the higher efficiency is the ventilation. Many thin-walled ridges of cathedral-shaped mounds in savanna give a considerable surface for gases and heat exchange. Contrary to thick-walled, capped-shaped mounds in forests, the small surface limits the dissipation of heat from mound to the cold environment.

Wind induced ventilation is a new theory suggested by Turner & Soar [109] on how the termite mound thermoregulates the internal air. They proposed that the structure of termite mound resembles lungs of human where mound resembles bronchi and nest resembles alveoli. These structural similarities indicate functional similarities where the air in alveolar and bronchi are poorly mixed like the air in the mound and the nest. The air exchange in bronchi branches and trachea is through forced air convection and in alveolar is through diffusion. However, the connection area between them, bronchi and bronchioles, works as a general regulator lung function. Similarly, through the structure of termite mound, the nest is relatively insulated from the mound, accordingly nest air is isolated from that in the mound. They suggested that the air movement in the mound is driven by wind. The air exchange between mound and nest occur in-between area through two ways. When the mound

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is cooler than nest, it occurs through "the frequent stable thermal stratification" and in the rest cases, air exchange happens through very small channels [109; p. 240]. Nevertheless, this theory was invalidated by King et al. [106] who applied pulsing wind from a fan to the termite mound and he proven that the flow speeds inside the mound is not induced.

The theory of ambient heat induced ventilation in termite mound suggested by Korb & Linsenmair [109] was agreed by King *et al.* [106]. However, they proposed that CO_2 is accumulating down in the mound and flushed out when the difference between temperature in flutes and the center is high (11 p.m. -12 a.m.). They stated that through a simple geometry, inhomogeneous thermal mass, and porosity, termite mound in forest uses the fluctuating day temperature for ventilation. The mound geometry consists of flutes and buttress like structures which distribute radially from a large central chimney. The chimney from the base, the subterranean nest, is peripherally connected to many of air channels inside flutes oriented upward which is gathered in the top to open again in the chimney. Such connective circulation lets the convective air flow from flutes to chimney at day and vice versa at night in a closed-loop convection circuit. The walls made of clay soil with high porosity 37-47% and the clay is a composition of small pore diameter granules. This make it resistant "to pressure-driven bulk flow across its thickness"; however, the high porosity of the walls helps highly in gases exchange through diffusion [106; p. 11589].

Working principles of convective cooling in the termite mound

- The mound architecture consists of central chimney and sided-channels which are linked to each other enhancing air circulation.
- The thinner the exterior walls, the higher the temperature gradient between air in chimney and channels. This results to higher diffusion rate and better air flow by stack effect meaning that temperature ingredient is the main driving force for air circulation in the mound
- When the difference between temperature in flutes and the center is high, flushes of CO_2 occurs.
- The larger the surface area, the more exchange for gases.
- The inhomogeneous thermal mass, wall porosity, orientation and location are key properties to keep mound in a constant temperature.
- The cathedral-shaped mound and its surface design can control the internal environment e.g., the shape and thin design of ridges can be easily heated up by sun making air less dense and this improves air circulation.

CONCLUSIONS

In this study, three of the most effective thermo regulating strategies in nature namely in extreme environments were analyzed from the perspective of heat transfer modes. The comparison studies resulted in abstracting the working principles for each cooling strategy which are based on the morphological features of the structure achieving the cooling function. The abstracted principles were summarized and interpreted through a simplified technical analysis to pave the way for engineers and architects to emulate them to practical designs. They can be used as a simple guide to design eco-friendly passive cooling design either for energy-efficient buildings or for technical cooling for bionic engineering and industrial machines. These cooling mechanisms can also be emulated to cool the circulating fluid in thermal power stations, oil refineries, petrochemical and other chemical plants. Emulating nature cooling techniques may contribute to decreasing the energy consumption of cooling systems which recently become a critical issue because of the high cost of fossil fuels and their catastrophic impacts on the environment.

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