

BIOMIMETICS FOR PASSIVE AIR CONDITIONED DESIGN FOR BUILDINGS
IN THE HOT ARID REGIONS

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“My dearest mum, dad, husband, sister Enas and family”
This is a result of your constant support

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ABSTRACT

The high energy consumption for air conditioning in buildings is a serious concern due to its consequences on the earth's ecological life. In nature, animals regulate their body temperature in extreme environments without prejudice to the environmental system. Therefore, this study aims to design a passive cooling unit for buildings in the hot arid regions by emulating biological cooling strategies in nature. It adopted a biomimetic exploratory method to determine three of the efficient biological cooling strategies in nature based on the morphological attributes. These are; cooling through animals' respiratory passages, thermal radiators and airflow cooling in termite mound. A comparative study was conducted on four case studies under each of the three cooling strategies to come up with the working principles that can be used as a guide to design a biomimetic cooling system. One of these strategies, the camel nasal respiratory cooling was simulated to design a cooling unit installed in wind towers for buildings. To validate the applicability of the camel nasal-inspired cooling design, experimental tests have been conducted in both wind tower and wind tunnel in a desert city, Seiyun in Yemen. The study main parameter was the design cooling efficiency for (i) three materials: clay, clay with jute fiber, and clay with wood wool pads, (ii) design height, and (iii) climatic environmental variables. The results showed that the best cooling efficiency among the three materials was the design of clay with jute fiber 85.2 %, followed by clay with wood wool pads 76.6 %, and clay 66.3 %. The former two designs have effectively dropped the temperature in hot arid climate up to 18.9 °C for jute design and 16.5 °C for wood wool design. This indicates that the bio-inspired design can replace the mechanical air conditioning system. Additionally, the cooling efficiency of the design increases by the increment of its height and the ambient temperature. However, it decreases with the increment of the inlet air wet-bulb temperature, air humidity, and air velocity. Thus, it can be concluded that emulating biological thermo-regulatory strategies is useful for the design of energy-efficient cooling systems. This study contributes to possible passive cooling design for buildings in the hot arid regions.

ABSTRAK

Penggunaan tenaga yang tinggi oleh penghawa dingin di sektor bangunan menjadi perhatian serius disebabkan oleh kesan-kesan negatif kepada hayat ekologi bumi. Secara semula jadi, haiwan mengawal suhu badan mereka dalam persekitaran suhu yang melampau tanpa menjejaskan sistem alam sekitar. Oleh itu, kajian ini bertujuan untuk mereka bentuk unit penyejukan pasif bagi bangunan di kawasan panas dan kering dengan meniru strategi penyejukan biologi dalam alam semula jadi. Ia menggunakan kaedah penerokaan biomimetik untuk menentukan tiga strategi penyejukan biologi semula jadi yang efisien berdasarkan sifat-sifat morfologi, iaitu penyejukan melalui laluan pernafasan haiwan, radiator terma dan penyejukan aliran udara di dalam busut anai-anai. Kajian komparatif dijalankan keatas empat kajian kes berdasarkan tiga strategi penyejukan tersebut untuk menghasilkan prinsip kerja yang boleh digunakan sebagai panduan untuk mereka bentuk sistem penyejukan biomimetik. Salah satu daripada strategi ini, penyejukan berasaskan pernafasan unta disimulasi untuk mereka bentuk unit penyejukan yang dipasang di menara angin dalam bangunan. Untuk mengesahkan kebolehgunaan reka bentuk penyejukan berasaskan pernafasan unta, ujian eksperimen telah dijalankan di kedua-dua menara angin dan terowong angin di bandar padang pasir, Seiyun di Yaman. Parameter kajian yang utama ialah kecekapan reka bentuk penyejukan berdasarkan kepada (i) tiga bahan iaitu tanah liat, kombinasi tanah liat dengan serat jut dan kombinasi tanah liat dengan pad aspen, (ii) ketinggian reka bentuk dan (iii) pembolehubah iklim persekitaran. Keputusan menunjukkan bahawa kecekapan penyejukan yang terbaik di antara ketiga-tiga bahan adalah reka bentuk tanah liat dengan serat jut iaitu 85.2 % diikuti dengan tanah liat dengan aspen 76.6 % dan tanah liat 66.3 %. Dua reka bentuk tersebut telah menurunkan suhu dalam iklim gurun sehingga 18.9 °C untuk reka bentuk tanah liat dengan serat jut dan 16.5 °C untuk reka bentuk dengan aspen. Ini menunjukkan bahawa reka bentuk inspirasi-bio boleh menggantikan sistem penghawa dingin mekanikal. Di samping itu, kecekapan reka bentuk penyejukan meningkat seiring dengan kenaikan ketinggian reka bentuk tersebut dan suhu sekitarnya Walau bagaimanapun, ia berkurangan dengan kenaikan suhu udara masuk wet-bulb, kelembapan udara dan halaju udara. Oleh itu, dapat disimpulkan bahawa dengan meniru strategi peraturan-termo biologi, ia adalah berguna untuk mereka bentuk system penyejukan yang cekap tenaga. Kajian ini menyumbang kepada reka bentuk penyejukan pasif untuk bangunan di kawasan yang panas dan kering.

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LIST OF ABBREVIATIONS

HVAC	-	Heating, Ventilating, and Air Conditioning
BWh	-	Hot Arid Desert
NDDCT	-	Natural Draft Dry Cooling Tower
PMV	-	Predicted Mean Vote
PCM	-	Phase Change Material
GHG	-	Greenhouse Gas
UHI	-	Urban Heat Island
SB	-	Stoma Brick
BIMPD	-	Parametric Design of Building Information Modelling
SMIT	-	Sustainably Minded Interactive Technology
AVAs	-	Arteriovenous Anastomoses
DC	-	Direct current
AC	-	Alternative current

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CHAPTER 1

INTRODUCTION

1.1 Introduction

As much as the industrial revolution of the 18th to 19th centuries were beneficial to the humanity development, it constituted a considerable risk for the balance of the ecological life on the earth and that is referred to the extensive use of fossil fuel and forest clearance (Humphrey *et al.*, 2008). People did not consider the warning calls of scholars and scientists regarding this risk until they touched the catastrophic results in the ground such as the increasing rate of global temperature, sea level, pollution, reduction in the biological diversity, resource depletion, violent storms and floods (Wilson, 2002). A number of awareness campaigns were launched in this regard under the name of sustainability and recently, biomimicry science was established to call for similar principles by mimicking nature's solutions. Biomimicry is the new multidisciplinary science, which adopts these sustainable values. It is the science of emulating the genius technology of biology which works "without guzzling fossil fuels, polluting the planet, or mortgaging" the future to solve human problems (Benyus, 1997; p.2).

In the 21st century, architects around the world become more conscious about the dangerous effects of consuming the electric energy on the environmental life. As a consequence, a new trend of sustainable architecture is established to call for sustainable solutions. It is the architecture that could get along with the natural ecosystem and solve man-made problems. Accordingly, Biomimetic architecture starts

to take a significant space in both scientific field and practical life. The biomimetic and sustainable architecture aims to decrease as much as possible the negative effects of the built architecture on the environment regarding energy and material. One of the core motives of these architectural trends is the energy efficiency of buildings.

Energy efficient building is still more confined to the academic field, while the architects around the world rely on the mechanical strategies to air conditioning the indoor spaces such as HVAC (heating, ventilating, and air conditioning) electrical devices. HVAC system is now a dominating technology used in the majority of the world cities' buildings especially offices. Studies showed that a significant part of the total electrical energy is consumed by the apparatuses used for indoor air conditioning purpose. An example of that is Gulf countries which consume 70 percent of the generated electricity for HVAC devices to meet the thermal comfort requirements of occupants (Sala *et al.*, 1999). Thermal comfort is the state of mind which expresses approval with the thermal condition of an architectural space which differs from person to another due to the nature of some factors like physical activity, age, clothing, and health (ASHRAE. 2004).

To deal with the built environment challenges, some architects turn to nature's solutions as a source of efficient structure, zero-waste system, energy saving and thermally control environment (Pawlyn, 2011), Some of the successful sample projects have been narrated by Gruber (2010), Pawlyn (2011) and Loonen (2015). The applications of the biomimetic architecture have proven the validity of emulating nature mechanisms to fulfill the desired purpose from a design and generate sustainable, energy-saving solutions (Lurie-Luke, 2014; Pacheco-Torgal, 2015; Abdullah *et al.*, 2018). In line with the above, this thesis studies the ability of emulating the thermoregulatory biological systems in nature to design passive cooling unit for buildings in the hot arid region.

This chapter, therefore, consists of eleven sections passing by problem statement, research's gap, aim, questions, objectives, methodology, significance of the study, scope, limitations and it finishes with an explanation of thesis structure.

1.2 Problem Statement

The overheating challenge of indoor air in the buildings in the hot arid desert cities such as Seiyun city is intolerable where the indoor air temperature reaches more than 35 °C (Al-Shibami and Ward, 2002). The overheating of the indoor air impacts negatively upon the productivity level of people and their health. To expel the trapped, hot air from the buildings and replace it with a colder air flow, people in the Middle East uses a conventional wind tower as a passive cooling technique. However, wind tower ability to cool indoor air is limited and it cannot meet the occupant thermal comfort standards (Bahadori *et al.*, 2008). A number of studies have improvised the wind tower cooling performance by integrating evaporative cooling design inside a tower such as Bahadori *et al.* (2008), Bahadori (1985), Badran (2003), and Bouchahm *et al.* (2011). However, the proposed heights of these designs are higher than the typical floor height in which the design heights are 8 m, 6-8 m, 4 m, 6.5 m; respectively. For this reason, these designs have not been used yet and applied in the architecture of hot arid regions and people largely depend on the mechanical air conditioning to cool indoor air. Therefore, there is a need to improve the cooling performance of this architectural element to create a passive alternative to the air conditioning systems.

On the other side, the energy used by building sector is responsible for a considerable percentage of GHG emissions in the world (Pérez-Lombard *et al.*, 2008). Due to the elevated air temperature in the desert cities, a considerable amount of energy is consumed to provide thermal comfort for residents. One of the most electricity-consuming countries in the Arabian Peninsula is Saudi Arabia where the electrical loads reached its peak in 31st August to 56500 Megawatt, announced in 2014 by Control Center for Electrical System in Saudi Arabia (Al-Arabiya, 2014). Around 75 % of the residential-electrical energy is consumed for air cooling purposes (Al-Sulaiman and Zubair, 1996). This high percentage seems to be applied by the hot arid cities around the world, for example, the United Arab Emirates (UAE) and Iran use more than 60 percent of the total energy consumption for air conditioning systems (Afshari *et al.*, 2014; Soflaei *et al.*, 2017). Similarly, in Kuwait and the Gulf States, the Heating, Ventilation, and Air Conditioning systems “consume more than 70 % of

the installed capacity of power generating units” (El-Dessouky *et al.*, 2004; p.255). In Australia, the non-residential buildings consume 70 % of the total energy for air conditioning units (Vakiloroaya, 2014). Consequently, buildings are responsible for most of the total consumed energy over than the other sectors such as transportation and industry.

What makes matters worse is the general orientation of constructing buildings with the concrete in many of the desert cities. It is due to the fact that the energy consumption increases highly in the modern architecture in compared to the older traditional buildings. An example of this is the vernacular mud buildings in Seiyun city which consumes only 120 kWh per month, however, new concrete buildings consumed 4312.5 kWh per month (AL-Shibami, 2004). Owing to the global warming, the energy consumption for cooling increases annually in a stronger and noteworthy manner (Hamza, 2008; Al-Shibami, 2004) which in its turn cause the growing problem of GHG Emissions, as seen in Figure 1.1. A report by U.S. Energy Information Administration stated that the total energy consumption of the Middle East has increased from 22.8 quadrillion Btu in 2005 to 31.7 quadrillion Btu in 2012. Consequently, with this average annual percent change that is 2.4 %, it is expected to be 45.4 quadrillion Btu in 2025 with 200 % increment on the energy consumption. As reported by U.S. Energy Information Administration, around 80 % of the energy consumption is generated by burning fossil fuels which are responsible for destroying the ecological and environmental systems of our earth. Therefore, there is a need to design eco-friendly, passive cooling designs to cut down the massive energy consumed for air conditioning systems in desert regions and reduce the negative impact of burning fossil fuel on the environmental and ecological life on the earth.

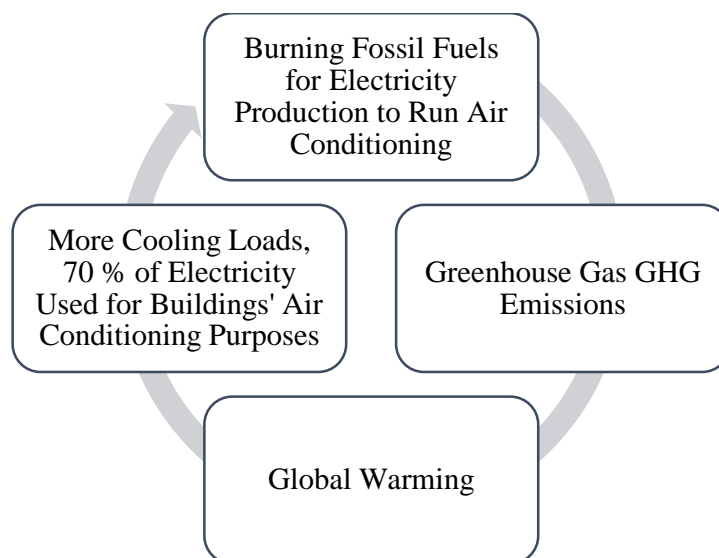


Figure 1.1: The closed loop relationship of mechanical air conditioning systems and global warming

1.3 Research Gap

Numerous studies have been conducted in passive indoor air cooling and the energy consumed for providing comfortable indoor environments. This topic has become the main scope of founding some journals such as journal of *Energy and Buildings* and *ASHRAE Journal*. As shown in Table 1.1, these studies can be classified into three categories, firstly, studies that are dedicated to examine the used cooling techniques in vernacular or traditional architecture and apply them in modern architecture, for example, Nguyen, et. al., (2011); Kimura, (1994); and Maleki, (2011). Secondly, studies that are depending on the latest facilities offered by technology and mechanical engineering to find out novel ways to provide thermal comfort to occupants for example, Zhou, et al., (2007); and Wenxing and Qisen, (2003). Thirdly, studies which have been recently established consider nature as a mentor to find out new inspiring sustainable mechanisms for air conditioning. However, the number of the architectural studies done on the latter is still little.

Despite the fact that analogy from natural systems is one of the effective ways of generating novel and sustainable solution, the research studies in this domain are limited (Chakrabarti, et al., 2005; Wilson, 2008; Pawlyn, 2011; Benyus, 1997). The

interest to emulate the smart mechanisms used in nature to control the thermal environment in buildings is negligible. Even the studies or some of the suggested designs that have been done in this respect are proto-designs and still superficial in handling such problem, an example of that is the proto-architectural unit design by Mazzoleni (2013) for air conditioning. She applies the physiological morphology of the polar bear skin without examining the validity of her suggested solutions.

The studies of Pawlyn (2011), Badarnah (2012) and Mazzoleni (2013) show a general mimicking solution for the different problems facing our built environment as shown in Figure 1.2. Whereby Pawlyn (2011) has generally discussed how nature could be the solutions' sourcebook for problems faced in science of buildings. He addressed different topics such as designing efficient structures, creating zero-waste systems, managing water and sustainably control thermal environment. However, Badarnah (2012) has suggested a systematic methodology for mimicking solutions from nature and addressed four different aspects and their application in suggested designs to verify the validity of her proposed methodology. The topics are natural ventilation, thermal regulation, and water harvesting, daylight control and none of them has been validated.

As for the proposed designs by Mazzoleni (2013), most of them are students' projects for an academic seminar in which the book addressed four topics in architecture and suggested twelve designs inspired from skin compositions and functions in nature. Therefore, it is noticed that the previous studies have addressed different topics in built environment including thermal control (Figure 1.2), but they have not studied them deeply in details. Even what has been inspired from nature in regard of thermal comfort by conditioning air is still negligible in term of the number of inspired cases and the way of handling them. Consequently, this study focuses on the thermoregulation adaptive mechanisms found in nature particularly cooling mechanisms and their application into architecture. Thermoregulation is the process whereby organism keeps its body temperature constant within certain ranges while the temperature in the surrounding environment fluctuates during day and seasons (Datta, 2002).

Table 1.1: The passive cooling studies showing the research gap in the literature

Cooling	Cooling technique	Author, year
Passive cooling in vernacular architecture	Wind tower	Mohamadabadi <i>et al.</i> (2018); Jomehzadeh <i>et al.</i> (2017); Al-Sallal (2017); Fathy (1986); Bahadori <i>et al.</i> (2014); Ameer <i>et al.</i> (2016); Hedaya <i>et al.</i> (2015)
	Wind tower with underground channel	Sadeghi & Kalantar (2018); (2016); Jafarian <i>et al.</i> (2010)
	Evaporative cooling integrated with wind tower	Badran (2003); Bahadori <i>et al.</i> (2008); Bouchahm <i>et al.</i> (2011); Ahmadikia <i>et al.</i> (2012); Saffari & Hosseinnia (2009)
	Cross ventilation	Michael <i>et al.</i> (2017); Toe <i>et al.</i> (2015); Aflaki <i>et al.</i> (2015); Fathy (1986)
	Solar control/ shading devices	Philokyprou <i>et al.</i> (2017); Kirimtat <i>et al.</i> (2016); Gil Crespo <i>et al.</i> (2015); Weber & Yannas (2013); Santamouris & Asimakopoulos (1996)
	Vaulted ceilings	Zhai & Previtali (2010); Saljoughinejad & Sharifabad (2015)
	Building shape	Givoni (1994); Wilson & Kiel (1985)
	Courtyards	Zakaria <i>et al.</i> (2018); Foruzanmehr (2015); Al-Mumin (2001); Safarzadeh & Bahadori (2005); Soflaei <i>et al.</i> (2016); Gamage <i>et al.</i> (2017); Zamani <i>et al.</i> (2018);
	Thick walls	Desogus <i>et al.</i> (2016); Kinnane <i>et al.</i> (2014); Damluji (1992)
	Wood Mushrabiya	Fathy (1986); Alrashed <i>et al.</i> (2017); Ashour (2018)
Clustering the buildings	Al-Sallal (2016); Damluji (1992)	
Mechanical and technological passive cooling systems	Evaporative cooler	Rafique <i>et al.</i> (2015); Cuce & Riffat (2016). Daou <i>et al.</i> (2006); Heidarinejad <i>et al.</i> (2009)
	Passive Down-draught Evaporative Cooling	Kang & Strand (2016); Aparicio-Ruiz <i>et al.</i> (2018); Chiesa (2017); Cuce & Riffat (2016).
	Solar chimney	Kasaeian <i>et al.</i> (2017); Khanal & Lei (2011); Jing <i>et al.</i> (2015); Imran <i>et al.</i> (2015); Khedari <i>et al.</i> (2000); Tan & Wong (2012);
	Phase change material	Sabbah <i>et al.</i> (2008); Waqas & Din (2013); Akeiber <i>et al.</i> (2016); Rao <i>et al.</i> (2016), Lee <i>et al.</i> (2015)
	Earth to air heat exchangers	Pfafferott (2003); Uddin <i>et al.</i> (2016); Ascione <i>et al.</i> (2016); Khabbaz <i>et al.</i> (2016); Misra <i>et al.</i> (2015)
	Trombe wall	Yedder & Bilgen (1991); Jaber & Ajib (2011); Chel <i>et al.</i> (2018); Koyunbaba & Yilmaz (2012)
Green facade	Pérez <i>et al.</i> (2017); Magliocco & Perini (2015); Manso & Castro-Gomes (2015); Pérez <i>et al.</i> (2011)a and b, Köhler (2008); Van Renterghem & Botteldooren (2009)	
Passive cooling in biomimetics	Bio-inspired material	Rotzetter <i>et al.</i> (2012); Craig <i>et al.</i> (2008); Han <i>et al.</i> (2015); Lienhard <i>et al.</i> (2011); Sung (2012); Hatton <i>et al.</i> (2013); Bengisu & Ferrara (2018).
	Bio-inspired design	Sekkei (2013); Šuklje <i>et al.</i> (2013); Yamanashi <i>et al.</i> , 2011; Abdullah <i>et al.</i> (2018)

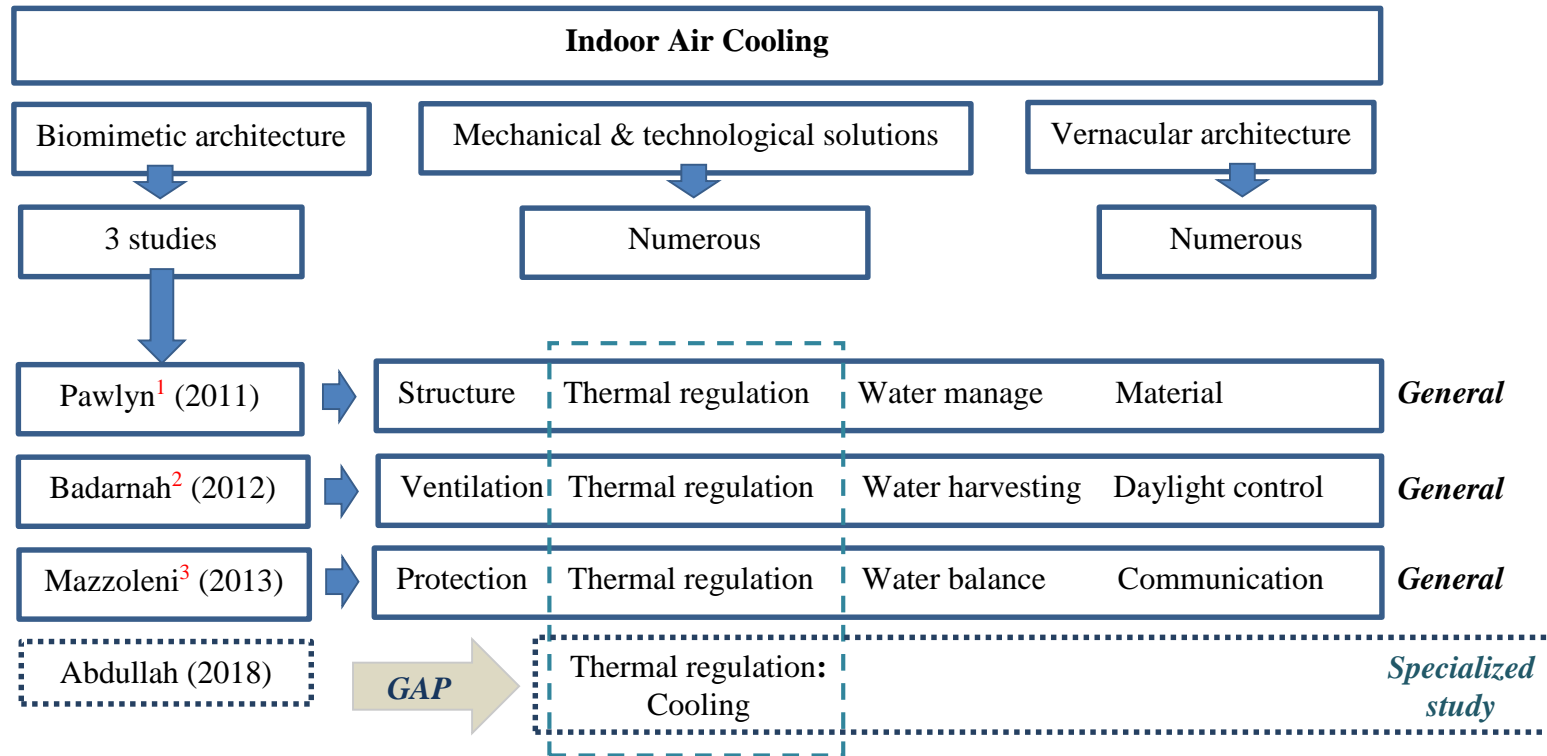


Figure 1.2: Research Gap

- 1- Book giving general examples of projects to publicize the notion of biomimetic architecture.
- 2- PhD thesis studied generally the four aspects mentioned above for verifying the validity of the biomimetic method suggested by the author.
- 3- Book suggested 12 architectural envelope designs for different functions by applying some characteristics of animal skins.

1.4 Research Aim

This study aims to innovate a passive cooling design for buildings in the hot and arid regions inspired from nature. In biology, a lot of research efforts have been dedicated to find out the mechanisms and principles organisms in nature use to thermoregulate their bodies and architecture for example, Schmidt-Nielsen, *et al.* (1971); Wathen *et al.* (1971); Heinrich and Esch (1994); Korb and Linsenmair (2000); Cain *et al.* (2006); Jones and Oldroyd (2006); and Tattersall *et al.* (2006). Their thermoregulation adaptations with the changing environmental variables are characterized by utilizing natural means with a minimal use of energy and local materials. Therefore, this investigation emulates some of the creatures' cooling mechanisms and use their working principles to generate sustainable solutions for a passive design for indoor air cooling.

1.5 Research Main Question

How to design passive cooling unit for buildings in the hot arid regions by emulating thermoregulatory strategies in nature which face the same challenges of thermal-fluctuations?

1.6 Research Objectives

The following objectives were set out to accomplish the research aim

1. To investigate the morphological thermoregulation adaptive mechanisms in organisms or their built architecture in the hot arid region;
2. To extract the working principles of the cooling mechanisms in organisms or their built architecture;
3. To mimic and apply the working principles of the cooling mechanism to a passive eco-friendly cooling design; and

4. To validate the cooling performance of the bio-inspired design for buildings in the hot and arid region.

1.7 Research Sub-questions

To answer the main question of this study, the subsequent questions were raised:

1. What are the morphological, thermoregulation or cooling mechanisms used by organisms to cope with the thermally-fluctuating climate in the hot arid region?
2. What are the working principles of these morphological cooling mechanisms?
3. How can the bio-inspired principles be efficiently applied into architecture?
4. How to evaluate the validity of the proposed design?

1.8 Research Methodology

To achieve the research objectives which were set out as a response to the research problem, the implementing methods and their processes were set out. Due to the need to inspire sustainable designs for passive indoor air cooling, architects tend to look for new source of inspiration for an efficient solution. Nature is the ultimate source of inspiration which need to be studied to come up with these smart, zero-energy solutions. This study required a comprehensive review in both biology and ecology in order to find out the cooling mechanisms in nature based on the morphological adaptation. The data were collected from the biological accessible journal articles, books, scientific films, and the other reliable internet sources such as the online library of AskNature by Biomimicry Institute which facilitates finding clue ideas for solutions of various design challenges. Research methodology has involved three phases of study that are exploration, selection and analysis, and finally embodiment and validity evaluation.

Firstly, the exploration phase included review in the literature for the cooling strategies in nature. A set of data was gathered on the different mechanisms organisms

used to regulate their body temperature and their built nest for survival purposes. Through reading, it is noticed that a number of organisms in nature share some mechanisms for regulating their body temperature such as using vasoconstriction and vasodilation by human and other mammals to regulate their body temperature.

Secondly, selection and analysis phase has involved a classification for some of these mechanisms into three patterns. Then, it is followed by a comparative study for four selected case studies under each pattern. The comparative study concluded by abstracting the working principles of each pattern. The selection is based on organisms' efficiency to cool their body temperature in extreme climates like desert and arctic. It is also based on the possibility of emulating such systems through their morphological adaptive features to architecture.

The last phase is the embodiment and the validity evaluation in which one of these mechanisms and its principles were embodied to an architectural cooling design. As a result, the evaluation of the design validity was based on the cooling efficiency law in mechanics. The investigated parameters of the study were the climatic environmental variables and the design parameters.

1.9 Significances of the Research

The importance of this study lies in three aspects;

1. The study adds to the body of knowledge new eco-friendly passive cooling design for indoor air inspired from nature's thermoregulation mechanisms.
2. By emulating nature's solution, the suggested design will be valuable for users' health, environment and economy. Firstly, using passive bio-inspired air cooling means in buildings in the hot arid region leads to provide their residents with a humidified, cold, and washed air in the hot seasons. This causes an increase of their productivity and provides a better quality of life. Secondly, the proposed bio-inspired design is a friendly environmental element. If used, it will contribute to a reduction in the greenhouse gas emission because it is

run passively without electrical energy. In addition, this design is made of local materials minimizing by that the negative ecological impact of buildings in their environment. By emulating nature to solve building problems, it is assumed to be a step to save and protect the ecosystem and diversity in the earth and live sustainably without inhibiting the chances of the future generations. Thirdly, it is also economic and cost-efficient due to the reduction in the operating cost of electricity.

3. In respect of architectural and mechanical engineering design, it suggests some design guide principles based on nature strategies to cool indoor air with passive means.

1.10 Scope and Limitations

Considering the fact that the thermoregulation strategies, particularly cooling mechanisms in nature are achieved by different types of adaptations, this study is limited to the thermoregulation mechanisms accomplished through the morphological configuration of a structure. This constitutes the scope of the study from the biological side to inspire cooling strategies and their effective principles. Form in nature is not only based on aesthetic, but also it performs specific function or multi-functions for surviving aspects and adaptation with the surrounding environmental variations. By virtue of architect's work nature, drawing, it is comprehensible and more applicable for his/her to emulate form in nature that is efficiently performing the required function for a specific architectural challenge. Additionally, laws of physics have proven the ability of morphological configuration to determine the flux of physical properties affecting the rate of energy flow which in turn affects our life (Vazquez, 2014). Therefore, exploiting such strategies, mechanisms and principles are resulting in the same output solutions. Furthermore, this study suggested a bio-inspired cooling design and explained the affecting factors on its performance such as design parameters and climatic variables of the air e.g., temperature, humidity, and air speed. The proposed cooling design is limited to the buildings in the hot and arid regions.

1.11 Structure of the Thesis

This section demonstrates the topics discussed in the thesis chapters where Figure 1.3 summarizes the structure of this study.

Chapter One: It summarizes the essence of this thesis. It highlights the background of the study and its challenge that is indoor overheating which was the main motivation for conducting this study. It also reveals the study gap where there are insufficient studies regarding the practical emulation of nature thermoregulation solutions to design an energy-efficient cooling unit for buildings. As a result, this became the research aim. To achieve the research aim of designing energy-efficient cooling unit, a set of objectives were set out and based on them the research questions were raised. Subsequently, a brief description of the methodology used to accomplish the research objectives is discussed. Furthermore, it emphasizes the significance of the study and the positive consequences of conducting this area of research. This chapter ends with defining the research scope, limitations, and thesis structure.

Chapter Two: This chapter presents an overview of the study challenge that is indoor overheating, its context and its negative impacts on the residents. Furthermore, it reviews the indoor thermal comfort requirements for occupants in this climate. For a further understanding of indoor cooling strategies, this chapter reviews the cooling methods in the desert architecture either by mechanical air conditioning systems or passive cooling elements in the vernacular architecture such as wind tower and evaporative cooling. This section reveals the possibilities of designing innovative passive air cooling means where the most effective one was cooling by water evaporation.

Chapter Three: This chapter is also part of the literature review where it describes the concept of biomimicry, its advantages, and applications in the buildings and architectural design. The chapter covers the literature on the applications of thermoregulation adaptive techniques in nature to architecture. This opens perceptions to understand how to deal with biomimicry notion and emulate nature solutions to the practical field of the architectural design. It further reviews the biomimetic methods

for a better understanding of their processes which start with searching for similar biological organisms that achieve the research challenge and end with emulating their solution strategies to a design.

Chapter Four: This chapter demonstrates in detail the main methodology used in this study to achieve its aim that is the biomimetic strategy. It covers the thermoregulation adaptive strategies used by organisms in nature to cope with the fluctuating climate of their environment in which three of them became the inspiring cooling strategies for the research challenge. Furthermore, this chapter includes the comparative study of the inspiring biological case studies and their findings. It also concluded with abstracting the working principles of the thermoregulation strategies used by these biological case studies. These principles can be used as inspiring directions for designing passive cooling units for buildings in the hot arid region.

Chapter Five: This chapter describes the process of the experimental study, equipment, measured parameters, materials, and the used tactics throughout the study. For further credibility, the experimental devices were calibrated, and another research procedure was done to gain the scientific trustworthiness of conducting the proper research process. It also demonstrates the hot arid desert climate and its climatic factors represented in the weather of Seiyun city in Yemen.

Chapter Six: This chapter presents the results of the experimental studies on the bio-inspired design. It clearly analyses the results and interprets them in accordance with the literature.

Chapter Seven: It presents the conclusions of the study built based on the finding discussed in Chapter Six. Furthermore, it demonstrates the implications of the findings and the study limitations. This chapter concludes by suggesting some of the recommendations for further research studies.

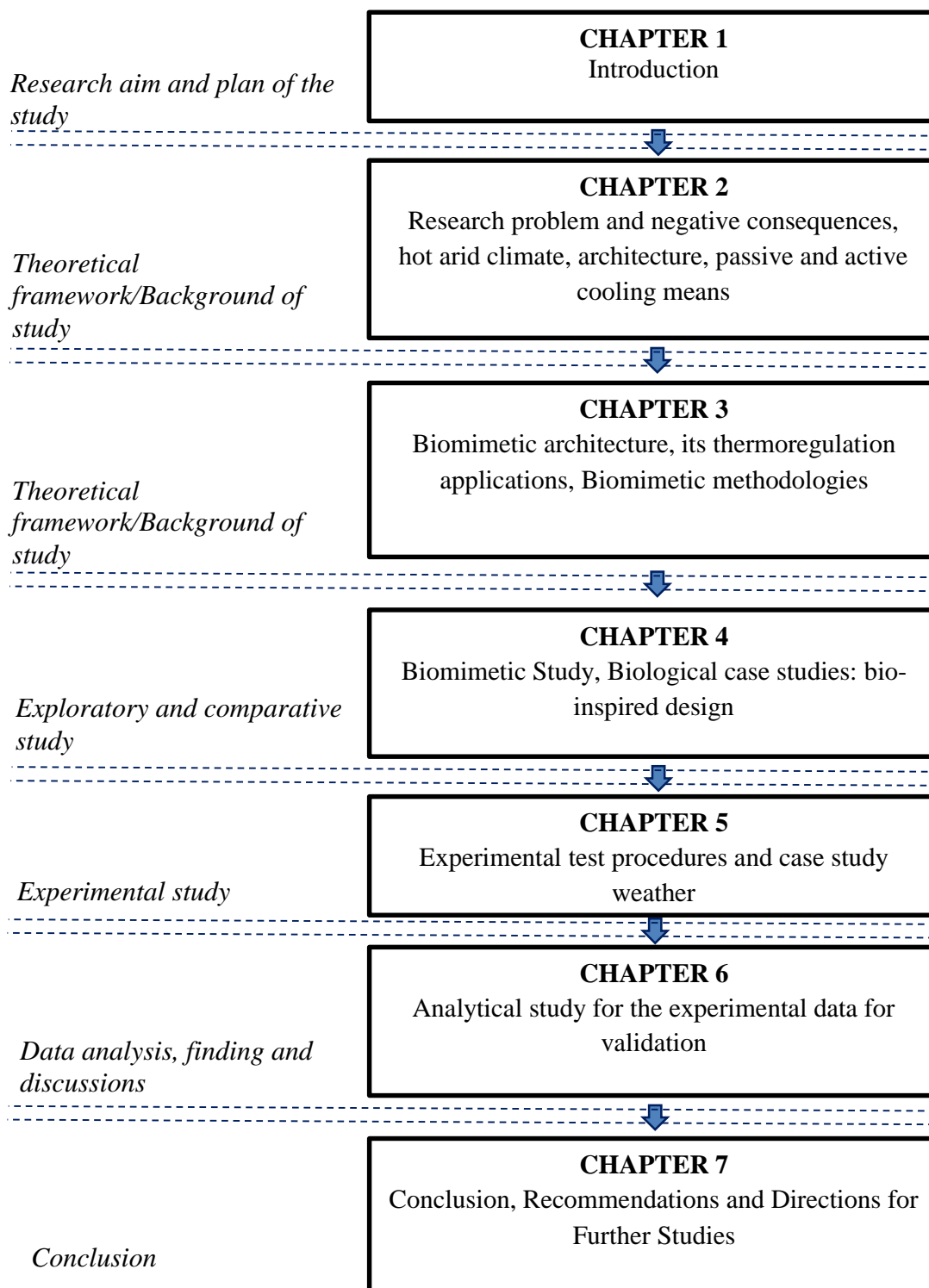


Figure 1.3: Summary of the thesis structure

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