From hygrothermal adaptation of endemic plants to meteorosensitive biomimetic architecture: case of Mediterranean biodiversity hotspot in Northeastern Algeria

Saida Teraa¹ · Meriama Bencherif¹

Received: 19 January 2021 / Accepted: 1 October 2021 / Published online: 3 November 2021
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract

This research consists in diagnosing the hygrothermal imbalance problem inside tourism buildings located at the edge of the Mediterranean Sea. In particular, we study the case of Ben M'Hidi tourism development area in Skikda coastline in Algeria. The southern room of "Royal Tulip" hotel was chosen as object of this study in order to investigate its internal hygrothermal behavior. Our study uses the problem-based approach for generating biomimetic architectural concepts that help to develop a meteorosensitive room's envelope depending on hygrothermic local conditions. Our proposed biomimetic design was inspired by the hygro-adaptive mechanism of the so-called endemic plant "Silene Amphorina". The focus of this paper is to compare the hygrothermal efficiency of the biomimetic envelope versus the real room's envelope. For this purpose, hygrothermal simulations were performed using the WUFI Plus[®] software. Our results show that the biomimetic hygrothermal behavior is more adapted than the real one. It has regulated the ambient temperature and it has reduced the internal humidity rate by around 20% in summer, 23% in mid-season and 35% in winter, which will enhance the internal hygrothermal comfort and ensuring the sustainability of the tourism building. In future works, we will be able to propose meteorosensitive envelope responses based on these results.

Keywords Biomimetic architecture · Hygrothermal comfort · Floristic endemism · Mediterranean biodiversity hotspot · Skikda coastline · WUFI Plus[®] software

Abbreviations

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers
[K] Kabylas-Numidia biodiversity district in northeastern Algeria
[K1] Great kabylia sector

✉ Meriama Bencherif
meriama.bencherif@univ-constantine3.dz

Saida Teraa
saida.teraa@univ-constantine3.dz

¹ Urbanism and Environment Laboratory, Faculty of Architecture and Urbanism, University of Constantine 3, Constantine, Algeria

[K2]	Small kabylia sector
[K3]	Numidia sector
HVAC	Heating, ventilation, and air conditioning
RH	Relative humidity
Tc	Comfort temperature
TDA	Tourism development area
WUFI	Wärme Und Feuchte Instationär (transient heat and moisture)

1 Introduction

The building sector constitutes a major actor in climate change and environmental pollution due to the energy consumption and greenhouse gas emissions. It is the most energy consuming sector in the world (Perez-Lombard et al., 2008). In Algeria, this sector represents more than 40% of total national energy consumption, thus, the need to promote energy efficiency.

Nowadays, architecture accounts for a significant part of the total energy consumption in developed countries (Perez-Lombard et al., 2008). Within this context, Building envelope plays a great role in the way systems adapt to environmental conditions, it is the principal key affecting energy efficiency (Homod et al., 2021), also, it is considered like ideal architectural element that could be optimized in order to maintain the desire hygrothermal comfort and minimizing the energy needs.

Building envelopes, consisting of the basic elements of walls, roofs, windows, and floors represent the interface between outdoor environment, in particular harsh weather conditions (such as extremes of temperature, humidity and solar radiation) and the indoor occupied spaces. Designing building envelopes that have the capacity to adapt to their climatic context will not only enhance its resiliency but also its sustainability, by requiring less energy to operate and employing resources more efficiently.

In recent years, active bio-inspired materials have been implemented largely in dynamic building envelope for different applications especially in responsive building facades depending only on local environmental stimulus (San Ha & Lu, 2020), for instance, the new Hydrogel that is characterized by its dynamic mechanism is capable to open and close like stomatal movements of stomata valves present in plant leaves in order to react to environment changing conditions such as temperature and moisture (Shahin, 2019; Gargava et al., 2016).

Consequently, a new contemporary architectural trend consists on designing a meteorosensitive building envelope based on sustainable adaptation principles that change their morphological and physiological properties or behavior over time to meet the multiple functional requirements of buildings (Chayaamor-Heil & Vitalis, 2021).

Nature with its 3.8 billion years of R&D provides a vast adaptation database that interact with changing climatic conditions. In this work, attention is focused on plants because they are a good example of this sustainable adaptation, they develop proven, sustainable and highly sophisticated solutions from billions of years to withstand harsh hygrothermic conditions, where analogue applications to building are relevant (Kopnina, 2015).

Within this context, Biomimicry is a philosophical interdisciplinary approach based on the integration of biology and technology, through the transformation from nature's principles into technological solution. This design discipline can be implemented in different

fields in a general, and in the field of architecture in particular for the design of a sustainable built environment (Benyus, 1997).

Relative humidity is one of the important climatic factors in building life, whether in the design phase of the envelope and its energy systems, or in the operational phase (de Dear and Brager, 2002). Additionally, the adequate design of the adaptive building envelope relies mainly on a stable hygrothermal equilibrium that is based on the understanding of coupled mechanisms of heat and humidity transfers through the envelope. Any modification impacting this hygrothermal equilibrium can cause an internal discomfort and architectural damages.

Royal Tulip hotel is chosen as a concrete case of this study, it is located in the tourism development area (TDA) of Ben M'Hidi, one of the urban development areas in Skikda coastline. Skikda, is an eco-coastal city that belong to a local biodiversity hotspot "Numidia [K3]" which is recently recognized in northeastern Algeria (Véla & Benhouhou, 2007). This city has a cool-summer Mediterranean climate with dry warm summers and mild winters and it is characterized by a high rate of air humidity all over the year (exceeds 80% RH, for relative humidity).

Tourism buildings existing in Skikda coastline on general and in the Ben M'Hidi TDA in particular are more and more unadaptives to the harsh external conditions include especially the very high rate of air humidity. Thus, they created an internal discomfort for the occupants by pushing them to use mechanical tools with high energy consumption importantly the heating, ventilation, and air conditioning (HVAC) systems in order to maintain the desired hygrothermal comfort.

Also, local architects ignore totally the climate specific conditions in their design process especially the excessive presence of humidity that cause of a big waste part of energy and even moisture damage in the building envelope components (mould growth, metals corrosion, freeze-thaw disorders, cracks, etc.). Also, architects use building materials that are poorly adapted to local context.

Therefore, this paper focuses only on the problem that threaten the indoor hygrothermal comfort of hotel rooms (at the scale of indoor living environment). For this reason, we will investigate the hygrothermal behavior of the real hotel room (real scenario) in order to predict its hygrothermal comfort level. The investigated hotel room has been simulated under WUFI Plus[®] software to determinate the technical problem (hygrothermal imbalance) informing the functional requirements to improve hygrothermal comfort.

However, the biogeographical region of Western Numidia [K3] contains a rich Phyto-Endemic heritage characterized by endless possibilities of hygrothermal responses, because endemic plants are strict local species that interact locally under the same hygrothermal conditions of buildings for billions of years in efficient and sustainable manner, without harming natural resources nor polluting the environment (Quézel & Santa, 1962).

The objective is to choose an emblematic endemic plant as an adapter champion in Numidian territory for analyzing first its biological mechanisms that adapt to contextual hygrothermic conditions and then imitating them in order to generate bio-concepts which can be considered thereafter as bases of architectural ideas to design a reactive envelope to local hygrothermic conditions. This will be done through a biomimicry methodology based on the Carl Hastrich's model and using whole dynamic hygrothermal simulation software (Künzel, 1995) to predict the indoor hygrothermal behavior of the biomimetic chamber (bio-inspired scenario) depending on material properties and boundary conditions.

The focus of this paper is to compare the hygrothermal behavior resulting from the real scenario of the hotel room versus the biomimetic scenario in order to explain that the hygrothermal adaption logics used by endemic plants can overcome the problem

of indoor hygrothermal comfort that is identified in the tourism building of Skikda coastline.

In addition, this study aims to propose new endemimetic responses (mimicked from endemism) in order to maintain a balanced hygrothermal comfort according to well-established standards inside hotel rooms and also to design a biomimetic envelope sensitive to variations in local hygrothermic parameters when strategies based on lessons learned from the endemic plant of [K3] are applied.

Plants employ different systems to respond to environment changes. They have always been one of the first inspiration sources for creating adaptive architecture, but the integration of biomimicry in the adaptive design has been recently became a revolutionary trend in architecture (Badarnah, 2017). For example, a study conducted in 2013 explores the potential of imitating the flowers mechanism in response to sunlight (opening and closing) in order to design a facade "breathing wall" that improves the thermal performance of buildings located in hot and arid zone of Sinai in Egypt (Elghawaby, 2013). Another study conducted in 2012 looks into the possibility of designing a greenhouse that is inspired from banana slug in order to create an adaptive envelope that changes dynamically according to weather conditions (Mazzoleni, 2013).

More recently, a contemporary biomimetic design that take inspiration from pine cone structure in order to create a responsive envelope to air humidity through meteorosensitive system based on a hygroscopic material, this project demonstrates the integration of responsive material into a functional modular and highly adaptable system in architectural dimension (Song et al., 2015; Holstov et al., 2017).

On the other hand, a new biomimetic and energy-plus building that produce their own power in Cairo (Egypt) designed by the Belgian architect, Vincent Callebaut. The project global system is inspired by the exchange process that occurs through plants stomata in order to create living structures that open, close, breathe and adapt to their environment.

In different example, the architecture agency "Jerry Tate" has explored the potential of transpiration in building that cools with water, without using a pump, this system imitates the capillary action of plants for transporting water upward (Pawlyn, 2011).

During history, architects and designers have looked to nature as a huge source of inspiration for different kinds of forms and function. Vernacular architecture reflects the environmental context by utilizing some adaptive solutions to control hygrothermic conditions and to promote improved energy performance of buildings. For example, the logic used in the Indonesian vernacular architecture shows that local envelope was designed according to strategies similar to those applied in nature. Moreover, these traditional strategies are very practical for regulating air humidity through different construction process such as the use of lightweight wood, orientation that optimizes sunlight, shape and interior disposition of spaces, high ceilings allowing natural vertical ventilation through roofs. For this reason, high gable roofs are very famous in tropical climate regions around the world (Lechner, 2014). This vernacular architecture combined with ecological way of life, constitutes a sustainable hygrothermal prototype, carrying knowledge and bioclimatic solutions in order to enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands.

In this paper, we firstly introduce the application of new biomimicry approach in sustainable architectural design. In fact, we focus on endemic plants as an important inspiration source for solving indoor hygrothermal discomfort that is taken as a main problem of our study. Section 2 presents the model adopted in our case study, which is chosen for the investigation of a real scenario. Section 3 presents our approach, detailing the model

application, step by step, and discusses biomimetic scenario results. Then, a comparison between studied scenarios is provided in Sect. 4. Finally, Sect. 5 concludes this paper.

2 Conceptual methodology and case study

Generally, the implementation of biomimicry in research is typically divided into two categories with various terminologies: Direct (problem-based) approach and indirect (solution-based) approach (Helms et al., 2009).

According to the first approach, an existing design problem "challenge" looks to nature, while in the second one, an interesting biological phenomenon guides our reflection to search potential applications. commonly, there exist three levels of mimicking in biomimicry: organism, behavior and ecosystem (Benyus, 1997; Badarnah, 2017).

2.1 Hastrich's model as a model of biomimetic design

For this study, the biomimicry framework methodology is based on Carl Hastrich's iterative spiral (Biomimicry Design Spiral). The direct approach of this spiral method, called "Challenge to biology design spiral", is chosen as the main biomimetic model for this research because it is considered as a more appropriate tool to help designers to guide the transfer of biological principles to architecture. More specifically, it can help us to reach our goal consisting to emulate the biological strategies of plant in order to conceive practical and easily implementable design.

In this approach, designers look to the living organisms for solutions. They first identify the problems and then matching them to organisms that have solved similar issues (Rossin, 2010). It is formalized according to different methodology structures and each one of them has its specificities. In this work, we are interested by "e" cycle method based on Hastrich's direct approach which consists of four steps followed by an evaluation phase (Allard, 2012). These phases are summarized by the following I4 acronyms: Identification, Interpretation, Inspection, Imitation, and Evaluation. The framework presented in Fig. 1 shows the biomimicry process of our adopted methodology approach (Based on Hastrich's Model).

The first step involves the identification of the real challenge in architecture (the problem). In the second step (Interpretation), the designer will necessarily need to cooperate with biologists in order to reframe the design challenge (function and context) in biological terms (Biologization). The third step (Inspection) consists on the selection of natural models which live in the same context conditions, then, an emblematic organism is chosen as adapter champion. After this, strategies inspired by this living organism are proposed, abstracted and imitated in the fourth step (Imitation). Finally, an evaluation phase takes place in order to assess the successes and failures of these bio-inspired strategies (through a comparison with life principles) (Rossin, 2010).

The endemic character is the common specific connection between all steps of our adopted methodology. The first step is based on the identification of an architectural problem that have a strong relationship with climate characterization of the study area. In both of the second and third steps, designers ask local nature how its endemic richness works against the same problem identified previously, and they will be inspired and informed how these endemic organisms have solved similar issues in order to create more sustainable buildings that adapt and behave like local nature.

Fig. 1 **a** Hastrich's direct approach (Challenge to Biology); **b** process of the Biomimetic methodological approach "Challenge to Biology Design Spiral"

2.2 Case study

2.2.1 Skikda: center of floristic endemism in Northern Algeria

The Mediterranean Basin is one of the important areas on Earth for plant biodiversity. It is the third hotspot in the world in terms of its endemic plants on the 34 global hotspots (the biodiversity hotspot is a biogeographic region with significant levels of biodiversity that is threatened by human habitation). According to this, 10 regional Mediterranean biodiversity hotspots have been identified (Quézel & Santa, 1962). However, following recent taxonomic revisions, another unknown hotspot is added to the ten already identified hotspots in the Mediterranean Basin which is "Kabylies-Numidia" district in northeast of Algeria (Véla & Benhouhou, 2007). This additional hotspot belongs to a larger biogeographical unit, which includes the major part of the Algerian–Tunisian Tell "Kabylies-Numidia-Kroumiria".

Algeria occupies the seventh position between the global hotspots in terms of richness in number of endemic taxa. Particularly, its eastern coastal area which is identified recently as a regional hotspot (Kabylies-Numidia sector) due to its well-known taxonomic richness, and its strong plant endemism. In this Algerian sector, researchers identified three local centers of floristic endemism: Great Kabylia [K1], Small Kabylia [K2] and Numidia [K3] (Véla & Benhouhou, 2007). In this paper, our study is limited to the western part of coastal Numidia [K3].

2.2.2 Numidia [K3]: unknown biodiversity hotspot

Coastal Numidia [K3] is a rich peninsula associated with high rate of original plant endemism (Quézel & Santa, 1962). It constitutes a local biogeographical crossroads that is delimited to the north by the Mediterranean Sea, to the South by a group of medium

altitude hills (Medjerda and Guelma massifs) and to the east by the Algerian–Tunisian border, and to the west by the Filfila massif.

Numidia is divided into two huge complexes which are separated by Seybousse River: (1) the Eastern Numidia that is composed of Annaba and El Kala complexes; and (2) the Western Numidia that is represented by Fetzara Lake, the Guerbes-Senhadja Wetland complex, and the Filfila mountains in Skikda.

Our study area "Western Numidia" is subject to high level of air humidity all over the year, due to the presence of various environmental factors (especially, its direct proximity to the sea and the different hydraulic potential existing in this region). On the other hand, Western Numidia contains several marshy lakes which belong to the wetland of Guerbes-Senhadja complex, in addition to its diversified relief mountains and sublittoral forest covering as well as the agricultural vocation of the region with a large irrigated perimeter.

2.2.3 Ben M'Hidi tourism development area: an important part of Numidian Chain

As a part of Western Numidia, Ben M'Hidi tourism development area (TDA) occupies a sandwiched position between sea and cliff. It extends linearly all along Wilayat Road N° 18 over a distance of 8,700 m, straddling two territories both of them belong to two neighboring municipalities, Skikda and Filfila. Out of a total area of 206.00 ha, 43.10 ha are suitable for development, with an estimated capacity of more than 300,000 summer visitors per year.

Ben M'Hidi TDA is presented in two different urban shape from the north to the south, the first urbanized part (housing, equipment, military barracks, canvas camp, etc.) takes straight bar shape along the East-West Road. The second part is presented by a long band with high level slope (30%) covered by shrubs, tufts and scrub.

2.3 Royal Tulip hotel: an original case study of Numidian Territory

The "Royal Tulip" hotel of Skikda is a five-star luxury hotel located on the highest mountain of the Ben M'Hidi TDA, in front of forest and with a panoramic seaside view that extends over 10 km (see Fig. 2). The hotel room taken as a test-cell is located in the fourth level floor exactly in the main facade, it has a rectangular shape, its treated floor area is 42.50 m² as illustrated in Fig. 3. Its characteristic length is 3.2 m and the width 4.5 m and its depth is 3.2 m. Details of this investigated room are shown in Figs. 3 and 4a. Royal Tulip hotel has 15 stories, its main facade is exposed to south orientation, the secondary one is exposed to the north.

There are four main reasons that this particular hotel was selected as the architectural object of our study:

Phytogeographical context. Royal Tulip hotel is located in Ben M'hidi TDA in Skikda, more specifically it is built in the mountain part of the western Numidia [K3] which is describes as a biodiversity regional hotspot on the Mediterranean Sea (Véla & Benhouhou, 2007) (see Sect. 2.2).

Numidia territory is characterized by its original taxonomic richness and especially its strong plant endemism. This highlights the fact that this study area provides a vast biological toolbox of unlimited solutions for resolving problems and finding more sustainable solutions to the architectural challenges.

Climatic context The investigated hotel is situated in Mediterranean city "Skikda" which is characterized by a high rate of air humidity all over the year (exceeds 80% RH).

Fig. 2 Location of Royal Tulip hotel in Ben M'Hidi TDA

Fig. 3 **a** Hotel main facade (Southern); **b** fourth floor plan of the hotel; **c** plan of investigated hotel room **d** interior views of the room

Fig. 4 The investigated hotel room

According to the specific comfort requirements determined by ASHRAE-2010 (ASHRAE for American Society of Heating, Refrigerating and Air-conditioning Engineers), the harsh hygrothermic conditions of this city are above comfort level (30–60% RH) most of the year. This means that, local buildings in this study region are threatened by the hygrothermal imbalance phenomenon which causes an internal hygrothermal discomfort for occupants. Also, it causes a moisture damage to building envelope components and

even waste of big part of energy consumption. Thus, investigation of this hotel will contribute to strengthened our research problematic related to climatic context (hygrothermal imbalance).

Tourism development context Royal Tulip hotel is one of characteristic five stars hotels built in Skikda, it is situated in Ben M'hidi TDA which is the longest beach in Algeria (10 km).

Additionally, Ben M'hidi TDA is one of the contemporary urban development areas in Skikda, out of a total area of 206.00 ha, 43.10 ha are suitable for development, with an estimated capacity of more than 300,000 summer visitors per year, for the 2030 horizon (SDAT, 2008). Thus, this strategic situation makes the hotel plays a key role in the local economic and leisure industry that's why we choose it as a basis for our study.

Architectural quality The construction system of Royal Tulip hotel is based on concrete wall envelope with post-beam structure as the main load-bearing element, with 30 cm thick double brick wall. Its building envelope is mainly composed of two materials glazing and aluminum cladding without any insulation coating, that's why, it has currently created a huge demand of HVAC systems.

Most of coastal hotels in Algeria have the same construction system, the same design manner, style and appearance. Based on this, we choose this hotel as a typically study case because it represents generally an architectural prototype of the majority identical hotels existing in Algerian coastline.

3 The Numidian phyto-endemism as a model for meteorosensitive biomimetic architecture

Our adopted research methodology of Hastrich's direct approach follows five main steps. We first identify the real architectural challenge "the problem" existing in our study context. Then, matching it to organism that have solved similar issues, in order to select the emblematic biological model which will be the main source of our inspiration. The final step is to abstract its functions for architecture.

3.1 Identification of the hygrothermal imbalance of the investigated hotel room

The identification of hygrothermal problem of an architectural envelope is very complex due to the interaction of several environmental (physical) and personal (physiological and psychological) variables. For this reason, we are based on Lavigne et al. (1994) vision who confirmed that hygrothermal comfort does not only depend on the temperature but also on air hygrometry.

The main objective of this phase is to investigate the real hygrothermal behavior of the hotel room in order to predict its interior comfort level. This room is situated on the fourth floor and it is exposed to South orientation. The reason why this this orientation is chosen, is that this orientation is less affected by air hygrometry all over the year, when compared against zones facing other orientations.

Scientifically, several mathematical models of coupled heat and moisture transport have been developed. In this work, we are interested by WUFI Plus® software (Wärme Und Feuchte Instationär - Heat and Humidity Transient) which is based on mathematical model of the hygrothermal envelope (Künzel, 1995). It is capable of simulating the unsteady temporal development of the heat and moisture profile inside the room's environment (Künzel,

Fig. 5 Real hygrothermal behavior of the investigated hotel room at internal environment scale during the summer period

Fig. 6 Real hygrothermal behavior of the investigated hotel room at internal environment scale during the midseason period

1995). Figure 4a, b respectively illustrates the geometry and the visualization of our case study room.

Within this context, a dynamic hygrothermal simulation of the room's envelope was performed using the WUFI Plus software to predict its indoor hygrothermal behavior (real scenario) depending on material properties and boundary conditions. Local climate data are extracted from the Swiss Meteonorm 7 software. Thus, hygrothermal comfort level in the room was analyzed by taking into account the evolution of indoor temperatures and internal air hygrometry during the three typical periods of the year. Obtained results of summer, midseason and winter periods are respectively presented in Figs. 5, 6 and 7, showing the internal hygrothermal conditions profiles of the simulated room.

Based on the adaptive model, opted for the ASHRAE-2010 standard equation in order to determine the comfortable zone of the indoor temperature (de Dear & Brager, 2002; ASHRAE, 2010). The city's seasonal comfort temperatures of Skikda (T_c) are 21.8 °C in winter, 25.47 °C in summer and 24.3 °C in midseason time. In addition, a temperature range (5 °C), near to the comfort temperature T_c , corresponds to the thermal acceptability of 90% of people, so the comfort zones are extended by ± 2.5 . It gives an adaptive range of temperature comfort between 19.3 °C–24.3 °C in winter, 21.8 °C–26.8 °C in midseason and 22.9 °C–27.9 °C in summer time.

The comparison between internal temperatures of the investigated hotel room obtained previously with the comfort limits/ T (ASHRAE-2010) of Skikda city shows that: The

Fig. 7 Real hygrothermal behavior of the investigated hotel room at internal environment scale during the winter period

internal summer temperature of the room is almost constant throughout the period and it is mainly situated in the thermal comfort band with a low amplitude of 4 °C between the minimum temperature (21 °C) and the maximum temperature (25 °C), this stability is due to its direct proximity with Mediterranean sea which guarantees the cooling of the air and ensures good air quality in summer. Unlike the fluctuating outside temperature which is marked by a high amplitude of 23 °C, between a maximum of (31 °C) and a minimum of (8 °C).

During the midseason period, the internal temperature of the room is below thermal comfort range (21.8 °C–26.8 °C), with a strong amplitude of 12.8 °C between a maximum of (21.5 °C) at the beginning of the midseason and a minimum of 8.7 °C at the end of midseason, while the outside temperature has a high amplitude of 25 °C.

In the winter season, we note that the internal room temperature is also below the comfort band identified previously (19.3 °C–24.3 °C), with a strong amplitude of 12.5 °C between a maximum of 18.5 °C and a minimum of 06 °C, while the outside temperature is very low (10 °C–15 °C) due to the Mediterranean climate of Skikda.

Comparison of the obtained interior temperatures of the investigated room, during three typical periods of the year with comfort temperatures (T_c), that are based on the adaptive model, reveals that the internal temperature of the investigated room is considered unacceptable except in summer.

In terms of indoor humidity, its summer value varies between 65% and 83% RH, with a maximum difference between indoor and outdoor relative humidity of 16% RH. During the midseason period, the internal relative humidity of the investigated hotel room is relatively stable with a difference of 17% RH between its maximum value 87% RH and its minimum value 70% RH. On the other hand, the internal relative humidity during winter period varies between 69% RH and 89% RH with a maximum difference between its indoor and outdoor relative humidity 20% RH.

This difference that is higher in winter is due to the fact of the lowering of the ambient temperature which induces the rise in relative humidity. By comparing these relative humidity values with limits of the optimum hygrothermal comfort band that are recommended by ASHRAE Standards (30%–60% RH). We observe that the internal relative humidity exceeds significantly the upper limit of this comfort band during the whole year.

According to that, it may be concluded that there exist an hygrothermal imbalance problem at the internal environment scale of the investigated hotel room i.e., the internal hygrothermic conditions are considered unacceptable through the year, which leads to

discomfort sensation of occupants. Hence, a big wasting of the necessary energy is noted and a moisture damages in the architectural room's envelope is detected.

3.2 Interpretation by the biologization of the architectural challenge

In this phase, we approximated the problem (Design Challenge) identified previously "hygrothermal imbalance" with a similar biological phenomenon present in local nature and which it has already solved (Rossin, 2010). To achieve this goal, we asked the following question: *Which natural environment(s) seem(s) to be close to the environment of our architectural problem?*

To answer this question, local biodiversity of our study area "Numidia [K3]" provides a vast database of mechanisms and hygrothermic adaptation strategies that can be implemented in the biomimetic adaptive envelope design to improve internal hygrothermal comfort.

In this research, we only focus on plants and their adaptation strategies for hygrothermic conditions as interesting biological models that are subject to the same hygrothermic conditions of buildings environment in Skikda. In order to investigate the previously identified problem to a phytobiological point of view (Biologization) (Rossin, 2010). For this purpose, interviews are conducted with local phytologists (botany laboratory of Nature and Life Sciences Department of Skikda University).

The analogies between humidity impacts observed on existing building in Skikda and on a plant in the same context are summarized in Fig. 8. It is observed that both of them have the same humidity impacts either in balanced or unbalanced state. In case of an hygrothermal imbalance, both of the states will have the same risks of pathologies related to humidity such as plant diseases, leaf bacterial pathogens, and infection that can attack the plant/hotel room envelopes.

There exist various common specifications related to local plants in Numidian territory and the selected room of the Royal Tulip hotel as shown in Fig. 9:

- Both hotel building and plant systems are exposed to the same climatic conditions (temperature, relative humidity, solar radiation, etc.). additionally, both of them must resist to harsh hygrometric conditions ($RH > 80\%$) in order to survive with a sustainable manner.
- Both of them have the same organization principles,
- Local plants are situated in the same environmental context of the hotel room (same coastal relief, same biogeographical situation: [K3]),
- Like the hotel rooms, plants are fixed objects that remain subject to specific location earth without moving,
- In terms of indoor comfort conditions, both of them need the same indoor relative humidity rate in order to achieve an internal hygrothermal balance: [30%–60% RH] for the hotel room and [30%–70% RH] inside the cells of plant leaf,

3.3 Inspection selection of the endemic adapter champion

In this step, extensive research was performed on local plants taxonomy in order to find the hygrothermic adaptation champion that responds successfully to the problem by asking the following question: *What is the plants category most challenged by the posed problem but which is little disturbed?*

Fig. 8 Biologization Process of the architectural problem "hygrothermal imbalance" towards a biological phenomenon "Moisture balance"

Fig. 9 Identifying analogy convergences between plants and hotel rooms

Following this questioning, endemic plants are the living organisms that are highly adaptable to hygrothermic context conditions. For this reason, phyto-endemic sample was chosen as a main source of inspiration because those plants are characterized by a very high responsive capacity towards hygrothermic disturbances of the surrounding environment.

In order to choose the endemic plant which will be considered as adapter champion of [K3], we are based on a collaborative process in form of surveys to involve both of

local phytologists and local inhabitants in the choice of inspiration source. Schema of Fig. 10 shows different steps of this process.

This process is based on two main aspects: (1) the functional part was performed in the form of a questionnaire with scientists (biologists, botanists, ecologists, researchers, etc.) which led to establish a list of highlighted local plants as strict endemics of Numidia [K3] (see Table 1); and (2) the survey part was completed by "in situ" questionnaires with local inhabitants (farmers, rural women, children, etc.), in order to choose the most aesthetically beautiful endemic plant (formal aspect) among four plants identified previously. The obtained results from this survey are shown in Table 2.

Concerning the functional aspect, the plant "Silene Amphorina" is chosen by 60% of local phytologists as a strictly endemic plant of [K3] because it has been found only on Filfila exactly in the mountains of Ben M'Hidi TDA (the study area) (Battandier et al., 1888). Also, according to local phytologists it is a strict endemic plant that is characterized by a high responsiveness capacity to local hygrothermic conditions when compared against other endemic plants.

In terms of aesthetic, *Silene Amphorina* attracts majority of local inhabitants (60%) because of its overall envelope appearance and its external shape. According to the local inhabitants' testimonies, this endemic plant characterizes the coastal dunes of Filfila for several years and it is the most beautiful plant in terms of shape, color and landscape views especially in the spring period.

Finally, from data analysis of the collaborative process results, it may be concluded that the "*Silene Colorata Amphorina*" is the champion endemic plant for perfect hygrothermal adaptation in Numidia territory and on which we will base our next phase of Imitation.

3.4 Imitation of the hygro-adaptive mechanism for meteorosensitive architectural design

This imitation step requires, first of all, through knowledge of the leaf tissue anatomy specific to endemic plant chosen as adapter champion of [K3] and its adaptation strategy to high rate of hygrometry. At a microscopic scale, this leaf tissue will be considered subsequently as a conceptual basis giving various hygrothermal responses applied in architectural design, in order to develop a room's reactive envelope that maintains internal hygrothermal comfort for hotel's occupants over the year. *Silene Amphorina* provides a variety of dynamic systems which interact with humidity conditions in the context. In this study, we are interested, by a dynamic mechanism that is sensitive to air humidity, this one is involved in stomatal transpiration phenomenon shown by the leaf surface of this endemic

Fig. 10 Collaboration process between local phytologists and local inhabitants in the study area

Table 1 List of emblematic endemic plants of [K3] identified by local phytologists through the collaborative process

Endemic plants of [K3]	References	Pictures	Geographical distribution
1. <i>Brassica fruticulosa</i> subsp. <i>Numidica</i> (Numidian endemic of northeastern Algeria)	Letourneux (Cosson, 1887; Battandier, 1888–1890; Maire, 1965) Quézel and Santa Flora (1962)	Véla (2007)	Garde Cap, Cap de Fer (Edough peninsula), Guerbes-Sanhadja Complex, Kef Fatima Beach in Skikda
2.. <i>Silene Colorata</i> ssp. <i>Amphorina</i> (Pomel) Batt (Numidian endemic of northeastern Algeria)	First collectors: Pomel (1874) Battandier and Trabut (1888), "Flore de l'Algérie (1), page n° 134"	Marouf (2011)	Silene Amphorina was reported only in West Numidian territory, in several corners of Ben M'Hidi TDA, Filfila. It grows on the coastal dunes of the TDA with high humidity
3. <i>Gemista numidica</i> Spach (Numidian endemic of northeastern Algeria)	First collector: Durieu de Maisonneuve (1841)	Toubal (2011)	This Algerian endemic is presented commonly on the hills of Annaba coastline, growing on degraded soils of cork forests and preferring a northern exposure on the coastal
4. <i>Hypericum afrum</i> Lam (Numidian endemic of northeastern Algeria)	Quézel & Santa Santa (1962), "Nouvelle flore de l'Algérie et des régions désertiques méridionales"	Belouahem-Abed (2011)	Endemic plant was reported in EL- Kala wetland

Table 2 Selection results through the collaborative process for selecting the phyto-endemic champion of hygrothermic-adaptation in [K3]

Endemic plants	Number of local phytologists	Number of local inhabitants
Brassica Numidica	01	05
Silene Amphorina	06	30
Genista numidica Spach	02	06
Hypericum afrum	01	09
Obtained results

plant. Stomatal transpiration is defined as the emission of excess water in the form of vapor by plant towards the ambient atmosphere, through tiny pores of elliptical shape presents in the leaf surfaces exactly in the aerial epidermal cells which called the stoma (plural stomata). The stoma is a tiny pore in a plant leaf surrounded by a pair of guard cells that regulate its opening and closure, and serves as the site for gas exchange (Jarvis & Mansfield, 1981).

Each individual stomate is formed of two specialized parenchyma cells known as guard cells which surround the stomatal pore. These kidney-shaped cells are surrounded by modified epidermal cells, known as subsidiary cells which supports in the movement of guard cells. Under the stomata, there exist a cavity "sub-stomatal cavity" that acts as a chamber connected with inter-cellular air space and surrounded by inner walls (mesophyll) which create a real internal humid atmosphere (Mesophyll is the soft chlorophyll-containing tissue of a leaf between the upper and lower layers of epidermis: involved in photosynthesis). It must be noted that all of the sub-stomatal cavity, stomatal pore, guard cell, subsidiary cell and epidermal cell are all together known as stomatal apparatus (Jarvis & Mansfield, 1981) (Fig. 11b, d).

Figure 11 shows the physiology of the stomatal behavior in response to air hygrometry in the surface leaf of *Silene Amphorina*. First, the water absorbed by roots is transferred to the top through xylem vessels (The xylem is the vascular tissue responsible for the upward conduction of water and nutrients from the roots) for reaching the leaves where it is diffused into the spongy parenchyma and inter-cellular spaces (the spongy parenchyma is the lower layer of the ground tissue of a leaf, characteristically containing irregularly shaped cells with relatively few chloroplasts and large intercellular spaces). Second diffusion across the chamber to the inner opening of the pore, third diffusion down the pore, and fourth diffusion from the outer opening of the pore outward to "infinity" (i.e. moving ambient air) (Pickard, 1982, 1981). This moisture gradient between the outside atmosphere and the inside of the sub-stomatal chamber supports transpiration and allowing water to evaporate at the interstices of the mesophyll cells which plays a significant role in cooling the leaves to maintain the plant's moisture balance (Lange et al., 2004).

Furthermore, stomata are sufficiently sensitive to air humidity, they open and close according to changing in the degree of humidity. When the guard cells are turgid (humid air RH > 70%) they well expand resulting the opening of stomata. On the other hand, when

Fig. 11 **a** The endemic plant champion of [K3] "Silene Colorata Amphorina", **b** morphological characteristics of the stomatal apparatus, **c** stomatal sensitivity mechanism to humidity, **d** schematic cross section of a stomatal apparatus and the way the humidity travels the internal space from sub-stomatal chamber to the external atmosphere

the guard cells lose water (dry air $RH < 30\%$) they become flaccid to stomatal closure. Thereby, the peri-stomatal transpiration plays a decisive role in this process, such that the guard cells are able to function as "humidity sensors" which measure the difference in humidity inside and outside the leaf. Thus, stomata are humidity sensors that relate the humid internal atmosphere of the leaf "inside the sub-stomatal chamber" with the external atmosphere by controlling the outflow of moisture and act as multi-sensory hydraulic valves. This stomatal dynamic behavior involved in the peri-stomatal transpiration maintains the moisture balance of the plant according to humidity changes by opening and closing which allows to the plant to adapt with humidity conditions. So, the stomata serve as hygro-adaptive valves (Gargava et al., 2016).

Transfer from stomata challenges into architectural design objectives will be carried out through design concepts capable of adapting to the same issues to ensure an internal hygro-thermal equilibrium. Thus, it will improve the desired hygrothermal comfort of the hotel's occupants and reduce their energy needs.

3.4.1 Developing biomimetic strategies

Designing with biomaterials for hygro-sensitive envelope reactive to local hygrothermic conditions Hygrothermal equilibrium inside the building's envelope is based mainly on the understanding of transferring and storing moisture mechanisms in its components which allows the control of the heat transfer and the air mass through efficient and appropriate choice of construction materials with adequate properties. New technologies of active and bio-inspired materials provide a new approach to creating 3D complex geometries and reversible surfaces with microstructures similar to stomata that react to changes in humidity. The aim is to improve the energy performance of the used materials for adaptive envelopes López et al. (2015). With this context, a researcher's

team from National University of Singapore (Nandakumar et al., 2018) has invented a novel gel-like material named hydrogel.

This bio-material is capable to extract water molecules from surrounding air and reduces relative humidity in a confined space without air-conditioning from 80% RH to 60% RH in less than 7 min. Also, it is capable to reduce in ambient temperature by more than 7 °C ; it performs 8 times commercial drying agents (Nandakumar et al., 2018).

The practical applications of this new hydrogel, are not only adapted to local hygro-thermic conditions, but also to occupants who need through the self-regulation of the internal hygrothermal comfort inside building envelopes. This hydrogel microstructure with excellent humidity responsiveness mimics the open and the close of stomata valves present in plant leaves which regulate moisture movement in and out of the leaves, thus, it is a humidity reactive material. This later can act as "smart" valves or membranes depending only on humidity stimulus level.

Additionally, this membrane behavior has the ability to convert moisture into reversible mechanical movement. It can change in shape, color, dimensions and physical states through ingrained properties of the material itself according to humidity stimulus, and which demonstrate the material capacity to adapt simultaneously to humidity changes to reduce energy waste and maintain a total hygrothermal comfort inside building (Khoo & Shin, 2018).

Adaptive value behind stomatal geometric morphology According to Meider's biophysical or biomathematical method (1968), the sub-stomatal chamber is geometrically represented by a hemisphere or hemi-ellipsoid delimited by the boundary mesophyll cell walls and set upon an equation plane (the epidermis) with a circular or elliptical hole (the stomatal pore). Figure 12 illustrates the geometric case of a hemispherical sub-stomatal chamber "the lumped circuit model". In this presentation, the characteristic dimensions of the chamber are usually shown as being much larger than the width of the pore.

Within this context, it is shown that the optimal chamber radius " Y " is several times larger than is the pore " X ". Also, the chamber's characteristic dimension " Y " should be at most twice the pore width " X ": " $Y \leq 2X$ " to minimize the water vapor efflux caused by transpiration phenomenon. Also, if the depth of this sub-stomatal chamber " Y " is more than twice of the pore width " X ", " $Y > 2X$ " it causes an increase of water loss (high stomatal transpiration) due to discharge of a large amount of moisture efflux from the stomatal cavity to the ambient air of external atmosphere (Fig. 11d) (Pickard, 1982).

For this study, the hotel room is considered by analogy as the sub-stomatal chamber present in surface leaf of the endemic plant of [K3]. Our main objective is to dehumidify the air inside the hotel room in order to ensure an internal hygrothermal balance, according to studies mentioned above this can only be done with the increase in the chamber dimensions " $Y \leq 2X$ ", which leads to decrease in interior humidity rate. Indeed, this helps to obtain an interior hygrothermal balance. Table 3 explains the geometric similarity between adaptive value of transpiration rate on the sub-stomatal chamber and the adaptive value of humidity level in the hotel room.

In order to investigate the effect of this bio-inspired geometric ratio " $Y > 2X$ " on the hygrothermal comfort level inside the biomimetic envelope, a parametric study was carried out; two parameters are evaluated, such that temperature and relative humidity. Also, three different dimensions were tested for predict the optimal design that balances its indoor hygrothermal comfort. Three different geometrical configurations are analyzed where the ratio between depth of the room " Y " and the width of the opening " X " are greater than or equal to " $2X$ ":

Fig. 12 Geometric idealization of the sub-stomatal chamber present in endemic plant leaves (*Source*: Pickard (1981) and adapted by authors, 2020)

- Case 1, where " $Y=2X$ ", taken as a reference case, the geometric ratio is minimum which gives the largest opening size,
- Case 2, where " $Y=3X$ ": the opening size is medium,
- Case 3, where " $Y=4X$ ": the opening size is the smallest among the three geometries.

To analyze the hygrothermal behavior of each studied case, hygrothermal simulations of the biomimetic room were carried out by means of WUFI Plus software (ver.3.2.0.1) which leads to the revealing of the best design that ensures internal hygrothermal equilibrium. Figure 13, 14 and 15 describe the parametric study for the prediction of hygrometric responses at scale of living environment of the biomimetic chamber in function of geometric ratio (Y : chamber depth/ X : opening width) for three cases.

Analysis of the simulated results shows that for the case 1 ($Y=2X$) where the bio-inspired dimensions of the biomimetic chamber's envelope give the largest opening size compared to the other cases, its hygrometric response graph presented in Fig. 13b shows that the minimum indoor hygrometry values are 43% in summer and 45% in winter, about the maximum hygrometry values, both of them exceed slightly 60%, and during midseason period, the indoor hygrometry value is between 40% and 60%. This could mean that the internal hygrometry of the biomimetic chamber's envelope corresponding to case 1 (reference case) is situated in the hygrothermal comfort band recommended by ASHRAE-2013 [30–60%]. According to that, the hygrothermal comfort of occupants is achieved and the internal hygrothermal balance is ensured in this reference case.

This is due to the integration of a new biomaterial which allows to regulate the internal relative humidity (López et al., 2015; Nandakumar et al., 2018), also to the bio-inspired

Table 3 Analogy between effect of the geometric ratio (X : pore width / Y : room depth) on the humidity level inside the chamber

Geometric ratio	Adaptive value "Sub-stomatal chamber"	Adaptive value "hotel room"
$Y \leq 2X$	Minimize water loss (low transpiration)	High rate of int HR (hygrothermal imbalance)
So $Y > 2X$	Increase water loss (optimal transpiration)	Decrease of int HR (hygrothermal balance)

Fig. 13 Case 1: Hygrothermal responses in the reference case of the geometric ratio " $Y = 2X$ "

Fig. 14 Case 2: Hygrothermal responses in the case of the geometric ratio " $Y = 3X$ "

Fig. 15 Case 3: Hygrothermal responses in the case of the geometric ratio " $Y = 4X$ "

dimensions of the biomimetic chamber's envelope which gives a larger opening. This geometric ratio corresponds to case 1 indicates a possible indoor air movement and increases the distribution of air flow path in the internal environment and promotes a continuous renewal of the indoor air while eliminating contaminants by the evacuation of stale air, thus, improving natural indoor ventilation which is considered as the enemy number one of indoor hygrometry condensation.

For case 2 (" $Y=3X$ "), where the geometric ratio " Y/X " of the biomimetic chamber's envelope gives the average opening size compared to the case before. In this case, the simulated humidity level maintains generally near to the optimum due to the integration of the new biomaterial except in winter when the humidity level rises above the maximum threshold due to the opening size reduction compared to the reference case, it should be noted that this reduction has a negative influence on natural ventilation, which becomes insufficient for the aeration of the whole interior space of the room during winter period.

For case 3 (" $Y=4X$ "), where the ratio " Y/X " of the biomimetic chamber's envelope gives the smallest opening size. Its hygrometric response graph presented in Fig. 15b above shows that the indoor humidity level exceeds greatly the upper limit of the hygrothermal comfort band during all the simulation time (summer, winter, midseason). Consequently, we conclude that the indoor environment is uncomfortable and the hygrothermal comfort is unacceptable during most of the time spent in the simulated biomimetic chamber.

This is due to its smaller dimension of the air entrance opening size compared to the two cases assessed previously, which influences negatively in the natural ventilation that becomes insufficient to aerate the whole interior space during the three typical periods of the year. In this case, the small dimension of the opening width compared to the long depth of the room does not allow to exploit the effect advantages of wind and thermal draft, which reduces the velocity of the internal air renewal rate, thus, ensuring an insufficient supply of fresh air and unacceptable comfort conditions (air speed and temperature), due to a poor distribution of these two parameters.

Generally, numerical results obtained from the proposed parametric study show that the best hygrothermal performance is observed in the case 1 response graph which is able to achieve good indoor air quality and acceptable indoor moisture all over the three typical periods of the year, whereas the worst one is detected in case 3 corresponding to the smaller opening size, this is due to its biomimetic design based on an ideal bio-inspired geometric ratio (Y : depth / X : opening width). This gives an optimum dimensioning " $Y=2X$ " favoring a better air flow inside the biomimetic chamber's envelope (natural ventilation performance). It may be concluded that case 1 seems to be the best and most adaptive design that ensures better indoor hygrothermal comfort comparatively to the other two geometries.

In addition, these results highlight the importance of taking into account the opening width and its ideal geometric relationship with the depth of the room during the early architectural design phase because the modification in the size of the opening can significantly influence the indoor comfort conditions as well as on the energy efficiency requirements. These results are consistent with those obtained by other studies in the same perspective, such as those by Sacht and Lukiantchuki (2017) and Koranteng et al., (2015).

3.5 Evaluation of the hygrothermal response according to life principles

The hygrothermal response of case 1 is the best solution when compared against proposed solutions by the other two cases. This optimal response is such that it makes it possible to improve the hygrothermal comfort inside the hotel room without using any HVAC system,

Fig. 16 Comparison of the hygrothermal response of the real scenario and the biomimetic scenario during the three typical periods of the year

thus improving the energy and environmental performance of the hotel without polluting the surrounding environment and ensuring not only its resilience but also its sustainability. For this purpose, durability is in accordance with the principles of life, and therefore could it be retained for the final design.

4 Discussion

In this comparative analysis, two scenarios were compared, a real and biomimetic scenario, before and after biomimetic improvement. According to the internal hygrometry profile of Fig. 16, obtained results show clearly that the biomimetic design, which is inspired from "Silene Amphorina", presents a better hygrothermal behavior during the three typical periods of the year compared to the actual envelope of the investigated hotel room.

Very significant differences in hygrometry rate were recorded between the two responses of the two investigated scenarios, where the optimal envelope of biomimetic chamber allowed reducing the relative humidity rate of the internal environment from a high rate which mainly exceeds 70% to a lower rate between 40% and 60% RH, which influence positively on occupant's hygrothermal sensation.

This is due to the particular hygrothermal properties and the reversible characteristics of the new bio-inspired material "Hydrogel" which constitutes the biomimetic chamber's envelope. This active material acts as an hygro-sensitive insulator that reacts dynamically

to humidity changes in the surrounding atmosphere and also it can maintain a good level of indoor hygrothermal comfort without using any source of energy.

This comfortable hygrothermal behavior is also due to the bio-inspired geometric ratio which was predicted by the parametric study as the optimal biomimetic design that improves the natural interior ventilation, thus ensuring a satisfactory hygrothermal sensation of the occupants and, consequently, reducing the use of electric energy (see Figs. 13, 14 and 15). On the contrary, the herein study envelope of the real hotel room exhibits a very bad hygrothermal behavior in the three typical periods of the year because the internal humidity level exceeds greatly the upper limit of the hygrothermal comfort zone recommended by ASHRAE-2013 standard (see Figs. 5, 6 and 7). In terms of temperature, the biomimetic behavior ensures better air flow inside the chamber's envelope, which gives more comfortable temperature values during all three periods of the year, compared to the temperature values of the real room behavior which are below the lower comfort band except in summer because of the direct proximity to the sea. Also, this is mainly due to the use of a classic envelope made by concrete wall and double brick without any system of insulation, in addition to that, responsible designers of this building did not take into account the bioclimatic specificities of the study context, particularly the high rate of air humidity most of the year.

Furthermore, these hygrothermal variations between the two responses of both scenarios have major impacts on the energy performance and also on the sustainability of the architectural envelope. About energy consumption, it can be concluded that for the biomimetic chamber's envelope, the energy requirements are low compared to the real chamber's envelope, due to the positive impact of bio-inspired material but also due to the ideal dimensions of the biomimetic envelope. These optimal dimensions allow to regulate both of the internal humidity and the ambient temperature without using any source of energy.

In terms of architectural sustainability, the real hygrothermal behavior of the herein study envelope can increase the probability of architectural humidity damages on the envelope components, especially mould growth that can lead to degradation inside the room, this would impact negatively the architectural durability of the hotel room (ASHRAE, 2010). Indeed, this real hygrothermal behavior seems to be a significant risk factor for respiratory viral diseases and epidemics caused by viruses such as severe acute respiratory syndrome coronavirus (SARS-CoV) and the newly emerging SARS-CoV-2 occur during the winter months (Li et al., 2020). Some research studies demonstrated that humidity rate that exceeds 60% RH promotes the spread of viruses and increases the rate of viral diseases transmission, including COVID-19, from person to person inside the room because the human respiratory system loses its ability to respond to pathogens. According to that, it may be concluded that the architectural design of this investigated hotel room allows the viability of this virus which increases the mortality rate especially in this period when the most hotels in Algerian coastline are currently reserved for the preventive quarantine of nationals stranded abroad as part of the preventive measures that have been taken to contain the spread of coronaviruses.

On the other hand, the good hygrothermal level inside the biomimetic chamber's envelope allows to reduce the risks of humidity damages in the architectural envelope and the most important is that the probability of mould growth will disappear. Thus, the architectural durability is therefore insured. In addition, this intermediate relative humidity (30%–60% RH) is not only recommended for good health of buildings, but also for the protection of the occupant's health during most of the time spent in the room (ASHRAE, 2010). Recent epidemiological and clinical studies have indicated that an ideal humidity for preventing aerosol respiratory viral transmission at room temperature appears to be

between 40 and 60% RH, this humidity rate offers the best conditions for human occupation because it reduces the growth of bacteria and biological organisms. Also, the rate at which chemical interactions occur are minimized. So, this biomimetic hygrothermal behavior allows reducing the coronavirus spread while allowing to limit its transmission inside the bio-inspired chamber (Moriyama et al., 2020).

Generally, our results highlight the importance of applying biomimicry in architectural design of hotel room's envelopes situated in Skikda coastline. The main goal of our approach was to solve the hygrothermal imbalance issue inside rooms through sustainable responses inspired from endemic plants existing in the neighboring ecosystems, to ensure healthy indoor air quality and hygrothermal comfort conditions. Moreover, our approach aimed to controlling indoor humidity in order to avoid moisture damages, consequently, reducing the energy efficiency of the building. It should also be noted that similar observations have been recorded in some recent studies in the same perspective, for example, by drawing inspiration from the biological strategies of the African frog and the beetle to design a biomimetic architectural envelope could reduce 66% of the building energy consumption according to Fechey-Lippens and Bhiwapurkar (2017).

Research potential In this paper, the proposed method is suitable for many kind buildings and it can be applied in other coastal areas because all the process stages involved in this spiral method are depending on the context of the study area. This research method that is based on local properties of the study area can be a reference guide for designing a local architecture with respect to that specific biogeographical region located in Mediterranean Basin or in all over the world.

The endemic character of our research method represents a great development potential for Algerian coastal cities as an innovative and original design methodology that will create an architectural diversity depending only on the diversity of endemic plants and local environmental factors.

5 Conclusion

This research highlights the fact that integration of biomimicry in early stages of the architectural design process can overcome the problem of hygrothermal comfort, i.e., the hygrothermal imbalance inside hotel rooms situated in Skikda coastline in Algeria.

The Biomimicry model adopted in our study is based on "Challenge to biology design spiral" developed by Carl Hastrich. The inspiration is taken from an endemic plant of [K3] area (so-called *Silene Amphorina*) that was chosen as the champion of the hygrothermal-adaptation in Numidian territory. In order to come up with improved building design concepts, the plant adaptation mechanism is used to help in developing a meteorosensitive biomimetic envelope that reacts to local hygrothermic conditions and appropriate to environmental context.

One of the objectives of the present study was also to demonstrate the hygrothermal efficiency of the adaptive biomimetic envelope versus the real envelope of the hotel chamber. In order to confirm this hypothesis, an hygrothermal dynamic simulations were carried out using the WUFI Plus[®] software in order to analyze the hygrothermal behavior of the hotel room "real scenario", then to analyze the hygrothermal behavior of the biomimetic hotel room "Bio-inspired scenario".

A comparative analysis between results of both scenarios indicated that the hygrothermal behavior of the biomimetic envelope is good than the behavior of the real room

envelope, which exhibits a poor hygrothermal response during all the year. Additionally, these results indicated that the biomimetic envelope can regulate the indoor ambient temperature throughout the year and it reduced the indoor humidity rate by around 20% in summer, 23% in mid-season and 35% in winter, which will enhance the internal hygrothermal comfort, thus reducing energy consumption and guaranteeing architectural sustainability for a long-time.

In future architectural implications, we will be able to propose meteorosensitive envelope responses based on these results. On this basis, we concluded that sustainable solutions of hygrothermal discomfort issue can be found in the neighboring ecosystems database of the study area that solved their problems from million years ago. There is no research in this field in Algeria, therefore, this paper is part of a larger study effort that aims to provide a biomimetic overview for practitioners, city decision makers, industrials and academics attempting to shift architecture paradigms.

Acknowledgements Authors are grateful to WUFI® for allowing them to use the software for this research / The Fraunhofer Institute for Building Physics (IBP). Stuttgart, Germany. The authors are also thankful to all individuals who have contributed to this work.

References

- Allard, O. (2012). *Comment les entreprises peuvent-elles intégrer le biomimétisme dans leur stratégie d'innovation*. Biomimicry Europa: Paris, France.
- ASHRAE A (2010) Standard 55: Thermal environmental conditions for human occupancy
- Badarnah, L. (2017). Form follows environment: Biomimetic approaches to building envelope design for environmental adaptation. *Buildings*, 7, 40.
- Battandier, J. A., Trabut, L., & Petit, P. C. M. (1888). *Flore De L'algérie: Contenant La Description De Toutes Les Plantes Signalées Jusqu'à Ce Jour*. Nabu Press.
- Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature*. HarperCollins Books.
- Chayaamor-Heil, N., & Vitalis, L. (2021). Biology and architecture: An ongoing hybridization of scientific knowledge and design practice by six architectural offices in france. *Frontiers of Architectural Research*, 10(2), 240–262.
- de Dear, R.J., & Brager, G.S. (2002). Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE standard 55. *Energy and Buildings* 34(6):549 – 561, special Issue on Thermal Comfort Standards
- Elghawaby, M. (2013). Vers un confort thermique grâce à de nouveaux concepts d'enveloppes de bâtiments, inspirés de la nature: le mur respirant comme un exemple biomimétique approprié aux bâtiments en zones chaudes. PhD thesis, Aix-Marseille university
- Fecheyr-Lippens, D., & Bhiwapurkar, P. (2017). Applying biomimicry to design building envelopes that lower energy consumption in a hot-humid climate. *Architectural Science Review*, 60(5), 360–370.
- Gargava, A., Arya, C., & Raghavan, S. (2016). Smart hydrogel-based valves inspired by the stomata in plants. *ACS Applied Materials & Interfaces*, 8(28), 18430–18438.
- Helms, M., Vattam, S. S., & Goel, A. K. (2009). Biologically inspired design: Process and products. *Design Studies*, 30(5), 606–622.
- Holstov, A., Farmer, G., & Bridgens, B. (2017). Sustainable materialisation of responsive architecture. *Sustainability*, 9(3), 435.
- Homod, R. Z., Almusaed, A., Almssad, A., Jaafar, M. K., Goodarzi, M., & Sahari, K. S. (2021). Effect of different building envelope materials on thermal comfort and air-conditioning energy savings: A case study in basra city, iraq. *Journal of Energy Storage*, 34, 101975.
- Jarvis, P. G., & Mansfield, T. A. (1981). *Stomatal physiology (society for experimental biology seminar series, no 137)*. Cambridge University Press.
- Khoo, C.K., & Shin, J.W. (2018). Designing with biomaterials for responsive architecture. In *36th international conference on education and research in computer aided design in Europe-eCAADe*
- Kopnina, H. (2015). Sustainability in environmental education: New strategic thinking. *Environment, Development and Sustainability*, 17(5), 987–1002.

- Koranteng, C., Essel, C., & Nkrumah, J. (2015). Passive analysis of the effect of window size and position on indoor comfort for residential rooms in Kumasi, Ghana. *International Journal on Architecture Science* 2(1)
- Künzel, H.M. (1995). Simultaneous heat and moisture transport in building components. One- and two-dimensional calculation using simple parameters IRB-Verlag Stuttgart 65
- Lange, O., Lösch, R., Schulze, E., & Kappen, L. (2004). Responses of stomata to changes in humidity. *Planta*, 100(1), 76–86.
- Lavigne, P., Brejon, P., & Fernandez, P. (1994). *Architecture climatique: une contribution au développement durable*. Édisud
- Lechner, N. (2014). *Heating, cooling, lighting: Sustainable design methods for architects*. Wiley.
- Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., Ren, R., Leung, K.S., Lau, E.H., & Wong, J.Y., et al., (2020). Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. *New England Journal of Medicine*
- López, M., Rubio, R., Martín, S., Croxford, B., & Jackson, R. (2015). Active materials for adaptive architectural envelopes based on plant adaptation principles. *Journal of Facade Design and Engineering*, 3(1), 27–38.
- Mazzoleni, I. (2013). *Architecture follows nature-biomimetic principles for innovative design* (Vol. 2). CRC Press.
- Moriyama, M., Hugentobler, W. J., & Iwasaki, A. (2020). Seasonality of respiratory viral infections. *Annual Review of Virology*, 7, 83–101.
- Nandakumar, D. K., Ravi, S. K., Zhang, Y., Guo, N., Zhang, C., & Tan, S. C. (2018). A super hygroscopic hydrogel for harnessing ambient humidity for energy conservation and harvesting. *Energy & Environmental Science*, 11(8), 2179–2187.
- Pawlyn, M. (2011). *Biomimicry in architecture*, 2nd edn. RIBA Publishing. <https://doi.org/10.4324/9780429346774>
- Perez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394–398.
- Pickard, W. F. (1981). How does the shape of the substomatal chamber affect transpirational water loss? *Mathematical Biosciences*, 56(1–2), 111–127.
- Pickard, W. F. (1982). Why is the substomatal chamber as large as it is? *Plant Physiology*, 69(4), 971–974.
- Quézel, P., & Santa, S. (1962). *Nouvelle flore d'Érie et des régions désertiques méridionales*. Éditions du Centre National de la Recherche Scientifique, Paris.
- Rossin, K.J. (2010). Biomimicry: nature's design process versus the designer's process. In: *Design and Nature 2010*, WIT Transactions on Ecology and the Environment, vol 138, pp 559–570
- Sacht, H., & Lukiantchuk, M. A. (2017). Windows size and the performance of natural ventilation. *Procedia Engineering*, 196, 972–979.
- San Ha, N., & Lu, G. (2020). A review of recent research on bio-inspired structures and materials for energy absorption applications. *Composites Part B: Engineering*, 181, 107496.
- SDAT MPfTD (2008) Book 3, the seven tourist poles (pot): Horizon 2030
- Shahin, H. S. M. (2019). Adaptive building envelopes of multistorey buildings as an example of high performance building skins. *Alexandria Engineering Journal*, 58(1), 345–352.
- Song, K., Yeom, E., Seo, S. J., Kim, K., Kim, H., Lim, J. H., & Lee, S. J. (2015). Journey of water in pine cones. *Scientific Reports*, 5(1), 1–8.
- Véla, E., & Benhouhou, S. (2007). Assessment of a new hotspot for plant biodiversity in the Mediterranean basin (North Africa). *Comptes Rendus Biologies*, 330(8), 589–605.