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A Framework for Enhancing Natural Ventilation in Hot-Arid Regions: A Bioclimatic Design Approach

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ABSTRACT

Bioclimatic architecture is a sustainable design approach that aims to create buildings that put local climate characteristics into consideration and utilize the natural environment to achieve thermal comfort and reduce energy consumption. Among the various strategies used in bioclimatic architecture, natural ventilation stands out as a cost-effective and eco-friendly method that allows for the flow of air through buildings to provide cooling and improve indoor air quality without relying on mechanical systems. With the growing concerns surrounding climate change and sustainable development, the use of natural ventilation techniques is becoming increasingly vital in buildings design. This paper investigates the importance of natural ventilation as one of the bioclimatic architecture strategies for sustainable building design in hot-arid regions characterized by extreme weather conditions, by providing an overview of the various natural ventilation strategies, including single-sided, double-sided, wind-induced, and stack ventilation and identifies the key factors affecting air movement to enhance thermal comfort and indoor air quality inside spaces. The research findings reveal a set of design guidelines that can be implemented to optimize natural ventilation in hot-arid regions. These guidelines cover building orientation, form, vegetation, and the design of openings and natural ventilation strategies that are most suitable for this climate.

1. Introduction

The term "Bioclimatic design" denotes a design approach that integrates "Biology" to fulfill human biological needs, "Climate" which is related to the prevailing climatic conditions of a particular site, and "Technology" used during the design process [1]. In this regard, bioclimatic architecture emphasizes climate as a pivotal factor in the design process, results in appropriate architectural solutions to achieve thermal comfort, improve indoor air quality, which represents biological needs necessary for human habitation in an environment conducive to optimal comfort and well-being, in addition mitigate the building's detrimental effect on the environment

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and respect the local climate [2, 3]. Additionally, it endeavors to attain energy efficiency and preservation of environmental resources by promoting the use of renewable energy sources and decreasing the demand for heating, cooling, lighting, and ventilation systems, hence reducing the cost of energy [4].

In commencing the construction of a building, a preliminary examination of the climatic attributes specific to its geographical placement becomes imperative. So, various classifications have been developed to enable a simplified and lucid representation of climatic data such as: Holdridge's Life Zone Classification, Trewartha's Climate Classification and Köppen-Geiger classification[5].

Köppen-Geiger (K-G) classification is the most widely recognized system for classifying climate data as researchers and scientists find it helpful for its clear and consistent categories, making it a popular choice for many studies and analyses. It was developed by climatologists Wladimir Köppen and Rudolf Geiger in the early 20th century and has undergone several revisions since then remains widely used due to its simplicity, adaptability, and ability to provide a broad overview of climate conditions across the globe[5,6].

It utilizes monthly temperature and precipitation data and comprises five main climatic groups, namely tropical (A), arid (B), temperate (C), continental (D), and polar (E) species, each of them contains several additional subtypes as in Fig. 1 [5].

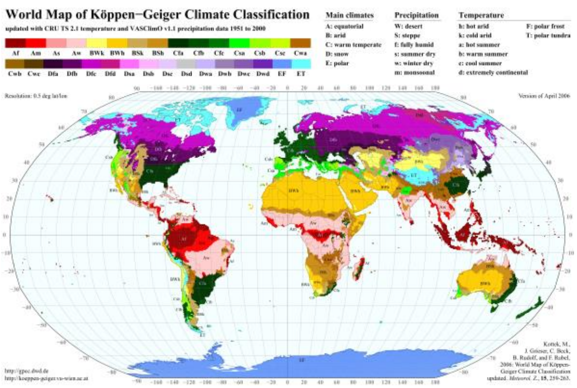


Fig. 1. Köppen-Geiger classification [6]

Based on the Köppen Climate Classification, the geographical location of Egypt lies within the latitudes of 23° and 32°. The southern and central regions are characterized by a "Hot-arid desert climate type" (BWh), whereas the coastal regions "Semi-arid Hot Climate Type" (BSh). These classifications indicate that Egypt has a hot-arid climate that persists throughout the year [7].

According to Givoni (1998), hot-arid regions are characterized by dehydration, clear skies facilitating solar heating during the day, and efficient radiation loss during the night [8]. This leads to intense direct solar radiation, resulting in high air temperatures that frequently exceed 50 degrees. The relative humidity fluctuates between 10 to 55%, and wind patterns are strong during midday and noon hours, with cool overnight temperatures. These regions also experience dust storms during the afternoon and receive a small amount of annual rainfall. Such weather conditions necessitate design strategies to mitigate their adverse effects [9, 10].

1.1. Research problem

Natural ventilation can be challenging in hot-arid regions due to harsh climatic conditions such as insufficient airflow during the hottest months of the year, as there may not be enough wind to provide adequate ventilation which can lead to stagnant air and make the indoor environment uncomfortable and potentially unhealthy. Additionally, dust and sandstorms can clog ventilation openings and reduce the effectiveness of natural ventilation systems. Moreover, brief periods of high humidity, as natural ventilation can make indoor conditions worse by bringing in humid air that makes it feel even hotter and more uncomfortable. In respect of these challenges, architects have to follow proper design guidelines to overcome these obstructions of natural ventilation in hot-arid regions, as the appropriate design considerations can facilitate natural ventilation, which may offer cooling and improve indoor air quality in buildings.

1.2. Research aim

This research aims to investigate natural ventilation as a bioclimatic architecture strategy in hot-arid regions and propose a comprehensive framework that integrates natural ventilation to enhance thermal comfort and indoor air quality. This framework will provide architects with simple guidelines to design buildings in these regions with greater efficacy.

1.3. Research methodology

The research will adopt a descriptive approach for literature review to investigate the attributes of designing for natural ventilation in hot-arid climates. The data collection process will involve scholarly articles, reports, and books on bioclimatic architecture and natural ventilation in hot-arid regions. The collected data will be critically analyzed to extract relevant information and identify common themes, key concepts, and design principles. The findings will be synthesized and organized to address the research aim and objectives and present a framework for the effective application of enhancing natural ventilation in buildings design of hot-arid regions.

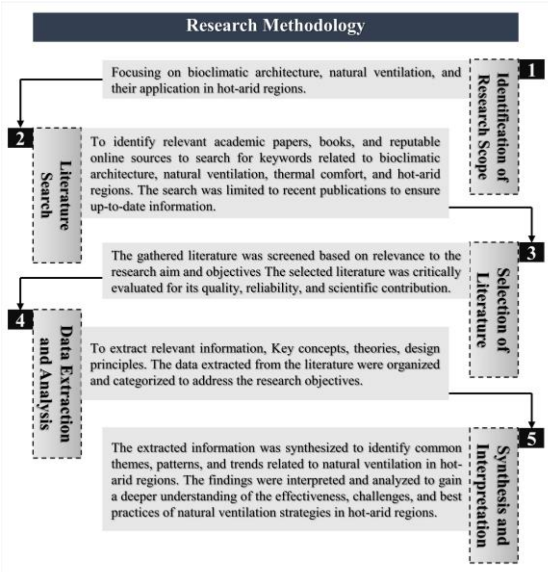


Fig. 2. Research methodology by Author

2. Bioclimatic architecture

2.1. The origin of bioclimatic architecture

The origins of integrating climate considerations in buildings can be traced back to ancient civilizations, wherein people's interactions with the environment influenced their preferences for specific climatic conditions. As the demand for durable housing grew, it became necessary to create buildings that were suitable for the local climate and capable of protecting inhabitants from extreme weather conditions [11]. Abbe Laugier, in his book "An Essay on Architecture" highlights the significance of the primitive cottage, as the initial architectural concept that met both functional and protective demands against natural forces[12]. The integration of climate, architecture, and comfort emerged in the "Vitruvius tripartite model" during the 15th to 30th BC, which was recognized as a substantial factor affecting the ecosystem [13].

The term "Bioclimatic design" was initially introduced by Olgay in his book, "Design with Climate: Bioclimatic Approach to Architectural Regionalism" This work extends the Vitruvius model by investigating the relation between building materials and vegetation, leading to a linear relationship between biology, climate, architecture, and technology [14,15], and resulting in a comprehensive theoretical understanding of designing a spatial environment suitable for human in various climatic zones. The bioclimatic chart, which identifies thermal comfort zones, is used to deduce this theoretical information [16].

The Bioclimatic chart illustrates the relation between dry bulb temperature and relative humidity and defines the optimal thermal comfort zone by specific temperature and relative humidity parameters, which range from 27.8° to 19.5° Celsius and 35: 65%, respectively [17].

In 1969, Givoni suggested a bioclimatic architecture model that focuses on identifying thermal comfort zones using average monthly climate data, including wind, humidity, and temperature [18, 19]. Givoni's chart, divided into different regions, requires distinct strategies for comfort within the building. The chart's x-axis is dry bulb temperature, measured in Celsius, while the y-axis is absolute humidity and curves illustrate relative humidity and wet bulb temperature [20]. The diagram defines the comfort zone as 19.5:27.5° C temperatures and 20:80 % relative humidity, with an "extended comfort zone" at higher or lower temperatures [1].

In 1971, Mahoney introduced a new approach to evaluating the environmental characteristics of different climate regions using climate analysis and a distinct methodology, which involved a three-stage process of concept, design development, and detailed drawings presented as tables [21]. The tables comprised six schemes, with the first four devoted to inputting climate data and comparing it against the thermal comfort zone, while the last two recommended design principles related to the planning, orientation, and shape of the building with respect to local climatic conditions [16, 22].

Finally, The Fanger model, which is a predictor of thermal sensation within spaces, represents thermal comfort through six variables [23], of which four are environmental variables: air speed, air temperature, radiant temperature, and humidity. Additionally, two variables represent personal factors: clothing and metabolic rate [23, 24].

These variables are utilized to develop the Predicted Mean Vote (PMV) equation, which estimates the thermal comfort level and predicted percentage of dissatisfied (PPD) as follows[25]:

$$PPD = 100 - 95 \times \exp(-0.0335 \times PMV^4 - 0.2179 \times PMV^2)$$

The PMV equation provides rates evaluated on the thermal sensation scale shown in Table 1, while PPD predicts the percentage of people likely to be dissatisfied with the environment [25].

Table 1. Thermal sensation scale

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

When the PMV value is between -0.5 to +0.5, and PPD is less than 10%, users' thermal comfort is achieved and if the result in the PMV equation approaches zero, users' satisfaction is at the maximum level [26,27].

2.2. Bioclimatic design approaches

Two distinct approaches have emerged to design bioclimatic buildings, as shown in Fig. 3 [1, 28, 29]:

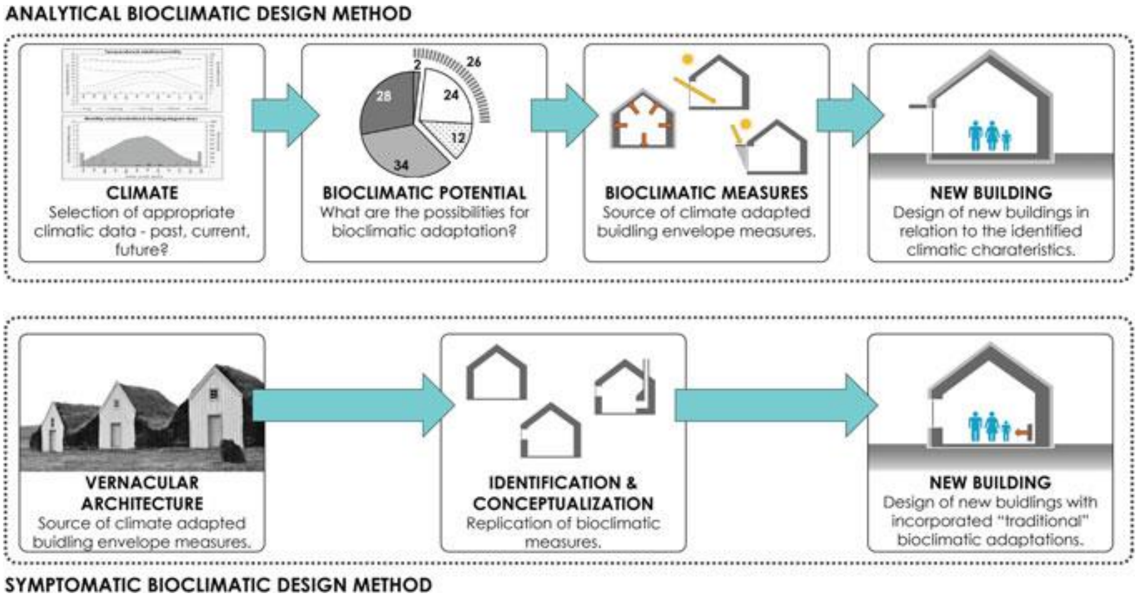


Fig. 3. Schematic representation of the design process for symptomatic (bottom) and analytical (top) methods of bioclimatic design [1]

- The first approach, called the "Symptomatic method", involves replicating vernacular solutions that exhibit bioclimatic features suited to specific climates. These features adapt to its site properties and have evolved over centuries through trial and error.
- The second approach, called the "Analytical method", entails analytical studies of the climatic characteristics of the site where the building is located, utilizing advanced digital technology to get a deeper understanding of the climate, which can propose the best solution during the design process.

2.3. Bioclimatic design strategies

It is important to conduct a preliminary assessment of the environmental conditions of a building site before implementing bioclimatic architectural strategies. This assessment must consider the overall climate of the region, the macroclimate, and the microclimate conditions [30]. The evaluation will determine the building's placement within the Givoni Bioclimatic chart and whether additional heating or cooling treatments are necessary to achieve thermal comfort. Theoretical analyses suggest that buildings outside the comfort zone will experience heat loss or gain, and various bioclimatic architectural strategies can be implemented to solve this issue as in Fig. 4 [1, 31].

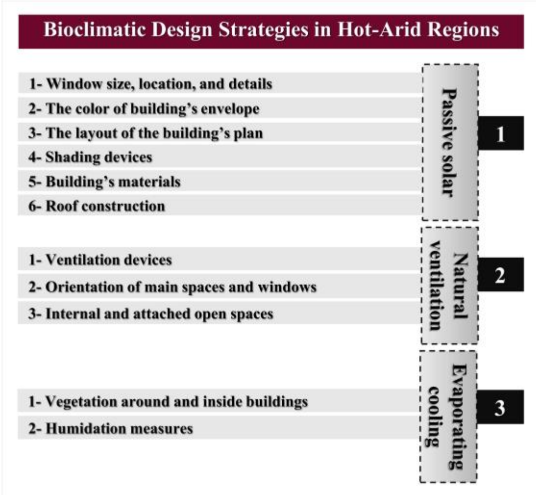


Fig. 4. Classification of bioclimatic design strategies in Hot-Arid Regions [9, 10]

The thermal performance of the buildings in hot-arid regions is affected by various design elements that impact user's comfort. These design elements include internal and attached open spaces, the orientation of spaces and windows, the building's plan layout, size and location of windows, shading devices, building materials, the color of the building's envelope, vegetation and water elements surrounding the building. To classify the strategies used in hot-arid regions, Mohamed (2010) has adopted Fathy's and Givoni's classifications, resulting in the identification of key strategies such as passive solar design, natural ventilation, and evaporative cooling [9, 10].

3. Natural ventilation

3.1. Definition

The natural ventilation strategy involves the replacement of stale indoor air with fresh outdoor air, driven by natural forces. This method provides several benefits, such as reducing elevated temperatures, removing odors, bacteria, dust, carbon dioxide, and smoke, as well as lowering a building's energy consumption[32].

3.2. How air moves?

The airflow pattern and temperature distribution in a building are regulated by two main forces [33]:

3.2.1. Wind-driven force

The air movement is attributable to the variation in wind pressure, which can be explicated through Bernoulli's equation as follows [34]:

$$P + (½) \times \rho \times v^2 + \rho \times g \times h = constant$$

The equation states that when the observed air height remains constant, fluid pressure is inversely proportional to the square of the velocity. This phenomenon is exemplified by a funnel-shaped tube shown in Fig. 5 with a side opening connected to another tube. As air is pumped into the funnel "with the same amount at the same time" and accelerates, there is a drop in air pressure at point A compared to point B. This pressure difference causes air to move from the high-pressure area to the low-pressure area, resulting in air being pulled through the side tube [24, 34].

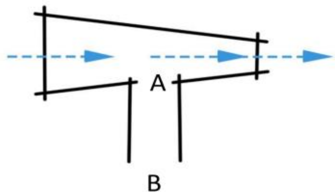


Fig. 5. Bernoulli's equation explanation [24]

Similarly, in buildings under the influence of outdoor winds, windward sides experience an increase in air pressure resulting in a positive pressure area, while the leeward sides form negative pressure zones due to air vortices. This pressure difference creates air movement within the building, and the rate of ventilation depends on the size of the openings that allow air to enter and exit and the wind's strength, see Fig. 6 [33].

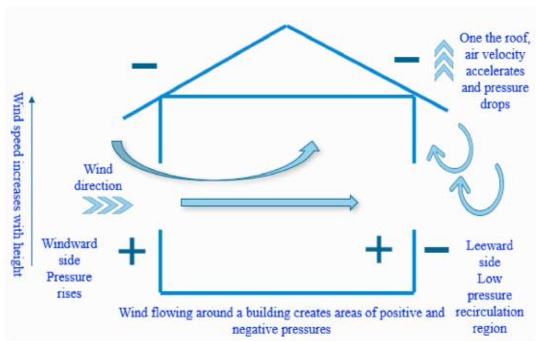


Fig. 6. Airflow caused by wind-driven force [33]

3.2.2. Buoyancy-driven force

The movement of air can be explained by the stack effect, which is caused by the heating of air molecules by the Sun leading to a rise in temperature and a decrease in air density near the Earth's surface. This warmer air rises, and cooler, denser air replaces it, causing a difference in pressure that generates air movement, which can also be described as thermal buoyancy, the chimney effect, or the stack effect [35]. On the building scale, when indoor air is warmer than outdoor air due to a heating source, the warm air moves upward, leading to higher pressure in the building than outside. This causes hot air to exit the building through upper openings and cold air to enter from outside. The airflow intensity is influenced mainly by the height difference between air entering and exiting the building and variations in air density, see Fig. 7 [33].

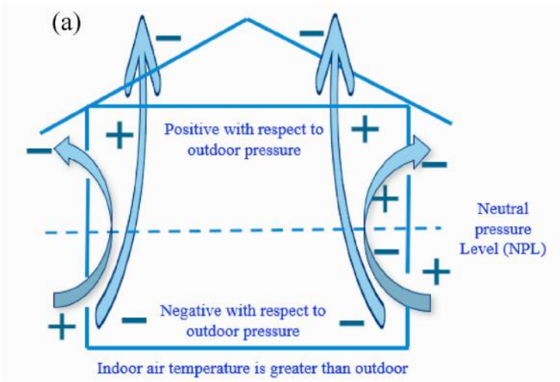


Fig. 7. Airflow caused by the stack effect [33]

To determine the airflow direction in buildings that rely on Buoyancy-driven force, it is essential to identify the neutral pressure level (NPL) for the building's openings [36].

Neutral Pressure Level

The neutral pressure level is a point of equilibrium between internal and external air pressures that serves as a link between areas of high and low pressure. This level is typically located closer to larger opening areas, with a greater distance resulting in higher pressure differentials and airflow, as shown in Fig. 8. The neutral level is usually positioned at 0.3 to 0.7 of the building's total height, and raising its height can help distribute fresh air to larger areas below [33, 37].

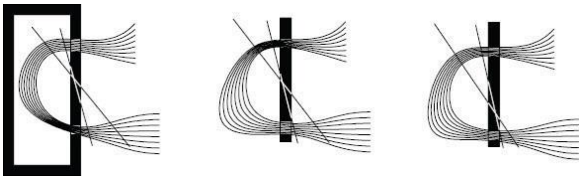


Fig. 8. Neutral level movement according to the opening area [36]

Designers should also create outlets for warm air above the neutral level to prevent user-occupied spaces from becoming excessively hot [36].

3.3. Effect of natural ventilation on thermal comfort

The use of natural ventilation is widely recognized as a practical and economical means of enhancing indoor thermal comfort in buildings by promoting air movement around occupants [38]. However, the effectiveness of this cooling strategy is contingent upon several critical factors in each environment [23]. Achieving an appropriate air velocity inside the building is a vital factor in the effectiveness of natural ventilation, as air velocities that are either too high or too low can cause discomfort among occupants [24]. Several studies have established acceptable air velocity levels, which are summarized in Table 2 [27]:

Table 2. Acceptable rates of air velocity [27]

Wind speed (m/s)	Remarks
Less than 1.6	Low wind speed
1.6 - 3.5	Acceptable wind speeds
3.5 - 5	High wind speed
More than 5	Unacceptable wind speeds

Additionally, relative air humidity is an important factor that influences natural ventilation since it affects the rate of evaporation from the body, and inadequate ventilation may lead to high relative humidity levels and moisture accumulation, resulting in reduced airflow to spaces, Table 3 shows the appropriate rates of relative humidity as follows [33].

Table 3. Appropriate rates of relative humidity [39]

Relative humidity (%)	Remarks
0 - 20	Uncomfortably dry
20 - 60	Comfort range
60 - 100	Uncomfortably wet

The air change rates between internal and external spaces are also essential. It is measured by ACH "Air Changes per hour" according to the equation [40]:

ACH = (Airflow in CFM × 60) / (Room Area × Ceiling Height)

The minimum air change rate allowed is 0.5 ACH [8], and the ideal air change rate for appropriate thermal performance is between 1.5 and 2 ACH [41]. Additionally, studies have shown that airflow rates below 10 liters/s can have negative health effects, especially on children and the elderly [36]. Furthermore, natural ventilation in hot-arid regions can significantly enhance thermal comfort efficiency by 30% to 35% compared to closed spaces, according to previous studies [42].

3.4. Natural ventilation strategies

There are four main strategies in the natural ventilation process included [43, 44]:

3.4.1. Single-sided ventilation

In this strategy, all openings of the building are located on one side only, which can achieve ventilation through pressure difference or stack effect or a combination of them, especially when the openings are located at different heights of the façade [44]. Studies have shown that a single opening can facilitate airflow due to wind pressure difference, provided that the width of the space does not exceed twice its height from the ground to the ceiling. For a space with two openings, the air is driven by the stack effect, and the maximum allowable depth is no more than 2.5 times the height of the space, as illustrated in Fig. 9 [33]. Additionally, the area of the openings in the wall is approximately 1/20 of the room area [36].

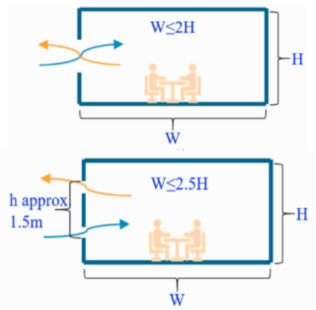


Fig. 9. Depth of the space compared to its height: single opening (top) – two openings (bottom) [33]

However, this ventilation strategy is undesired when designing for hot-arid climates as it is deemed ineffective [8], and if necessary, it is recommended that two wide-spaced windows be installed on the wall to enhance ventilation performance, as illustrated in Fig. 10 [45].

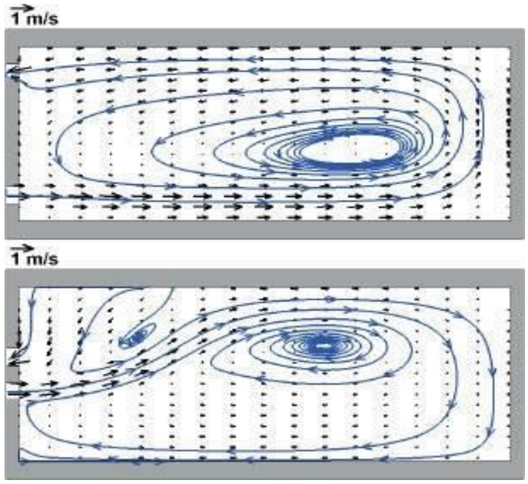


Fig. 10. Effect of the space between openings on air distribution inside spaces: wide-spaced (top) – close-spaced (bottom) [36]

3.4.2. Double-sided ventilation

The implementation of a double-sided ventilation strategy can increase the maximum depth of the space, which permits the ingress of air from one opening and egress from the other [45]. This strategy can be classified into two categories:

Cross-ventilation:

Openings are placed on opposite facades of the building , with air being drawn into the internal space by the difference in air pressure [44]. It is recommended that the depth of the space should not exceed five times its height from floor to ceiling, as shown in Fig. 11 [33].

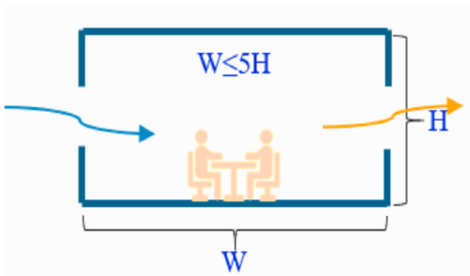


Fig. 11. Depth of the space compared to its height in cross-ventilation strategy [33]

Corner-ventilation:

It is very similar to cross ventilation but occurs between two adjacent walls, as Fig. 12 [44].

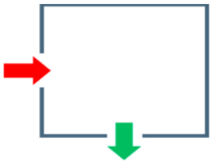


Fig. 12. Corner-ventilation

Based on several previous research studies, it has been demonstrated that cross-ventilation is more effective than single-sided in hot-arid climates [8, 42], as it produces higher indoor air speed values. Moreover, it increases the building's ability to achieve thermal comfort by 20% to 25% [46, 47].

3.4.3. Wind-induced ventilation

In this strategy, air movement is a result of naturally occurring pressure variations [48]. Various elements, such as Wind Catchers, Rotating Ventilator, or Venturi roofs, are used to harness wind movement, see Fig. 13 [37], by positioning them on building rooftops to optimize exposure to outdoor winds, whereby air is drawn and directed downwards the building through vents as a result of the pressure of the accumulated air. Simultaneously, an opposing pressure causes air to be extracted from the building through a specific opening to air exits [33].

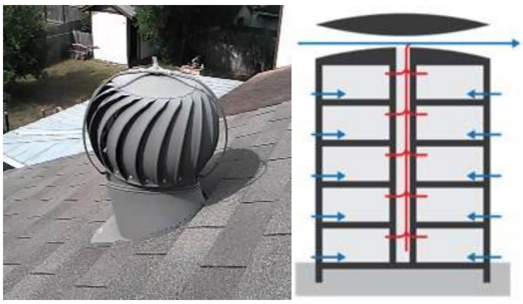


Fig. 13. Air movement through: Rotating Ventilator (left) - Venturi roof (right) [37, 49]

In hot-arid regions, the use of Wind Catchers has been applied to alleviate issues associated with utilizing wind for ventilation, such as air pollution and the influence of urban patterns on airflow, particularly in uniformly high buildings. It consists of openings oriented to one or more directions (up to eight) at the top of a building, see Fig. 14 [1, 10, 50].

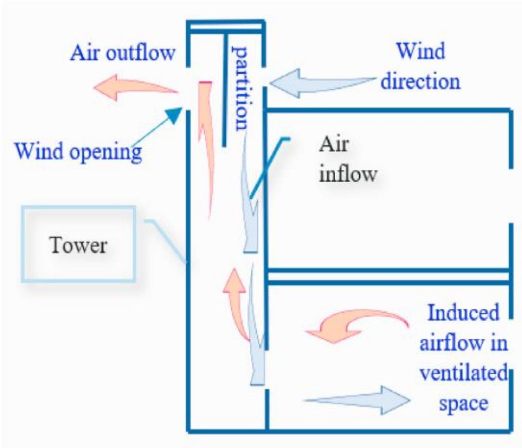


Fig. 14. Air movement inside wind catchers [33]

3.4.4. Stack ventilation

To implement this strategy that results from variations in air temperature, three key requirements for air circulation must be applied: lower openings that allow fresh air to enter the space, upper openings from which warm air can exit, and a source of heat, either internal or external [33]. Various elements use this ventilation strategy, such as Solar Chimneys, Trombe wall, Double Skin Facade, atrium, and courtyards, as shown in Fig. 15 [37].

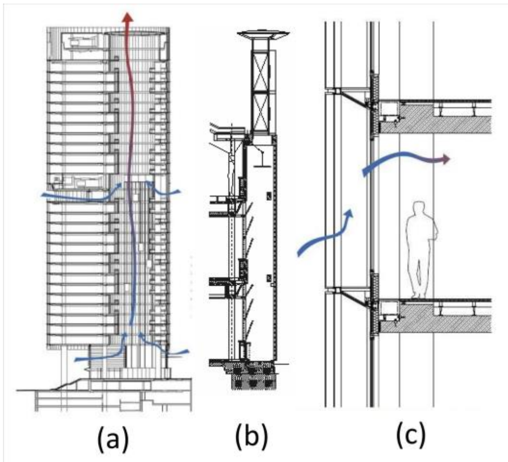


Fig. 15. Air movement through: atrium (a) – solar chimney (b) – double skin façade (c) [51, 52]

In hot-arid climates, one of the widely adopted ventilation elements that rely on the stack effect is the courtyard, see Fig. 16, as the orientation of spaces towards it facilitates air movement inside the building [8, 10, 53].

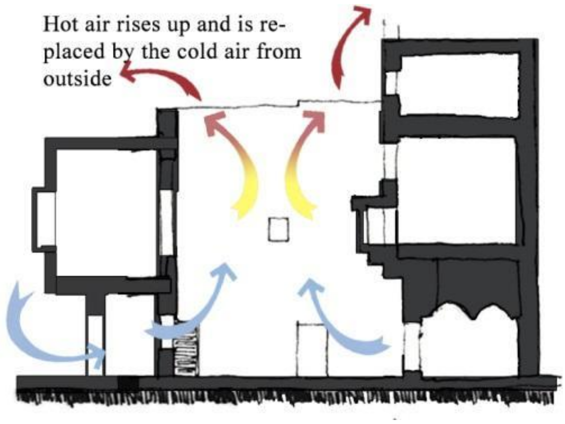


Fig. 16. Air movement inside the courtyard [35]

3.5. Factors Affecting Air Movement

Various factors impact the airflow inside and around a building, regarding its velocity and direction as follows [24, 54]:

3.5.1. Site typology

Wind speeds increase as the altitude from the Earth's surface increases, which can be attributed to fewer obstructions that impede wind movement [54].

3.5.2. Site vegetation

Wind speeds experience a significant reduction upon entering a region with dense trees, decreasing by 60-80% after 30 meters, 50% after 60 meters, and reaching 7% of their initial value after 120 meters. It is also observed that tall trees change the wind direction, as shown in Fig. 17 after the wind has traveled up to five times the height of the tree, and the wind does not touch the ground until ten times the height of the tree [54].

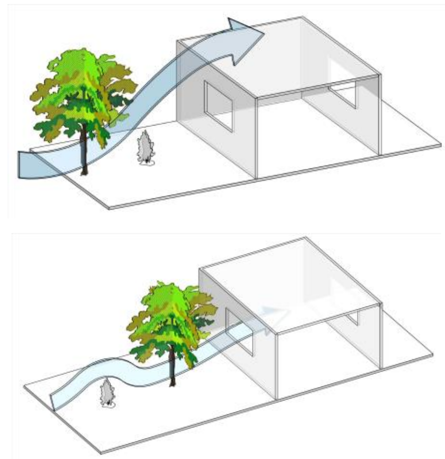


Fig. 17. Using trees to direct air away (top) and into (bottom) the building [Author]

In hot-arid environments, vegetation can affect temperatures and wind speeds through evaporating cooling also. Previous studies found that a 20% increase in vegetation resulted in temperature reductions of up to 3 degrees. Similarly, another study showed that a 20% increase in vegetation led to decreased radiation levels, improved wind speed, and a cooler environment by 2.33° [55]. Furthermore, planting specific trees species like Arabian acacia, albizia, and camphor around buildings can help mitigate the effects of dust and sand-laden wind from the south [56].

3.5.3. Urban pattern

The configuration of buildings, including their height and pattern, can impact wind movement. The distribution of uniform blocks, either in parallel or reciprocal rows, can significantly reduce the turbulent air behind the building, known as wind Shadow, where wind speeds decrease, see Fig. 18 [54].

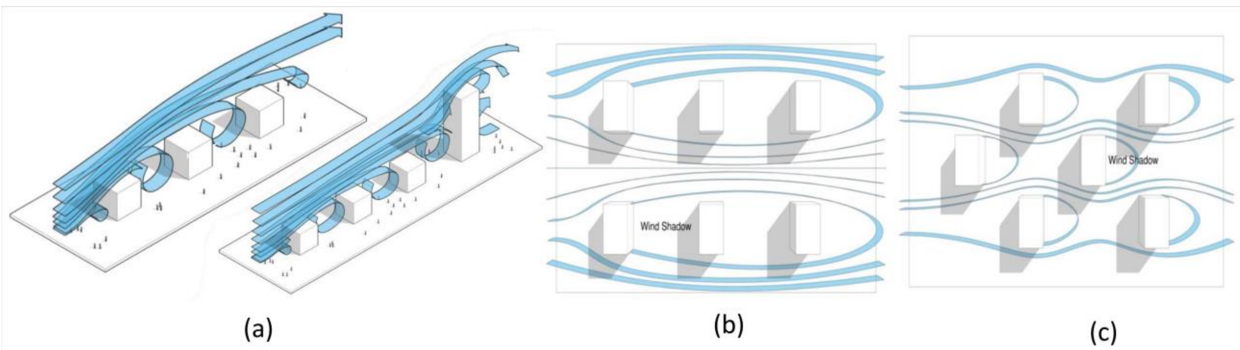


Fig. 18. The effect of buildings hight on wind shadow pattern (a) – wind shadow of parallel urban pattern (b) – wind shadow of reciprocal urban pattern (c) [Author]

Compact and dense urban patterns in regions with hot-arid climates provide protection to buildings against sandstorms while enhancing cooling winds and providing shadows on exterior surfaces, thus decreasing heat gain [41, 45, 52].

3.5.4. Building form and orientation

The building's orientation to wind flow direction induces vortices that vary depending on the wind pressure, building shape, and orientation, as indicated in Fig. 19 [54].

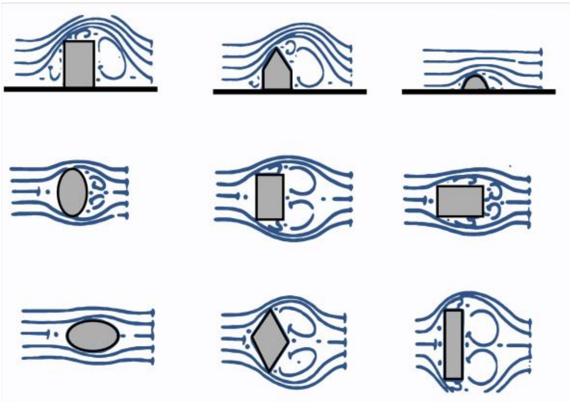


Fig. 19. Effect of building shape on wind pattern [54]

In hot-arid regions, the recommended building design involves a compact form with a low ratio of surface building area to its volume, while promoting natural ventilation [45, 52]. For shading purposes, it is preferable to align the building's longitudinal axis in an east-west direction [10]. This orientation does not necessitate alterations towards wind direction, and if necessary, it can be directed at any angle between 0-30 degrees of the prevailing wind direction, which also corresponds to an east-west orientation of 15-45° [45].

3.5.5. Openings orientation

The direction of vents relative to wind direction impacts airflow within spaces, as shown in Fig. 20 [24]. For effective air movement in hot-arid regions, Fathy (1986) suggests that openings should be oriented perpendicular to the prevailing wind (north-west), and along the east-west axis to mitigate solar radiation. So, he proposes a direction of (North-East-East) for openings, which is ideal if a cross-ventilation strategy is applied. However, for other ventilation elements such as wind catchers, it is recommended to retain the east-west axis orientation to avoid solar radiation [10].

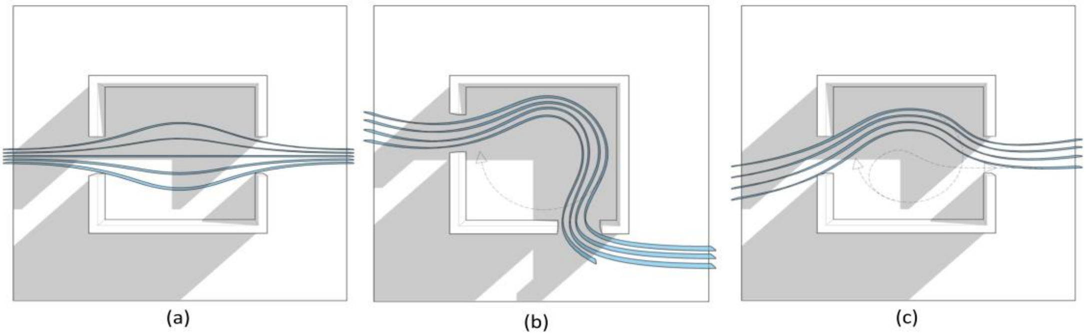


Fig. 20. Two opposite openings and vertical wind (a) - Two adjacent openings and vertical wind (b) - Two opposite openings and tilted wind (c) [Author]

Givoni (1998) also suggests that ventilation in hot-arid climates can be improved by directing openings within 30-60° of the wind direction [8], while recent studies indicate that openings with an angle of 45° relative to the wind direction can result in better and more efficient air movement and distribution within the space more than perpendicular [41, 52, 57].

3.5.6. Openings level

The airflow within a space is affected by the level of openings on the walls [54], as openings at a high-level result in air purification at this level without causing any significant air movement for the occupants, see Fig. 21 . Therefore, air outlets are recommended to be placed at high levels on the walls to expel the accumulated hot air in the space [45]. On the other hand, air inlets are recommended to be placed at the user level within the space [35].

In hot-arid regions, it is recommended to position openings at different heights on opposing walls to enhance natural ventilation, allowing air to enter through the windward side and exit through the leeward side of the wall [41].

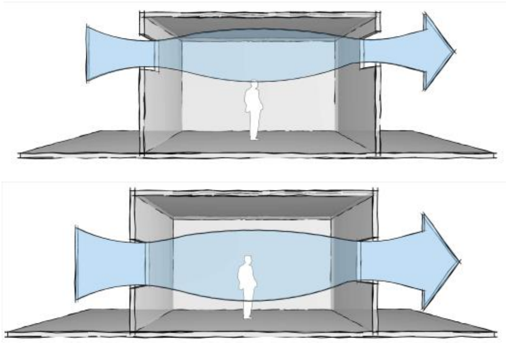


Fig. 21. High-level openings result in bad ventilation (top) - Two opposite openings at a human level for good ventilation (bottom) [Author]

The recommended sill height for openings depends on the user status, as shown in Table 4.

Table 4. openings sill height recommendation [27]

Sill height (m)	Status
0.75	For sitting on the chair
0.60	For sitting on the bed
0.40	For sitting on the floor

3.5.7. Openings size

The variation in dimensions of openings affects air velocity and flow [54], as it creates notable pressure differences, which can increase the airflow rate into the space, see Fig. 22 [36, 41]. Several natural ventilation standards recommend a 4:5% ratio between the openings area and the floor area of the space as optimal [27, 58].

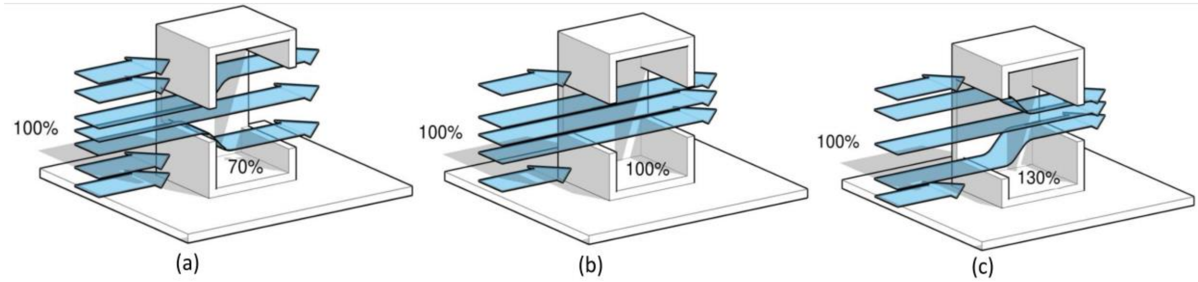


Fig. 22. Variation in air flow rates within a space due to variation in the air inlet and outlet size – (a) the inlet is smaller than the outlet – (b) the inlet and outlet are the same – (c) the inlet is bigger than the outlet size [Author]

In the context of designing openings in hot-arid areas, several studies have suggested that the north facade should have the largest proportion of the openings area, while the south and west facades should have fewer openings area, which can be increased with shading elements [8, 10]. Givoni (1998) suggested using small windows of about 5% to 10% of the floor area [8]. On the other hand, Al Masri (2010) suggested that the proportion of entrance and exit openings should not be less than 3% to 5% of the space area [41], and Kaddour et al (2022) recommend the portion of openings should also be not less than 4% of the net occupied area [59]. Another study has suggested that the area of the openings in space should not exceed 20% of the total walls area to achieve good distribution of air, and the ratio of the opening area related to its wall area should not exceed 40% [60]. Additionally, Habitat (2014) pointed out that 10 : 20 % of the north or south façade should be openable [45]. Another study concluded that the optimal openings area is about 20:30 % of the facade area [61]. Also, Soflaei et al (2016) studied the four facades of buildings located in hot-arid regions and found that the area of openings in the north facade ranged between 17% to 33% in normal cases and sometimes increased in some cases to 94% of the facade area, while the openings area in the north and south facades ranged from 21% to 29%, and the east and west ranged from 17% to 18% of the facade area [47]. As indicated by Alshuhail et al (2020), the optimum ratio of opening area related to the wall is between 10:30 %. Also, Golabzadeh (2020) concluded that to achieve optimal ventilation, openings in the north facade should be at least 50% and in the south no more than 20% of the facade area [52].

3.5.8. Internal partitions

The internal partitions in the space can control the direction and velocity of air, as illustrated in. Fig. 23, as decreasing barriers leads to easier airflow. Studies have found that placing partitions near the air inlet results in the lowest air velocity, while positioning them near the air outlet leads to the most desirable ventilation state [54].

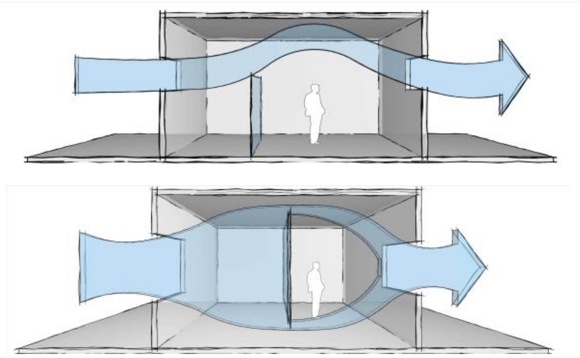
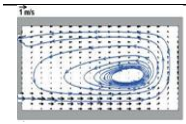
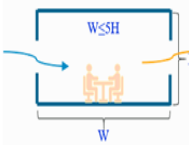
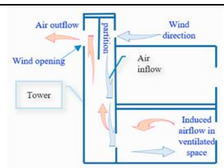
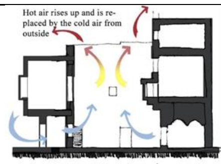


Fig. 23. The effect of partitions on wind direction – partition near inlet (top) – partition near outlet (bottom) [Author]

4. Results and Discussion

Bioclimatic architecture has become a popular approach in designing buildings that are energy-efficient, environmentally friendly, and comfortable for occupants. In summary, this paper highlights the significance of natural ventilation in bioclimatic architecture as a sustainable and effective strategy for creating comfortable indoor environments in hot-arid regions, where high temperatures and low humidity pose significant challenges to building design. The research provides valuable insights and recommendations, as shown in Table 5, for architects

Table 5. Proposed guidelines for enhancing natural ventilation in hot-arid regions [Author]

Guidelines		Natural ventilation strategies (hot-arid regions)			
		1	2	3	4
		Single-sided ventilation	Double-sided ventilation	Wind-induced ventilation	Stack ventilation
					
		Undesired and if necessary, it is recommended two wide-spaced windows.	Cross-ventilation is more effective than single-sided or corner-ventilation.	Wind Catchers is one of the widely adopted ventilation elements that rely on this strategy.	One of the widely adopted ventilation elements that rely on the stack effect is the courtyard.
1. Urban	Vegetation	- 20% of the site. - Planting trees like Arabian acacia, albizia, and camphor.			
	Pattern	- Compact and dense.			
2. Building	Form	- Compact form. - Low ratio of surface building area to its volume.			
	Orientation	- East-west direction for shading purposes. - 0-30° from perpendicular angel of the wind direction (North-west) for ventilation purposes.			
3. Openings	Orientation	- North-East-East preferred if a cross-ventilation strategy is applied. - East-west axis for other ventilation elements such as wind catchers. - 30-60° from perpendicular angel of wind direction.			
	level	- It is recommended to position openings at different heights. - Air outlets are recommended to be placed at high levels and air inlets to be placed at the user level within the space.			
	Size	- Windows are about 3% to 10% of the floor area. - The openings area should not exceed 20% of the total walls area. - The opening area related to its wall area should not exceed 40%. - The openings area in the north façade doesn't exceed 40% in normal cases and increases in some cases to 94% of the facade area. - The openings area in the south facades doesn't exceed 20%. - The east and west ranged from 10% to 30% of the facade area. - The inlet size of the airflow is preferred to be bigger than the outlet size.			
4. Internal partitions		- Partitions near the air outlet leads to the most desirable ventilation state.			

and building designers seeking to implement natural ventilation techniques in their sustainable building designs in hot-arid areas.

5. Conclusion

Natural ventilation is an important bioclimatic design strategy in promoting thermal comfort, especially in hot-arid regions. By addressing the specific problem of high temperatures, humidity, sandstorms, insufficient airflow and considering the challenges that faces architects while building in this climatic area, the research provides insights into effective design principles and strategies for achieving efficient natural ventilation in these regions. This will enable a comprehensive examination of existing knowledge and best practices in bioclimatic architecture and natural ventilation. Accordingly, it will contribute to the development of sustainable building practices and enhance the understanding of how to create comfortable and environmentally responsive built environments in hot-arid regions.

Regarding future research, the conclusions drawn from this literature analysis can guide future studies to develop regional guidelines as the guidelines provided in the research could serve as a basis for developing region-specific guidelines for bioclimatic design in hot-arid areas. Different climates within these regions may have specific considerations, and further research could refine the guidelines accordingly.

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