

IMPACT OF BREATHING FACADES AND BIOMIMICRY ON VENTILATION AND INDOOR AIR QUALITY

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Abstract

Introduction: One of the most pressing challenges today is global warming, which has significantly increased building temperatures. Developing cost-effective solutions to mitigate indoor overheating is therefore a key architectural task. This paper examines the impact of breathing facades on ventilation and indoor air quality, with a particular focus on the relationship between biomimicry and facade design. It emphasizes how biomimicry can inspire architects to address environmental challenges and explores the concept of “breathing skins” through two case studies. **Purpose of the study:** The study aims to analyze the connection between biomimicry and breathing facades, and to evaluate their effectiveness in enhancing indoor air quality and reducing building temperatures. **Methods:** The methodology combines inductive and analytical approaches within the framework of a systematic literature review, complemented by comparative analysis to assess the performance of innovative facade systems. **Results** indicate that smart breathing facades have significant potential to reduce pollution levels and improve urban livability.

Keywords: breathing facades, sustainable architecture, biomimicry, ventilation, indoor air quality.

Introduction

Poor indoor air quality negatively affects the health, learning capacity, and productivity of building occupants. In existing structures, facade ventilation systems are commonly used to enhance indoor air quality; however, their effectiveness remains limited due to susceptibility to wind conditions and ambient temperature fluctuations. Breathing facades represent an innovative approach to building envelope design, aiming to improve energy efficiency, enhance indoor air quality, and support climate change mitigation (Omran et al., 2016). By integrating intelligent systems, these facades can adapt to dynamic environmental conditions, thereby optimizing thermal comfort and sustainability (Moloney, 2006). This paper provides an overview of breathing facades, emphasizing their advantages and potential applications in contemporary architecture.

Objectives

The objective of this study is to examine the role of biomimicry in architecture, with particular attention to technologies that mitigate indoor temperature extremes by enhancing ventilation and air quality through the use of breathing facades. The research highlights six innovative facade systems: intelligent facades, climate adaptive building shells, vertical greenery systems, phase change materials, thermo-bimetals, and breathing walls. These systems are evaluated through a comparative analysis to identify their effectiveness and potential applications.

The study specifically focuses on facade systems that integrate breathing mechanisms, both on the exterior and interior of buildings. Fig. 1 illustrates the main objectives of the research.

Issues and Challenges

The rise in indoor temperatures represents one of the major global challenges of the 21st century, with climate change expected to cause long-term impacts on the built environment. Recently, new generations of materials and treatments have been developed to reduce air pollutants. The key challenge, however, lies in ensuring that such materials and systems not only contribute to mitigating global warming but also effectively improve indoor air quality. Breathing facades, along with other innovative ventilation strategies, hold significant potential in addressing these challenges (Imbabi and Peacock, 2003).

Methods

This study employs inductive and analytical approaches within the framework of a systematic literature review, aiming to identify the most effective techniques for reducing indoor temperatures through the use of breathing facades. Particular attention is given to biomimicry-inspired concepts that contribute to environmental goals by establishing the relationship between natural systems and breathing facade design. The research also examines differences among innovative facade systems in this context. At an advanced stage, a comparative analysis was applied to evaluate the effectiveness of selected techniques.

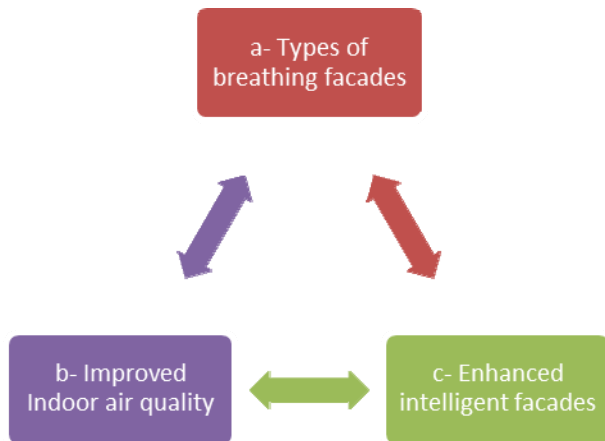


Fig. 1. Objectives of the study

A comprehensive review of relevant literature was conducted using academic databases such as Scopus, ScienceDirect, and Google Scholar. The search strategy relied on targeted keywords, including “breathing facades”, “sustainable architecture”, “biomimicry”, “ventilation”, and “indoor air quality”.

Literature Selection Criteria

To ensure both relevance and academic rigor, a set of criteria was established to select studies included in the literature review. The selection process was guided by the following requirements:

- The study must directly address the relationship between biomimicry, architecture, and architectural technologies or applications.
- It must provide a clear critical or applied analysis that contributes to understanding the design or technical dimensions of the topic.
- It must be published in peer-reviewed scientific journals, preferably between 1997 and 2024.

Studies were excluded if they:

- Lacked analytical depth or relied on general descriptions without a direct connection to the research topic.
- Focused exclusively on technical aspects without considering the design or conceptual dimensions.
- Were not published in reliable academic sources or could not be verified.

According to the reviewed literature, the research methodology was divided into two complementary components:

Analytical Methodology

A thematic analysis approach was applied to classify the literature into conceptual themes that formed the analytical framework of the study: (i) an overview of biomimicry and its applications in architecture, (ii) an examination of breathing skin systems supported by two practical experiments, and (iii) a detailed analysis of the behavioral

characteristics and methods of six innovative facade systems classified as “breathing facades”.

Comparative Analysis

Following the thematic analysis, a comparative evaluation was conducted among the six identified facade systems. The comparison focused on identifying the strengths and weaknesses of each case, thereby extracting general trends. This comparative analysis was essential to achieving the research objective: reducing indoor temperatures and improving air quality through the implementation of breathing facades.

Biomimicry in Architecture

Biomimicry offers architects a framework for addressing environmental challenges by drawing inspiration from natural systems (Benyus, 1997). It is a science grounded in the study and simulation of nature, particularly the interactions of living organisms with their environments (Nkandu and Alibaba, 2018). From this perspective, the environment is understood as inherently balanced, and by applying its principles to building design, architects can develop effective solutions to various issues. Biomimicry is commonly categorized into three levels: organism, behavior, and ecosystem, as illustrated in Fig. 2.

An example of the organism level is the lotus flower, whose leaves possess a natural self-cleaning property. This characteristic has been adapted to develop self-cleaning paints for building surfaces (Ensikat et al., 2011) (Fig. 3). At the behavioral level, a well-known example is the ant colony, where ants construct vertical air channels that facilitate the expulsion of indoor air to the outside. This principle has been applied in architectural design to reduce heating and cooling energy demand by up to 10 % (Pawlyn, 2019), as illustrated in Fig. 4. Finally, the ecosystem level represents the integration of organismal and behavioral strategies, emphasizing



Fig. 2. Three levels of biomimicry



Fig. 3. The texture of lotus flower leaves

the interaction of sustainable designs with their surrounding environment.

Breathing Skin System

Extreme weather conditions, such as those found in the Arctic, present significant challenges to life; yet organisms like polar bears thrive in these

environments. Their survival is largely due to thermoregulatory adaptations, such as dense white fur, which protects them from extreme cold. Thermoregulation is an internal response to external conditions, aiming to maintain thermal balance within the organism — a form of homeostasis. Homeostasis represents thermal stability, allowing the body to use minimal energy to regulate temperature (Craig, 2018). When applied to building envelopes, these principles inspire automatic thermoregulatory systems, enhancing energy efficiency. The body maintains internal homeostasis through a feedback loop (Becker, 2016; Turner, 2016). The neuroendocrine system detects deviations from normal conditions and transmits these signals to the brain, which then activates regulatory organs to respond to external changes, thereby restoring balance. This process represents the negative feedback loop of temperature regulation. Such biological mechanisms inspire the design of intelligent buildings, providing a model for energy-efficient, self-regulating systems.

Natural ventilation for high-rise buildings (termite model)

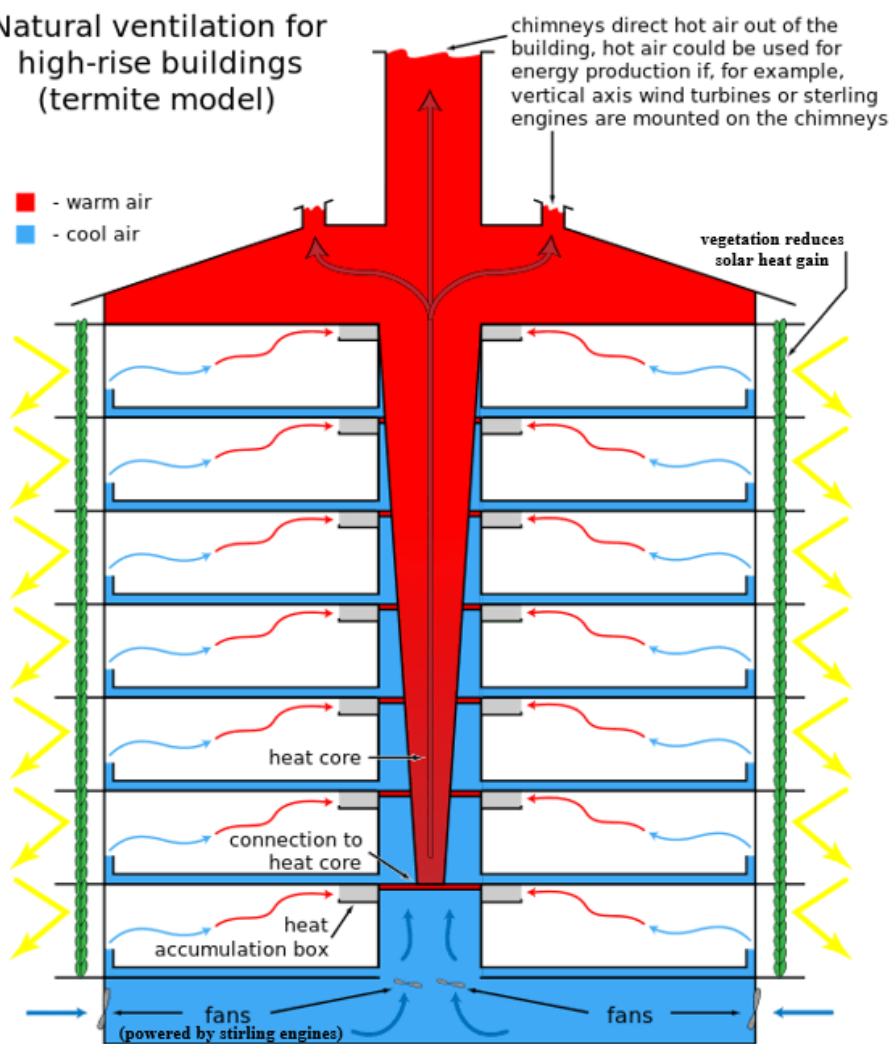


Fig. 4. A schematic showing the natural ventilation used in the Eastgate building, Harare

Human respiration also plays a critical role in sustaining life and thermoregulation. Lung-inspired experiments have demonstrated the ability to self-regulate temperature. Heat exchange in respiration occurs primarily in the diaphragm and alveoli, as illustrated in Fig. 5. Respiration consists of two main processes: external respiration, involving inhalation and exhalation, and internal respiration, which is the gas exchange between oxygen and carbon dioxide. Oxygen-rich air entering the lungs is transported via blood vessels to the alveoli, where internal respiration is closely linked to metabolism. Thus, biomimicry of respiration encompasses both external and internal mechanisms, offering valuable insights for the design of intelligent, energy-efficient building envelopes.

Pneumatic Design

The organic respiration process serves as a model for the breathing skin, a type of wall that employs passive or active ventilation. It can regulate environmental factors such as solar radiation, relative humidity, and surface temperature, as illustrated in Fig. 6, providing a comprehensive framework for environmental thermal evaluation.

The two case studies analyzed in this research applied different methodological approaches, both relying on pneumatic mechanisms to create favorable indoor environmental conditions.

Becker (2016) developed a breathing skin, illustrated in Fig. 7, in a showroom project inspired by organic skins that allow air to enter through small, tube-like apertures in the wall. The system regulates airflow, incident velocity, ambient temperature, and sound dispersion. Internal airspeed stabilizes naturally through the wall design. The wall features a reversed air duct mechanism that enables control over air volume, airspeed, and anticipated temperature variations, influenced by its morphological configuration. Solar transmittance is modulated through the color of the material: transparent and dark opaque polycarbonate sheets are used in the air ducts in two color variations (Laird, 2016). By adjusting the positioning of these colors relative to the Sun's orientation, the transparent wall can be rendered translucent or opaque, thereby

managing solar gain while optimizing airflow through the air pockets.

The second case study focuses on a project that employed a light sensor to monitor changes in the external environment. This project was designed and implemented by a group of students from the Institute for Advanced Architecture of Catalonia (IAAC). The system, referred to as the adaptive pneumatic skin (Fig. 8), is an adaptive wall that actively regulates airflow in response to environmental conditions. The wall's breathing mechanism, inspired by the human nervous system, allows it to respond dynamically to external stimuli. According to the system's programming, when the light sensor detects a specific level of solar radiation, the air valve opens to activate the air compressor, releasing air through the pneumatic pipes. Each balloon inflates as the air flows through its apertures, mimicking the process of inhalation and exhalation observed in animals. Unlike the previous breathing skin project, this system incorporates a mechanical feedback loop that actively responds to environmental variables, adjusting the indoor environment accordingly. It regulates indoor conditions and light permeability by reacting to changes in both external light and temperature (IAAC, 2019). The materials used in the balloons further influence the internal environment. Constructed in multiple colors with varying visual transmittances, the membrane also functions as a dynamic solar shading device, as its transparency changes in response to air pressure levels (IAAC, 2019).

The two case studies discussed above are both inspired by biomimicry, particularly the influence of breathing and pneumatic mechanisms on indoor temperature regulation. Although both systems demonstrated favorable effects on internal conditions, their embedded control strategies differ. Since the breathing skin relies solely on external wind pressure, the fluctuations in internal conditions closely mirror those of the external environment. As a predominantly passive system, it lacks the capacity to self-correct and reach an optimal internal state. In contrast, the adaptive pneumatic skin incorporates automated control using light sensors to detect

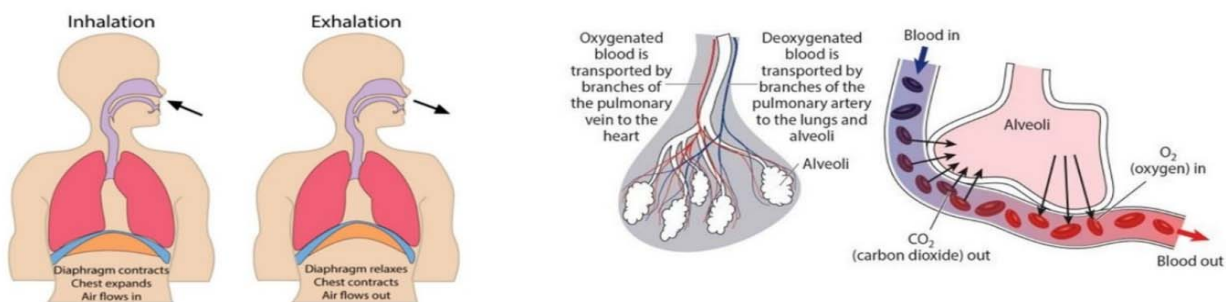


Fig. 5. External (left) and internal (right) respiration

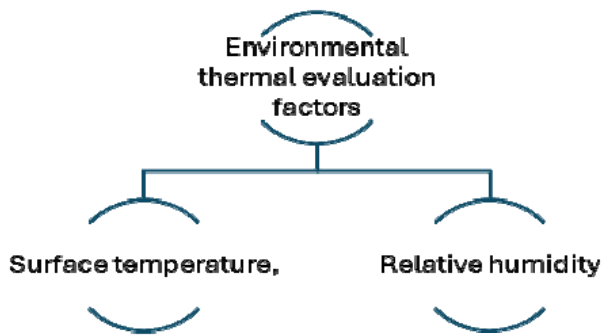


Fig. 6. Environmental thermal evaluation factors

environmental changes. This mechanical feedback system enables the indoor environment to adjust more precisely and maintain desired conditions.

Smart Materials Analysis

Enhancing energy efficiency in the building sector is one of the most effective strategies for ensuring sustainability and conserving natural resources for future generations. The energy performance of a building is closely linked to the condition of its envelope, as efficient envelopes minimize energy

consumption for heating, cooling, and ventilation. Smart building skins are capable of responding to both the surrounding environment and external weather conditions (Beaven and Vincent, 2004). By incorporating environment-responsive materials and adaptive design strategies, energy consumption can be significantly reduced. Smart materials, which react dynamically to changes in their surroundings, play a crucial role in these adaptive systems (Addington and Schodek, 2005).

The following section provides a detailed analysis of behavioral traits and smart facade strategies, which can serve as a foundation for energy simulations and physical experiments. Six advanced facade technologies are examined: intelligent facades, phase change materials, vertical greenery systems, thermo-bimetals, breathing walls, and climate adaptive building shells. Each technology is evaluated based on its behavioral response to environmental changes and its potential to reduce energy consumption.

Intelligent Facade

Intelligent facades integrate a variety of technologies designed to reduce energy

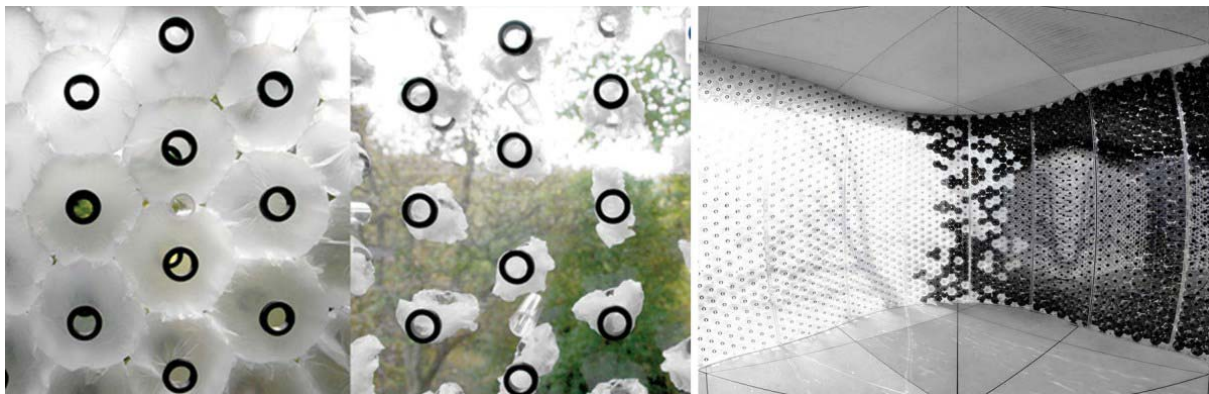


Fig. 7. Breathing skin

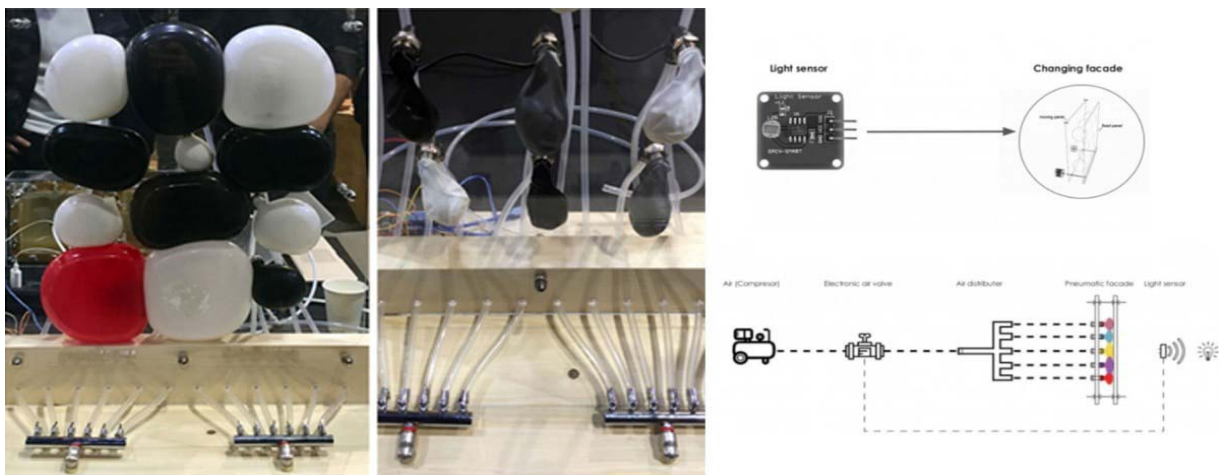


Fig. 8. Adaptive pneumatic skin

consumption and enhance indoor comfort (Omrany et al., 2016). The terms “smart materials” and “intelligent facades” are often used interchangeably, as both involve interactive, responsive, and adaptive environmental functions. The development of intelligent envelopes increasingly relies on smart materials capable of generating energy and autonomously activating in response to environmental conditions (Velikov and Thün, 2013). Compared to traditional responsive systems, intelligent facades incorporate more sophisticated electronic control mechanisms to actively improve sustainability (Moloney, 2006). In this context, an intelligent facade refers to an integrated environmental control system that simultaneously aims to reduce energy consumption and enhance internal comfort (Fig. 9).

For an intelligent facade to be responsive, it must consider three key environmental parameters: the context, the occupant, and the weather (Omrany et al., 2016) (Fig. 10). External temperature is a critical factor in responding to fluctuating conditions, while the wall must also adapt to the preferences of individual occupants and the specific context of the building (Skelly, 2000).

An external wall system can be classified as a new functional wall if it achieves energy efficiency and indoor thermal comfort by responding to internal or external environmental conditions. If it additionally incorporates intelligent features that actively promote sustainability, it qualifies as an intelligent facade. The classification depends primarily on the behavioral and functional attributes of the wall rather than its material type or structural function. Reactivity and enhanced energy efficiency are two core characteristics of intelligent facades. According to Skelly, an intelligent facade embodies five distinct traits and responds to contextual factors, as illustrated in Fig. 11. By integrating these traits, an intelligent facade achieves two objectives: reducing energy use and improving internal thermal comfort while engaging dynamically with its surroundings.

Climate Adaptive Building Shells (CABS)

Similar to intelligent facades, climate adaptive building shells (CABS) are described using terms such as “adaptable”, “intelligent”, “smart”, “responsive”, and “kinetic”, but they possess distinct characteristics. The external structural components of the building shell, such as the roof and walls, provide a boundary between the interior and exterior environments (Loonen et al., 2013). CABS facades act as external shields, protecting interior spaces from environmental influences. A notable example is the Al Bahr Towers project in Abu Dhabi (Fig. 12), which incorporates an adaptive external shading system to respond to solar radiation. The Arup Group developed the external shading system and its operating mechanism, while AHR Architects designed the tower structure.

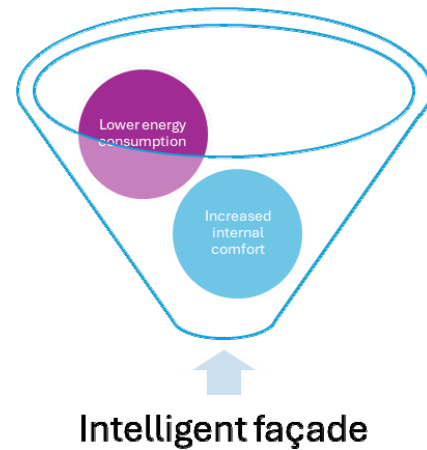


Fig. 9. Goals of an intelligent facade

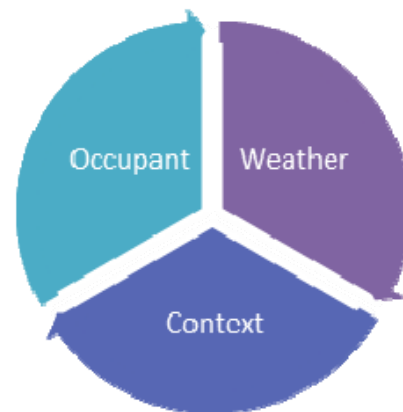


Fig. 10. Three environmental factors or parameters for responsiveness

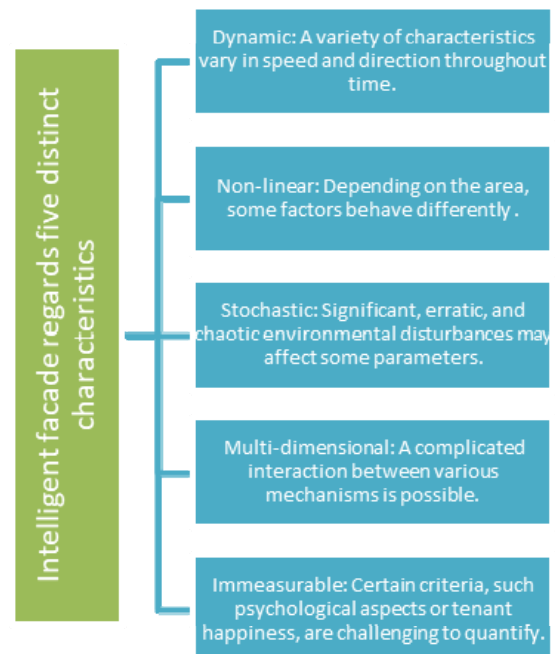


Fig. 11. Five distinct characteristics of an intelligent facade

The project features a two-layer facade, with movable shading elements attached to the exterior of the curtain wall surrounding the cylindrical tower. Solar tracking software controls the movement of these components, opening and closing them in response to the Sun's position, thereby optimizing the building's environmental performance (Autodesk, 2017). The primary advantage of this two-layer facade system is its ability to regulate energy flows and enhance indoor comfort by limiting solar heat gain. Similar to intelligent facades, CABS improve thermal comfort and energy efficiency. However, CABS distinguish themselves through three defining characteristics: adaptability, multi-functionality, and evolutionary capacity, making it possible to utilize dynamic facade elements more extensively than traditional intelligent walls.

Vertical Greenery System (VGS)

Vertical greenery systems (VGSs) can influence both surface and ambient temperatures, thereby enhancing the thermal performance of buildings. By reducing the demand for cooling energy, these systems contribute to environmental sustainability. VGSs, commonly referred to as green walls, vertical gardens, or green facades, have been widely adopted as a sustainable architectural practice worldwide (Fig. 13). The cooling effect of VGSs is achieved through a combination of plant shading, low solar absorbance, low-albedo surfaces, evapotranspiration, and the insulating properties of vegetation. These mechanisms collectively reduce the surface temperature of building walls (Pan and Chu, 2016). In tropical climates, VGSs reduce surface wall temperatures by up to 11.58°C (Wong et al., 2010). Furthermore, VGSs installed on south- and west-facing facades can reduce the building's cooling load by 1.4 % to 28.4 %, depending on the specific conditions of the building (Omrany et al., 2016).

Phase Change Materials (PCMs)

Phase change materials (PCMs) are widely used in thermal energy storage systems due to their

ability to absorb heat under normal conditions and release it when needed. Over the past decade, PCM technology has attracted considerable attention for its energy efficiency, sustainability, and heat storage capabilities. When integrated with natural ventilation systems, PCMs can provide significant reductions in cooling loads. The key mechanism of PCMs is phase change, which occurs when materials repeatedly melt and solidify at specific ambient temperatures. This allows building envelope materials to transition between solid and liquid states, absorbing or releasing heat in the process. Paraffin wax, a common organic PCM, changes phase in response to temperature fluctuations, effectively storing or releasing thermal energy as needed (Faircloth et al., 2018). In building applications, PCMs help reduce HVAC sizing by utilizing thermal energy storage systems to offset peak energy loads. Studies in Germany have shown that integrating macro-encapsulated PCMs with building materials can lower indoor temperatures by up to 4°C (Schossig et al., 2005) (Fig. 14). PCMs represent a smart and environmentally friendly solution that enhances indoor thermal comfort, improves indoor air quality, and contributes to energy savings. Building envelopes with high heat-capacity materials utilize stored energy more efficiently during periods of deficit.

Thermo-bimetals

Thermo-bimetal is an innovative smart material. These materials can change shape and move in response to variations in temperature or humidity without requiring external energy. To control self-ventilation systems, thermo-bimetals have been experimented with as adaptive components capable of opening and closing pores autonomously (Sung, 2016) (Fig. 15). Incorporating these dynamic morphological elements into building envelopes enhances indoor comfort and energy efficiency. A thermo-bimetal consists of two layers of metal with different coefficients of thermal expansion; when heated, the material curls in a certain direction. The double-layered sheet metal, such as TM2 defined by



Fig. 12. Climate adaptive building shells

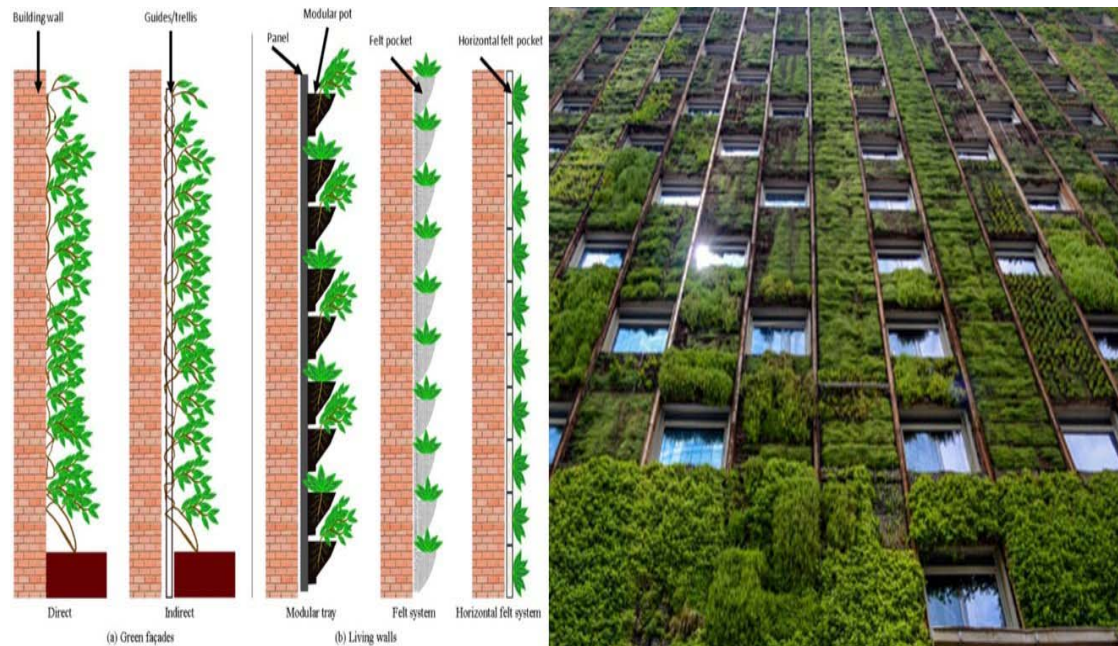


Fig. 13. Example of VGS types (left); VGS (right)

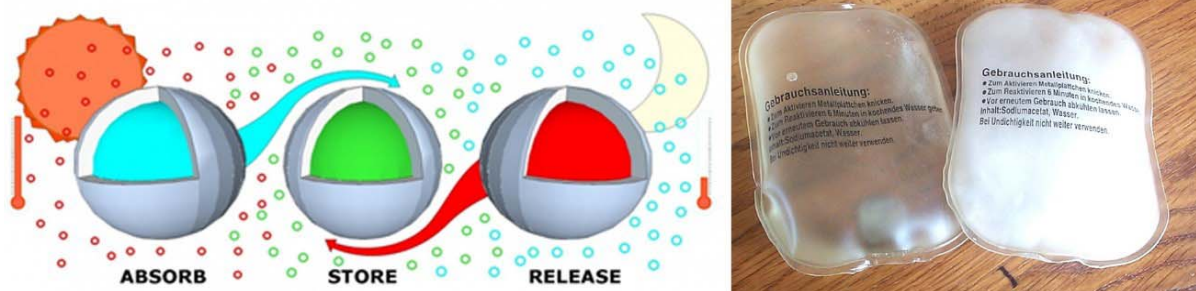


Fig. 14. Schematic diagram of macro-encapsulated PCMs (left); PCMs (right)



Fig. 15. Thermo-bimetals for natural ventilation effects

ASTM (American Society for Testing and Materials), typically includes an Invar layer with a low coefficient of expansion, while the outer layer expands more rapidly. In practical applications, such as the Pivot Shading System project, thermo-bimetals are used as shading devices. By curling in response to temperature changes, the system can regulate solar

heat gain and control light penetration (Sung, 2011). Buildings incorporating thermo-bimetals benefit from reduced energy consumption and improved indoor air quality.

Breathing Walls

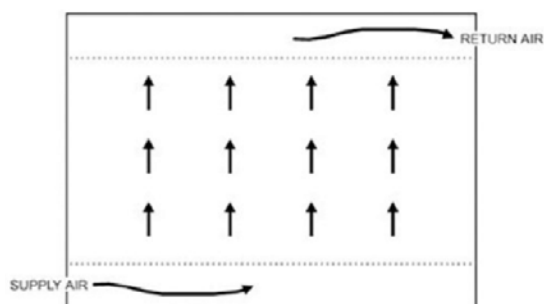
Breathing walls utilize natural ventilation to introduce outdoor air into the building. By employing

active or passive decompression, these systems draw clean air from the exterior, creating a dynamic insulating effect (Imbabi and Peacock, 2003). This approach combines natural ventilation with dynamic insulation, allowing the building envelope to “breathe” and providing two key benefits. The primary advantage of a breathing wall is the removal of indoor pollutants, delivering cleaner and filtered air to occupants. The secondary benefit is an increase in building energy efficiency, achieved through reduced thermal conductivity of the walls.

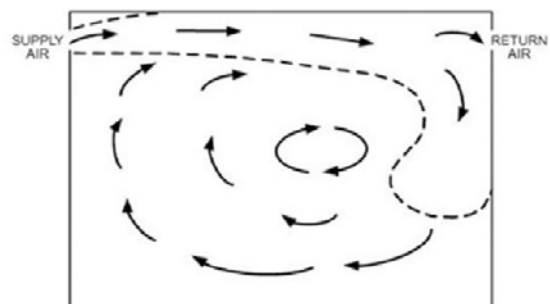
Natural Ventilation

Air ventilation is essential for maintaining proper indoor air quality, as it facilitates air movement and exchange. Building ventilation can occur through mechanical or natural means, both designed to regulate air cycles and enhance indoor air quality. Air leakage caused by differences in air pressure can produce a stacking effect within the building. Mechanical ventilation systems utilize components such as intake louvers, exhaust grilles, fans, and ductwork to purposefully circulate air into and out of the structure (ASHRAE, 2017).

Passive natural ventilation is commonly employed in breathing walls. A hollow gap in the double-layer walls allows wind pressure to induce air buoyancy, promoting airflow that removes indoor pollutants while supplying clean outdoor air. When outdoor air enters the wall system, it alters room airflow patterns and diffuses throughout the space. Two primary flow types are observed: displacement flow and entrainment flow (Fig. 16). Displacement flow utilizes buoyancy to move supplied air upward without turbulence, efficiently expelling indoor airborne contaminants through exhaust outlets. Entrainment flow combines indoor air with incoming clean air, creating a turbulent flux for distribution. However, effective mixing can be limited when air pressure is low or airflow velocity is insufficient. Maintaining appropriate air pressure and speed is crucial for the efficient removal of airborne pollutants. Proper indoor air quality and pressure management are essential to prevent the accumulation of indoor pollutants (ASHRAE, 2017).



Displacement airflow



Entrainment airflow

Fig. 16. Airflow movements

Results

Based on the preceding discussion, all six innovative facade systems — climate adaptive building shells, vertical greenery systems, phase change materials, thermo-bimetals, intelligent facades, and breathing walls — demonstrate the capacity to respond to climate-related environmental changes. Table presents a comparative analysis of these technologies according to three criteria: response to climate change, electricity consumption, and impact on indoor air quality.

All six innovative facade systems are capable of responding to climate change to enhance environmental performance. Their passive or active responses can be evaluated using various metrics that reflect improvements in environmental conditions. Five of the six systems operate passively, requiring no electricity to adjust to environmental stimuli; only CABS rely on electrical power to actuate shape changes in response to solar movement.

Thermo-bimetals exhibit morphological changes triggered by ambient temperature, providing consistent adaptation to environmental variations. PCMs and VGSs also demonstrate passive responses through physical or thermal transformations.

Intelligent facades and CABS produce kinetic changes via physical motion, with CABS additionally responding to temperature through integrated sensors. In contrast, PCMs, thermo-bimetals, and breathing walls react spontaneously due to their intrinsic properties. Both breathing walls and PCMs, which actively respond to thermal variations, demonstrate the potential to influence energy flow within the building.

Conclusions

This research examined the relationship between biomimicry and breathing facades through an analysis of innovative facade systems. The results indicate that thermo-bimetals and breathing walls can reduce energy consumption and improve indoor air quality by moderating building temperatures.

Comparative analysis of innovative facade technologies

		Intelligent Facade	Climate Adaptive Building Shells	Vertical Greenery System	Phase Change Materials	Thermo-bimetals	Breathing Walls
Response to climate change	Responsive	✓	✓	✓	✓	✓	✓
	Attributes	temperature sensors	solar movement	environmental adaptability	environmental adaptability	ambient air temperature	✓
	Electricity consumption	x	✓	x	x	x	x
	Impact on indoor air quality	x	x	x	x	✓	✓

In addition, breathing facades enhance indoor air quality through natural or mechanical ventilation, demonstrating significant potential to decrease inflow air temperatures. Proper building ventilation also contributes to lowering interior temperatures. These findings highlight the importance of integrating breathing facades into architectural design processes to optimize indoor air quality, user comfort, and energy efficiency. The study contributes to both the theoretical and applied understanding of architectural responses to changing environmental conditions.

Despite these insights, several limitations should be noted. The study focused primarily on humid tropical, Mediterranean, and temperate maritime climates, which may limit the generalizability of the results. In hot, dry desert climates, additional design considerations, such as double dust protection, would be necessary. Furthermore, the analysis was largely theoretical, lacking field testing, actual performance data, or user feedback. Future research should expand the climatic range, incorporate quantitative field measurements, and evaluate user experience to enhance the accuracy and applicability of the findings.

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ВЛИЯНИЕ «ДЫШАЩИХ» ФАСАДОВ И БИОМИМИКРИИ НА ВЕНТИЛЯЦИЮ И КАЧЕСТВО ВОЗДУХА В ПОМЕЩЕНИЯХ

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Аннотация

Введение: Одной из наиболее актуальных проблем современности является глобальное потепление, которое существенно повышает температуру внутри зданий. Разработка экономически эффективных решений для снижения перегрева помещений представляет собой важную архитектурную задачу. В данной работе рассматривается влияние «дышащих» фасадов на вентиляцию и качество воздуха в помещениях, с особым акцентом на связь между биомимикрией и проектированием фасадов. Уделяется внимание тому, как биомимикрия вдохновляет архитекторов на решение экологических проблем. На ряде примеров исследуется концепция «дышащих оболочек».

Цель исследования — анализ взаимосвязи между биомимикрией и «дышащими» фасадами, а также оценка их эффективности в улучшении качества воздуха в помещениях и снижении температуры в зданиях. **Методы:** используются индуктивный и аналитический подходы в рамках систематического обзора литературы, дополненного сравнительным анализом для оценки эффективности инновационных фасадных систем. **Результаты:** полученные данные свидетельствуют о том, что интеллектуальные «дышащие» фасады обладают значительным потенциалом снижения уровня загрязнения и повышения комфорта проживания в городской среде.

Ключевые слова: «дышащие» фасады, устойчивая архитектура, биомимикрия, вентиляция, качество воздуха в помещениях.