Thermochromic Biomimicry in Architecture: Bioinspired Strategies for Adaptive and Energy-efficient Buildings

Biomimética Termocrômica na Arquitetura: Estratégias Bioinspiradas para Edifícios Adaptativos e Energeticamente Eficientes

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Abstract: This paper investigates bio-inspired thermochromic properties with potential applications in sustainable construction, drawing on the biological systems of plant leaves and flowers. It explores concepts related to natural thermochromic responses and biological modulation processes based on chromatophores, structures, and pigmentation that influence the absorption of light and heat. The analysis integrates principles of biomimetics, architecture, and materials science, assessing the potential of bio-inspired strategies for optimising energy efficiency in buildings. By examining the natural thermal regulation mechanisms found in plants, the study identifies possibilities for adapting these systems to the built environment. The research highlights how biological principles can underpin sustainable architectural solutions, contributing to reduced energy consumption and environmental impact. This work underscores the importance of biomimetics as an innovative tool to integrate functionality, aesthetics, and sustainability, driving advancements in the construction sector and forging connections between intelligent design and natural processes.

Keywords: Biomimetics; Thermochromism; Sustainable Architecture; Thermal Regulation; Material Science.

Resumo: O artigo investiga as propriedades termocrômicas bio-inspiradas com potencial de aplicação em construções sustentáveis, fundamentando-se em sistemas biológicos de folhas de plantas e flores. São explorados conceitos sobre respostas termocrômicas naturais e processos de modulação biológica baseados em cromatóforos, estruturas e pigmentações que influenciam a absorção de luz e calor. A análise integra princípios de biomimética, arquitetura e ciência dos materiais, avaliando o potencial de estratégias bio-inspiradas na otimização da eficiência energética de edificações. Ao observar os mecanismos naturais de regulação térmica presentes em plantas, o estudo identifica possibilidades de adaptação desses sistemas ao ambiente construído. A pesquisa destaca como princípios biológicos podem fundamentar soluções arquitetônicas sustentáveis, contribuindo para a redução do consumo energético e do impacto ambiental. Este trabalho reforça a relevância da biomimética como ferramenta inovadora para integrar funcionalidade, estética e sustentabilidade, promovendo avanços no setor da construção civil e estabelecendo conexões entre design inteligente e processos naturais.

Palavras-chave: Biomimética; Termocromismo; Arquitetura Sustentável; Regulação Térmica; Ciência dos Materiais.

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Resumen: El artículo investiga las propiedades termocrómicas bioinspiradas con potencial de aplicación en construcciones sostenibles, basándose en los sistemas biológicos de las hojas de las plantas y las flores. Se exploran conceptos sobre respuestas termocrómicas naturales y procesos de modulación biológica basados en cromatóforos, estructuras y pigmentaciones que influyen en la absorción de luz y calor. El análisis integra principios de biomimética, arquitectura y ciencia de los materiales, evaluando el potencial de las estrategias bioinspiradas en la optimización de la eficiencia energética de los edificios. Al observar los mecanismos naturales de regulación térmica presentes en las plantas, el estudio identifica posibilidades de adaptación de estos sistemas al entorno construido. La investigación destaca cómo los principios biológicos pueden fundamentar soluciones arquitectónicas sostenibles, contribuyendo a la reducción del consumo energético y del impacto ambiental. Este trabajo refuerza la relevancia de la biomimética como herramienta innovadora para integrar funcionalidad, estética y sostenibilidad, promoviendo avances en el sector de la construcción civil y estableciendo conexiones entre el diseño inteligente y los procesos naturales.

Palabras clave: Biomimética; Termocromismo; Arquitectura Sostenible; Regulación Térmica; Ciencia de los Materiales.

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1 INTRODUCTION

Biomimetics is an interdisciplinary approach that utilises nature as a source of inspiration to solve human challenges, create sustainable technologies, and develop innovations in engineering, design, and sustainability (Benyus, 2011). This practice is based on the observation and replication of natural strategies, employing processes and tactics as references to create design solutions that combine efficiency and functionality.

> Biomimicry is innovation inspired by nature […] Nature has already solved many of the problems we are grappling with […] Our challenge is to learn from these solutions and adapt them to human needs […] The conscious emulation of life's genius is what biomimicry is all about (Benyus, 1997).

This perspective highlights nature as a resource for learning rather than merely an object of study, reinforcing the idea of the "Theory of Knowledge in Biomimetics," discussed by Dicks (2024), which advocates for the direct acquisition of knowledge through natural processes to foster sustainable innovations. Such a view shifts the role of science and design from an extractive paradigm to a collaborative one, where ecosystems are considered partners and teachers rather than passive resources. In architecture, this translates into new frameworks that prioritise adaptation, resilience, and circularity.

Following the approach proposed by Lima et al. (2025), nature is employed as a reference, allowing the assessment of the sustainability of human initiatives based on natural patterns and processes. Additionally, it serves as a measure, encouraging a new perspective in which natural systems are perceived as a source of inspiration (Lima et al., 2025). This is particularly relevant to the built environment, a major driver of global energy use and greenhouse-gas emissions. Learning from organisms that have evolved highly efficient thermoregulatory strategies over evolutionary timescales provides a robust scientific basis for tackling contemporary climate challenges and informing the design of envelopes that adaptively mediate heat and light.

Studies such as those by Gong et al. (2024) demonstrate that natural organisms possess the ability to modify their colours in response to external stimuli, whether for thermal regulation, communication, or camouflage. These mechanisms have attracted interest in fields such as architecture, design, and the textile industry due to their potential to optimise the functional performance of materials. Colour change, once perceived primarily as an aesthetic phenomenon, is increasingly recognised as a functional and ecological process. Thermochromism thus bridges physics, biology, and cultural expression, opening possibilities for materials that are simultaneously efficient and meaningful.

Within the context of this paper, the importance of bio-inspired thermal regulation is highlighted as an approach to developing sustainable solutions in the built environment. By replicating structures and mechanisms found in natural organisms—such as plant leaves, scales, and butterfly wings—it is possible to propose design principles based on materials capable of altering their thermal properties in response to temperature changes, promoting energy efficiency and thermal comfort in indoor environments (Gong et al., 2024). This also aligns with the growing demand for adaptive façades, capable of responding in real time to external climatic conditions, minimising reliance on mechanical heating and cooling systems, and enhancing the resilience of urban areas facing global warming.

In the construction industry, biomimetic strategies have shown great promise in the development of materials and structures that balance high technical performance with a reduced environmental footprint. According to Oztürk et al. (2024), nature-inspired solutions often lead to innovations that lower energy consumption, optimise resource use, and enhance urban biodiversity. Integrating biomimetic principles into glass design, for instance, presents a compelling approach to addressing contemporary challenges related to thermal comfort, energy efficiency, and the seamless integration of buildings within their natural surroundings (Oztürk et al., 2024). Moreover, recent experiments with phase-change materials, self-shading surfaces, and thermochromic coatings illustrate how hybridisation between biomimicry and advanced materials science can yield multifunctional solutions that are simultaneously ecological and technologically advanced.

Nature offers a vast array of energy-efficient solutions, including thermal regulation and climate-adaptive design, which enable the effective use of natural resources such as heat, light, rain, and wind. As a result, the thermal regulation mechanisms employed by living organisms are increasingly being studied and translated into architectural applications, reinforcing biomimicry as a key strategy for sustainability. Beyond their technical efficiency, these mechanisms embody principles of resilience, adaptability, and co-evolution that can reframe how cities are conceived: not as static entities, but as dynamic ecosystems integrated with their climatic and cultural contexts.

This article aims to explore bioinspired thermochromic properties with potential applications in architectural design and construction. To this end, biological systems—such as plant leaves and flowers, which exhibit adaptive responses to temperature fluctuations—serve as key references. By bridging biomimetics, architecture, and materials science, the study seeks to identify natural strategies that could inform innovative, sustainable, and high-performance design solutions.

Specifically, the research aims to: a) identify and analyse concepts related to thermochromic properties observed in nature; b) explore biological modulation processes associated with thermal regulation, structures, and pigmentation; c) determine potential adaptations of these mechanisms for the built environment.

By advancing the understanding of biomimetic principles in architecture, this study aims to foster the adoption of nature-inspired strategies that seamlessly integrate functionality, sustainability, and innovation—ultimately enhancing thermal comfort and energy efficiency in the built environment. Additionally, it seeks to highlight the broader cultural and social relevance of adaptive materials: façades that shift colour with the seasons can foster public awareness of environmental change, enrich urban identity, and promote a deeper connection between human experience and ecological processes.

2 THEORETICAL FRAMEWORK

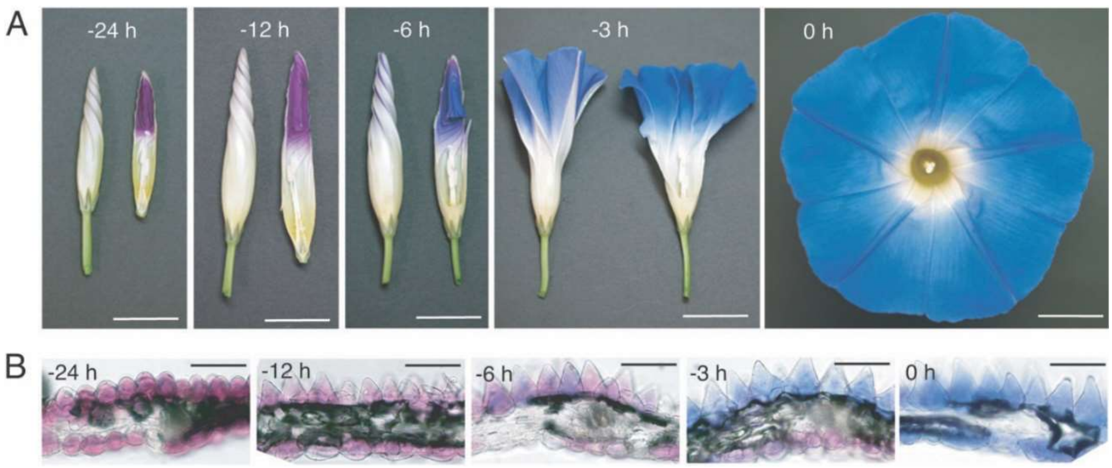
2.1 Thermochromic Responses in Nature

Thermochromism refers to the ability of certain materials or systems to modify their physical, chemical, or biological properties in response to temperature variations, drawing on specific forms and functions observed in nature. These high-temperature-resistant materials can alter properties such as colour, shape, or rigidity (Lima et al., 2025). This adaptability enables their application in specialised sectors, integrating technological solutions, processes, or practices designed to address specific energy and environmental demands.

In nature, this property is evident across a wide range of organisms, particularly in plants, where it is linked to adaptive processes that optimise physiological functions under varying environmental conditions. A well-known example occurs in the leaves of deciduous trees—plants that shed their foliage at specific times of the year in response to climatic changes—where seasonal temperature variations trigger changes in leaf colour. These transformations not only signal senescence but also serve as a protective function, mitigating thermal and light stress in photosynthetic tissues (Koski et al., 2020).

Flowers of certain species, such as Ipomoea tricolor (Figure 1), also exhibit petal tissue structures and pigment distribution patterns that alter their coloration in response to ambient temperature. These changes may influence pollinator attraction at different times of the day or across seasons, thereby optimising the plant's reproductive success (Harrap et al., 2024). Moreover, according to researchers, the biological mechanisms underpinning these colour shifts include temperature-sensitive pigments, such as anthocyanins—naturally occurring pigments that produce a range of colours—which contribute to heat dissipation and provide protection against ultraviolet radiation.

Figure 1 – (A) Changes in petal coloration and expansive growth of *Ipomoea tricolor* (Mexican morning glory) [bar = 2cm]; transverse sections at different stages of flower development [bar = 50μm].



Source: Yoshida et al., 2009.

In panel A, the temporal sequence of external modifications in the floral bud is observed, from -24 h until full flower opening (0 h). The process is characterised by the expansive growth of the petals and the gradual alteration of colour, which shifts from a purplish tone to an intense blue, as a result of the metabolic regulation of pigments such as anthocyanins. In panel B, cross-sections of the petals at different stages reveal progressive cell expansion and the redistribution of pigments, confirming the direct relationship between internal structural modifications and the visible external chromatic variation. In this way, the figure integrates both macro- and microscopic evidence, demonstrating the synchrony between morphological and biochemical processes during anthesis of the species (Yoshida et al., 2009).

Another significant biological mechanism occurs in the epidermal structures of leaves, which may either reflect or absorb heat depending on temperature conditions (Koski et al., 2020). This process involves physiological and morphological alterations that enable plants to modulate the interaction of the leaf surface with solar radiation, functioning as an adaptive strategy across different environments.

Colour changes play an important role not only in regulating the efficiency of light capture but also in protecting internal tissues against thermal and photo-oxidative damage, ensuring the balance between photosynthesis and photoprotection (Figure 2). According to Koski et al. (2020), during winter, some plant species display darker pigmentation, generally associated with the accumulation of anthocyanins, which increases heat absorption and favours the maintenance of metabolic activity at reduced temperatures. Conversely, in summer, lighter colours or the deposition of epicuticular waxes reflect excessive radiation, preventing leaf overheating and reducing water loss through transpiration.

These chromatic mechanisms therefore constitute an example of phenotypic plasticity, evidencing the capacity of plants to respond dynamically to seasonal and climatic variations, ensuring greater adaptive efficiency in distinct ecosystems.

Figure 2 – A *Fragaria vesca* (wild strawberry) rosette exhibits summer and/or winter leaves at different stages throughout the dormancy period (a-d). In the images, winter leaves are numbered according to their order of emergence, whereas summer leaves remain unnumbered.

Source: Åström et al., 2015.

Figure 2 shows the leaf rosette of *Fragaria vesca* (wild strawberry) throughout the dormancy period, highlighting the alternation between summer and winter leaves (Åström et al., 2015). The winter leaves, numbered according to their order of emergence, display reddish pigmentation due to the accumulation of anthocyanins, serving as protection against excessive radiation and low temperatures, whereas the summer leaves remain unnumbered and undergo progressive senescence.

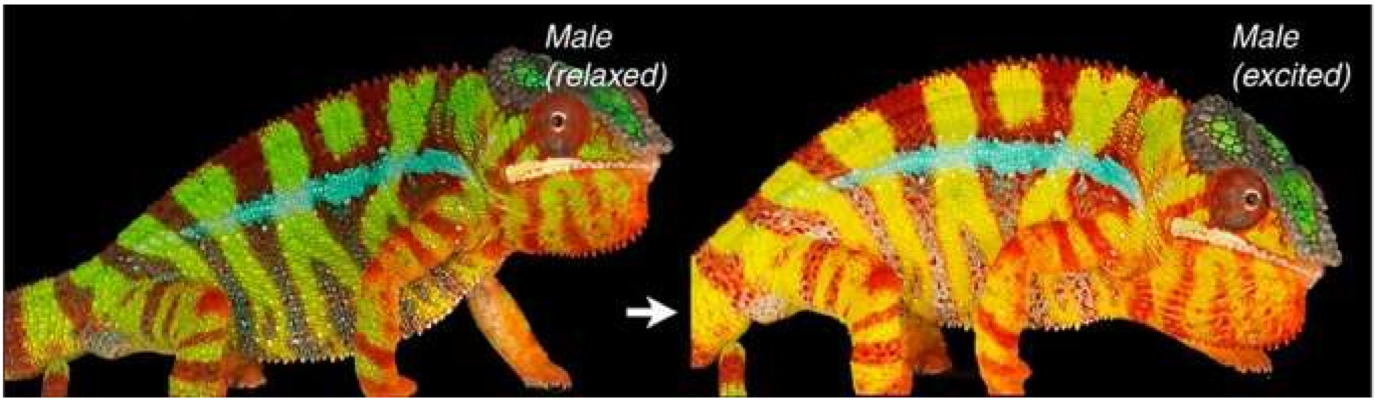
Thermochromic responses play a crucial role in plant survival across environments with varying temperatures. By enhancing energy exchange efficiency and providing protection against environmental stress, these adaptive mechanisms contribute to the resilience of vegetation. The interaction between biological, chemical, and ecological processes underpins these adaptations, allowing plants to thrive in diverse ecosystems.

2.2 Biological Modulation: Chromatophores, Structures, and Pigmentation

Chromatophores are specialised cells found in various organisms, including fish, reptiles, amphibians, and cephalopods, enabling rapid and controlled changes in skin or body structure pigmentation (Vinther, 2015). These modifications are essential for functions such as camouflage, communication, mate attraction, and thermal regulation.

In cephalopods, according to Gong et al. (2024), chromatophores contain elastic pigment sacs that can expand or contract through neurologically controlled muscles. This process alters the skin's surface appearance, allowing for instantaneous colour and pattern changes. Other cellular layers complement this function, such as iridophores (Figure 3), which reflect light to create iridescent effects, and leucophores, which scatter white light and contribute to background pigmentation (Gong et al., 2024).

Figure 3 – Male chameleons show colour changes that can be reserved, changing from green when they are calm to yellow in moments of excitement, displaying vertical blue stripes under the red pigment cells.

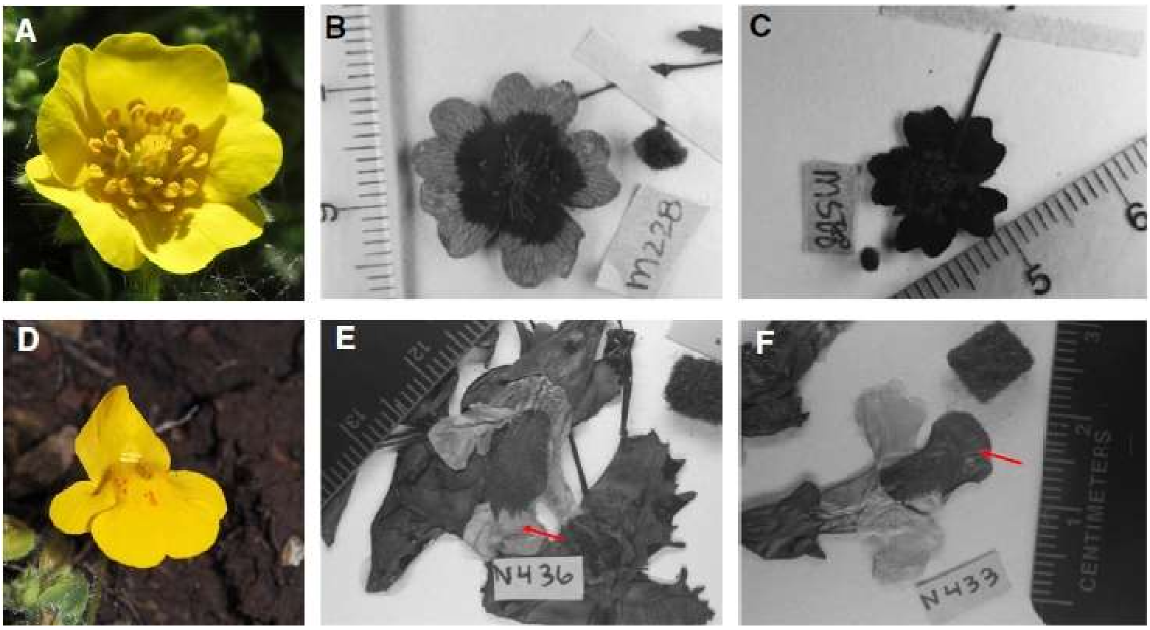


Source: Gong et al., 2024.

The regulation of these cells varies among different groups of organisms. In cephalopods (Figure 4), neurological signals play a dominant role, enabling rapid responses. According to Gong et al. (2024), in reptiles, colour changes occur more slowly and are primarily regulated by hormonal fluctuations that influence pigment distribution within chromatophores.

The pigments found in chromatophores are essential for colour modulation and thermal absorption. Among the most significant are melanin, which absorbs a broad spectrum of visible and infrared light, producing dark tones that enhance heat absorption, and carotenoids, responsible for yellow, orange, and red hues, often derived from dietary sources (Koski et al., 2020). Additionally, biological structures, such as nanoscale layers in flowers (as shown in Figure 4), generate specific colour patterns due to light interference. These structures can alter the way light is reflected depending on the angle of incidence, creating dynamic colouration effects (Koski et al., 2020)

Figure 4 – Example of species exposed to different environmental conditions. A-C) Specimens with anthers protected by floral tissue; B-E) reduced area of UV-absorbing pigmentation on the petals; D-F) darker areas of the petals, exposed to environmental conditions, acting as regions of higher UV absorption.



Source: Koski et al., 2020.

In the images in Figure 4, variations in floral pigmentation under different environmental conditions are shown (Koski et al., 2020). In A–C, the anthers remain protected by floral tissue and a reduced area of UV-absorbing pigmentation is observed. In D–F, darker regions on the petals (red arrows) are highlighted, associated with increased UV absorption and possible protective mechanisms against environmental stresses.

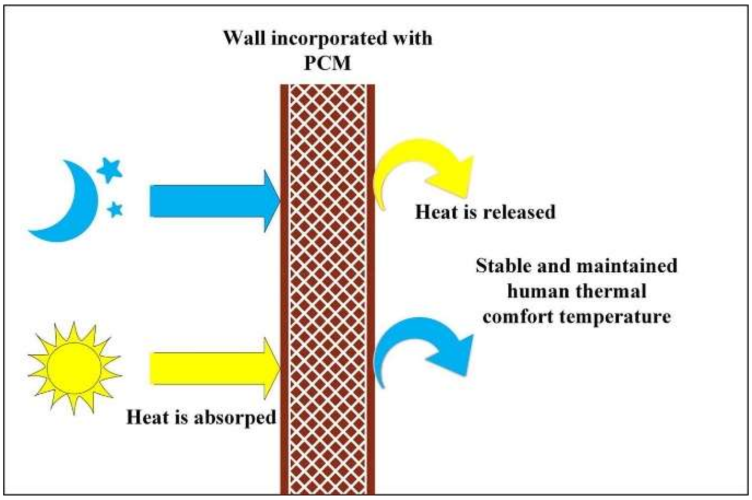
Beyond their visual function, colour changes play a crucial role in thermal regulation. Darker pigmentation enhances heat absorption in colder environments, while lighter surfaces reflect light, reducing thermal absorption in warmer climates. Thus, chromatophores, in combination with specialised structures and pigments, represent an advanced evolutionary strategy that integrates environmental cues, physiological functions, and behaviour.

2.3 Architectural and Material Sciences

Contemporary architecture is increasingly aligned with advancements in materials science, particularly in relation to thermal regulation and energy efficiency in buildings. The careful selection of materials can significantly reduce a building's energy consumption, minimising the need for artificial heating and cooling (Ashrae, 2019).

Beyond traditional materials, the introduction of responsive materials designed for heating and cooling applications, such as Phase Change Materials (PCMs) (Figure 5), has transformed the construction industry. These materials, which can alter their properties in response to external stimuli such as temperature and humidity, enhance energy efficiency and contribute to more sustainable building solutions (Swellam et al., 2023).

Figure 5 – Schematic detail of the PMC application.



Source: Swellam et al., 2023.

The schematic detail in Figure 5 shows the functioning of walls incorporated with phase change materials (PCMs), highlighting their contribution to human thermal comfort. According to the authors, during the day, the building element absorbs excess heat from solar radiation, acting as a thermal reservoir and reducing heat overload in the indoor environment. At night, the stored heat is gradually released, which contributes to maintaining more stable temperatures. This mechanism mitigates daily thermal fluctuations and reduces the energy demand for air conditioning, constituting a passive energy efficiency strategy applied to the built environment (Swellam et al., 2023).

Other technologies include thermosensitive glass (Figure 6), which adjusts its transparency in response to solar exposure, aiding in strategies to meet specific environmental demands (Ferreira et al., 2024). These innovations not only reduce energy consumption but also extend the lifespan of materials and lower the operational costs of buildings.

Figure 6 – a) Electrochromic system, which changes its transparency, becoming semi-transparent; b) Thermochromic system, which adjusts its colour and opacity in response to sunlight.

Source: Lima et al., 2025.

Figure 6 presents two types of smart glazing systems applied to the modulation of solar radiation in the built environment. In (a), the electrochromic system is shown, capable of varying its transparency and becoming semi-transparent under electrical stimuli, thereby regulating the entry of natural light and heat. In (b), the thermochromic system is illustrated, which autonomously adjusts colour and opacity in response to solar incidence, providing dynamic shading and reducing internal thermal load. Both systems represent sustainable technological solutions aimed at enhancing energy efficiency and environmental comfort in buildings (Lima et al., 2025).

The efficiency of thermal regulation in buildings is directly influenced by the selection and performance of materials. Advances in construction materials and techniques highlight the importance of integrating architectural design with materials science to enhance sustainability and energy performance. A multidisciplinary approach is fundamental to developing buildings that minimise environmental impact while optimising comfort and efficiency.

3 METHODOLOGY

The research adopts an exploratory and qualitative approach, grounded in a review of scientific literature on biomimetics, natural thermochromic properties, and their potential applications in the built environment. The methodology was structured into three main stages:

Firstly, a survey of theoretical and experimental studies related to thermochromic properties observed in nature. The selection focused on studies investigating: thermochromic responses in natural organisms, such as plant leaves and flowers; biological processes of thermal modulation mediated by chromatophores, structural pigmentation and colour variations in response to temperature; applications of biomimetics in architecture.

Secondly, based on the material collected, a descriptive and interpretative analysis of the biological mechanisms that regulate thermochromic properties was carried out. This analysis focused on identifying natural structures that promote temperature-related colour changes; biological strategies for controlling light and heat absorption; relationships between these strategies and the principles of thermochromism.

The information extracted was organised into categories that reflect the most relevant aspects of biological mechanisms for application in the built environment, such as thermal functionality, adaptability and potential for design inspiration.

Finally, the information on natural thermochromic properties was related to the challenges and opportunities in the built environment. To do this, an interdisciplinary approach was adopted, seeking to connect the principles of thermal modulation identified in nature to potential architectural adaptations. The analysis prioritised aspects such as: how natural strategies may inform architectural solutions for thermal comfort; the impact of these solutions on the energy efficiency of buildings; limitations and challenges in applying these principles in the built environment.

The results of the analysis were synthesised into theoretical proposals that explore how natural mechanisms can inspire design strategies in the context of sustainable architecture.

4 NATURAL STRATEGIES FOR THERMAL REGULATION

In the vast diversity of nature, both flora and fauna generate colour through pigments, bioluminescence, or structural colouration, as highlighted in a specialised study by Bhushan (2018) on biomimetic structural colouration. This includes plant leaves and flowers, which have evolved natural strategies to regulate temperature and optimise sunlight utilisation.

Thermochromism, for instance, is a characteristic found in certain species that enables colour changes in response to temperature fluctuations, thereby influencing the absorption or reflection of solar radiation. This mechanism is essential for preventing overheating and maintaining optimal conditions for photosynthesis (Koski et al., 2020).

Although references discussing thermochromism in leaves and flowers, particularly those exhibiting direct colour changes due to temperature variations, are relatively scarce, we propose a selection of tropical species that display adaptations potentially relevant for biomimetic studies. Table 1 presents examples of plant leaves that exhibit colour variations in response to thermal changes, contributing to temperature regulation.

Table 1: Suggestions based on plant leaves and flowers for thermal regulation.

Inspirations for thermochromism in leaves and flowers		
Plants	**Thermochromism Strategy**	**Biomimetic Inspiration**
Alocasia spp. Elephant Ear	They have large leaves with varying shades, such as dark green and silver, shades that can reflect or absorb light differently, helping with thermal regulation (Koski et al., 2020).	Exploration of surfaces with microstructures to reflect heat, reducing the absorption of thermal radiation.
Calathea spp. Prayer Plant	Leaves with patterns that change slightly depending on light and humidity, vibrant colours on the underside. This allows for efficient photosynthesis and reduced water loss (Davies et al., 2012).	Use of pigments that simulate seasonal changes or that adjust their colours depending on the temperature, optimising thermal control.
Rex Begonia Begonia Rex	It has leaves with varied colours, including silver and red. Colour can help control the amount of light and heat absorbed (Davies et al., 2012).	Leaf structural pigments can inspire materials that change their thermal properties based on temperature.
Heliconia spp. Lobster Claw	Leaves in bright shades of red, yellow and orange are able to reflect infrared light, helping to regulate heat (Castro et al., 2011).	Surfaces that optimise interaction with thermal and visual radiation, promoting both thermal and aesthetic regulation.
Anthurium andraeanum Laceleaf	The shiny epidermis of the bracts can reflect light and heat. In addition, the leaves have hydrophobic properties that contribute to temperature regulation (Collette et al., 2004).	Development of surfaces with a glossy finish and thermal self-regulation to improve passive heat control.
Eucalyptus spp. Eucalyptus	They contain compounds in the leaves that can reflect different wavelengths of light depending on how the temperature varies (Kisekka et al., 2020).	They play a role in thermal regulation, a phenomenon that has been studied for applications in intelligent coatings and sustainable materials.
Magnolia spp. Magnolia	They have a special structure, with a waxy surface and specialised cells that reflect light differently as the temperature varies (Wang et al., 2018).	Type of natural adaptation to create intelligent coatings and inks that respond to thermal variations, applications in sustainable architecture, functional fabrics and even electronic devices.

Source: Authors, 2025.

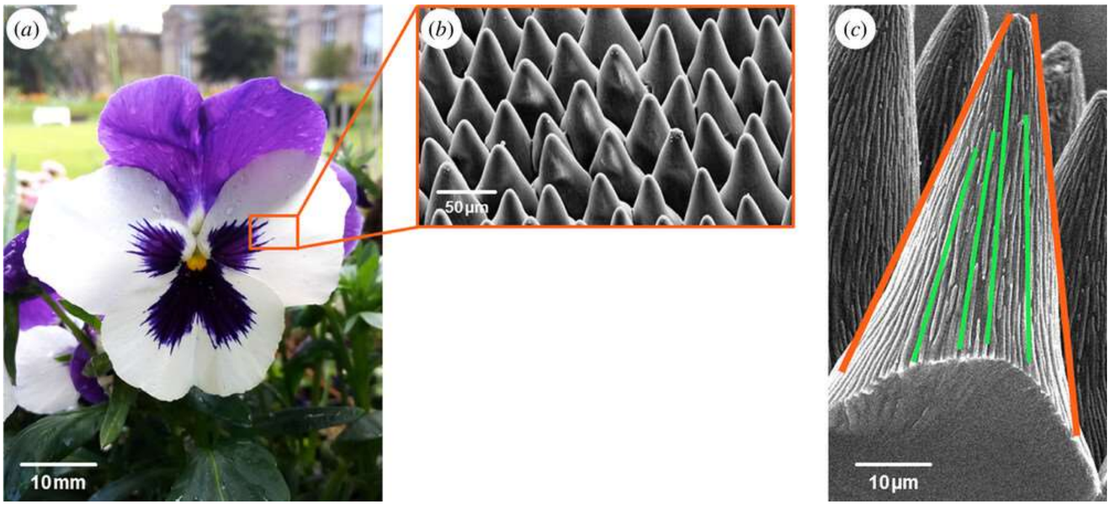
The plants presented exhibit structural and chemical adaptations that enable thermal regulation in hot and humid environments, inspiring biomimetic research for the development of sustainable materials.

Certain species undergo colour changes in response to temperature variations, which has led to the creation of thermochromic coatings for buildings and smart textiles that adjust their colour based on heat exposure. Additionally, the presence of waxy microstructures on leaves such as those of magnolia and eucalyptus enhances heat reflection and light dispersion, influencing the design of nanostructured surfaces for architectural and textile applications.

Some plants also possess highly reflective surfaces in the infrared spectrum, reducing heat absorption—a feature that has inspired the development of thermal control glass and more efficient building materials. These bioinspired innovations contribute to technologies that enhance thermal comfort while reducing energy consumption across various applications.

Although there is still a scarcity of specific studies on some plant species, broader research confirms that vegetative surfaces covered by epicuticular waxes exhibit high reflectance in the near-infrared spectrum, reducing heat absorption and preventing overheating. Furthermore, spectral analyses demonstrate that seasonal changes in leaf colour are directly related to thermal emissivity and the regulation of plant tissue temperature (Figure 7) (Schmager et al., 2017).

Figure 7 – The petals of Viola flowers (a) exhibit an elaborate conical shape with small surface roughness (b, c). Together, these conical structures and their roughness enhance light capture.

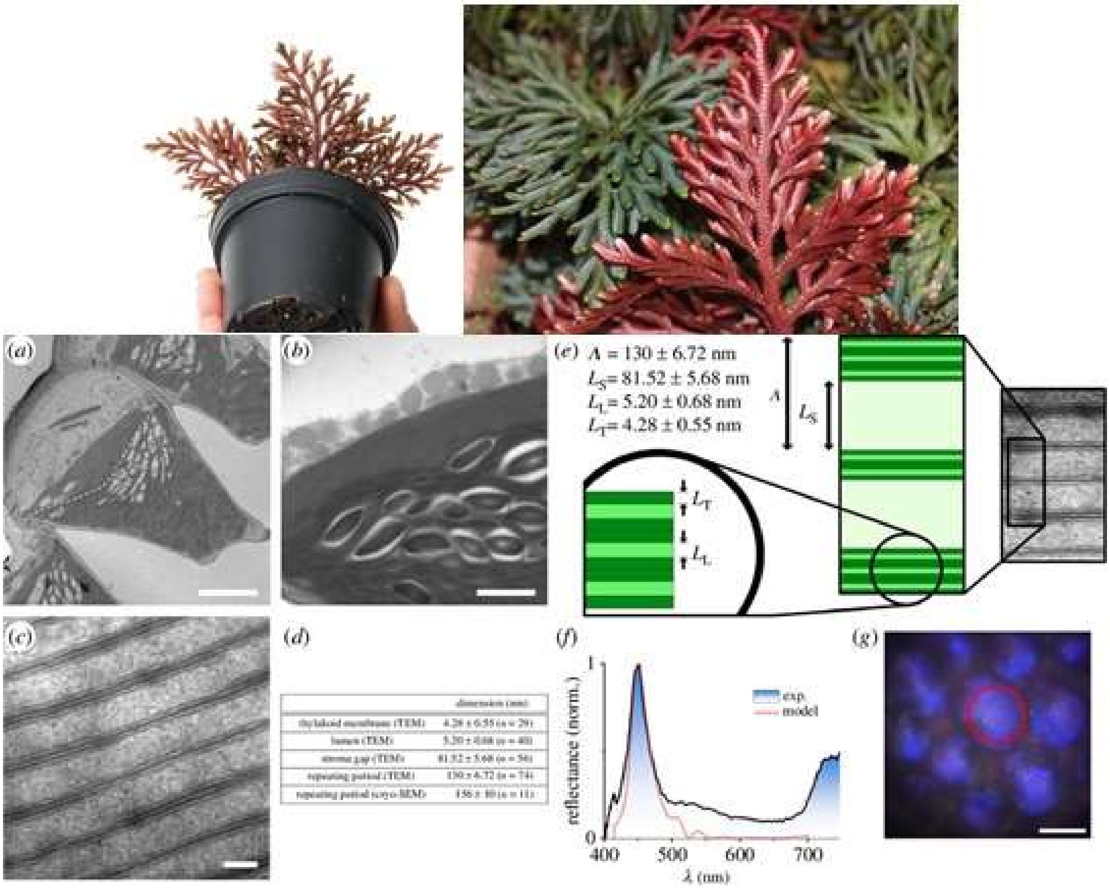


Source: Schmager et al., 2017.

The microstructure of Viola (*Viola* sp.) petals, highlighting how natural arrangements influence the interaction with light. In (a), the macroscopic morphology of the petal is shown; in (b), the magnification under electron microscopy reveals the presence of regularly distributed conical structures; and in (c), it is noted that these structures exhibit additional surface roughness.

Other studies on plant leaves highlight specialised structures that significantly enhance light absorption. Among these, bizonoplasts, identified in the unique plant species *Selaginella erythropus*, a type of spikemoss, constitute a remarkable example of natural photonics, inspiring biomimetic research for the development of advanced optical materials (Figure 8).

Figure 8 – Presence of bizonoplasts in the epidermis of *Selaginella erythropus* leaves.



Source: Masters et al., 2018.

Figure 8 illustrates the bizonoplasts present in the epidermis of Selaginella erythropus leaves, specialised organelles characterised by a highly organised multilayered internal arrangement. These structures are formed by periodically stacked thylakoids, interspersed with lumen and stroma regions, functioning as natural systems capable of modulating the interaction with light radiation (Masters et al., 2018). This configuration results in selective reflection within the blue range of the visible spectrum, a phenomenon confirmed by spectral analyses, optical modelling, and light microscopy observation. Such features reveal an evolutionary adaptation that enhances the capture and utilisation of solar energy, while also providing insights for biomimetic research aimed at the development of photonic materials applicable to innovative and efficient surfaces.

This evidences a broad field of application, ranging from sustainable architecture, where the heat-reflecting capacity of Anthurium and Heliconia directly inspires the development of cool paints, coatings, and roofs, to smart materials, in which the pigments of Calathea or the composition of Eucalyptus serve as models for creating sensors, packaging, and functional fabrics that respond autonomously to temperature. Moreover, the specialised structure of Magnolia points towards advanced applications in electronic devices and high-performance textiles that require efficient passive thermal management.

5 RESULTS AND DISCUSSION

These natural thermal regulation strategies illustrate how organisms have evolved to overcome environmental challenges, offering valuable inspiration for bioengineering and the development of innovative thermoregulating materials.

The potential applications of these principles in architecture are significant. The development of responsive materials for buildings could lead to major advancements, particularly in techniques inspired by natural patterns. According to Andrade et al. (2024), the nastic movements of leaves provide insights into incorporating nature’s adaptive wisdom into human solutions, fostering sustainability in construction.

Another example involves plants that respond to external stimuli through movements known as tropisms. As noted by Lopéz et al. (2017), certain plants react to changes in light, temperature, or water through dynamic mechanisms. Additionally, alternative applications of bioinspired materials could lead to more sustainable construction practices, optimising energy consumption and enhancing thermal comfort for occupants (Novikova, 2023).

Bioinspired solutions offer several advantages in terms of energy efficiency, as they help reduce electricity consumption for heating and cooling while contributing to a more adaptive and environmentally integrated architectural design. These innovative approaches have the potential to transform how we design and construct buildings, fostering a greater synergy between technology and nature.

However, there are significant challenges and limitations to implementing these strategies on a large scale. Replicating biological mechanisms at an architectural scale presents technical difficulties, as many natural processes involve highly complex structures and dynamic materials that currently lack synthetic counterparts with comparable performance (Andrade et al., 2024). Moreover, the research and development costs associated with these innovative materials can be high, limiting their immediate economic viability. From an environmental perspective, it is also essential to assess the impact of producing and disposing of new bioinspired materials, ensuring that their adoption does not result in unintended negative consequences.

Beyond these considerations, another relevant aspect is the scalability of thermochromic responses. While biological systems often operate at the micro or nanoscale, architectural applications require macro-scale solutions capable of withstanding long-term exposure to weathering, UV radiation, and mechanical stress. This raises questions about durability, maintenance, and cost-efficiency in real-world scenarios.

In addition, a promising research direction is the synergy between bioinspired thermochromic systems and other emerging technologies. Integrating these materials with phase change materials (PCMs), electrochromic glass, or even building-integrated photovoltaics could multiply their efficiency. Such hybrid systems may allow façades to regulate heat and light and also to generate energy or store it, expanding their role beyond passive thermal modulation. The convergence of bioinspiration with nanotechnology and smart coatings opens a pathway to multifunctional envelopes that combine energy generation, storage, and adaptive behaviour.

Furthermore, there is a lack of standardised methods to evaluate the performance of bioinspired thermochromic materials in architectural contexts. Most studies remain confined to laboratory conditions, with limited empirical evidence from built prototypes or large-scale applications. Integrating life-cycle assessment (LCA) into the development process could provide valuable insights into the ecological benefits and trade-offs of these materials. Standardisation efforts would also help align experimental advances with certification protocols such as LEED (Leadership in Energy and Environmental Design), facilitating market acceptance.

Finally, it is important to highlight the social and aesthetic dimensions of bioinspired thermoregulation. Thermochromic façades and coatings do not only influence energy performance but can also impact urban identity and user experience through dynamic colour variations. These aesthetic qualities may transform buildings into living surfaces that interact with climate and seasons, reinforcing cultural narratives and user engagement. Considering the role of colour in environmental psychology, adaptive façades could support well-being while redefining urban landscapes.

From a governance perspective, the adoption of bioinspired thermochromic technologies also depends on public policies and regulatory frameworks. Incentives for sustainable construction, green building codes, and innovation-driven procurement can accelerate their integration into mainstream practice. Without adequate regulatory support, even the most promising technologies may face slow diffusion. Therefore, interdisciplinary collaboration between designers, scientists, policymakers, and industry stakeholders is essential to bridge the gap between experimental research and real-world implementation.

6 CONCLUSION

By examining the thermochromic responses observed in natural organisms—such as plants and cephalopods—this research has highlighted the capacity of biological systems to dynamically modulate light and thermal energy, offering insights for the development of adaptive, high-performance materials in the built environment.

One of the most innovative aspects of this investigation lies in the identification of thermochromic strategies in plant species and their potential to inspire the development of climate-responsive materials. The study of chromatophores, structural pigmentation, and temperature-sensitive pigments provides a foundation for designing surfaces that adapt to environmental variations, thereby enhancing energy efficiency and thermal comfort in buildings. This aligns with recent advances in biomimetic materials and adaptive façade technologies, reinforcing the role of bioinspiration as a driver for potential architectural solutions.

The relevance of structural colouration and thermal modulation mechanisms found in biological systems becomes evident, demonstrating how nature has evolved highly efficient solutions for managing solar radiation and heat dissipation. The identification of plant species with thermochromic properties suggests new pathways for research and material innovation, particularly in the development of coatings and smart textiles that dynamically respond to temperature fluctuations.

As a theoretical study based on a literature review, the conclusions are limited to the scope of the references analysed and the interpretation of the available data. Future studies should focus on experimental validation, material performance testing, and the integration of thermochromic biomimetic solutions into real-world architectural applications.

Moreover, the integration of digital simulation tools, such as parametric modelling and environmental analysis software, could play a crucial role in bridging the gap between biological principles and architectural practice. These tools enable the prediction of thermal performance, visual outcomes, and user comfort, thereby facilitating the optimisation of bioinspired materials before full-scale implementation.

In addition, collaboration across disciplines — architecture, biology, materials science, and engineering — is fundamental for advancing research in this field. By combining experimental evidence with computational design strategies, it is possible to accelerate innovation and ensure that bioinspired thermochromic systems are feasible and also sustainable in practice.

Finally, the integration of biomimetics, materials science, and architectural design presents new perspectives for the development of adaptive and energy-efficient buildings. Advancing the understanding of natural thermoregulation mechanisms and applying responsive materials will enable architecture to incorporate nature-inspired adaptation strategies, reducing dependence on mechanical climate control systems and fostering a more balanced relationship between the built environment and its climatic context.

Ultimately, the potential of thermochromic biomimetic strategies lies not only in improving building performance but also in reshaping the cultural and aesthetic dimensions of architecture, creating dynamic and resilient environments that embody a deeper dialogue between nature and design.

Equally important is the social dimension: adaptive façades capable of expressing climate variations through colour and material transformation may contribute to public awareness of environmental change, enhancing community engagement with sustainability. In this sense, buildings become active pedagogical agents in the urban fabric, reinforcing ecological consciousness and fostering new cultural identities shaped by dynamic interaction with climate.

For future research, it is crucial to advance from laboratory and theoretical studies towards in-situ experiments, long-term monitoring of built prototypes, and integration with certification frameworks that evaluate performance in real-world conditions. Expanding comparative studies across climatic zones, exploring hybridisation with renewable energy systems, and assessing user perception and comfort are essential steps to consolidate the feasibility and desirability of bioinspired thermochromic applications.

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Conflict Declaration

Nothing to declare.

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