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Smart materials for biomimetic building envelopes: current trends and potential applications

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ABSTRACT

To reduce the energy consumption of buildings and limit their impact on the environment, greater attention has been paid, in recent years, to adaptive building envelopes technologies. Combining the dual function of sensors and actuators, smart materials are configured as excellent allies of adaptive technologies. Their responsiveness facilitates the dynamic interaction between the building and the environment through the building envelope configured as a living interface, similar to the skin of natural organisms. This study aims to explore the current trends and potential applications of smart materials to define biomimetic solutions for environmentally adaptive building envelopes. Starting from specifying the fine distinction between adaptive and responsive solutions, the PRISMA method is used to conduct a systematic literature review, together with a bibliometric analysis, to identify the main common occurrences of the keywords, the predominant geographical areas and the main sources. Only materials that respond to the environmental triggers of light, temperature and water were considered to create a design matrix that enriches the implementation phase of the biomimetic-Adaptive Model and provides researchers with a new useful tool for the biomimetic design phases. The study shows how smart materials can be used to realise the responsive functions of the biomimetic envelope, capable of regulating temperature, shielding solar radiation, filtering or reacting to variable environmental parameters. The application of smart materials in architecture is still limited, paving the way for future research discoveries and synergistic collaboration between architectural technologies, biology, and material sciences, and leading to a more sustainable built environment.

1. Introduction

Buildings account for about 30 % of global energy consumption and 27 % of total energy sector emissions [1,2]. To meet the Net Zero Emissions scenario and achieve international climate neutrality targets by 2050, significant changes are needed in the building sector to reduce energy demand. The building envelope is responsible for a significant part of the energy efficiency of buildings, where it can be considered not only a physical and protective barrier, but also as a mediator between the indoor and outdoor environments [3–9]. The International Energy Agency (IEA) 2022 Report [10] point out the importance of integrating high-performance building envelopes to reduce building heat demands and ensure occupant comfort. For example, performance improvement is provided by thermal insulation or high efficiency glasses, providing certain indoor comfort improvements, but require additional solutions to tackle pressing energy challenges [11,12]. During climate change [13], buildings face unusual environmental conditions and events - including extreme temperatures, and extreme rainfall that change rapidly even within a single day - for which conventional materials and techniques are not always sufficient. The microclimatic conditions in the surrounding environment of a building influences its energy demand [14], where building envelopes need to be considered as an integral part of the building and designed in a way that allows them to respond to changing conditions.

In recent years, there has been growing interest in responsive and climate adaptive envelope solutions to reduce embodied and operational carbon emissions [15]. A large part of these responsive technologies is activated and controlled by automation technologies that react to weather conditions in real time using sensors and actuators [12]. Another way for the building envelope to adapt is by the activities of the users, changing the configuration of the building envelope manually: e.

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Abbreviations

ART	Auto-Responsive Technology
bio-AM	Biomimetic Adaptive Model
CABS	Climate Adaptive Building Shells
CO_2	Carbon dioxide
GHG	Greenhouse Gas
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCE	Liquid Crystal Elastomer
NiTi	Nickel-titanium (Nitinol)
RBE	Responsive Building Elements
SLR	Systematic Literature Review
SMAs	Shape Memory Alloys
SMCs	Shape Memory Ceramics
SMHs	Shape Memory Hybrids
SMMs	Shape Memory Materials
SMPs	Shape Memory Polymers
T_iO_2	Titanium dioxide
UV	Ultraviolet
VO_2	Vanadium dioxide

g., venetian and/or roller blinds [16]. All these solutions, while adapting to users' needs and/or changes in environmental conditions, require additional energy to function through the automation systems. This is associated with high maintenance and management costs, but also with high energy consumption. Smart materials represent a class of materials that can sense and respond to stimuli emanating from the environment by adapting to changing environmental conditions [17–19].

Nature offers a large database of adaptive and responsive solutions to survive in their changing environments. For example, plants activate behavioral strategies by physical movements to modify their morphological configuration hence improving performance, e.g. in terms of photosynthesis [20]. Emulating functional principles from natural systems to design solutions for buildings, i.e. *biomimetics*, has the potential to provide improved technologies with less energy demands [21–25]. Creating parallels between the movements of plants in response to environmental triggers and the kinetic movements provided by smart materials can facilitate the biomimetic design process to develop kinetic façade solutions that adapt to their environment.

This study aims to expand the knowledge of smart materials applications to buildings and identify the potential application of smart materials to biomimetic building envelopes to enhance the environmental responsiveness of technical solutions and reduce operational energy demands to meet more sustainable targets. Biomimetic design with the use of responsive smart materials is in line with several goals related to climate change and reduction of energy consumption, such as the Sustainable Development Goals (SDGs) proposed in the 2030 Agenda [26], in particular SDG7 (Affordable and Clean Energy), SDG11 (Sustainable Cities and Communities), SDG12 (Responsible Consumption and Production) and SDG13 (Climate Action).

It is necessary to consider the building as a living organism [27] that is related both to the environment and to the whole of biotic (living factors) and abiotic factors (non-living factors) of the ecosystem in which it is built [16]. Similar to the biological skin, the new envelope must interact with the surrounding changing environment [28]. The concept of the *living envelope,* proposed by Badarnah [27], describes different strategies for addressing environmental challenges regulating air: move, exchange; regulating heat: gain, retain, dissipate, prevent; regulating water: gain, conserve, transport, lose; regulating light: manage intensity. Further six responsive functions were described by Sommese et al. [6] in the context of the adaptive building envelope that depend on a specific environmental factor (input): regulate (e.g. temperature and air), shield (e.g. cold and radiation), transfer (e.g. heat, water, light, air), reflect (e.g. radiation), store (e.g. heat and water), transform (e.g. energy). By activating these functions, one obtains a building envelope that is able to interact dynamically with the environment, through a response strategy similar to that of natural organisms. Each of these living beings, whether animal or plant, interacts and adapts to the conditions of its habitat in order to survive.

This review was conducted on the basis of the following research questions:

1. What are the main trends in smart materials in the literature, in terms of definitions, terminology, countries and sources?
2. How have smart materials been applied to building envelopes?
3. What responsive functions are embedded in current building envelope applications?
4. What are the benefits of applying smart materials in biomimetic design for adaptive building envelopes?
5. What are the limits of research on smart materials for biomimetic adaptive building envelopes?

These questions have informed the different parts of this study and are aligned with the sections of this paper: Section 2 describes the methodology used in this study; Section 3 presents the theoretical background on adaptive and responsive solutions; Section 4 presents the bibliometric analysis of existing literature to define the current trends in smart materials in building envelopes; Section 5 analyses the latest studies on smart materials and classifies them according to their responsiveness to light, temperature and water; Section 6 proposes the biomimetic design matrix to implement biomimetic Adaptive Model (bio-AM). Finally, in sections 7 and 8, the results and conclusions are discussed.

In summary, the study has revealed that although the investigation of the applicability of smart materials to biomimetic envelopes has been underway for several years, the materialisation and associated applications are currently scarce. Most of the various biomimetic design proposals found in the literature are conceptual designs [27,29,30], often supported by parametric approaches [31–33], where the choice of materials and their complex production becomes challenging. Some other solutions develop into prototypes or become exhibition pavilions [34]. Furthermore, this study proposes a novel biomimetic design matrix that integrates the findings on responsive materials and their potential applications with the bio-AM [6], where classifications of responsiveness are correlated with certain environmental triggers to enrich the implementation phase of the (bio-AM) for the design of environmentally adaptive building envelopes for the future. Following the proposed approach, it will be potentially possible to obtain a responsive solution for the building envelope, with materials and/or technologies that are able to respond to different environmental aspects such as light, temperature or water, and bring us closer to meeting sustainable target goals.

2. Methods: a systematic literature review

To define the current trends, characteristics and potential applications of smart materials related to biomimetic design for environmentally adaptive building envelopes, the methodological approach of this study is a systematic literature review (SLR) [35]. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines [36,37] were followed. PRISMA method combines a systematic review with a meta-analysis. The former is used to obtain a holistic picture of a particular topic, while the latter is used to summarize empirical studies and provide interesting results that allow a quantitative analysis [38]. Fig. 1 shows the research approach characterized by four phases of data processing: data identification, data screening, data included, and meta-analysis.

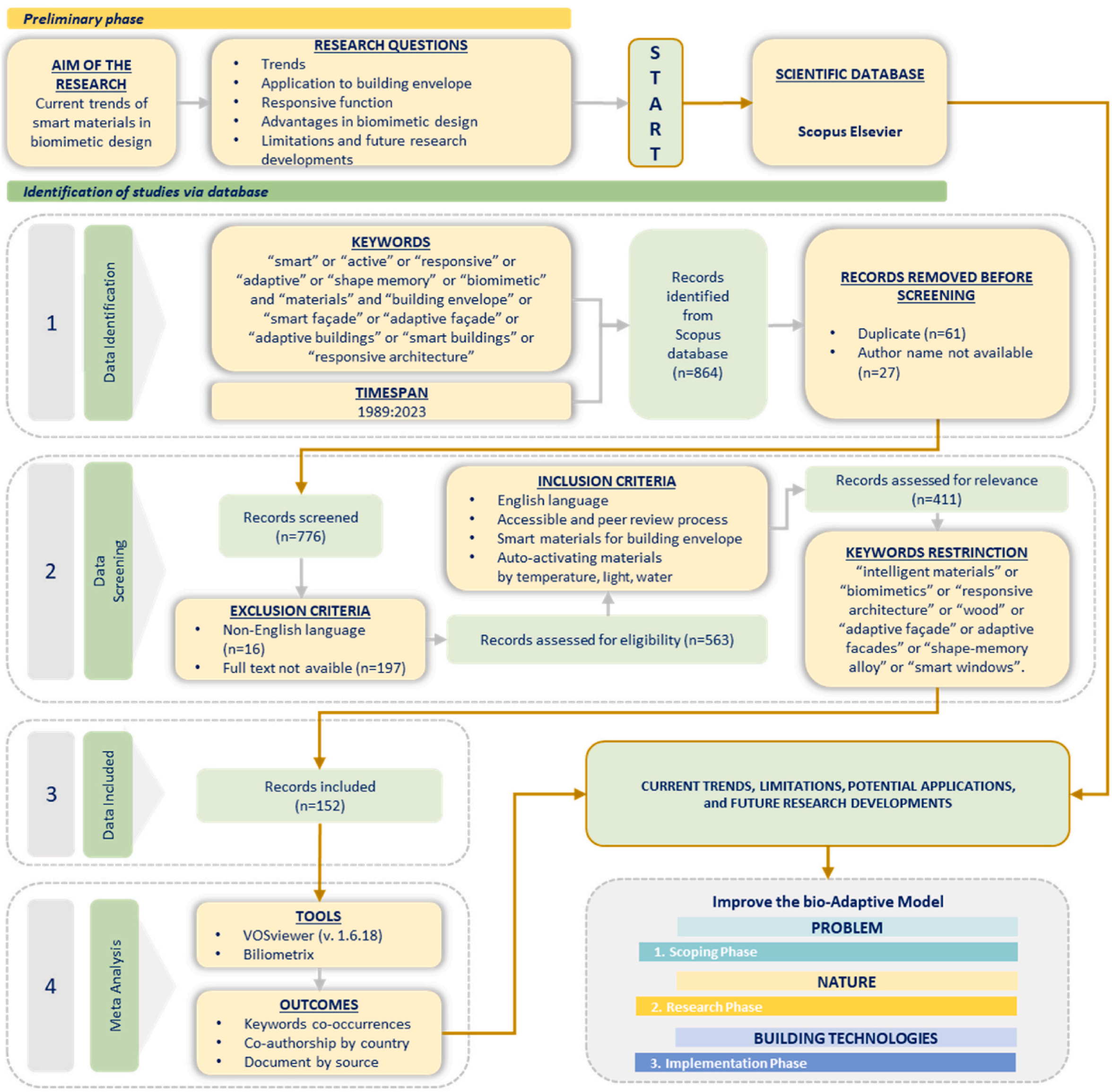

Fig. 1. Methodological framework of the research.

2.1. Data identification

After formulating the research questions, the next step is to search for documents in the official online database. For the following study, only the Scopus Elsevier database was searched for "title-abstract-keywords", using the following research string: (("smart") or ("active") or ("responsive") or ("adaptive") or ("shape memory") or ("biomimetic") and ("materials") and ("building envelope") or ("smart façade") or

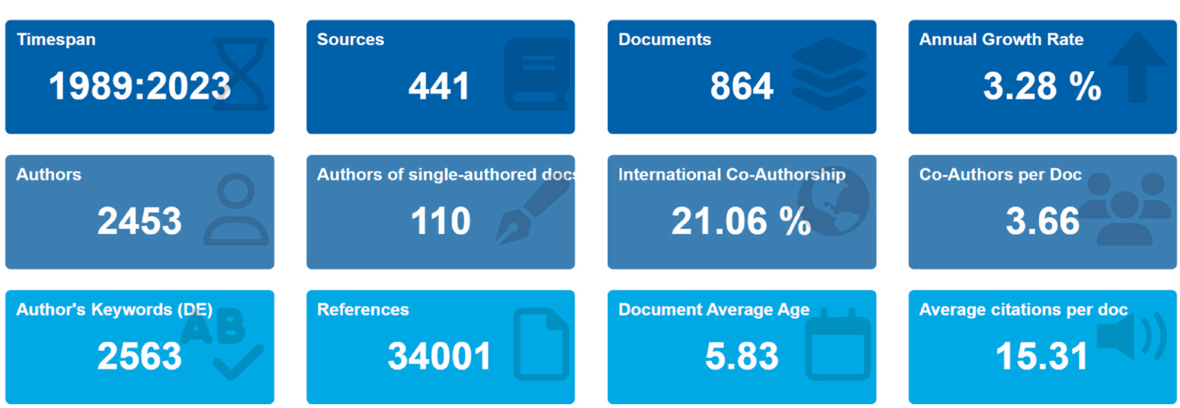

Fig. 2. Overview of main information plot. Screenshot from Bibliometrix software.

("adaptive façade") or ("adaptive buildings") or ("smart buildings") or ("responsive architecture")).

A search of the Scopus database (retrieved on 02 January 2023) identified 864 references from 441 different sources potentially suitable for this study. The main sources of information are journals, conference proceedings, and books. The documents cover the period 1989–2023; no time restrictions were applied. Results from different geographical areas were included in the study in order to get a complete overview of the topic development in different parts of the world. Fig. 2 contains important information on the data identified, using the Bibliometrix software [39].

2.2. Data screening and inclusion criteria

To proceed with the screening and analysis of the documents identified in the previous step, the following inclusion criteria were defined:

- The publication must be written in English.
- The publication must be accessible and peer-reviewed.
- The publications must deal with the properties and applications of smart materials in the building envelope.
- Publications on smart materials are preferred in connection with environmental responsive functions.

In this step, 16 papers were removed because they were not written in English and 197 were excluded because some data or the full paper was not available. Next, 563 datasets were screened for eligibility, so, a further restriction of the search was done. Of all the keywords extracted from Scopus (n = 157) only the following (n = 8) were considered: ("intelligent materials") or ("biomimetics") or ("responsive architecture") or ("wood") or ("adaptive façade") or ("adaptive facades") or ("shape-memory alloy") or ("smart windows").

2.3. Data included

Of the 563 papers selected in the data screening phase, only 152 records were selected as included data after restricting the number of keywords in the Scopus database (in terms of all keywords identified in the search of title-abstract-keywords (TIT-ABS-KEY), rather than keywords chosen by the authors). In this literature review, only responsive materials, triggered by variations in temperature, light and/or water were considered.

2.4. Meta-analysis

To answer the research question about the current trend of smart and responsive materials in the scientific literature, a quantitative analysis was conducted using the included phase data (phase 3). Specifically:

i) the co-occurrence of keywords was compared to identify the main clusters and related links;
ii) the origin of the authorship to understand the geographical distribution of the manuscripts;
iii) the sources of the documents, such as the main journals selected for publication.

Two tools for bibliometric analysis were used for this study: VOSviewer and Bibliometrix. Version 1.6.18 of the VOSviewer software [40] was used to create and display bibliometric networks such as co-authorship, citation networks, and co-occurrence networks of keywords [44]. The open-access Bibliometrix is a open-source software developed by Aria and Cuccurullo [41] was used to perform comprehensive quantitative research analysis and scientific mapping of current literature on the defined topic.

3. Environmentally adaptive building envelopes: theoretical background

Adaptive building envelopes allow the building to respond to environmental changes that vary across different time scales by modifying some of their properties via sensors, actuators or external control mechanisms, or intrinsically via properties embedded in the material [42]. There are different types depending on the modes of adaptation (static or dynamic), on the technologies used (high-tech or low-tech) and on the materials. The context of application also varies from different systems (curtain wall, double skin façade, etc.) to type of components (insulation layer, shading, etc.) and to material properties [6]. Bedon et al. [43] propose three levels of classification: *mode of change*, *type of activation*, and *triggering event*, where material related kinematics, geometrical and mechanical aspects should be taken into consideration. An adaptive envelope can react and adapt immediately and reversibly to external environmental factors, either extrinsically via sensors, actuators or external control mechanisms, or intrinsically via properties embedded in the material [42].

Several studies have investigated the concept of adaptive building envelopes resulting in different terminologies to describe it, and most frequent ones are *responsive* and *kinetic* [34–41]. Hasselaar [44] suggests the difference between adaptive and reactive, specifying that reactive simply means reacting to a change (e.g. lowering the shutters or opening the windows) and not adapting to it, while adaptive implies the ability to adjust and adapt to new and changing conditions in an autonomous way. The 2009 IEA report [45] proposes the concept of Responsive Building Elements (RBE), which refers to a building component that responds in a controlled way to changes in external conditions or to occupant intervention. In Loonen [46,47], Climate Adaptive Building Shells (CABS) are defined as shells that can reversibly change their properties in response to external environmental changes. Badarnah [27] proposes three categories for adaptation: *flexible*, *transformable*, and *responsive*, where their distinctions are based on the types of variables (e.g. spatial change), physical attributes (e.g. configuration at component or material level), and time dependence (e.g. responding to stimuli in real-time). Orhon [16] distinguishes two types of reactivity based on the type of system or response mechanism: active, when the response is carried out by automated devices capable of sensing the stimulus and implementing and regulating the technical function; passive when the function is carried out directly by the material, which activates certain response functions autonomously, therefore without the use of technical sensing, regulation and actuation systems.

Barozzi et al. [48] propose a classification of the most common adaptive shading systems: kinematic, dynamic, retractable, transformable, adaptive and responsive. Tabadkani et al. [49] present a study in which they characterise the different types of adaptive façades (active, passive, biomimetic, kinematic, intelligent, interactive, movable, responsive, smart and switchable), including responsive façades, and limits them to those façades that require an act of reaction by changing the properties of the material or the mechanical behaviour. Santos et al. [50,51] define Auto-Responsive Technologies (ART) as technologies and materials that function in an intrinsic and reversible mode because they can self-regulate thanks to an adaptive behaviour activated by environmental stimuli with changes in the intrinsic properties of the materials. Conversely, Carlucci [52] provides an overview of smart and responsive technologies applied to building envelopes by defining adaptive technologies as a subclass of responsive technologies. The work of Menges et al. [53] focuses on embedded responsiveness, referring to the autonomous response of materials to environmental stimuli. Al-obaidi et al. [54] note that the concept of adaptation is much broader than the concept of responsiveness, as the adaptive approach optimises functionality and reduces waste. Frighi [55] proposes a general definition of a "*smart/advanced/adaptive building*", meaning a structure that interacts with the surrounding environment through different technologies and devices, and they further elaborate that smart adaptive building envelopes have three main functions: *adjust* its performance to hourly, diurnal or seasonal variations, *adapting* to said variations at the macro level by considering the envelope as a whole or at the micro level by a single material, *controlling* the variations at the extrinsic level by sensors, processors and actuators or at the intrinsic level by the intrinsic properties of the materials [55].

From this overview, it is evident that there is no common definition in the scientific literature, as each author emphasises some concepts over others, and the terms, such as “*adaptive*” and “*responsive*”, are often used interchangeably. The etymological meaning of the term *responsiveness* implies the property of reacting to something or someone [56], while the term *adaptation* implies the process of change to adapt to different conditions [57]. In the biological field, on the other hand, the term *adaptation* refers to the physiological, morphological or behavioural change of natural organisms in response to changing environmental conditions [58], while the term *responsiveness* refers to the ability of living matter to respond to a stimulus [59].

Although these terms are often used as synonyms, they imply a subtle difference that allows to say that adaptivity is something that changes due to various conditions and therefore depends on the surrounding environment, while responsiveness is a property of a material or a system to respond to something. Therefore, an adaptive material (or system) can also be defined as responsive, but a responsive material (or system) is not necessarily adaptive. Consequently, it is possible to define responsiveness as a performance, as a property of the material that makes up the building envelope, and adaptation as a requirement in relation to the potential demands on the building envelope itself.

The ability of the adaptive envelope to respond to environmental stimuli and, eventually, return to its original configuration depending on environmental variations, allows to link the concept of “adaptation” and “responsiveness” with that of “resilience”. The term resilience (from the Latin re-silio, to go back, to regress), indeed, implies the ability of an element to respond to trauma, such as extreme events or variable environmental conditions, and then recover and return to its original state. In the field of biology, this concept also refers to the ability of organisms to recover their form after trauma. In the field of ecology, an ecosystem is considered resilient ifit can withstand all disturbances without suffering permanent or irreversible damage and quickly returns to its initial conditions. In materials science, resilience is defined as the amount of energy that a material can absorb and then return to its original state [60]. It can thus be concluded that a resilient system or material occupies an intermediate position between adaptive and responsive, based on its ability to return to recover after responding to a change in the environment. This concept is related to that of smart materials, which are described in detail in the following sections.

4. Current trends of smart materials applications: bibliometric analysis

In accordance with the various steps set out in the methodology, a bibliometric analysis was carried out to identify current trends in the international scientific literature on smart materials. The quantitative bibliometric analysis was carried out for the data included phase (phase 3; n = 152). Each map is characterized by nodes (or bubbles) connected by the lines; the size of the nodes (or bubbles) indicates the frequency of occurrence or citations, while the lines represent the connection between the two concurrent keywords, creating a network map [61–63]. The distance between the two nodes indicates the relatedness between them; the closer the nodes are to each other, the more related they are.

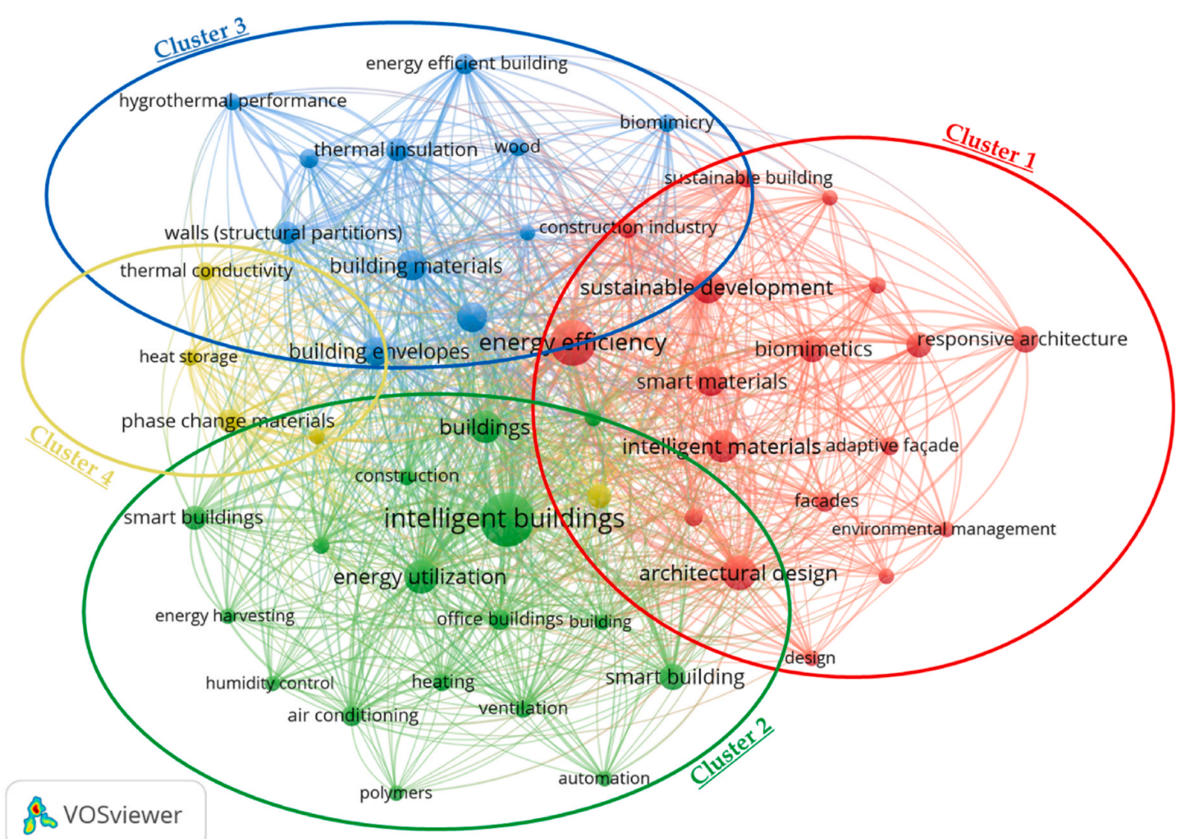

Fig. 3. Network visualization of keywords co-occurrences of data included. The size of nodes represents the frequency of occurrence, the lines between the nodes represents the co-occurrences of the keywords. The distance between the nodes indicates the relatedness between two keywords. Identification of four main clusters: cluster 1 (red) – 18 items related to smart materials and energy efficiency; cluster 2 (green) – 17 items related to intelligent building performances; cluster 3 (blue) – 11 items related to materials for building envelopes; cluster 4 (yellow) – 5 items related to phase change materials. Created by VOSviewer software on March 2023.

4.1. Terminologies and keywords

Fig. 3 shows the network diagram of the co-occurrence of the keywords. The minimum number of co-occurrences was set at 10; so, only 51 of the 3255 keywords, identified in the data included phase, meet the threshold, in 4 cluster groups: smart materials and energy efficiency (cluster 1), performance of intelligent buildings (cluster 2), materials for building envelope (cluster 3), phase change materials (cluster 4).

Table 1 shows the keywords in each of the four clusters identified in Fig. 3. Cluster number one, indicated by the red colour, shows a close correlation between smart materials, responsive and adaptive architectures, and the concept of sustainability and energy efficiency. Even the word biomimetics can be found among the keywords of cluster 1. The keywords of the second cluster (green) are related to smart buildings and the control of some internal parameters, such as ventilation, air conditioning, and humidity, which are related to the use of energy. The main keywords of cluster 3 (blue) concern the building envelope and related energy efficiency solutions, thermal insulation and building materials. Finally, cluster 4 (yellow) is characterized by only 4 items, among which phase change materials, heat storage, and thermal conductivity dominate. In summary, cluster number 1 supports the following manuscript. Through the co-occurrence of keywords, it highlights the attention of scientific-academic research in the field of responsive solutions, able to propose adaptable buildings to limit energy consumption and achieve sustainable development goals.

4.2. Geographical location

Fig. 4 shows the results of the bibliometric analysis based on co-authorship using countries as the unit of analysis. The minimum number of documents in a country was set at 1. The results show that 52 countries meet the thresholds at the data included stage, but only the countries with more than 10 documents are selected for the co-authorship network. The results show that only 9 countries meet the thresholds. Fig. 4 shows four clusters. Cluster 1, coloured red, includes the United States, the United Kingdom, China and Egypt. Cluster 2 (green) includes Germany, Switzerland and the Netherlands, while cluster 3 (blue) includes Italy and Spain. Finally, cluster 4 (yellow), concerns Australia, which is the only country in this cluster, but has links to at least 6 countries. The size of the bubbles shows that the United States and Italy have more documents on the topics analysed in this study. The analysis revealed 68 documents from USA and 42 from Italy, with 979 and 504 citations, respectively. Table 2 shows the countries with more than ten documents and the number of citations.

Table 1
Keywords of the four identified clusters of keywords co-occurrences.

Cluster	Keywords
1. smart materials and energy efficiency	adaptive facades, adaptive façade, architectural design, architecture, biomimetics, construction industry, design, energy efficiency, environmental management, facades, intelligent materials, responsive architecture, shape-memory alloy, smart materials, sustainability, sustainable architecture, sustainable building, sustainable development.
2. intelligent building performances	air conditioning, automation, building, buildings, construction, energy harvesting, energy utilization, heating, humidity control, intelligent buildings, office buildings, performance assessment, polymers, smart building, smart buildings, structural design, ventilation.
3. materials for building envelopes	biomimicry, building envelope, building envelopes, building materials, energy efficient building, hygrothermal performance, moisture, solar buildings, thermal insulation, walls (structural partitions), wood.
4. phase change materials	energy conservation, heat storage, phase change materials, solar energy, thermal conductivity.

4.3. Publication source

Fig. 5 shows the bibliographic analysis by document source, and the relationship between documents and citations. The minimum number of documents is set at 1. For the data included phase, the result is that 187 sources meet the thresholds. The size of the node is proportional to the number of publications. The journals with the most documents are "Energy Procedia" (12) and "Energy and Buildings" (10). They are followed by "Construction and building materials", "Journal of façade design and engineering" and "Journal of building engineering". Table 3 shows the distribution of documents and citations in the different journals (only sources with more than 5 documents are considered in this table) and the total link strength, which is the total strength of links from one journal to other journals.

4.4. Discussion of bibliometric analysis

Fig. 6 shows a three-field plot summarising all the previous information and describing the relationship between keywords, countries, and journals. The height of the rectangular nodes is proportional to the frequency of keywords, a country and a journal, in the collaborative network, while the width of the lines between the nodes varies with the number of links [64]. The results show that the United States and Italy, followed by China, Germany, and the United Kingdom, have the most links to smart materials and biomimetic responsive architecture. The United States has the most contributions to the journal “Construction and Building material”, while Italy contributes more to the “Journal of façade design and engineerin” and the journal “Energy procedia”.

The bibliometric analysis, carried out in the present study, analyses and measures the data of the scientific literature using a quantitative research method, which made it possible to discuss several advantages:

- The analysis of “publication source” allows to identify the most important journals in the field, based on the number of documents they have published on the topic. In this way, researchers can not only keep up to date with the latest research, but also identify where the majority of research is published and target their future contributions accordingly.
- Identifying the common occurrence of keywords in each cluster showed the connection between different topics in the literature. For example, in cluster 1, the term “biomimetic” highlighted the relationship between biomimetic approaches and smart materials for energy efficiency and sustainability. Understanding these connections can reveal opportunities for collaborations and new research directions to promote energy efficiency and, more generally, the achievement of the Sustainable Development Goals.
- When analysing the “geographical location”, it was found that documents from the United States and Italy achieved the highest number of citations (979 and 504 respectively); this means that these countries are particularly active and engaged in research on this topic and the results of their research have a significant impact on the scientific community. Furthermore, clustering improves the understanding of international collaboration among experts.

Overall, the results of the bibliometric analysis conducted in this study provide an overview of international collaborations, the importance of research and the impact of citations. Researchers can use this information to identify potential partners for collaboration and understand the leading countries in the field of smart materials. In addition, the analysis can highlight areas where further research is needed, fostering opportunities for new research collaborations.

5. Characteristics and applications of smart materials: a review

Smart materials have different performance characteristics depending on the presence or absence of an external stimulus and can combine

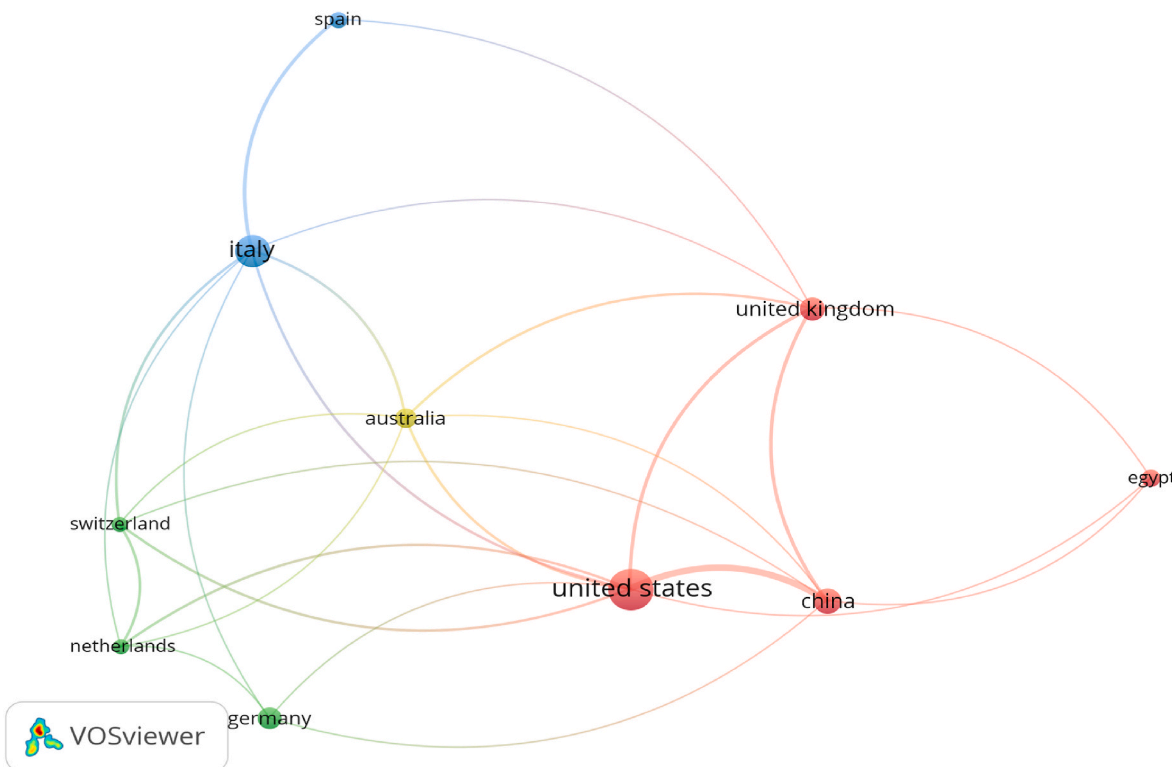

Fig. 4. Network visualization of co-authorship by country. The size of nodes represents the frequency of occurrence, the lines between the nodes represents the co-occurrences of the co-authorship. Identification of four main clusters: cluster 1 (red) – 4 items – USA, UK, China and Egypt; cluster 2 (green) – 3 items – Germany, Switzerland, Netherlands; cluster 3 (blue) – 2 items – Spain and Italy; cluster 4 (yellow) – 1 item - Australia. Created by VOSviewer software on March 2023.

Table 2
Number of documents and of citations for country in the four identified clusters.

Cluster	Country	Documents	Citations
1	United States	68	979
	United Kingdom	22	257
	China	26	255
	Egypt	12	45
2	Germany	19	463
	Switzerland	10	164
	Netherlands	10	84
3	Spain	11	96
	Italy	42	504
4	Australia	15	306

the dual function of a sensor and an actuator: the first senses the change in the external stimulus and sends it to the second, which changes the properties of the material [65–67]. In this way, sensors and actuators are already integrated into the matrix of the material itself [68], without the need to consume additional energy [11]. Sobczyk et al. [69], in classifying smart materials, emphasise their dual use as actuators or sensors. In the sensory configuration, a smart material changes its non-mechanical properties, e.g. physical or chemical properties, in response to a mechanical stress, while in an activating configuration, a smart material deforms in response to a non-mechanical stimulus, such as a change in temperature or exposure to light [69].

In recent years, various smart materials such as shape memory materials (SMMs), piezoelectric materials, thermobimetals, thermochromics and others, have been developed [66,70,71]. Shape memory materials (SMMs), when exposed to certain stimuli (such as thermal, magnetic, electrical energy, light intensity, stress, etc.), can recover their original shape after near plastic deformation and distortion. The change in material properties may be perceptible to the naked eye by a change in geometric shape, or it may be imperceptible visually. In 2022, Behera [72] proposed a classification of SMMs into: Shape Memory Alloys (SMA), Shape Memory Polymers (SMP), Shape Memory Ceramics (SMC) and Shape Memory Hybrids (SMH).

Some smart materials are activated by an electrical stimulus, such as electrochromic or piezoelectric materials, but this involves additional energy consumption, with consequence on urban microclimate, in term of pollution and gas GHG. Therefore, in this study, only responsive materials triggered by environmental parameters, such as light, temperature and/or water are investigated.

Several studies, on the application of smart materials in the fields of architecture and engineering, have been presented in the literature. Aresta [73], in 2017, presented a catalogue of materials for innovative façade components in proposing responsive strategies that allow facades to be autonomous and self-sufficient. Juaristi et al. [74], in 2018, presented different application configurations of smart and multifunctional materials for adaptive opaque facades. The same authors also presented a comparative analysis [75] of promising materials and technologies for the design of climate-adaptive facades, showing that the combination of adaptive technologies and smart materials can optimize the façade performance. Zarzycki and Decker [76], in 2019, present a review about the use of active materials as materials that change shape and phase. Villegas et al. [12], in 2020, provided an overview of passive and adaptive building envelope systems with active materials and defined the benefits of their application. In 2021, Sobczyk et al. [69] presented the application potential of smart materials, used as sensors and actuators, for the fields of architecture, and concluded that some of them need further research in order to be used in these field.

These studies, presented in the form of reviews of the scientific literature, refer to the potential applications of smart materials in architecture, but do not emphasise their advantage for biomimetic design. Tabadkani et al. [49], in classifying adaptive façade typologies, finds that biomimetic systems are applicable by using the intrinsic specifications of the materials as actuators to control adaptation. Contrary,

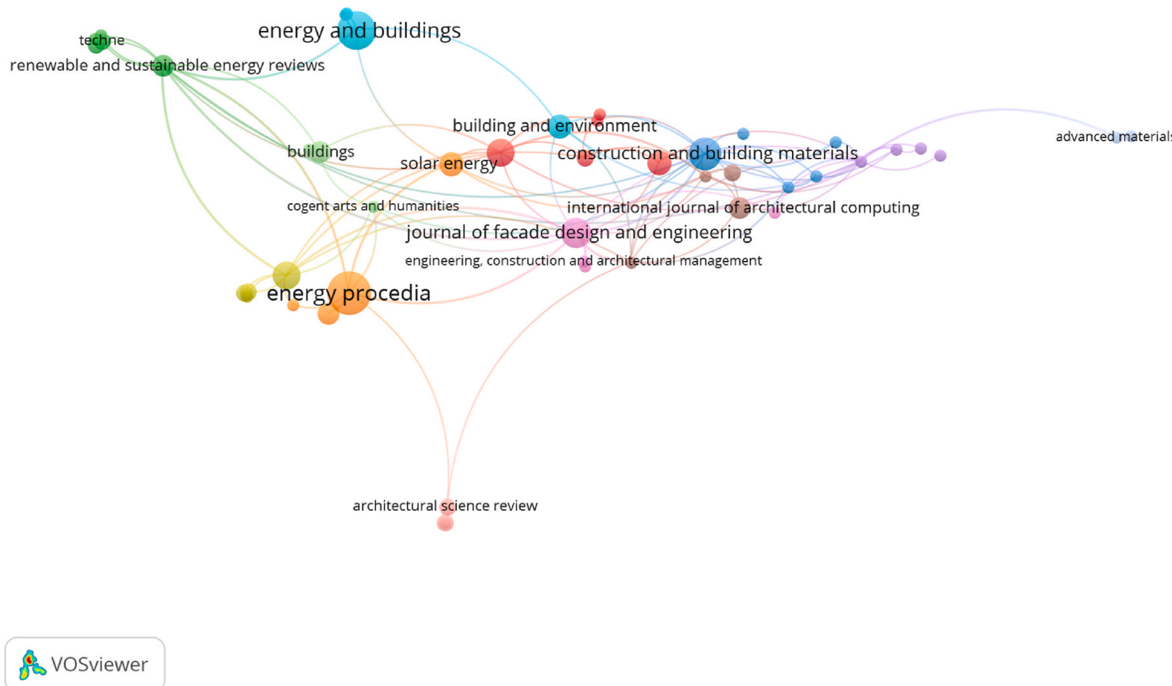

Fig. 5. Network visualization of document source. The size of nodes represents the quantity of publications, the lines between the nodes represents the co-occurrences of the sources. The distance between the nodes indicates the relatedness between two sources. Created by VOSviewer software on March 2023.

Table 3
List of journal with more than 5 publications about smart materials.

Source	Documents	Citations	Total link strength
Journal of façade design and engineering	6	75	21
Construction and building materials	7	185	16
Procedia engineering	5	122	12
Energy procedia	12	181	10
Journal of building engineering	5	105	10
Energy and buildings	10	198	6

Mansori et al. [28], in 2022, introduced the Material Driven Adaptive Design (MDAD) model, which moves away from systems adaptive to mechanical control and focuses on control systems based on the intrinsic responsive function of materials. In this way, it emulates the "cognitive decision-making" from the biological field and proposes a self-responsive and autonomous design through smart materials [28]. Fiorito et al. [65] provide an overview of innovative building envelopes with the integration of smart materials, paying particular attention to biomimetic principles for the movements of shape-changing solar shading devices. Al-obaidi et al. [54] gave an overview of biomimetic facades and classified the adaptive materials according to their reaction to temperature, light, humidity and carbon dioxide. Lopez et al. [30,77] also propose a methodology for biomimetic design and point out some smart materials that could be used for architectural facades. Sommese et al. [6], in proposing the bio-Adaptive Model (bio-AM), based on plants adaptation strategies, have highlighted the importance of smart materials in transferring nature's responsive functions to architectural technologies. Ahamed et al. [78] propose a classification of biomimetic materials based on their reactivity to light, temperature and humidity. Sommese and Ausiello [79] have also presented different biomimetic application examples using smart materials and classified them according to the environmental trigger (light, water, temperature, CO_2). Chayaamor-Heil et al. [80] presented an overview of nature-based materials used in architecture and construction, including biomimetic self-cleaning and self-repairing materials and bionspired smart materials. The following subsections report on the latest applications of smart materials in the field of architecture and construction. Only materials that react to changes in temperature, light and water have been considered.

5.1. Thermobimetals

Thermobimetals consist of two laminated metal layers with different coefficients of thermal expansion, so that they bend when the temperature is increased [77,81,82]. When heated, one layer expands more than the other and a bending of the material itself occurs. The greater the difference in thermal expansion, the greater the resulting displacement. A thermobimetal is defined by the American Society for Testing Materials as "*a composite material, usually in the form of sheet or strip, comprising two or more materials of any appropriate nature, metallic or otherwise, which, by virtue of the differing expansivities of the components, tends to alter its curvature when its temperature is changed*" [83].

The applications of thermobimetals in architecture are quite new and still very limited. An interesting application is the installation "Bloom" proposed by Doris Sung in 2012. The responsive installation consists of about 14000 thermobimetallic plates that bend when exposed to sunlight and an ambient temperature above 21 °C, thus creating a self -shading effect. In summary, the thermobimetal panels of the pavilion are closed when the temperature is low and open when the temperature is high [79,84].

5.2. Shape memory alloys

Shape Memory Alloys combine shape memory properties with superelasticity; the former allows the alloys to return to their original state when heated, while superelasticity allows for high deformation [85,86]. The transition from the austensitic parent phase at high temperatures to the martensitic phase at low temperatures involves two main features: the shape memory effect and the superelasticity effect [72]. When the alloy is in the martensitic phase, i.e. when it is exposed to low temperatures, it tends to deform. On the other hand, when exposed

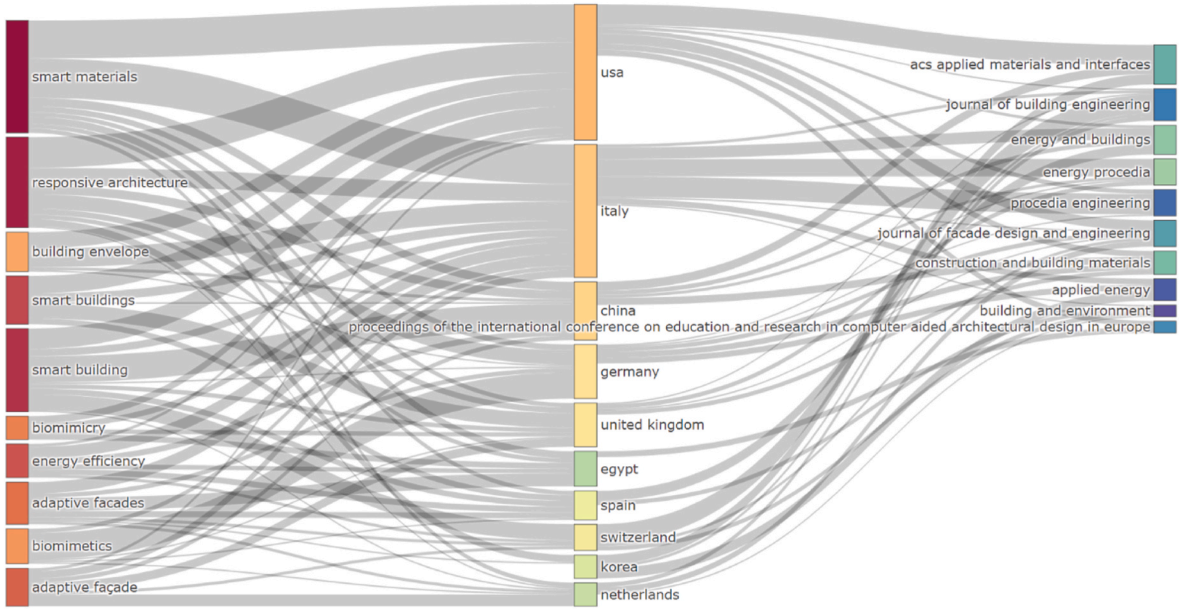

Fig. 6. Three field plot keywords (left), countries (middle) and sources (right). The height of the rectangles represents the frequency; the thickness of the lines is proportional to the number of links. Created by Bibliometrix software on March 2023.

to high temperatures, the alloy returns to its original shape [72,79,87,88]. The shape memory effect can be unidirectional (one-way) or bidirectional (two-way). In the case of one-way SMA, the deformation caused by heating at the end of the first transformation cycle is permanent, i.e. not recoverable or plastic; a two-way SMA, on the other hand, has the ability to store and recover the shape of the hot phase (austenite) and cold phase (martensite) after heating and cooling, respectively [89]. Consequently, two-way SMAs can function as on/off actuators [89]. Among the applications based on Shape Memory Alloys in the architectural field, the nickel-titanium alloy (NiTi) emerges, often used as an actuator. These systems use springs or pre-compressed wires that return to their original shape after a temperature rise [12]. NiTi-based alloys have been shown to have a better shape memory effect, improve pseudoelastic effects, and have good machinability and corrosion resistance [90]. An interesting example of this application is the device called Airflow(er) for regulating the airflow and temperature [91], which was inspired by the kinetic movement of petals of a crocus flower due to the temperature difference caused by the day-night cycle. This device, in a square module, is characterized by four triangular openings connected by a shape memory alloy wire. The imitation of the kinetic reaction is ensured by the use of a wire made of a nickel-titanium-based shape memory alloy. At low temperatures, the wire deforms and opens that the four doors connected to it to allow air flow; at higher temperatures, the filament returns to its original position [79,91]. Kuru et al. [92] transferred the mechanisms of Echinocactus grusoni to develop a photochromic folding rib morphology, with an expansion and contraction mechanism triggered by temperature differences, which activates the intelligent shape memory alloy (SMA). The totality of these morphologies, inscribed in a hexagonal shape, results in a three-dimensional photochromic glazing that regulates light, and gains triggered by the sun. Fang et al. [93] presented a study on a shape memory alloy-based cladding to promote adaptive ventilation in buildings, which works according to an opening and closing mechanism; the wires of SMA are relaxed and form a closed surface when the temperature is lower than the transformation temperature, preventing the circulation of airflow in the building. If, on the other hand the ambient temperature exceeds the transformation temperature, the wires contract, the facade panel bends, and openings are created that allow the circulation of the airflow in the building. Kim et al. [94] proposed a flexible building façade by combining a pneumatic flexible elastomer with a hybrid memory alloy to create a lightweight, gearless, light-adaptive façade module.

It is evident that shape memory alloys in most cases combine the dual function of actuators and sensors. Formentini and Lenci [95] also proposed an aluminium panel for ventilated facades that responds to thermal variations using shape memory alloys; thanks to the action of Nitinol (Ni–Ti) the panel opens to allow natural ventilation in the gap between the cladding and the internal wall, while in winter it closes to allow thermal insulation of the building thanks to the resting air in the cavity.

5.3. Thermochromic

Thermochromic materials reversibly change their colour or optical properties when exposed to temperature changes [96,97]. In this way, a dual response to light and temperature can be achieved [98]. Devices with thermochromic materials adjust the transmittance according to their own temperature. When the temperature is below the critical transition temperature, the material behaves like a semiconductor and reflects less light, while when the temperature is above the critical transition temperature, it behaves like a semimetal and increases reflection [52]. In recent years, the scientific community has paid particular attention to thermochromic windows, which are able to change their state from transparent to coloured in response to temperature changes [99,100]. Unlike traditional smart windows, which require an external power supply to adjust the optical properties of the materials, resulting in high energy consumption, thermochromic smart windows with solar control dynamically adjust the optical properties thanks to the heat absorption by the photothermal materials [103,104].

Garshasbi and Santamouris [101] have provided an overview of thermochromic materials and highlighted the advantages of their application in combating urban overheating compared to conventional heat-reflecting materials. Among the state-of-the-art thermochromic materials, Vanadium Dioxide VO_2 shows great potential as it is able to modulate the transmission of light [102,103]. VO_2 allows the transition from a transparent state (low temperatures) to an opaque state (high temperatures) thanks to the thermally induced phase transition [104,105]. Recently, Li et al. [106] proposed an in-situ technique to fabricate a film with highly dispersed VO_2 nanoparticles (HD-VN), demonstrating the excellent light transmittance value of the film and the solar energy modulation efficiency. Sirvent et al. [107] proposed a smart materials study to investigate the feasibility of adding VO_2-based thermochromic powder with cement-based materials to develop an opaque smart material for building envelope cladding and evaluate its thermochromic performance. This study showed that the stronger modulation of reflectance was achieved with a higher dust concentration on the surface. Ke et al. [108] integrated active plasmonic vanadium dioxide VO_2 nanoparticles (NPs) into elastomers to achieve adaptive solar modulation and demonstrated high solar energy modulation and improved energy savings for buildings.

5.4. Thermo responsive polymers

Another interesting smart material studied in the scientific literature are shape memory polymers (SMPs), responsive materials that can return to their original shape in response to external stimuli [109–111]. Li et al. [112] propose a new category of thermos-responsive smart windows with deformable surface morphology using thermos-responsive shape memory polymers and an optical coating. This butterfly wing-like smart window (BSW) is capable of reversibly transforming from an originally inclined shape to a temporarily flat shape when heated. Walter et al. [113] presented a study on the use of a thermos-responsive shape memory polymer (SMP) to regulate airflow through the building envelope and provide natural ventilation, showing how this material allows autonomous adaptation to environmental conditions. Among SMPs, liquid crystal elastomers (LCEs) are ideally suited as actuators that respond to thermal stimuli, thanks to their thermomechanical behaviour [109,114,115]. They represent a class of anisotropic materials that combine the elasticity of rubber with liquid crystals, resulting in a change of shape when subjected to a thermal stimulus [116,117], via a liquid crystal-isotropic phase transition. This transition can be stimulated by heat and light through photothermal or photochemical reactions [118]. Heating and cooling of LCEs leads to elongation of the material, which is often visible in the form of contraction, flexion or oscillation. LCEs are capable of acting as both sensors and actuators, autonomously. Kularatne et al. [116], suggest potential applications for LCEs as optical devices and candidate soft actuators. In a recent study, Schwartz et al. [119] present LCEs in the context of innovations for the built environment and emphasise the possibility of their integration in the field of kinetic buildings thanks to their autonomy, which eliminates the need for motors, wiring or other external means of activation. In 2022, Walter et al. [120] integrated a thermoresponsive polymer memory foam into a climate-adaptive building envelope to regulate airflow and allow natural cooling of the structure.thermoresponsive polymer memory foam into a climate-adaptive building envelope to regulate airflow and allow natural cooling of the structure.

5.5. Photochromic

Photochromic materials change colour reversibly in response to changes in light intensity [121]; they are able to pass from the transparent state to the coloured one [99,122].The material is activated in the presence of a light stimulus and shows a colour and reduced transparency [123]. The colour disappears when the stimulus is removed as the material returns to its original molecular configuration [124,125]. Applying photochromic coatings with different colours/tints to window glass is one of the current research approaches to find better energy saving techniques [121]. Photochromic materials, such as glass, have advantages in terms of energy savings. In fact, in 2022, Cannavale et al. [126] presented a research article on the constructive integration of spirooxazine-based photochromic films into transparent polymethyl methacrylate matrices and showed how photochromic glass significantly reduces energy consumption compared to conventional glass. In addition, Marchini et al. [127] proposed the development of a translucent, photoluminescent smart window coating that protects against glare during the day and avoids the need for artificial lighting in the evening.

5.6. Light responsive polymers

Light responsive polymers change shape when exposed to UV rays and offer directional shape memory movements. Light-stimulated shape memory polymers must be equipped with light-sensitive functional groups or fillers such as cinnamic acid or azobenzenes, which act as molecular switches. The light does not change the temperature, but only the cross-linking density in the material matrix [72].

Back in 2006, Jiang et al. [128] dealt with the light-triggered movements of shape memory polymers and showed how they can temporarily change their shape and only return to their original and permanent form when irradiated with light of a suitable wavelength. Xue et al. [129] designed a smart sub-environmental diurnal radiative heating (SDRC) building cladding that combines sunlight-induced fluorescence, particle scattering and broadband emissivity of materials.

5.7. Photocatalytic materials

Photocatalytic materials are metallic compounds such as titanium dioxide that respond to UV radiation by oxidising the organic material they come into contact with [17].

Ausiello [130] highlights the intelligence of titanium dioxide nanoparticles, which maintain a stable appearance over time but show active behaviour in terms of their performance. The self-cleaning ability is achieved by the photocatalyst-induced change in the roughness of the surface in the nanometre range, which changes from hydrophobic to smooth and thus superhydrophilic. The process is reversible, because with the end of UV irradiation the hydrophobic states gradually become red again. The behaviour of titanium dioxide is studied by analysing the biological behaviour of the lotus leaf, which, immersed in muddy water, always appears shiny and clean. The mechanism spontaneously triggered by sunlight is due to the presence of advancing nanoparticles that prevent the water droplets from remaining on the leaf surface, but instead allow them to slide off and carry dust or insects with them [131]. The anti-pollution effect, on the other hand, is achieved through the effect of photocatalysis, i.e. a chemical redox reaction that converts pollutants into harmless substances by accelerating the oxidation processes occurring in nature through the TiO_2 [130]. The application areas of TiO_2 range from photocatalytic cements for mortar, concrete or plaster to photocatalytic paints, floor coverings or glass with hydrophilic and self-cleaning surfaces.

5.8. Wood

Wood is a natural material that, although not always counted among the intelligent materials, responds to climatic stimuli by using its hygroscopic and anisotropic abilities. This property makes it one of the most studied materials in the literature. Anisotropy is the property according to which the physical properties of the material differ in the different dimensions. Hygroscopicity refers to the ability of the material to absorb and release moisture from the environment while maintaining a particulate equilibrium. During the process of moisture absorption and release, the material physically changes; depending on the water content, the wood produces easily perceptible movements such as curvature or bending. Pinecone scales are a good example of this. During the transition from the wet to the dry state, they activate a passive bending movement caused by the swelling or shrinking of the double-layered tissues that characterise their structure [132,133]. Plant cell walls are characterised by rigid cellulose fibrils that impede the movement of the swellable matrix; in fact, swelling occurs preferentially in the direction perpendicular to the fibrils [134]. Such organisms behave like natural actuators. Holstov et al. [135,136] have explored the possibility of adaptive systems using wood-based hygromorphic materials, highlighting the opportunity they offer for the development of architectures that respond passively to the environment. Various experiments and application examples can be found in the literature to define meteorologically sensitive solutions capable of regulating the climatic challenges associated with the presence of water in the environment [137–140]. The most frequently cited projects are the Meteorosensitive Hygroskin Pavilion and the Meteorosensitive Morphology - Hygroscope, by Achim Menges. Both projects are inspired by the passive reaction of pinecones to environmental stimuli. When the air is dry, the scales of fir cones fold outwards and release the seeds [135]; when the humidity is high, they close. Based on this behaviour, the two pavilions are examples of biomimetic design, i.e. inspired by nature. Recently, Zhan et al. [137] investigated the transfer of the principles of hygroscopic movements of plants to biomimetic building systems made of wood [137] investigated the transfer of the principles of hygroscopic movements of plants to biomimetic building systems made of wood.

5.9. Hydrogel

Another material that can be named for its reaction to water absorption or evaporation is hydrogel. Hydrogel-based materials represent a group of polymeric materials with a three-dimensional structure that swell when they absorb water, thanks to the hydrophilic properties that give the material the ability to combine with and shop water [141–143]. Natural hydrogels have been replaced by synthetic ones because they can absorb more water [141]. Some hydrogels are sensitive to external stimuli such as temperature, light, electric fields, etc. [142]. This material can swell or shrink while acting as an actuator. Zhang et al. [144] propose a smart window model with a three-layer sandwich structure that is both electrically and thermally responsive and is able to transition from a highly transparent state to a milky white state by utilising the capabilities of the H+ and Li+ doped hydrogel HPC-PAA.

5.10. Summary

Table 4 shows the results of the literature review. The different materials described in the previous sections were classified based on the three main environmental triggers (temperatures, light, water) in order to assign to each of them a responsive function useful for biomimetic design and to create adaptive envelope solutions that can respond to the three main environmental triggers. Among the different solutions analysed, the materials that are activated independently of the effect of the temperature trigger predominate. This is especially true for the studies with shape memory alloys. The main responsive functions that smart materials have been able to ensure so far are mainly related to solar control, regulation of air flows and daylight, and thus thermal and visual comfort.

6. New guidelines for biomimetic design

The dynamic nature of smart materials and their response to changing conditions make their application in architecture interesting to find solutions that can adapt to the climate and are able to passively emulate the functional behaviour of nature. The results of the present study make it possible to extend the phases of the bio-Adaptive Model (bio-AM) [6] to propose clear guidelines for applications in different contexts and with different challenges related to environmental factors. The bio-AM is an iterative problem-based approach (Fig. 7) that aims to facilitate the transfer of responsive mechanisms from nature (plants) to technologies for climate-adaptive building envelopes. It is characterised by three phases: Scoping, Research, and Implementation. While the first two phases respectively concern the definition of the challenge to be met and the search for adaptive strategies from the biological domain (i.e. plants), the third phase is about the abstraction of the biological principles and the corresponding transfer into adaptive technologies through intelligent materials that can perceive and respond to environmental stimuli.

6.1. Parallels between plants movements, intelligent responsive materials and kinetic movements of façades

The adaptive parallelism between nature and architectural technologies is possible thanks to the study of the functional and adaptive strategies of plants, which, although seemingly inert, activate different strategies to survive the environmental triggers typical of their habitats. Adaptive strategies are divided into morphological when they concern form and the aesthetic aspect, physiological when they concern metabolic aspects, and behavioural when they concern movements [5,6,30,146]. Biological organisms are equipped with cells, tissues or organs that enable them to respond automatically and adaptively to ecosystemic environmental factors. A flower that follows the position of the sun by changing its orientation, petals that open or close in response to light or temperature, or scales of pinecones that close in response to moisture, pores that regulate evapotranspiration, are just a few examples of self-responding biological organisms.

Plant movements repeat according to daily or seasonal cycles and based on environmental triggers. The most important movements of plants were described by Darwin, who divided them into tropic movements when they depend on the direction of the stimulus and nastic movements when they are independent of it [20]. Fig. 8 shows some

Table 4
Summary of the most analysed materials in the scientific literature, grouped according to the three main triggers: light, temperatures, and water. **Output:** Color Change (CC), Shape Change (SC), Non-Visible Change (NVC). **Responsive function**: Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Abiotic factor:** Temperature (T), Air (A), Light (L), Water (W).

Environmental trigger	Materials	Sub-materials	Principal reference	Output	*Responsive function*	*Abiotic factor*	Advantages of application
Light	Photochromic	Spirooxazine	[125,126]	CC	Reg/Sh	L	Limit glare problem
	Light Responsive Polymer	Azobenzene	[128,129]	CC/SC	Sh	L	Regulation of solar radiation
	Photocatalitic	Titanium dioxide (TiO_2)	[130]	NVC	Reg/Tm	A	Self-cleaning Anti-pollution
Temperature	Thermobimetals	–	[84]	SC	Reg/Sh	L/A	Modulation of solar radiation Regulation of air flows
	Shape Memory Alloys	Nickel Titanium alloy (NiTi)	[92,93,95]	SC	Reg/Sh	L/A	Movement actuators for façade panels
	Thermochromic	Vanadium dioxide (VO_2) nanoparticles	[108,112]	CC	Reg/Sh/R	L	Adaptive solar modulation; Energy saving
	Shape Memory Polymers	Liquid Cristal Elastomer (LCE)	[119]	SC	Reg	A	Autonomous adaptation to environmental conditions
Water	Wood	–	[135,145]	SC	Reg	A	Autonomous regulation of humidity
	Hydrogel	Hydrogel HPC-PAA	[144]	SC	Reg/S	W	Water absorbtion

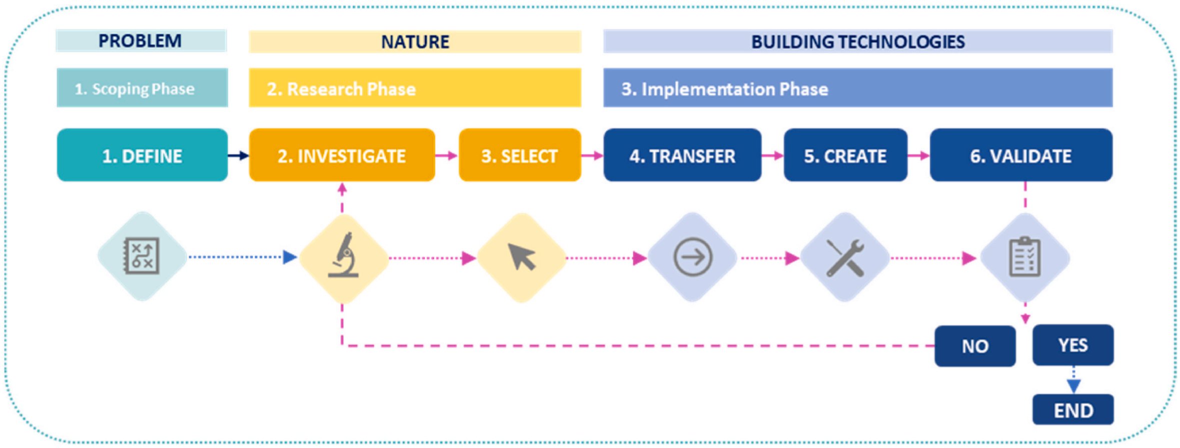

Fig. 7. General framework of bio-adaptive model [6].

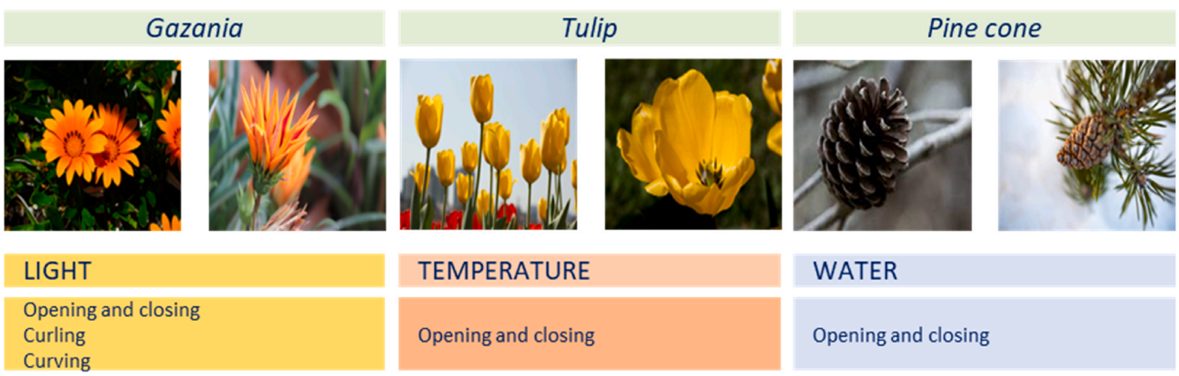

Fig. 8. Some examples of vegetal organisms movements.

examples of behavioural strategies of plant organisms that activate movements in response to environmental triggers such as light, temperature and water.

Smart materials, thanks to their ability to respond autonomously, are configured as excellent allies for mimicking biomimetic functions and behaviours, and thus for biomimetic design. The ability to self-activate to environmental triggers enables the development of façade systems or components that provide some of the key responsive functions of a biomimetic adaptive envelope, including shielding, modulation, reflection and filtering. As plants are characterized by reversibly repeating cyclic and modular adaptive behaviour mechanisms, it is necessary to favour smart reversible or two-way materials (as in the case of some thermo responsive materials), as the process needs to be replicated over time according to variable cycles on a seasonal and daily basis. SMPs are much more deformable than SMA, which have a more limited deformation capacity; SMPs have much lower recovery stresses than SMAs, which have high stiffness [147]. Moreover, in the case of SMA and SMP, it is appropriate to consider the reversible shape change, whose studies show even weaker mechanical performance compared to the unidirectional equivalent [147].

6.2. Matrix of biomimetic design

Fig. 9 shows a biomimetic design matrix that helps researchers select responsive materials capable of providing a specific kinetic movement of the building façade depending on climatic factors (light, water or temperature). The matrix consists of three main lines, each relating to a climatic factor (light, temperature and water) and seven columns. Each column contains different features that apply to the study in the biological domain (phase 2 of the bio-adaptive model) and to the transfer of natural principles into technologies with smart materials (phase 3 of the bio-adaptive model). The lines between the cells indicate the connections between them and the functions that can be ensured. It is possible to read the matrix from left to right (i.e. starting from the climatic challenge) or vice versa (i.e. starting from the material). The movements of the plants and the kinetic movements were synthesised by bending, opening and closing, curving and arching. Depending on the characteristics of the adaptive building envelope, the response time can vary from seconds to hours, from daily to seasonal scales. The six responsive functions considered are those defined by Sommese et al. [6].

Below is an example of how to read and use the matrix in relation to the "light" challenge: assuming that a regulation function of light radiation must be ensured by a kinetic folding movement, it is possible to interpret the matrix by reading it from left to right, entering the macroline "light" and following the "folding" motion that leads to a "shape change" as output; thus, it's possible to determine that the responsive materials that can ensure this reaction are Shape Memory Polymers. Otherwise, it is possible to read the matrix from right to left to find out which responsive functions a particular material can ensure. For example, if entering "light" in the "materials" column and selecting "photochromic", this will lead to the output "colour change" and the responsive functions "regulate, shield and reflect" that the material guarantees by folding, curling, curving or expanding and contracting, depending on the choices and design needs.

7. Discussion: advantages and limitations

The applications of smart materials in architecture are still limited; many of them are prototypes or used in small temporary pavilions. The various studies found in the literature describe the advantages of their

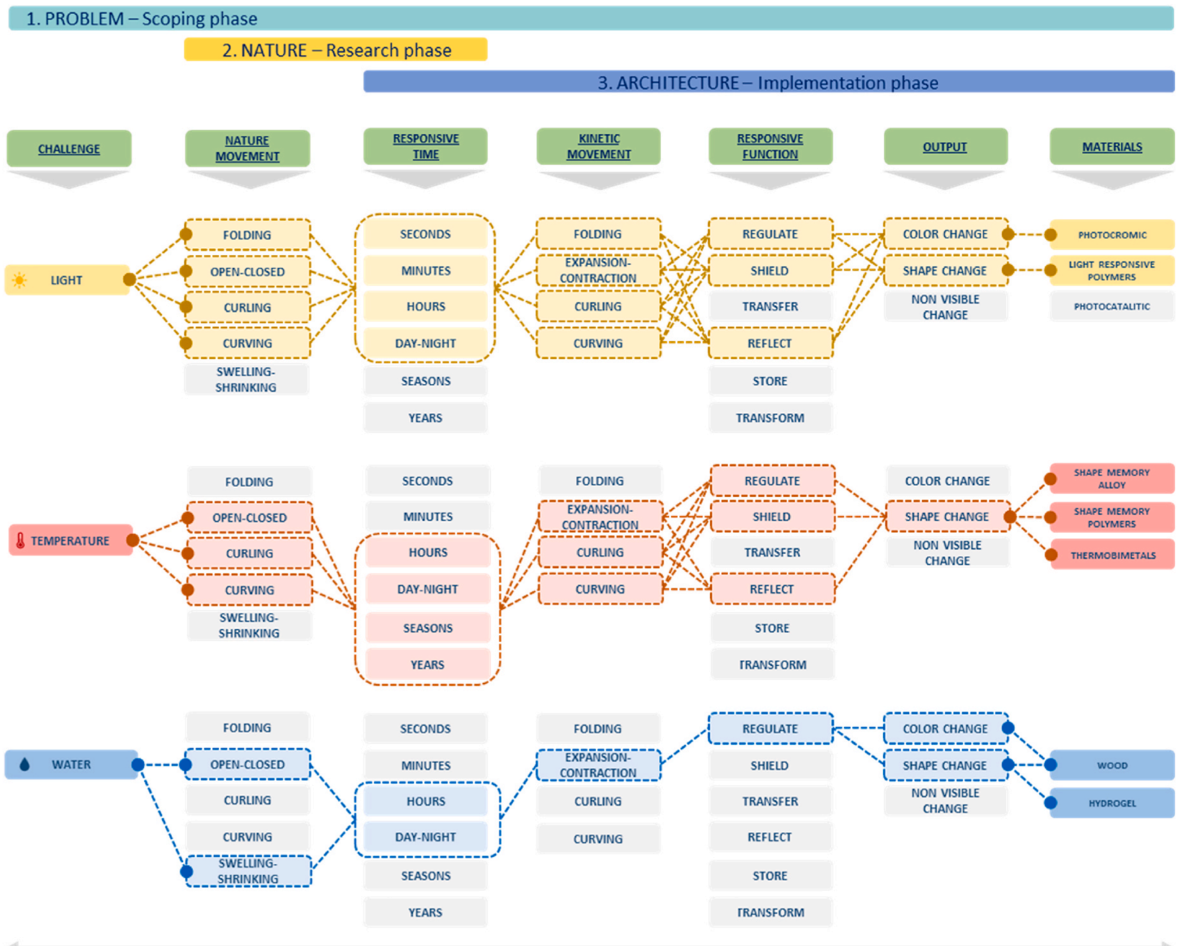

Fig. 9. Matrix of biomimetic design based on smart responsive materials.

application in building envelopes. Thus, the readiness of smart materials for biomimetic design is still at an early stage of development. Further experimental laboratory studies are needed to define the evaluation and verification stages of some parameters, including modulation, motion cyclicity, dimensions and durability. Laboratory tests and simulations with dynamic modelling software will make it possible to obtain useful feedback on the designed technological solutions before they are used in buildings. It is also necessary to examine the manufacturing techniques of these materials and the relative complexity of the production process [148].

Among the different solutions analysed, the materials that are independently activated by the action of the thermal trigger predominate. The temperature-responsive shape memory materials are the most commonly used and/or studied materials in the field of architecture. Shape memory polymers are less expensive than shape memory alloys. Furthermore, the shape memory effect can be triggered by different stimuli or by several stimuli at the same time such as temperature and humidity [149]. The scientific literature repeatedly points out that piezoelectric technologies are considered the most mature class of smart materials [150]. Nevertheless, they were excluded from this study because they are not able to react autonomously to environmental stimuli.

In many cases, smart materials are used as sensors and actuators that can activate different functions depending on triggers in the environment. In other words, they are used to control physical variables. At the same time, these solutions are configured as a possible strategy to reduce energy consumption while ensuring indoor comfort. The use of these materials leads to a reduction in the consumption of fossil fuels in buildings [151], as their ability to adapt to external conditions and their relative deformability can directly benefit indoor comfort, especially lighting levels natural ventilation, and hygrothermal comfort. The use of smart materials favours the adaptability of the building envelope to environmental conditions and improves not only the resilience of buildings but also that of urban areas thanks to the use of environmental triggers for their activation that do not require additional energy consumption. While smart materials have been researched in other fields for a long time, the study of smart materials in the field of architecture is still in its infancy. Therefore, it is necessary to deepen this concept by defining the possibilities and limits with regard to the state of the art.

In summary, the advantages and limitations of using smart materials can be described as follows:

- Smart materials combine the function of a sensor and an actuator by being activated by environmental triggers through the modification of their intrinsic properties;
- Self-activating smart materials can be considered as no-tech materials and therefore do not require additional automation tools for their activation, which reduces energy consumption;
- In cases where the application of these materials is appropriate, the ability to use environmental factors as a passive trigger for adaptation and the relative reduction in energy consumption means that the solution can be counted among the resilient solutions;
- The ability to change colour, shape and appearance allows not only the execution of precise functions, but also the definition of a new architectural style that contributes to the aesthetic quality of the

built environment. Indeed, smart materials have also shown benefits in aesthetic terms [152];

- The complexity of the production system, which is not simple and immediate;
- The efficiency of application at the macro scale, because so far the main applications are at the micro and nano scale, especially in fields other than construction;
- The durability of the environmental impact of these materials during their life cycle;
- The cyclicality and repeatability of the actuation cycle to understand how often the material can ensure its responsive behaviour;
- Production and installation costs.

8. Conclusions

The need for dynamic envelopes capable of interacting with the environment, as is the case with natural organisms, has increased research into the development of advanced technologies and materials for potential applications to buildings. Smart materials are excellent candidates to achieve interaction with and responsiveness to the environment. To understand the current trends and potential applications of smart materials in the field of biomimetic design for building envelopes, a systematic literature review was conducted. The main focus was on responsive properties that enable autonomous adaptation to changes in environmental conditions such as temperature, water and light by using the intrinsic properties of the material itself, thus avoiding artificial triggers that consume energy. This study has shown that so far more knowledge has been gained about thermo-responsive materials, followed by materials that respond to light.

In the first part of this study, a bibliometric analysis was carried out to identify the main correlations in the scientific literature in terms of keywords, the countries most involved in the topic of smart materials for the adaptive envelope and the main journals dealing with this topic. It can be concluded that Italy and the United States are the countries where research on this topic is the most advanced and also the most cited, which means that the resulting research is effective in terms of results. This aspect is useful for the reader-researcher who can understand what has been done and what is still missing and with whom to potentially carry out international and multidisciplinary collaboration.

In the second part, the smart materials that emerged from the analysis of the papers included in the systematic review were classified according to their responsiveness to the three main environmental factors, such as temperature, light and water. The classification of smart responsive materials has made it possible to create a biomimetic matrix to integrate the bio-AM. It is configured as an important tool for researchers approaching the early stages of biomimetic design, by which they can identify the smart responsive material that best fits the responsive functions required by the envelope they are designing.

Biomimetic solutions using smart materials inspired by nature, where efficiency is a fundamental principle, can lead to the development of systems that use fewer resources (materials and energy) and achieve improved performance. Consequently, the use of smart materials offers significant benefits in achieving several goals of the Agenda 2030 and ESG (Environmental, Social, Governance) factors by contributing to environmental sustainability and promoting innovation and economic growth. Companies and organisations that invest in biomimetic design using smart materials can also gain a competitive advantage by offering innovative and sustainable solutions that meet the needs of environmentally conscious consumers and investors.

Although various studies are underway, the application of smart materials in the field of building technology remains a major challenge. Increased collaboration between experts from biology and materials science is essential to promote interdisciplinarity and achieve better results.

This study also makes recommendations for future research, including the need to develop physical prototypes to test the effectiveness of applying smart materials in buildings. In particular, there is a need to evaluate the response time and modularity of the material under specific environmental conditions. As these are solutions that anticipate future passive technologies, or rather, that do not require the use of additional energy, thus limiting the environmental impact, a life cycle analysis (LCA) would be desirable to understand the impact of these materials on the environment.

Author contributions

Francesco Sommese: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Software, Data curation, Writing - original draft preparation, Writing - review and editing, Visualization. **Lidia Badarnah:** Conceptualization, Methodology, Analysis, Resources, Writing - review and editing, Supervision. **Gigliola Ausiello:** Conceptualization, Resources, Writing - review and editing, Supervision.

All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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