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Review

A Review of Passive Solar Heating and Cooling Technologies Based on Bioclimatic and Vernacular Architecture

Julia Lima Toroxel [1] **and Sandra Monteiro Silva** [2,*]

[1] Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal; pg45081@alunos.uminho.pt
[2] University of Minho, ISISE, ARISE, Department of Civil Engineering, 4800-058 Guimarães, Portugal
* Correspondence: sms@civil.uminho.pt

Abstract: The increase in global average temperature, mainly due to the high rate of greenhouse gas emissions, has triggered severe global warming and climate change. In Europe, the building sector accounts for a significant portion of emissions and energy consumption, prompting attention on nearly-zero-energy buildings (nZEBs) and zero-carbon buildings, as they play a pivotal role in reaching the goal of climate neutrality by 2050. Passive systems offer a promising solution, optimizing energy usage by better adapting buildings to their local climates. This paper reviews the state-of-the-art of passive heating and cooling techniques, exploring their contributions to contemporary architecture and showcasing their features and adaptability across different climates. Furthermore, the link between traditional and bioclimatic architecture is assessed. Recent years have witnessed a surge in publications on bioclimatic solar passive strategies, reflecting an intensified debate on climate change. Europe leads research in this area, aligned with initiatives like the Green Deal and Fit for 55. While dynamic simulation software is widely utilized for energy efficiency analysis, there remains limited integration of Building Information Modeling (BIM) and life cycle analysis (LCA) tools, which could enhance holistic assessments.

Keywords: bioclimatic architecture; vernacular architecture; passive systems; nZEBs; zero-carbon buildings

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1. Introduction

The increase in global average temperature, mainly due to the high rate of anthropogenic emissions of greenhouse gases (GHGs) into the atmosphere, is leading to a climate change scenario with increasingly severe impacts. According to an emissions report published in 2022, if current economic policies persist, by the end of the century, the average annual temperature will increase by 2.8 °C [1], a milestone that threatens the integrity of oceans and ecosystems and severely compromises life on the planet.

In 2016, through the Paris Agreement [2], more than 190 countries agreed to take measures and develop strategies to keep this temperature increase below 2.0 °C, preferably limited to 1.5 °C, thus significantly reducing the risks and impacts of climate change. In 2019, the European Union (EU), which positions itself at the forefront of the fight against climate change, fostering climate ambition and setting global standards [3], published the European Green Deal, which aims to transform the EU into a climate-neutral economy with net-zero greenhouse gas emissions by 2050 [4].

Part of the strategy to achieve the objectives by 2050 includes the Fit for 55 package of proposals, which aims to review and update European legislation to align its goals with a 55% reduction in greenhouse gas emissions by 2030. Among the proposals in the package are the adoption of a Carbon Market (EU ETS), a system of emission limits and trading for high-energy-demand industries, a Climate Social Fund system aimed at providing support measures and investment for the road transport sector and the most vulnerable residential and business sectors, and new proposals to accelerate energy efficiency and reduce energy consumption in public buildings in Member States [5].

The building sector in Europe accounts for 40% of the total energy consumption, representing the sector with the highest energy needs in the economy [6]. The energy used for heating, cooling, and DHW (domestic hot water) constitutes 80% of the total energy consumed by households. The building stock also accounts for 36% of the European economy's total greenhouse gas emissions [6]. It is clear, therefore, that making buildings more energy efficient and less dependent on fossil fuels is crucial for Europe to achieve its goals by 2050.

Within the range of currently available strategies and technologies, implementing techniques to reduce buildings' energy needs and investing in efficient equipment are among the more economically viable options to substantially reduce greenhouse gas emissions in the sector [7]. Bioclimatic construction strategies and passive heating and cooling systems can significantly contribute to designing buildings with nearly-zero-energy needs, known as nZEBs, and carbon-neutral buildings.

The European Energy Performance of Buildings Directive (EPBD) recast from 2010 [8], the Proposal for the revision of the EPBD approved in December 2023 [6], and related European standards [9] (later replaced by [10,11]) have also established guidelines for Indoor Environmental Quality (IEQ), including thermal, visual, and acoustic comfort and indoor air quality. The publications emphasize how optimizing IEQ parameters enhances energy efficiency in buildings, as improved ventilation, insulation, and lighting control reduce energy consumption while fostering occupant comfort. The 2010 recast of the EPBD [8] emphasizes implementing passive systems in buildings and resilient strategies to enhance thermal performance during extreme climates. Furthermore, both the 2010 EPBD recast [8] and the most recent Proposal for the revision [6] highlight the need to focus on measures that prevent overheating and encourage the further development and application of passive cooling techniques, especially those that enhance indoor climate conditions and the microclimate surrounding buildings.

Hence, the study of the energy potential of passive systems, often evolved from vernacular construction techniques, proves opportune. Since ancient times, vernacular architecture has been based on the architectural form and passive solar systems to ensure acceptable indoor comfort levels [12], as cited in [13]. Many of these constructions can achieve satisfactory thermal comfort levels indoors for most of the year through passive means and, sometimes, perform even better than contemporary constructions [14].

In this context, this paper constitutes a comprehensive review of solar passive heating and cooling systems for buildings. Vernacular and bioclimatic architecture concepts will be defined. Subsequently, different passive cooling and heating techniques will be presented, and mechanisms to mitigate overheating in the latter will be reviewed, alongside a systematic assessment of academic studies regarding these topics. The main results and identified gaps found in the literature will be addressed. This paper aims to disseminate information about passive solar systems, which play a pivotal role in achieving climate neutrality in the building sector.

2. Methodology

Search engines such as Scopus, ScienceDirect, ResearchGate, and Google Scholar were used to formulate this review paper and find relevant content about the topics addressed. Some of the keywords used were passive solar techniques, bioclimatic and vernacular architecture, nZEBs, sustainable buildings, and more topic-specific keywords such as thermal inertia in buildings, attached sunspaces, and building overheating assessment were also used. The keywords were frequently cross-referenced, e.g., sunspaces + bioclimatic architecture, to obtain more targeted results. The research spans 2022 to early 2024, encompassing mainly English and Portuguese literature.

A discernible increase in the number of publications over recent decades was noted among the referenced documents in this paper. This reflects a growing interest and demand for bioclimatic architecture and passive systems topics. Most of these works were published between 2011 and 2020 (Figure 1).

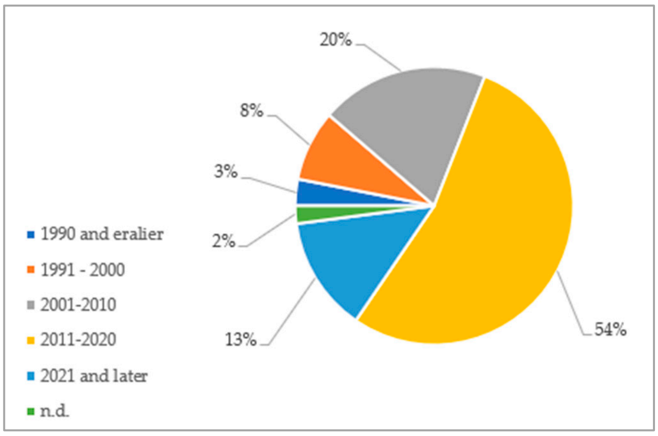

Figure 1. Referenced literature by publishing decade.

The criteria for selecting publications were primarily based on the number of citations, the content described in the title, and its relevance to the subject. Emphasis was placed on prioritizing the most relevant publications and articles published after 2000. However, consideration was also given to some earlier publications, as topics related to vernacular architecture are not novel, thus embracing a broader temporal scope. After manually selecting the content and conducting a brief review of abstracts, 71 relevant publications among conference proceedings, journal articles, books, dissertations, theses, and other relevant sources were retained and categorized by year, type of publication, location, and main assessed subjects. This referenced literature, which is systematically explored in the next chapter, can be found in Table 1.

Table 1. Reviewed literature by year of publication.

Ref.	Title	Year	Type of Publication	Location	Main Assessed Subjects
[15]	Arquitectura Tradicional Portuguesa	1992	Book	Portugal	Portuguese vernacular houses per type and space-use
[16]	Sunspace Basics	1994	White Paper	US	sunspaces
[17]	Cooling without air conditioning	1998	Article	India	passive downdraught evaporative cooling
[18]	Uso de Inércia Térmica no Clima Subtropical Estudo de Caso em Florianópolis-SC	1999	Master's Dissertation	Brazil	thermal inertia
[19]	Glazed balconies and sunspaces—energy savers or energy wasters?	2000	Article	Denmark	glazed balcony, sunspace
[20]	Measures used to lower building energy consumption and their cost-effectiveness	2002	Article	Cyprus	natural ventilation, solar shading, types of glazing, orientation and shape of building, thermal mass
[21]	Analysis of energy saving using natural ventilation in a traditional Italian building	2003	Article	Italy	natural ventilation
[22]	Modeling energy efficiency of bioclimatic buildings	2004	Article	Greece	solar water heaters, shading, natural ventilation, greenhouses, and thermal storage walls

Table 1. *Cont.*

Ref.	Title	Year	Type of Publication	Location	Main Assessed Subjects
[23]	Modeling of solar passive techniques for roof cooling in arid regions	2004	Article	India	insulation beneath the roof, evaporative cooling above the roof and a roof pond with a movable insulation system
[24]	Recovery of Spanish vernacular construction as a model of bioclimatic architecture	2004	Review Paper	Spain	high thermal capacity, use of solar radiation, protection against solar radiation, rainfall, wind, and cold temperature
[25]	Edifício SOLAR XXI: Um edifício energeticamente eficiente em Portugal	2005	White Paper	Portugal	thermal insulation, sun use, earth tubes, natural light, sun shading, natural ventilation
[26]	Habitar sob uma segunda pele: estratégias para a redução do impacto ambiental de construções solares passivas em climas temperados	2005	Doctoral Thesis	Portugal	solar passive buildings
[27]	Passive options for solar cooling of buildings in arid areas	2006	Article	Egypt	white painted roof, use of thermal insulation above or below the roof, water pond roof with and without movable insulation, evaporative cooling, solar chimney
[28]	Passive Design for Thermal Comfort in Hot Humid Climates	2007	Review Paper	UK	natural ventilation, evaporative cooling, shadings, light-colored surfaces, radiant cooling, green roofs, passive dehumidification, thermal mass
[29]	La belleza termodinámica	2008	Essay	Spain	thermodynamics principles in architecture
[30]	Optical properties and influence of reflective coatings on the energy demand and thermal comfort in dwellings at Mediterranean latitudes	2008	Conference Paper	Ireland	reflective coatings, building geometry, thermal capacity, natural ventilation, window shading
[31]	Building Sustainability Assessment	2010	Article	Portugal, Finland	sustainability assessment of a whole building
[32]	Impacts of form-design in shading transitional spaces: the Brazilian veranda	2010	Conference Paper	Brazil	transitional shaded spaces, verandas
[33]	Innovative solar windows for cooling-demand climate	2010	Article	China	advanced variable tint glazing, solar-screen, airflow and electricity conversion window systems, water-flow windows
[34]	Review of intelligent building construction: A passive solar architecture approach	2010	Review Paper	India	window to wall ratio, the orientation of the building, sun shade, window details,
[35]	Review of passive solar heating and cooling technologies	2010	Review Paper	UK	Trombe wall, solar chimney, unglazed transpired solar facade, solar roof, evaporative cooling
[36]	Analysis of thermal performance of building attached sunspace	2011	Article	Jordan	attached sunspaces

Table 1. *Cont.*

Ref.	Title	Year	Type of Publication	Location	Main Assessed Subjects
[37]	CFD analysis of heat collection in a glazed gallery	2011	Article	Spain	glazed balcony
[38]	Passive Low Energy Architecture in Hot and Dry Climate	2011	Review Paper	Malaysia/ UK	interception and reflection of solar gains, building orientation, insulation, natural ventilation, radiant cooling, evaporative cooling
[39]	Reabilitação de casas tradicionais em madeira do litoral norte e centro de Portugal	2011	Conference Paper	Portugal	Renovation of traditional Portuguese vernacular timber house
[40]	Solar passive techniques in the vernacular buildings of coastal regions in Nagapattinam, TamilNadu, India—a qualitative and quantitative analysis	2011	Article	India	natural cross ventilation, wind catchers, low thermal capacity materials, overhangs, internal courtyards
[41]	Wohnanlage in Dornbirn. Mit Faktor zehn ins 21. Jahrhundert	2011	Trade Journal Publication	Austria	glazed balcony
[42]	An overview of passive cooling techniques in buildings: design concepts and architectural interventions	2012	Review Paper	Romania	several passive cooling techniques
[43]	Argamassas Térmicas Sustentáveis: O Contributo dos Materiais de Mudança de Fase	2012	Conference Paper	Portugal	mortars with PCM
[44]	Solar Load Ratio and ISO 13790 methodologies: Indirect gains from sunspaces	2012	Article	Portugal	sunspaces
[45]	Vernacular Traditions: contemporary architecture	2012	Book	India	vernacular architecture from India
[46]	Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency	2013	Review Paper	Portugal	incorporation of PCMs into building elements
[47]	Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives	2013	Review Paper	UK	natural ventilation, use of sunlight (under the scope of infection control)
[48]	Portuguese vernacular architecture: the contribution of vernacular materials and design approaches for sustainable construction	2014	Article	Portugal	high thermal inertia, use of light colors, courtyards
[49]	Arquitetura Vernácula, Arquitetura Bioclimática e Eficiência Energética	2015	Conference Paper	Portugal	glazed balconies, high thermal capacity, natural ventilation, courtyard, solar radiation reflection
[50]	Glazed space thermal simulation with IDA-ICE 4.61 software—Suitability analysis with case study	2015	Article	Finland	glazed spaces

Table 1. *Cont.*

Ref.	Title	Year	Type of Publication	Location	Main Assessed Subjects
[51]	Review of bioclimatic architecture strategies for achieving thermal comfort	2015	Review Paper	Spain	passive and active solar heating, humidification, solar protection, thermal mass, evaporative cooling, natural and mechanical ventilation, air conditioning
[52]	Space Cooling in Buildings in Hot and Humid Climates—a Review of the Effect of Humidity on the Applicability of Existing Cooling Techniques	2015	Review Paper, Conference Paper	UK	evaporative cooling, natural ventilation, radiant cooling, earth tubes
[53]	Thermal performance of glazed balconies within heavy weight/thermal mass buildings in Beirut, Lebanon's hot climate	2015	Article	Lebanon	glazed balcony, thermal mass
[54]	Análise comparativa dos métodos da ISO 13790 e sua adequabilidade na estimativa das necessidades de energia para aquecimento e arrefecimento e da temperatura do ar interior	2016	Master's Dissertation	Portugal	building energy needs estimative methods
[55]	Biomimetic and Bioclimatic Approach to Contemporary Architectural design on the Example of CSET Building	2016	Conference Paper	Poland	natural ventilation, green roof, double skin facade, south-concentrated windows, biomimetics
[56]	Contribution of the solar systems to the nZEB and ZEB design concept in Portugal—Energy, economics and environmental life cycle analysis	2016	Article	Portugal	solar systems, ZEBs, nZEBs
[57]	Effects of added glazing on Balcony indoor temperatures: Field monitorings	2016	Article	Finland	glazed balconies
[58]	Energy saving potential of natural ventilation in China: The impact of ambient air pollution	2016	Article	China	natural ventilation
[59]	Glazed balconies as passive greenhouse systems—Potential of their use in Poland	2016	Article	Poland	glazed balconies
[60]	Solar energy materials for glazing technologies	2016	Review Paper	Greece	insulated and PCM glazing, reflecting, electrochromic, thermochromic, photovoltaic and water flow-based glazing
[61]	Thermal performance and cost analysis of mortars made with PCM and different binders	2016	Article	Portugal	mortars with PCM
[62]	Energy Saving Potential and Interior Temperatures of Glazed Spaces: Evaluation through monitorings and Simulations	2017	Doctoral Thesis	Finland	glazed spaces

Table 1. *Cont.*

Ref.	Title	Year	Type of Publication	Location	Main Assessed Subjects
[63]	The impact of thermal mass on building energy consumption	2017	Article	UK	thermal mass
[64]	The passive solar heating technologies in rural school buildings in cold climates in China	2017	Article	China	direct-gain window, Trombe wall, attached sunspace
[65]	The right to the sun in the urban design	2017	Review Paper	Italy	solar envelope, building orientation, urban morphology through solar gains
[66]	A framework for building overhang design using Building Information Modeling and Life Cycle Assessment	2018	Article	Cyprus, Lithuania	overhangs, sun shading
[67]	Thermal inertia in buildings: A review of impacts across climate and building use	2018	Review Paper	Belgium	thermal inertia
[68]	A Comparative Study of Traditional and Contemporary Building Envelope Construction Techniques in Terms of Thermal Comfort and Energy Efficiency in Hot and Humid Climates	2019	Article	Turkey	floor-to-ceiling height; insulation placement; material properties
[69]	Effects of the geometry of residential buildings with a sunspace on their energy performance	2019	Article	Serbia	building geometry, sunspaces
[70]	Net-zero building designs in hot and humid climates: A state-of-art	2019	Review Paper	India	wind tower, solar chimney, natural ventilation
[71]	Passive cooling techniques for building and their applicability in different climatic zones—The state of art	2019	Review Paper	India	solar control, shading devices, window glazing, presence of vegetation and water surface, thermal mass, PCM integrated into walls, ceilings, roofs, and windows
[72]	A Review of Balcony Impacts on the Indoor Environmental Quality of Dwellings	2020	Review Paper	Portugal	glazed and unglazed balconies
[73]	Determination of optimal thermal inertia of building materials for housing in different Chilean climate zones	2020	Article	Chile	thermal inertia
[74]	Technological options and strategies towards zero energy buildings contributing to climate change mitigation: A systematic review	2020	Review Paper	Spain/ Italy	building envelopes, natural ventilation, shading systems, sun use, integration of greenery in buildings, heat pumps, advanced glazing, energy production and storage, PCM
[75]	Thermal Comfort Aspects of Solar Gains during the Heating Season	2020	Article	Hungary	large glazed areas (analyzing thermal discomfort in the heating season)

Table 1. *Cont.*

Ref.	Title	Year	Type of Publication	Location	Main Assessed Subjects
[10]	Thermal Performance and Comfort Condition Analysis in a Vernacular Building with a Glazed Balcony	2020	Article	Portugal	glazed balcony
[76]	Automação em Arquitetura Bioclimática	2021	Master's Dissertation	Portugal	Trombe wall, sun use and natural ventilation managed with automation
[77]	Exploring Climate-Change Impacts on Energy Efficiency and Overheating Vulnerability of Bioclimatic Residential Buildings under Central European Climate	2021	Article	Slovenia	high thermal capacity materials, natural ventilation, south-concentrated windows, window shading
[78]	Overheating assessment in flats with glazed balconies in warm-summer humid continental climate	2021	Article	Poland	glazed balcony
[79]	Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition	2021	Review Paper	International Research	resilient cooling, overheating mitigation, climate resilience
[80]	Bioclimatic Architecture Strategies in Denmark: A Review of Current and Future Directions	2022	Review Paper	Denmark	solar gains, thermal insulation, high thermal capacity, natural ventilation, solar shading
[81]	Use of sunspaces to obtain energy savings by preheating the intake air of the ventilation system: Analysis of its main characteristics in the different Spanish climate zones.	2022	Article	Spain	sunspaces
[82]	A study on evaporative cooling capacity of a novel green wall to control ventilating air temperature	2023	Article	Canada	evaporative cooling, green wall
[83]	Biomimicry in Architecture: A Review of Definitions, Case Studies, and Design Methods	2023	Review	Belgium	biomimetics in architecture
[84]	Experimental comparison on the performance of radiative, reflective and evaporative cooling in extremely hot climate: A case study in Chongqing, China	2024	Article	China	radiative, reflective, and evaporative cooling

3. Review of State of the Art

After analyzing the referred documents, it was found that the majority of the selected publications—69% of the reviewed content—stem from studies conducted in European countries, reinforcing the continent's leading role in the fight against climate change and the reduction in carbon emissions. It is followed by Asia, with 21% of the publications, South America, with 4%, North America, with 3% and Africa, with 1.5% of the reviewed literature. An additional 1.5% of the reviewed publications result from collaborative intercontinental studies.

Categorically, articles constitute the majority, representing 48% of the reviewed documents, followed by review papers at 28% (Figure 2). Regarding methodology, dynamic simulation and field monitoring are the prevalent methods used for assessing the energy performance of passive systems, featured in 23 [19–21,23,30,32,33,36,37,44,50,53,54,58,59,62,64,66,68,69,73,77,81] and 19 [17,18,26,27,39,40,48,57,75,76,78,84] of all papers, respectively. Widely used software, such as EnergyPlus (https://energyplus.net/), DesignBuilder (https://designbuilder.co.uk/), and TRNSYS (https://www.trnsys.com/), has demonstrated reliability in evaluating building thermo-energy systems. These tools are frequently employed in conjunction with field monitoring in buildings or using physical prototype models for calibration purposes.

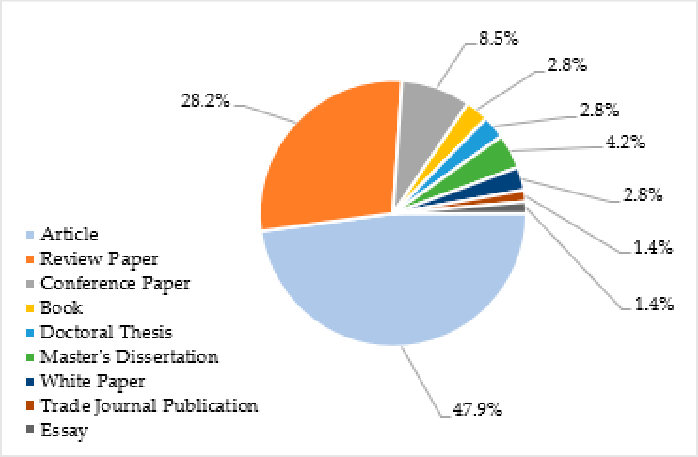

Figure 2. Reviewed literature by publication type.

In the subsequent subsections, this study will provide an in-depth overview of topics related to vernacular and bioclimatic architecture, along with passive cooling and heating techniques, presenting a synthesis of the comprehensive state-of-the-art review. Specific attention will be given to the main characteristics, adaptability to different climates, and energy-saving potential of passive heating and cooling systems. Finally, a concise discussion on research trends on such subjects will ensue, followed by the identification of existing gaps in the state of the art concerning bioclimatic architecture and passive solar systems.

3.1. Bioclimatic and Vernacular Architectures

Vernacular architecture can be described as the traditional architecture of a specific region, developed and gradually perfected over the years by its people. Through the observation of nature and empirical methods, this architecture has been refined to become a set of construction techniques and architectural typologies adapted to the natural and climatic determinants of the environment where they are located. It also bears strong traces of its society's economy, history, culture, and beliefs [15], being most commonly applied to residential buildings [85], as cited in [40].

Even in small regions or countries, it is possible to find diverse types of traditional constructions suitable for different geographic, climatic, cultural, and economic contexts. Taking Portugal as an example, a country in the extreme southwest of Europe with a continental area of 89,102 km^2; [86]—smaller than the state of Indiana in the US, and the autonomous community of Castile and León in Spain—extending for no more than 580 km between the northern and southern extremes, it is possible to find a rich range of vernacular architecture types belonging to specific regions and containing characteristic traits of these.

In the northern part of the country and the central mid/highlands region, temperatures are milder during the summer, and winters are colder and rainier. Due to abundant natural stones, such as granite and schist, traditional houses are generally constructed using these materials (Figure 3, above, left) [15]. Openings are oriented in the quadrant between south and west to ensure greater solar gains during the winter. They typically have two floors, with the upper floor used for living spaces, while the ground floor traditionally served as a warehouse and for animal husbandry, which also provided an additional source of heat [15].

Figure 3. (**above**, **left**) A three-story stone house with glazed balconies to improve solar gains, in Salzedas, North Portuguese region; (**above**, **right**) wooden hut in Mira Beach, on the country's central coastline; (**below**) an earthen single-story house in Moura, in the southern region of Alentejo. Reproduced with permission from Jorge Fernandes.

Along the coastline, especially in the central portion, the "palheiros", or wooden huts (Figure 3, above, right), dating back to settlements linked to fishing activities that intensified in the 18th century [39], are the characteristic constructions. Built with pine boards, painted in intense ochre colors, and arranged vertically or horizontally, these houses were usually elevated on stilts to distance them from the shifting sands of the shores. They were initially temporary dwellings used by fishermen and bathers during warmer seasons, i.e., between summer and autumn [39].

In the Portuguese southern region, characterized by long, hot summers, mild and less rainy winters, and a scarcity of stone, one can observe the typical architecture built in adobe or rammed earth [15]. Often single story, it adopts aspects from the constructions in hot and dry climate regions, such as thick walls with high thermal inertia, painted white, and with small openings—strategies for maintaining a cooler temperature indoors than the warm temperature outside (Figure 3, below).

In general, vernacular architecture can be understood as a manifestation of design adapted to the environment. It relies on passive techniques to minimize unfavorable climate conditions and achieve better comfort levels indoors [51,77] without depending on energy-consuming active mechanisms. Tipnis [45] states that "vernacular dwellings are inherently sustainable in design and are responsive to the climate, culture, and socio-economics conditions of the area". It is, therefore, considered a precursor and an important foundation of bioclimatic architecture, and the link between both is explored in several publications [24,38,45,48,49,68,77].

On the other hand, contemporary bioclimatic architecture combines passive principles inspired by vernacular architecture with up-to-date strategies and technologies [55,77]. It is grounded in minimizing the severe environmental impacts the construction sector generates. It contributes to the design of nearly-zero-energy buildings, or nZEBs [51], while also adapting to levels of comfort and functionality compatible with the needs of contemporary society [76].

Unlike the symptomatic design method developed through empirical means associated with traditional architecture, contemporary bioclimatic architecture is based on in-depth analyses of the local climate [87], as cited in [80]—where long-term climate changes should be included—to determine appropriate strategies. These strategies often involve integrating sophisticated active systems capable of reducing energy consumption and enhancing thermal comfort during the operational phase of buildings [77].

Applying a bioclimatic approach to construction involves recognizing that cultural, social, and economic aspects remain crucial in developing sustainable architecture [31,55]. A publication [14] advocates for the study and valorization of traditional architecture as a means of rescuing and maintaining the heritage of a region, and many research endeavors arise precisely from the desire to quantify and scientifically demonstrate the contributions that these traditional techniques can make to contemporary constructions [14,40,48]. Another author [55] further argues that bioclimatic architecture should be able to adapt to the local environment and enhance its ecosystem, seeking to contribute to its integrity and biodiversity.

Adopting bioclimatic strategies in the design of buildings is the first step toward reducing their energy needs and minimizing the reliance on mechanical heating, cooling, and ventilation systems [14,74]. Passive and bioclimatic strategies, coupled with integrating renewable energy sources and using energy-efficient devices and systems, pave the way for developing nZEBs [56] and carbon-neutral buildings.

3.2. Solar Passive Techniques

Contemporary architecture tends to rely on active climate control devices to ensure thermal comfort indoors [51], leading to high energy consumption throughout the building's operational phase. On the other hand, bioclimatic architecture proposes reversing the values attributed to the systems that are currently employed. The Behling Diagram graphically depicts this reversal of values—discussed in [29] and later in [48]—composed of two triangles representing the hierarchy of systems in present-day architecture and bioclimatic architecture, referred to here as the "architecture of the future" (Figure 4). Fernandes et al. [48] suggest adding a third triangle representing architecture from the past, based on architectural form and passive systems, considering it the foundation for architecture in the future.

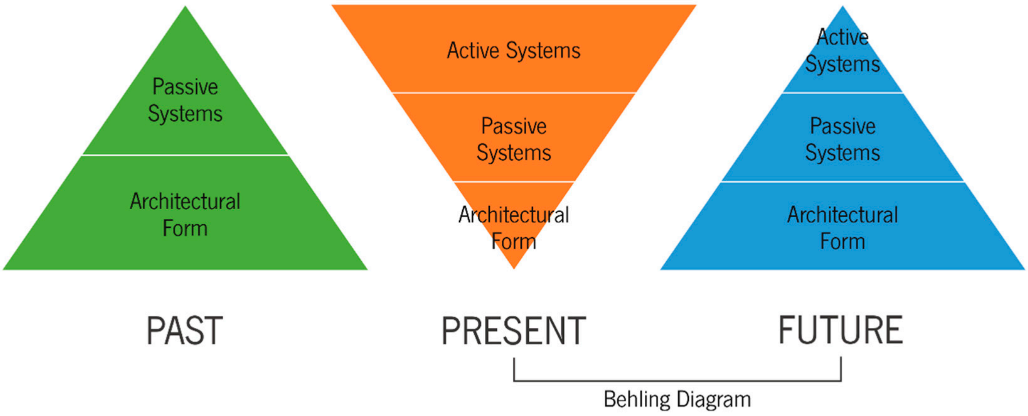

Figure 4. Behling Diagram representing the hierarchy of systems in present and future architecture, with the addition of the triangle representing the past. Adapted and reproduced with permission from Jorge Fernandes [48].

While contemporary constructions rely on an additive concept (more sophisticated and expensive buildings, with more layers and more active systems), as described by [29], the "architecture of the future" is based on the resurgence of the primacy of architectural form and passive systems over active systems. In this architecture, the thermal energy flow occurs preferably by natural means, i.e., radiation, conduction, or convection [42], rather than through the extensive use of electrical devices. Together, these systems form the basis of a technically and aesthetically hybrid design concept, combining high technology with elementary and passive construction systems [29].

Bioclimatic architecture is firmly based on responsiveness to the climate [77]. Several authors conduct their studies using a specific climate as a starting point, subsequently analyzing the suitable bioclimatic techniques [28,33,38,52,73]. Given the importance of the relationship between the built environment and the natural environment for the thermo-energy performance of buildings [14], and consistent with the statement in [40] that "any good building should relate and respond to the climate", it is necessary, prior to planning a building and defining suitable bioclimatic strategies, to analyze the local climate.

On the one hand, the climatic contexts and urban geometries found worldwide are practically infinite, meaning that there is no single solution or ideal geometry to be followed for constructing appropriately in relation to the climate [88], as cited in [22]. On the other hand, when analyzing architecture and its possibilities, simplifying these climatic contexts is advisable [49]. The categorization proposed by Olgyay and Olgyay [89] groups them into four main climate types: cold, hot and dry, hot and humid, and temperate, as shown in Table 2. In addition to climate, factors such as the terrain's topography; solar path; presence of shaded areas; size, mass, and volume that the building requires; availability of materials; and local regulations must also be considered in the design of bioclimatic buildings [22].

Table 2. Four main climate types proposed by Olgyay and Olgyay [49,89].

Climate Type	Description of Main Characteristics
Cold	Typical climate of high latitude regions or mid-latitudes combined with high altitude. It has very low temperatures throughout the year, especially in winter, with scarce solar radiation and high snowfall. Winds are aggressive, mainly from the pole corresponding to its latitude.
Hot and Dry	Typical climate of continental regions near the equator (desert areas), with high average annual temperature and significant daily thermal amplitude. Humidity levels are very low, and solar radiation is intense and direct. Precipitation is rare in hot and dry regions, leading to sparse vegetation. Winds are hot and dusty, sometimes very aggressive.
Hot and Humid	Typical climate of tropical coastal regions. Characterized by high average annual temperatures and reduced daily and seasonal thermal amplitudes. These regions usually have high humidity levels, frequent cloud cover, and heavy seasonal rains. Solar radiation is intense and mostly diffuse. Winds are variable and can generate typhoons.
Temperate	A complex type of climate that, throughout the year, exhibits characteristics similar to the other three climate types but less intense. It has four well-defined seasons.

Some passive techniques and systems can be used for both cooling and heating purposes, and they must be intentionally planned considering the intended effect, whether to heat or cool the building. If poorly designed, these techniques may be inefficient or even cause a rebound effect, meaning the opposite effect to what is desired is achieved, ultimately compromising the efficiency of the building rather than enhancing it.

Given the alarming predictions of climate change [90], it is increasingly important to focus on the resilience of buildings, ensuring they can better respond to extreme variations in climate and temperature. In Europe, especially in more northern regions, passive systems commonly used in buildings aim to enhance solar gains for interior heating. With the rise in global average temperature, it is essential to reassess such systems to make them less vulnerable to overheating, as seen in [77,78].

3.2.1. Passive Cooling Techniques

In hot climate regions, such as those near the equator and the tropics and temperate regions during cooling seasons, promoting heat loss from the interior and mitigating solar gains are crucial for maintaining thermal comfort indoors and preventing overheating situations [42]. To achieve these objectives, a range of passive cooling techniques can be applied to the buildings to improve their thermal behavior and reduce the need to use energy-consuming active cooling systems.

To promote heat loss from the interior, favorable conditions and natural elements of the buildings' context can be used as heat sinks. As specified in [42], these environmental heat sinks can include the outdoor air, water masses, the night sky, and the surrounding building ground, as long as these elements are at a lower temperature than the indoor air, and there are means to promote the heat transfer from the latter to the former.

Mitigating the solar gains through radiation can be achieved by the use of barriers that control the solar incidence onto the building's envelope or into its interior (like using shading devices or high thermal mass envelopes), preventing them from absorbing and transmitting high amounts of energy that can cause overheating situations.

Natural Ventilation

This strategy is based on transferring heat from the building's interior to the exterior through wind pressure or the buoyancy effect, which naturally induces the movement of air masses due to temperature and density differences [35,70]. In this natural convection process, warm and less dense air ascends, while cold and denser air descends in a cyclic movement, facilitating heat transport.

Wind-driven ventilation forces are responsible for increasing air flow much more than buoyancy-driven forces [91], as cited in [70]. However, utilizing both principles simultaneously in a building can guarantee its natural ventilation in all conditions. An investigation employing dynamic simulation concluded that, through natural ventilation promoted by open windows, the indoor temperature could be decreased by approximately 2 °C with one air change per hour, 3 °C with two air changes per hour, and 7 °C with 11 air changes per hour [20]. The authors also stated that the annual cooling load could be reduced by almost 8%. Another study based on dynamic simulation stated that up to 78% of the cooling energy usage of a building can be potentially reduced by natural ventilation, depending on the local weather, but the technique's potential can be significantly affected by air pollution [58].

The natural ventilation of the building can be enhanced through various construction configurations, such as promoting air mass displacement by verticalized internal spaces (Figure 5a) and incorporating outlets on the ceiling and at the top of the room to encourage the stack effect and provide an escape path for hot air collected at the top [42] (Figure 5b). An example of the practical application of these techniques is the Eastgate building in Zimbabwe, where natural ventilation and the stack effect are used (inspired by termite mounds), contributing to a reduction of 65% in the building's energy costs while providing good thermal comfort [83].

Natural ventilation can also be improved by the presence of courtyards (Figure 5c) or simply through openings on opposite sides of a room that promote cross-natural ventilation (Figure 5d). These techniques are highly effective in hot and humid climates, because they promote the exchange of heated indoor air with fresh outdoor air and contribute to the mitigation of discomfort caused by excess humidity [70] as they enhance evaporative heat loss from the skin.

Another example of cooling techniques is natural ventilation through earth tubes (Figure 5e), where the ground serves as a heat sink, given that the temperature of deeper soil layers remains practically constant all year and cooler than the exterior air in warmer seasons and climates [52]. The technique is well adapted to hot and dry climates; however, its application in hot and humid regions should be carefully assessed, as condensation may occur in the pipes, leading to an increase in the relative humidity of the surroundings [52].

This system was successfully applied in contemporary buildings around the world, like the SOLAR XII Building in Portugal [25] and the Centre for Sustainable Energy Technologies (CSET) in China [55]. In the latter, the technique is also employed for heating purposes during winter, taking advantage of the natural temperature difference between air and earth, as stated by the author [55].

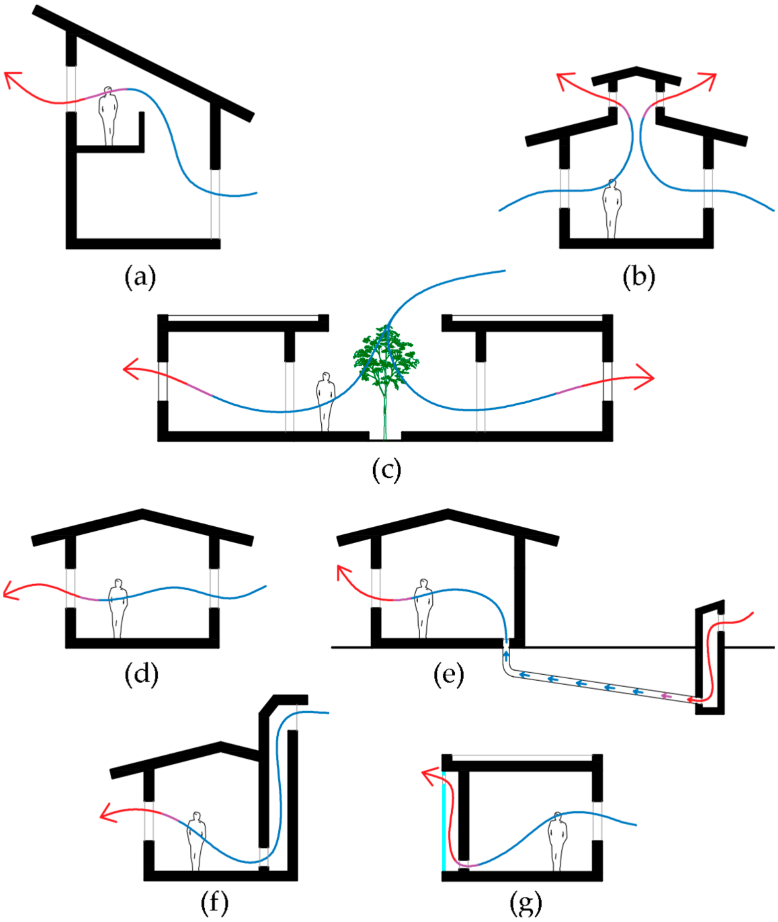

Figure 5. Example of natural ventilation techniques: (**a**) vertically arranged spaces that enhance air circulation; (**b**) stack effect; (**c**) courtyards; (**d**) cross ventilation; (**e**) ventilation through earth tubes; (**f**) ventilation towers; (**g**) Trombe walls with ventilation valves.

In wind towers (Figure 5f), the air enters through top openings, is cooled, becomes denser, and descends—the cooled air then enters the room through inlets on the bottom of the tower, and the presence of outlets on the other side of the room can promote a cool air draft through the room [42]. The tower's height is directly proportional to the airflow volume accomplished; on the other hand, the more openings it has, the lower the airflow [70]. In hot, dry climates, moisture mechanisms like wetted pads, clay conduits, cloth curtains, and misters can also be added to facilitate evaporative cooling [70]. A study conducted in India, where a wind tower equipped with water misters was constructed in an existing building, reported that the electrical energy consumption of the building was reduced by 64% thanks to the system [17].

Trombe walls are a system formed by a massive wall covered by exterior glazing and an air channel between these layers, where the solar energy is absorbed through the glazing and stored in the wall [51]. It is a technique generally used for passive heating, but some types of Trombe walls are also adapted for cooling [71] by enhancing air flow within the building induced by the buoyancy effect. Using dampers and vents on the top and on the bottom of the glazing and of the wall, the heated air can be drained to the outside in summer when these elements are correctly operated (as shown in Figure 5g), facilitating the room's air movement for cooling the indoors in summer [35].

Evaporative Cooling

The phase change from liquid to vapor from the moisture in a structure can facilitate its surface cooling by the dissipation of heat during evaporation [84]. As [28] explains, "water left on a surface of a building has a natural tendency to evaporate in order to achieve phase equilibrium with the water vapor in the surrounding air. As it evaporates, every gram of water extracts about 2550 J of heat from its environment". Some authors [35] defend evaporative cooling as the oldest cooling technique. Under ideal conditions, it is the most efficient among building passive cooling techniques, capable of reducing indoor air temperature by almost 10 °C in hot and arid climates [27]. However, direct evaporative cooling might not be as efficient in hot and humid climates due to the high amount of moisture in the air. In these cases, indirect evaporative cooling systems are more indicated. Different from the direct techniques, where only one hot air stream is directly exposed to water, these also have a second air stream flowing separately through a dry environment. The wet "working" air absorbs heat from the dry "product" air, which is cooled without additional moisture being introduced [35].

There are several ways to integrate direct evaporative cooling techniques in buildings, such as through greenery around the building, green roofs, or green walls that provide passive cooling benefits through plant transpiration (Figure 6a,b) [51,82]. An experiment utilizing a prototype model of a green wall composed of hydroponically grown ryegrass vegetated porous concrete tile concluded, through laboratory tests, that the element could reduce inlet air temperature from 50 °C to approximately 24 °C [82]. The authors also noted that a 30 cm grass layer exhibited the highest cooling rate.

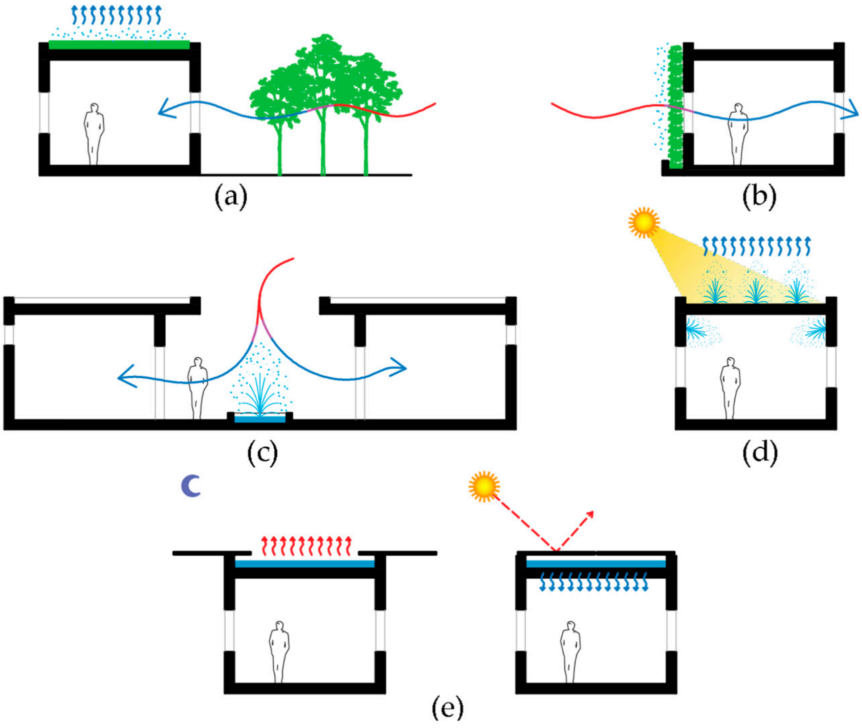

Figure 6. Evaporative cooling techniques: (**a**) through the presence of vegetation around the building and green roofs; (**b**) green facades; (**c**) with the presence of ponds and water fountains; (**d**) water misters on surfaces exposed to radiation and indoors; (**e**) through roof ponds with movable insulation.

In addition to vegetated building elements, field monitoring in a vernacular villa in the south of Portugal, where the climate is mainly hot and dry, demonstrated that the presence of a courtyard with abundant trees and a water fountain (Figure 6c) also contributes to evaporative cooling [48]. In the case study, this setup significantly influenced the creation of a microclimate near the building, increasing relative air humidity and maintaining lower air temperatures compared to the city center, with a maximum difference of approximately 9 °C.

Another way to promote evaporative cooling is using water misters indoors or on the top of roofs (Figure 6d). A study using physical roof models showed that constantly wetted roofs exhibited a limited increase in their exterior surface temperature, but the effectiveness of the technique would otherwise decrease with the dissipation of the moisture [84].

A study based on thermal numeric models concluded that roof ponds can maintain a moderate surface temperature range between 25 °C and 40 °C in arid regions [23]. This system can have its efficiency enhanced due to the presence of movable insulation, as shown in Figure 6e. In this case, the insulation should be closed during the day to protect the pond from direct radiation. The pond provides cooling to the room during the day due to its nocturnal cooling process, facilitated by opening the movable insulation which allows long wavelength radiation loss [23].

Protection against Solar Radiation

In regions with hot climates and during the summer in temperate climates, controlling solar incidence on buildings, thus minimizing solar gains, is crucial for maintaining thermal comfort indoors while preventing overheating and reducing mechanical cooling loads. The control of solar gains on the building can be achieved by intercepting the sunlight through shading devices or reflecting it, having proper building orientation, and having the correct sizing of the building envelope and its openings [38].

The interception of sunlight through shading can be achieved, whether by having wide eaves (Figure 7a), overhangs (Figure 7b), or brise-soleils (Figure 7c), among other shading construction elements, as well as through tall structures around the building and the presence of trees (Figure 7d). In this last case, deciduous trees provide shading during summer, yet they allow the desirable radiation to pass through as they drop their leaves in winter. Thus, these trees are best located on the south and southwest sides of the building [42]. Vertical fix elements like fins and other buildings are best located on the east and west sides of the building, as they protect from intense sun at low angles during summer [42]. In winter, these elements are not a considerable barrier for the desirable radiation since the latter falls primarily through the south facade.

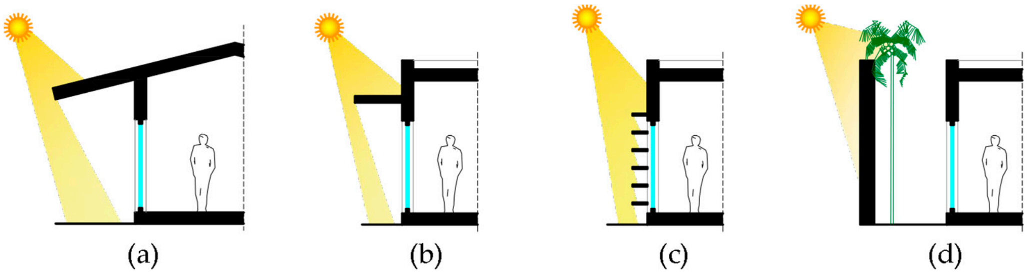

Figure 7. Shading by: (**a**) wide eaves; (**b**) overhangs; (**c**) brise-soleils; (**d**) nearby structures and vegetation.

Proper interception of solar radiation can result in a significant reduction in the energy consumption for cooling a building. Through dynamic simulation, a study reported that the presence of overhangs on the facade may lead to a reduction of 7% in the annual cooling load of a building with single walls and no roof insulation and up to 19% in a house with walls and roof with 50 mm insulation [20]. The external fixed shading devices are often the most efficient, as they intercept sunlight before it reaches the facade or windows [34]. Research conducted in Brazil [32], based on parametric dynamic simulations, explored the efficiency of the verandas, a traditional shading transitional space used throughout the country as a way to protect the building from excessive radiation. It was concluded that, in the specific assessed regions, deep, elongated verandas with enclosed sides are more effective in blocking solar radiation, especially when facing east, west, and north orientations.

In temperate and cold climates, shading elements, when designed appropriately, can offer the necessary shading during the cooling season without obstructing the desirable solar incidence during the heating months. For instance, a study [38] proposes overhangs with a depth of 76 cm positioned 40 cm above south-facing windows as ideal for regions between latitudes 30° and 50° N.

Reflection is a traditional strategy for protection against solar radiation, commonly found in Mediterranean vernacular architecture [30]. Light-colored and smooth surfaces exhibit lower surface temperatures when exposed to direct solar radiation [28] due to their higher reflection coefficient (albedo), reducing light absorption that transforms into thermal energy. In buildings, reflection can be achieved using light-colored, smooth finishing on walls and roofs and reflective and low-emissivity glazing (Figure 8).

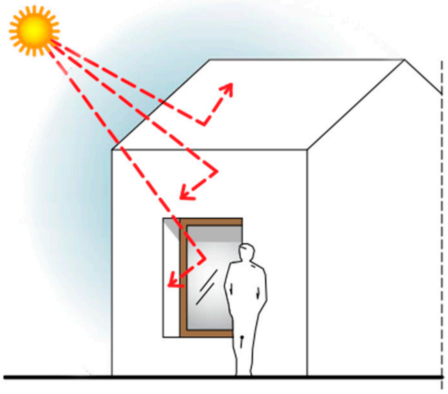

Figure 8. Cooling by radiation reflection by light-colored and smooth surfaces and reflective glazing.

An experiment conducted in 1998 in Israel demonstrated that a light-colored roof reaches temperatures approximately 10 °C above the ambient air temperature, whereas dark-colored roofs can attain temperatures up to 50 °C higher [92], as cited in [38].

As for the use of low-E (low emissivity) glazing—which reflects the radiant heat and allows more visible light to pass through, differently from reflexive glazing that reflects the solar radiation and reduces the transmission of visible light—placing a low-E film on the surface of the inner pane of a double-pane glazing system results in a 48% reduction in room heat gain compared to a single clear glass pane. This reduction is observed even when the glass surface temperature is elevated (over 40 °C) [33].

Proper orientation of facades and the correct sizing of surfaces that will receive solar gains are essential for the energy performance of a building. Buildings that are arranged longitudinally parallel to the east–west axis, meaning the broader facades face the north–south axis, are better aligned with the solar path [38,69]. During the summer, the most intense solar radiation will impact the east and west facades, which, having a smaller surface area, will absorb less radiation. Meanwhile, the south facade (considering a building in the Northern Hemisphere) can be easily protected by shading devices, like overhangs, as the sun is at a higher angle. These overhangs do not block the desired solar gains during winter due to the lower sun angle. A study based on dynamic simulation concluded that an elongated building shape with the longer facade facing south is most favorable for reduced heating energy consumption. For the same window-to-wall ratios (WWRs), this shape is also optimal for minimizing cooling energy consumption [69]. Another study [38] suggests that a building facing about 15° east of south would have the ideal orientation; hence, the east and west facades would receive even less solar radiation during the summer, reducing the likelihood of overheating (Figure 9).

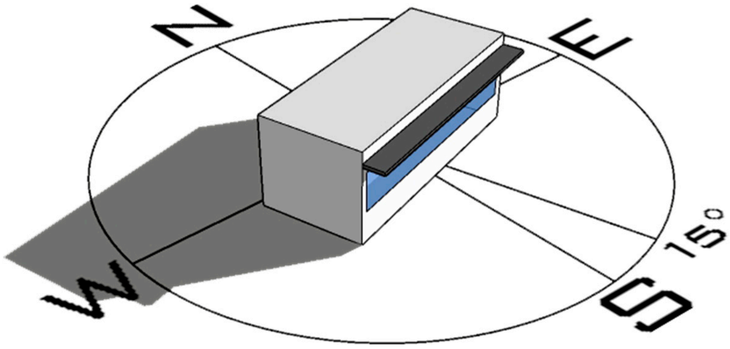

Figure 9. Ideal orientation of a building according to the solar path throughout the year.

Large glazed areas facing south can improve the heat gains through solar radiation to the buildings since the solar exposure time is longer on the southern facade than on others during winter [69]. In summer, however, this high WWR (window-to-wall ratio) can increase energy consumption for cooling. The building may be more susceptible to overheating, thus leading to high thermal discomfort conditions. Shading mechanisms are efficient in maintaining stable comfort levels. Authors [75] highlight that since they are rarely activated during winter, overheating situations can occur even during this time of year in buildings with high WWR on the south facade.

Cooling by Building's Thermal Inertia

Construction materials are capable, to varying degrees, of absorbing, transmitting, reflecting, storing, and emitting the energy they receive, whether from natural or artificial sources. Opaque elements in a building (walls, roofs, floors) can contribute to the control of heat gains or losses—depending on their thermal insulation—and to the thermal inertia of the construction [26].

The thermal inertia of a material is related to its thermal capacity, which is the product of density, thickness, and the specific heat of the material. For construction materials, the term "thermal mass" is commonly used because the thermal capacity of these materials often strongly depends on their mass [18,26]. However, this term is not sufficient to describe the complexity of the thermal inertia phenomenon of materials, as thermal conductivity is also a parameter with a significant influence [67]. A study asserts that construction materials with a density close to 2500 kg/m^3; and low thermal conductivity are closer to an ideal thermal inertia, providing greater thermal comfort in buildings [73]. As for currently existing materials, wood and light concrete are the ones that better approximate these characteristics.

Cooling by thermal inertia occurs due to the delayed dissipation of heat received through solar radiation by the building envelope elements during the day. These elements absorb a portion of the radiation without overheating, avoiding temperature oscillations and heat peaks throughout the day [18]. This radiation is stored in the form of thermal energy, which is then slowly released with a time delay.

In regions with hot and dry climates characterized by significant daily temperature variations—hot days and cold nights—it is possible to use the heat stored by the envelope to warm the spaces during the nighttime, maintaining a stable indoor temperature (Figure 10a). Research based on field temperature monitoring demonstrated that the high thermal inertia of a Portuguese vernacular building located in a region with hot and dry summers contributed to maintaining a nearly constant indoor temperature despite significant fluctuations in outdoor temperatures throughout the day [48]. In hot regions with low daily temperature variations, nighttime ventilation of the spaces is necessary to maintain comfortable thermal conditions (Figure 10b). Thermal inertia can, therefore, act both as a cooling mechanism—by avoiding heat peaks—and as a passive heating mechanism. A study conducted in the southern region of Brazil, involving field monitoring of four buildings, concluded that high thermal inertia proved beneficial during both warm and cold periods in the specific assessed location. This area experiences a warm and humid climate during the summer but is also subject to cold fronts throughout the year [32].

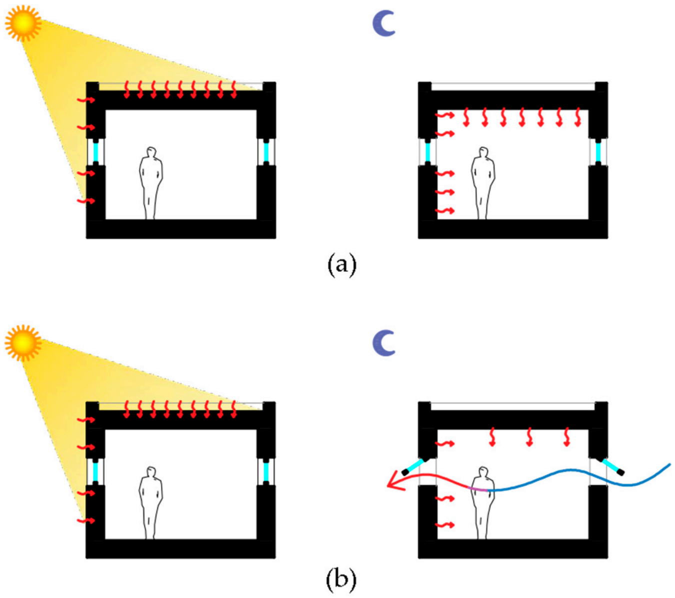

Figure 10. Thermal inertia as (**a**) a cooling/heating technique, and (**b**) a cooling technique combined with night ventilation.

Thermal inertia can be more efficient in enhancing the thermal performance of a building when specifically applied to elements that receive higher solar radiation (i.e., southern and western facades) [67]. The authors [67] note that the greater the WWR of the envelope, the higher the thermal inertia of its opaque surfaces should be. The thermal capacity of internal elements such as partition walls and floors should not be neglected, as they also contribute to reducing fluctuations in the indoor air temperature.

The greater the delay in dissipating stored heat, the more efficient the system [51]. Materials such as concrete, earth, ceramics, and dense wood can be used to ensure thermal inertia in buildings [73]. Water and phase change materials (PCMs) can also be used to increase the thermal storage capacity of building elements [26]. PCMs can reduce ambient temperature fluctuations through phase change processes [61]. At elevated temperatures, the material changes from solid to liquid, absorbing energy from the environment. As the temperature decreases, the material transitions from liquid to solid, releasing energy back into the surroundings [43,46]. PCMs can be incorporated into several construction elements, e.g., in walls through the use of mortars with PCM in its composition.

Factors that can compromise the thermal inertia of a building include the use of covering layers with high thermal resistance on their interior, as well as the use of insulation on the internal surfaces. These can compromise the thermal balance between the indoor air and the envelope structures, affecting the latter's heat storage and release capacity [93].

Additionally, elements with excessively high thicknesses can be detrimental to their effective thermal capacity, as in these cases, the core layers may not be able to receive and accumulate heat, representing an excess of material that is energetically inefficient [26,67].

3.2.2. Passive Heating Techniques

In temperate and cold climate regions, the correct and sufficient solar exposure of a building plays a pivotal role in ensuring its operation and energy efficiencies. In 1995, the publication of an article asserting that buildings should have at least two hours of solar exposure during winter influenced various countries to establish their own regulations regarding the minimum hours of solar exposure in residential buildings [94], as cited in [34]. The "right to sunlight" has been a concept of significant importance in the development of architecture and urban planning for centuries, dating back to the Roman urban laws of the

6th century with their heliocamini, as well as the concept of "solar envelope" developed in the 1980s [65]. Furthermore, authors [47] discuss the benefits of sunlight exposure for people's health. Direct and diffuse sunlight can have a bactericidal effect, which is important in mitigating the spread of some infections indoors. The authors also highlight the impact of sunlight, even coming through glazed windows, in enhancing people's well-being and its positive effects on psychiatric conditions. Moreover, sunlight provides time cues to the body, helps regulate its biological rhythm, and may enhance people's immunological activity [47].

Regarding the benefits of sun exposure for the energy efficiency of buildings, passive heating techniques rely on converting solar gains into thermal energy [59]. This energy can come from direct solar gains, where solar radiation hits the interior of the building and its surfaces directly, thus heating them, or from indirect solar gains—the interior spaces are heated through the thermal energy accumulated in adjacent building elements or systems, transported to these spaces either through air movement, i.e., natural convection, or by conduction through partition elements. The success of utilizing solar radiation for building heating depends highly on the orientation and size of its windows and the thermal inertia of the building. Thus, the role of construction materials should not be overlooked [34].

Using passive heating techniques is very important in designing buildings with low energy needs, as buildings requiring heating, essentially those in cold climates, typically consume more energy than those requiring cooling, i.e., those in hot climates [22]. Additionally, in temperate climate regions, the heating season is often longer than the cooling season [54].

Direct Solar Gains (Radiation)

Direct-gain systems utilize direct solar radiation that penetrates the building through the glazing, heating the interior surfaces as it reaches them. The envelope, in turn, generally features good insulation to minimize heat losses and preserve it indoors for a longer period.

As mentioned in Section Protection against Solar Radiation, the building should ideally have its main facades facing the north–south axis, with the south facade having a window-to-wall ratio suitable for the desired amount of solar radiation in the interior spaces [34]. In addition to windows (Figure 11a), these solar gains can also be ensured through openings in the roof (Figure 11b) and clerestories (Figure 11c).

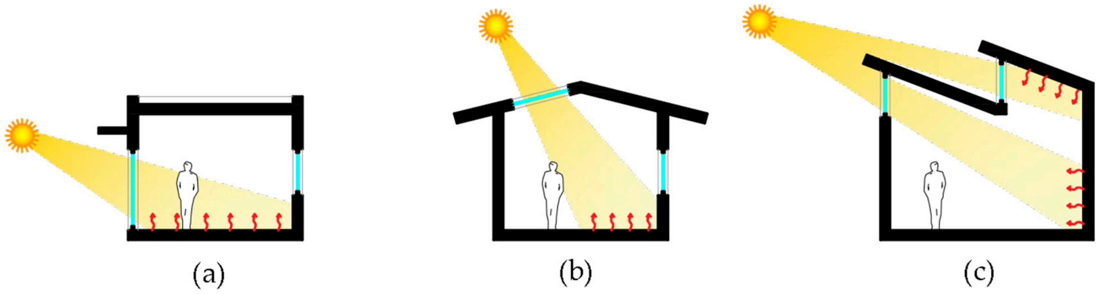

Figure 11. Direct solar heating through (**a**) glazed facades; (**b**) roof openings; (**c**) clerestories.

The presence of inclined glazed surfaces in the envelope, e.g., in the roof, contributes to higher solar gains for a significant part of the year. On the other hand, vertical glazed surfaces are more advantageous for gains during the winter since the sun is lower, and the more perpendicularly the solar radiation hits the glass, the greater the gains through the element [81]. Thus, in a passive heating system, the presence of inclined glazed surfaces in the roof may result in more losses than thermal gains in the winter, while in summer, it may pose a higher risk of overheating in the room [16].

These fenestrations should ideally be composed of technologically advanced glazing systems, i.e., the ones with both low U-values (thermal transmittance coefficient) and g-values (solar radiation transmittance coefficient) [60], leading to better control of solar heat gains and thermal losses without compromising the passage of desired radiation or visible light.

Some of the advanced technologies applied in building glazing are reflective glazing, electrochromic and thermochromic windows, windows with multiple glass panes, and double-glazed windows filled with air or other gases [60]. Well-sized shading mechanisms, as presented in Section Protection against Solar Radiation, are also a means to control solar gains without compromising the entry of desired radiation during the heating season.

Indirect Solar Gains (Convection and Conduction)

Indirect solar gains can be described as those captured in zones adjacent to the main environment, where heat is transferred to the latter, either through the dividing wall, by conduction—the transmission of thermal agitation between adjacent molecules in an element [54]—or by convection—the exchange of air at different temperatures between spaces [44]. Indirect solar gains systems often work as buffer zones, reducing indoor temperature oscillation. On the other hand, in buildings with passive heating systems through direct solar gains, the temperature variation indoors tends to be higher [64].

Among the techniques for heating through indirect solar gains are the previously mentioned envelopes with high thermal inertia (Figure 12a), which store the heat obtained from solar radiation during the day and release it at night, thus assisting in maintaining a more stable internal temperature. Water tanks are also used to increase the thermal inertia of the roof and as a heat storage element (Figure 12b). As stated, this technique is well adapted for a hot climate with significant daily temperature variations. However, the strategy can often be a drawback in cold climates, especially when dependent on a heat source with variable efficiency, such as solar radiation. In these cases, high thermal inertia structures often present a higher heating load than low thermal mass structures [63].

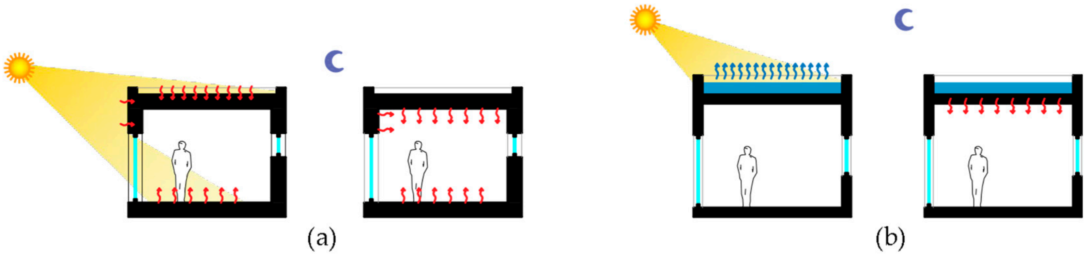

Figure 12. Indirect solar heating techniques include (**a**) high thermal inertia envelope; (**b**) water tank roofs.

Another technique is the Trombe wall (Figure 13a), which absorbs solar gains through its glazed facade and stores it as thermal energy in the partition wall with the adjacent room. This wall is typically massive and entirely opaque. The room is then heated either by conduction, through the wall, or by convection when the open vents on the top and bottom of the partition wall allow the exchange of cold air from the environment with the heated air from the narrow air chamber of the Trombe wall. Research based on field temperature monitoring and dynamic simulations concluded that the presence of a Trombe wall led to lower temperature fluctuations in the adjacent room during the heating period, compared to other passive heating techniques such as sunspaces and direct-gain windows [64].

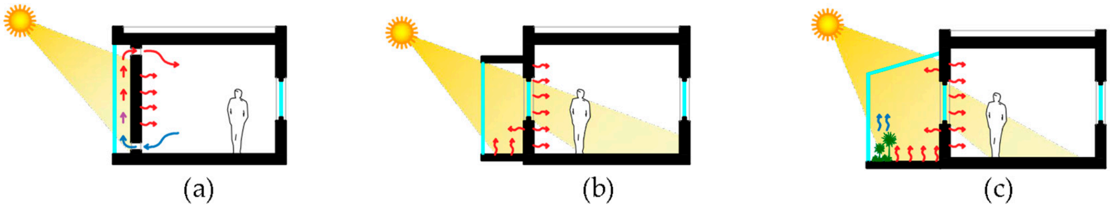

Figure 13. Indirect solar heating techniques include (**a**) Trombe wall; (**b**) glazed balconies; (**c**) greenhouses/sunspaces.

There are also glazed balconies (Figure 13b), which act as a buffer zone between the interior and exterior of the building, preheating the air that infiltrates the adjacent spaces and mitigating their heat losses [95], as cited in [59]. They differ from Trombe walls by being accessible to occupants through the existence of doors and windows in the dividing wall and by having sufficient area to be considered an extension of the building's usable space. A study showed, through in situ measurements, that the average temperature inside glazed balconies in Finland was at least 5 °C higher than the external temperature throughout the year [57]. Another study conducted in Portugal through temperature monitoring in a vernacular glazed balcony showed that the temperature in this space, during winter, is, on average, 10 °C above the outdoor temperature [14]. Narrower glazed balconies extending along nearly the entire building facade tend to be more efficient, as they minimize heat losses from adjacent spaces and provide more natural light incidence in these areas [62]. Studies based on dynamic simulations show that glazed balconies with good solar exposure can lead to reductions of up to 30% in the building's heating load [37,59]. A different analysis showed that relative energy savings in buildings with attached glazed spaces are higher in more central/southern regions of Europe (varying between 17.9% in Paris and 42.2% in Barcelona) than in northern regions (between 10.9% in Seinäjoki and 13.9% in Stockholm). On the other hand, considering absolute energy savings in kilowatt-hours, the reduction was higher in the latter region than in the former—up to 749 kWh in Turku, Finland [50]. In a project performed in Austria, heating requirements in a multifamily house were reduced from 250 kWh/m^2; to 14 kWh/m^2; post-refurbishment process, which included glazed balconies and other energy efficiency improvement techniques in the building [41].

Finally, greenhouses or sunspaces attached to the building (Figure 13c), which typically serve as an extension of the living space and are often for plant cultivation, are also a passive heating system. They tend to have a high WWR on the facade, sometimes including a glazed roof. This extensive glazing aims to maximize the absorption of solar radiation by the greenhouses. However, it may lead to more intense heat peaks in the warmer months and result in higher thermal losses from the interior to the exterior during colder nights [62]. A study based on parametric dynamic simulation explored this counter-effect between increased glazed areas and heat gain and heat loss [36]. The authors concluded that other passive techniques, such as natural ventilation and internal shading as curtains, need to be employed to control excessive heat gains and heat losses to keep sunspaces operating efficiently. Furthermore, the presence of vegetation in the greenhouses can also hinder their effectiveness as a passive building heating technique, as plants absorb energy and promote water evaporation, thus reducing the temperature in the room, as stated in [16].

Preventing Overheating in Passive Heating Systems

In various studies assessing passive heating systems worldwide, a notable issue with overheating has been observed [14,53,57,78], especially (but not only) during the warmer months. To mitigate thermal discomfort situations and the risks to occupants' well-being and health, considering the likely increase in heatwaves due to climate change, the integration of effective strategies to prevent intense heat peaks in buildings with these systems is crucial. Among the key recommendations found in the existing literature on the subject [16,19,34,36,53,75,78] are:

- Equipping glazed surfaces with externally installed shading devices, activating them (when movable) before radiation reaches the glazed surface. Additionally, adopting curtains and blinds on the internal side of glazed surfaces is encouraged. Both interior and exterior movable shading devices can also be activated during colder nights to reduce nocturnal heat losses, thus acting as movable insulations.
- Providing natural ventilation by opening windows to the exterior and keeping ventilation valves clean and unobstructed when these exist.
- Discouraging the presence of glazing on the east and west faces of south-oriented passive solar systems as glazed balconies and sunspaces. Solid opaque walls are

preferable on the lateral ends, as they block unwanted solar gains from these faces during warmer months and reduce heat losses during colder seasons by reducing the glazed area.

- Using high-performance windows, such as multiple-pane windows, can help reduce gains from solar radiation due to their lower radiation transmission coefficient. However, since they are more insulating and experience lower thermal losses to the exterior, the use of these windows can contribute to system overheating during peak heat periods. The appropriate operation of shading devices and natural ventilation is crucial to maintaining the optimal performance of passive heating systems with high-performance windows.

Furthermore, the proper use of spaces by their occupants is vital for maximizing the potential energy reduction of bioclimatic structures [14,22,41,62,78], especially those that rely on the activation of shading devices and the opening of windows for natural ventilation to maintain acceptable internal thermal comfort levels. When occupants neglect such actions, heat peaks may become more frequent, and some passive techniques may lose their effectiveness or even worsen the energy performance of buildings; as Tzikopoulos et al. [22] state, "educated and mindful users help realize the full energy savings potential of a bioclimatic structure".

In general, another method of assessing the vulnerability to overheat in buildings is to add this as a crucial step to the project planning process, including assessing the building's behavior considering future climate scenarios [79], as cited in [77]. The widespread availability of dynamic simulation software facilitates the integration of this practice into the stages of designing low-energy and carbon-neutral buildings.

3.2.3. Results

Regarding the reviewed publications concerning bioclimatic solar passive strategies that contribute to low-energy consumption and carbon-neutral buildings, some tendencies identified in the publications can be highlighted:

The large majority of the reviewed documents were published in the decade between 2011 and 2020. This could reflect the increased debate on climate change, which has been intensifying in recent years. The implementation of the Paris Agreement in 2015 marks a significant step forward, catalyzing efforts to address environmental issues, as seen in the rise of publications on the subject.

Regarding the analysis of publications by location, Europe stands out as a leader in research. This highlights the impact and importance of establishing clear plans to address environmental issues, such as the Green Deal and the Fit for 55 initiatives. In contrast, there appear to be comparatively fewer publications from other developed regions, notably North America, despite their considerable influence and potential to make substantial contributions to the topics discussed in this paper.

The use of dynamic simulation software has been widely employed in studies analyzing the energy efficiency of passive systems and bioclimatic buildings. These tools enable rapid and inexpensive prediction of the energy performance of these structures, proving to be essential instruments in both the pre-design and design stages of buildings. For more reliable results, many studies also rely on in situ measurements or the construction of prototypical physical models, in conjunction with simulation software, to calibrate the digital models. However, few studies have utilized Building Information Modeling (BIM) platforms and life cycle analysis (LCA) tools within software applications, which could further contribute to holistic and comprehensive analyses of building techniques. LCA methods were explicitly described in [56,66], while BIM use appears just in [66].

It can be observed that research on passive systems is often motivated by a desire to validate scientifically traditional techniques from specific countries or regions. This approach contributes to a less stigmatized or romanticized interpretation of these techniques, as highlighted in [96], and also to the revival of local cultural traits in contemporary contexts. On the other hand, studies also advocate for the dissemination and universalization of these techniques, regardless of regionalism, and their applicability in specific climatic contexts worldwide, as stated in [51].

In summary, the review reveals that a large portion of the research concludes with positive assessments of the potential of passive systems to enhance the energy efficiency of buildings when properly designed and operated, with these conditions often being emphasized. However, existing limitations of techniques are also properly delineated [35,48,49,58,59,68,81]. A few studies ultimately conclude that the analyzed techniques are inefficient in certain contexts [22,53,63].

3.2.4. Gaps and Development Potential in Existing Literature about Solar Passive Systems

Various studies of passive solar systems analyzed argue that these techniques can benefit buildings' energy efficiency. However, as stated in other publications [62,72], part of the analyses is narrow in focus, concentrating the analysis solely on the energy efficiency of the systems and disregarding other important factors such as their impact on buildings' occupants' comfort, e.g., thermal and visual comfort, the costs involved in the construction and during the building's operational phase, or analysis that considers the efficiency of passive systems in light of predictions of climate change for the upcoming decades.

For a more holistic analysis of bioclimatic buildings and techniques, BIM and LCA software could be more frequently applied, as these tools offer a comprehensive understanding of a building's lifecycle, from conception to demolition or reuse.

Additionally, in some studies, the natural physics phenomena involved in passive systems are poorly addressed and described, which may result in incomplete information and cause deviations in the results, as stated in studies that assessed the effects of thermal inertia in buildings [63,67].

Furthermore, researchers frequently encounter the perpetuation of outdated terms and inaccurate data when assessing passive systems based on vernacular techniques. Resorting to traditional techniques is viewed as a means to "evoke" the origins of architecture and its good practice, as discussed regarding the concept of the primitive hut [97]. A romanticized and simplistic interpretation of these systems, even within scientific studies, is not uncommon, which adds little to the scientific knowledge on the subject; on the contrary, it may hinder the advancement of knowledge in this regard and settle unrealistic expectations of passive systems [96]. As stated by Fernandes et al. [48], vernacular buildings and techniques alone may often not ensure that the current standards on thermal comfort are fully met, but they can provide valuable clues on how to optimize the energy efficiency of contemporary structures.

4. Conclusions

The state-of-the-art review regarding passive building techniques reveals that these can be efficient means for planning buildings that are less dependent on energy consumption, bringing the building stock closer to achieving the zero-carbon goals. There are several techniques tailored for either cooling, heating, or both purposes, which are suitable for specific climate types where they can exhibit enhanced efficiency. Choosing the ideal passive systems for a building requires a prior in-depth analysis of the local climate. Furthermore, this analysis should also contemplate the buildings' surrounding conditions, solar path, and the supply of available materials, while acknowledging intangible factors such as local culture and economy. However, efficient solar passive techniques should not be limited to regionalism and should be encouraged to be used globally.

The sometimes-romanticized interpretation of vernacular architecture and its passive systems, often portraying them as a noble and superior form of architecture, should be avoided. It is crucial to consistently conduct a critical analysis of these passive techniques, relying on experiments, mathematical models, measurements, and dynamic simulations to obtain results that confirm their efficiency and assess the benefits (or lack thereof) when applied in modern constructions. The review shows that field measurements and dynamic simulations are widely used methods in assessing passive systems, with a special focus on the latter. This approach fosters reliable results through a practical and inexpensive method, which can also be executed remotely.

Furthermore, the analysis of the efficiency of passive cooling and heating techniques should undergo a more holistic approach, not only assessing the benefits for the building's energy efficiency but also conducting a life cycle analysis of the entire system, its impact on occupant comfort, and an economic analysis, as well as an assessment of the system's long-term performance. Dynamic simulation programs, powered by climatic data from predicted future scenarios, can be used as decision-making tools during design processes today.

A critical and in-depth approach to utilizing traditional architectural principles and passive systems in contemporary architecture is vital for fostering sustainable building practices. This perspective addresses the immediate energy efficiency concerns and aligns with the broader goal of mitigating climate change. Through establishing clear plans to address environmental issues, governments can also help to foment more research on these essential topics.

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