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Review

Advances in Retrofitting Strategies for Energy Efficiency in Tropical Climates: A Systematic Review and Analysis

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Abstract: The global construction industry significantly contributes to energy consumption and greenhouse gas emissions, necessitating immediate action for sustainable development. Recognizing the impact of buildings on emissions, the United Nations has set ambitious energy-related goals for 2030. Retrofitting buildings emerges as a strategic method for reducing energy consumption, offering lower environmental impact and life cycle costs. However, retrofitting is a complex process influenced by diverse factors such as policies, available resources, techniques, building-specific data, and uncertainties. Thus, this paper reviews the existing literature on retrofitting strategies for tropical and humid climates to identify effective approaches for enhancing energy efficiency, thermal comfort, and overall building performance in these regions. Through comprehensive analyses, including bibliometric analysis using VOSviewer version 1.6.18 and systematic assessments, this study investigates various retrofitting strategies. This study categorizes tropical climates into Af (Tropical Rainforest Climate) and Aw (Tropical Savanna Climate) based on the Köppen climate classification. It reveals distinct emphases, with Af climates concentrating on office buildings and Aw climates prioritizing residential structures. Passive strategies were predominantly favored in office buildings, with glazing being the most commonly implemented approach. Residential structures, on the other hand, adopted a combination of passive strategies such as phase change materials along with active methods like appliance replacement. Educational buildings tended to rely on passive strategies, including roof covers, shading, and glazing. The absence of specific cost values underscores the importance of establishing baseline metrics, revealing significant challenges in retrofit techniques. This study further highlights an opportunity to explore passive methods in educational buildings, stressing the need for comprehensive guidelines, especially in institutional settings. Moreover, it emphasizes the urgency for ambitious regulations to address carbon emissions and optimize energy efficiency in tropical climates.

Keywords: building; energy efficiency; humid; NZEB; retrofit; tropical climate; tropics

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1. Introduction

The building sector holds a significant position in energy consumption and greenhouse gas (GHG) emissions. Presently, it constitutes 35% of the global energy usage and is responsible for 38% of the energy-related CO2 emissions [1,2]. Building operations contribute 28% of the annual CO2 emissions, while building materials and construction add another 11% annually [3]. Emissions from the construction industry are of particular concern, highlighting the imperative to transition towards green buildings and low-carbon construction materials to mitigate GHG emissions. Endeavors aimed at reducing emissions and curbing energy consumption within the building sector are essential for attaining global sustainability objectives. The building sector's impact on GHG emissions significantly contributes to climate change [2,4,5]. Buildings play a crucial role in the United Nations' Sustainable Development Goals (SDGs) report [6] by contributing directly and indirectly to various SDG targets [7,8]. Implementing sustainable building practices is vital for realizing the SDGs concerning health, sustainable consumption, sustainable cities, and other related objectives, requiring further action to achieve energy-related goals by 2030, as outlined in the United Nations' Sustainable Development Goals report [6].

Recognizing the significance of enhancing energy efficiency, international regulatory bodies, including the Energy Performance of Buildings Directive (EPBD), mandated nearly zero energy consumption for buildings after 2020. The revised directive will help achieve the goal of reducing emissions by at least 60% in the building sector by 2030 compared with 2015 and attaining climate neutrality by 2050 [9].

Building retrofitting, an effective strategy to lower energy consumption and identify energy-saving opportunities based on building conditions, types, and functions, boasts relatively lower environmental impact and life cycle costs than redevelopment [10,11]. However, retrofitting is a multifaceted process influenced by factors like policies and regulations [12], available resources, preferred techniques [13], building-specific data, human elements, and uncertainties [14]. This comprehensive procedure involves energy audits, performance evaluations, identification of energy conservation benefits, economic analyses, risk assessments, and measurement and verification of energy savings [15].

Given the substantial upfront investment required to retrofit a building against annual energy savings, building owners often hesitate because of uncertainties about the investment's value [10]. Hence, conducting a Cost–Benefit Analysis (CBA) becomes crucial to assess the economic and financial implications across various retrofitting levels, enabling informed and effective decision-making [16].

Building retrofitting has a different focus depending on the weather and country. Some focus on measures established for windows (United States [17]), HVAC systems (United States [17], Thailand [18], Vietnam [19]), financial incentives (European Union [20], India [21], Japan [22], Canada [23]), subsidies (European Union [24], India [21], Japan [22]), targets for green building construction (China [25]), improving cooling systems (Singapore[26], Indonesia [27], Philippines [28], Cambodia [29], Bangladesh [30], Sri Lanka [31]), energy performance (Singapore [26], Cambodia [29], Bangladesh [30]), thermal comfort (Malaysia [32], Sri Lanka [31]), improving insulation (Thailand [18], Philippines [28]), and building envelopes (Indonesia [27]).

Also, there exists substantial research focusing on various facets of building energy management, including model calibration [33,34], simulation [35], retrofit solution selection [36], life cycle cost (LCC) computation [37], and establishing optimal decision-making models [38,39]. However, more studies need to systematically study the different strategies for retrofitting in hot and humid weather. Such a study could serve as a comprehensive solution for building owners to assess the feasibility of energy retrofit projects, particularly in tropical regions where climate significantly influences energy consumption patterns and retrofitting strategies [40].

For instance, because of varying energy consumption patterns between different types of buildings, especially institutions, and their relatively constrained financial resources [41], it becomes imperative to investigate the cost–benefit viability of energy retrofitting projects specifically tailored for institutional buildings in tropical climates.

This research stands out for its meticulous analysis and synthesis of the available literature concerning retrofitting strategies focused on buildings in tropical and humid climates. By concentrating on enhancing energy efficiency, thermal comfort, and overall building performance within these challenging environmental conditions, this study aims to uncover the most effective methods, metrics, approaches, and techniques. Its originality lies in its focused exploration of retrofitting strategies uniquely suited to tropical and humid climates, offering a specialized perspective on addressing the sustainability challenges of these regions. Through its comprehensive review, this research aims to provide valuable insights and recommendations for professionals and research, contributing to the advancement of sustainable building practices in tropical and humid climates.

The present study expands upon retrofit research conducted in tropical climates. Section 2 delves into a comprehensive literature examination, incorporating bibliometric and scientometric analyses. Section 3 presents the outcomes obtained by implementing the previously outlined methodology. Lastly, Section 4 delineates the most pertinent retrofitting strategies suitable for tropical climates and accentuates, compares, and analyzes various strategies while discussing future research directions from this study.

2. Materials and Methods

The methodology implemented is divided into two parts as follows: bibliometric and systematic analysis. The next section explains each part in detail.

2.1. Literature Search Strategy

Regarding data collection, to identify the different applications based on retrofit in buildings, an examination of the literature was carried out using the search strategy presented in Figure 1. The selection of the final papers on this research included four steps as follows:

a. To gather as many studies as possible, the use of scientific databases such as Google Scholar, Science Direct, and Springer were selected.
b. The search was performed in each of the scientific databases. The main co-word combinations and Boolean operators were retrofit AND building AND "energy efficiency"; retrofit AND building AND "energy efficiency" AND (NZEB OR nZEB); retrofit AND building; retrofit AND (NZEB OR nZEB), which returned a total of 34,553 documents.
c. An exclusion criterion was applied, limiting the research to English and a period of the last five years (2018–2024) and using the Boolean operators, which returned a total of 16,649 documents.
d. The papers were analyzed using a combination of additional co-word combinations and Boolean operators to include tropic/tropical climate/humid; the combinations were the following: retrofit AND building AND "energy efficiency" AND (tropics OR "tropical climate" OR humid); retrofit AND building AND "energy efficiency" AND (NZEB OR nZEB) AND (tropics OR "tropical climate" OR humid); retrofit AND building AND (tropics OR "tropical climate" OR humid); retrofit AND (NZEB OR nZEB) AND (tropics OR "tropical climate" OR humid), which returned a total of 2211 documents.

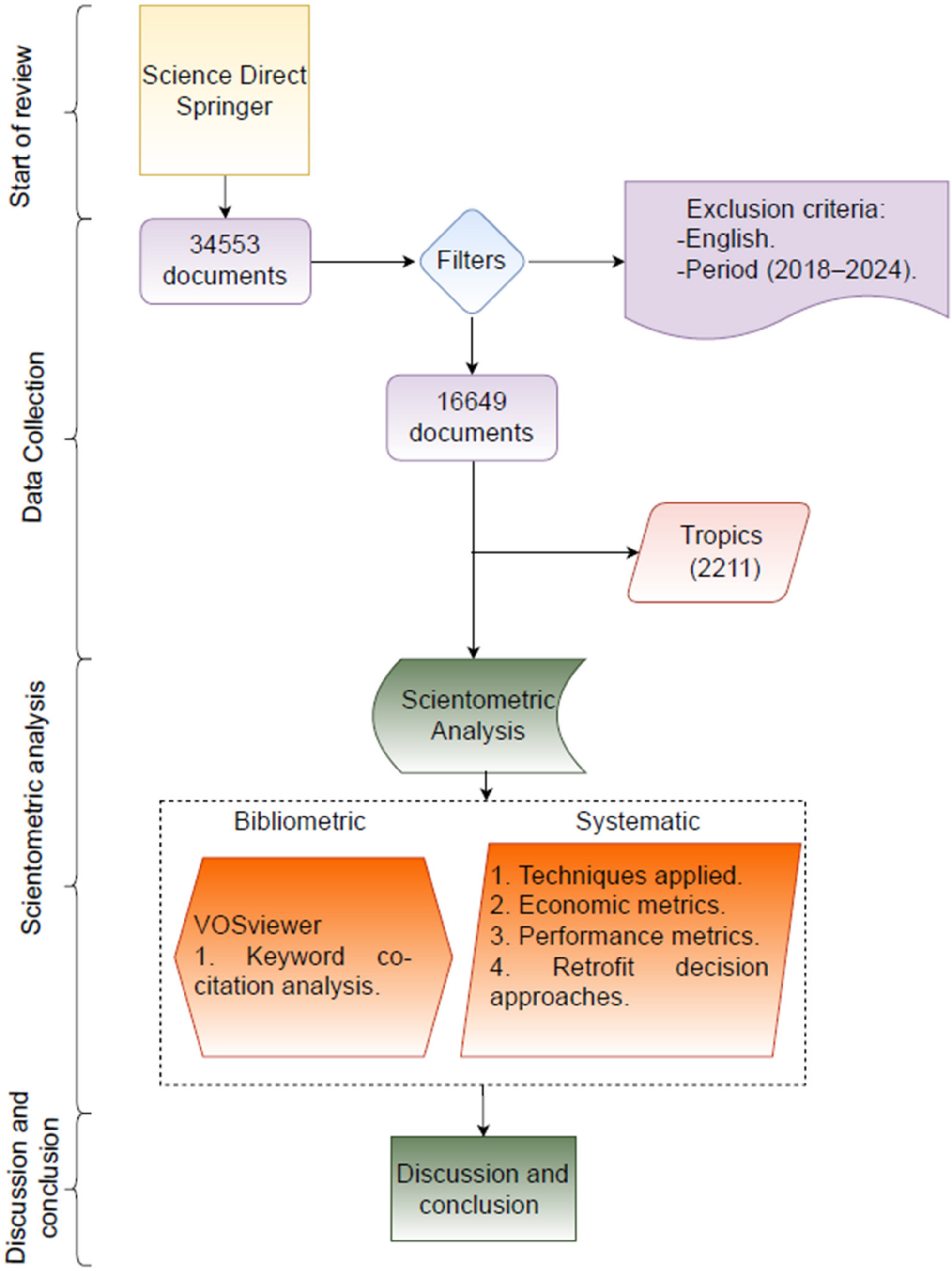


Figure 1. Research methodological process.

2.2. Scientometric Analysis

The final documents were analyzed using bibliometric and systematic analyses, both of which are explained in detail hereafter.

2.2.1. Bibliometric Analysis

A large number of documents from Section 1 in the data collection are presented. A bibliometric mapping tool named "VOSviewer" was used to analyze the information. VOSviewer has the advantage of presenting an informative visualization. VOSviewer is a free computer program that is especially useful for displaying large bibliometric maps in a way that is easy to interpret [42,43].

The bibliometric analysis was conducted, the map was created based on bibliographic data, the RIS file was uploaded, and the keyword co-occurrence analysis was selected. Tables 1 and 2 list the query used for searching and the quantity of documents. Table 3 shows the most common keywords in the retrofit analysis, where some words were similar and thus grouped under similar keywords, as listed in Table 4. Once the keywords were grouped, a thesaurus file was used to merge the keywords.

Table 1. Query used for searching and the quantity of documents.

Keywords	Number of Documents	Period
retrofit AND building AND "energy efficiency"	10,299	2000–2024
retrofit AND building AND "energy efficiency" AND (NZEB OR nZEB)	753	2010–2024
retrofit AND building	22,672	2000–2024
retrofit AND (NZEB OR nZEB)	829	2010–2024
retrofit AND building AND "energy efficiency" AND (tropics OR "tropical climate" OR humid)	1444	2000–2024
retrofit AND building AND "energy efficiency" AND (NZEB OR nZEB) AND (tropics OR "tropical climate" OR humid)	166	2012–2024
retrofit AND building AND (tropics OR "tropical climate" OR humid)	2117	2000–2024
retrofit AND (NZEB OR nZEB) AND (tropics OR "tropical climate" OR humid)	178	2012–2023

Table 2. The query used to search for several documents in the last five years.

Keywords	Number of Documents	Period
retrofit AND building AND "energy efficiency"	5107	2018–2024
retrofit AND building AND "energy efficiency" AND (NZEB OR nZEB)	504	2018–2023
retrofit AND building	10488	2018–2024
retrofit AND (NZEB OR nZEB)	550	2018–2024
retrofit AND building AND "energy efficiency" AND (tropics OR "tropical climate" OR humid)	812	2018–2024
retrofit AND building AND "energy efficiency" AND (NZEB OR nZEB) AND (tropics OR "tropical climate" OR humid)	130	2018–2023
retrofit AND building AND (tropics OR "tropical climate" OR humid)	1131	2018–2024
retrofit AND (NZEB OR nZEB) AND (tropics OR "tropical climate" OR humid)	138	2018–2023

Table 3. List of the most keywords that occurred in the retrofit search.

Keywords	Occurrence
energy efficiency	762
thermal comfort	298
retrofit	282
energy retrofit	183
building retrofit	179
climate change	160
energy consumption	152
sustainability	129
nzeb	126

buildings	123
residential buildings	121
renewable energy	116
energy saving	111
optimization	108

Table 4. Related terms are grouped under the stated keyword.

Keyword	Terms Grouped with the Keyword
buildings	building; building energy efficiency; building stock
energy efficiency	energy saving; energy performance; energy savings; building energy performance
nzeb	zero energy building; net-zero energy building; nearly zero energy building; net zero energy building; net-zero; nearly zero energy buildings; net zero energy buildings; net-zero energy buildings; zero energy buildings; nearly zero energy; nzebs; net zero energy; zeb; nearly zero energy building (nzeb); nearly zero-energy building (nzeb); nearly-zero energy buildings; net zero energy building (nzeb); net-zero buildings; near zero energy buildings; nearly zero energy buildings (nzebs); nearly zero energy buildings (nzebs); net-zero emissions buildings; net-zero energy rural house; nzeb target; near zero energy building; nearly-zero and positive energy paradigms; net zero energy buildings (nzebs); net-zero, ghg emissions; zero energy buildings (zebs); zero energy solar household; zero-carbon building; zero-energy targets; net-zero energy
PEB	positive energy buildings (pebs)
residential buildings	residential building; residential
retrofit	energy retrofit; building retrofit; seismic retrofit; retrofitting; building renovation; building energy retrofit; building retrofitting; existing buildings; existing building; renovation energy retrofits; refurbishment; green retrofit; building retrofits; energy-efficient retrofit; energy retrofitting; deep energy retrofit; green retrofitting; retrofits; building refurbishment; energy renovation; retrofit delivery; retrofit measures; retrofit scenarios; deep retrofit; retrofitting strategies; deep renovation; energy efficiency retrofit; home energy retrofit; rehabilitation; domestic retrofit; energetic retrofit; existing residentials; housing retrofit; passive energy-saving retrofit; retrofit double glazing; retrofit guidelines; retrofit market; sustainable building renovation; sustainable building upgrade; zero energy building renovation; building energy renovation; building energy retrofits; building envelope retrofits; cost-optimal retrofit; façade retrofit; retrofitting measures; social housing retrofit; sustainable retrofit; thermal retrofit; deep retrofitting; renovation strategies; residential building retrofit; retrofit interventions
thermal comfort	adaptive thermal comfort; indoor thermal comfort; outdoor thermal comfort
tropical climate	tropics; hot and humid climate; hot and humid climates; hot-humid climates; hot/warm and humid climates

2.2.2. Systematic Analysis

A complete review of the preselected articles was needed to select sources that provided information related to retrofitted buildings and techniques applied. The final papers were selected by reviewing the title, abstract, and keywords.

The criteria employed in the literature selection included the following. (i) Retrofit in buildings in the last five years (2018–2023). (ii) Retrofit in buildings of any type. (iii) Retrofit in humid or tropical climates.

Finally, information on different retrofitting strategies in buildings and technical strategies applied in retrofitting were classified.

3. Results

The results of this study are presented in two parts. Section 2.2.1 explains the bibliometric analysis, and Section 2.2.2 explains the systematic analysis.

3.1. Bibliometric Analysis

Keyword Co-Citation Analysis

The number of documents listed in Table 1 is based on the primary co-word combinations and Boolean operators mentioned in the reviewed articles, excluding the specified exclusion criteria. The majority of these documents are from 2000 onwards. On the contrary, Table 2 includes exclusion criteria related to a recent five-year period.

Table 3 displays the most frequently appearing keywords along with their respective co-occurrence counts based on the completion of data collection and document exportation using Vosviewer. "Energy efficiency" emerges as the most prevalent keyword, exhibiting the highest frequency among all keywords and demonstrating connections to all other clusters. Subsequently, "thermal comfort" ranks as the second most frequent term, followed by "retrofit" in third place.

In the visual representation, 7318 keywords were considered, of which 1115 met the specified threshold criteria. The visualization in Figures 2 and 3 involves 1000 links and showcases 995 items. Figure 2 illustrates the interconnectedness of keywords and their links, with different colors denoting distinct clusters within the network. Meanwhile, Figure 3 depicts the network's links and co-occurrences of keywords across a timescale, highlighting recent years in yellow.

In Figure 4, the keywords "tropical climate" and "tropics" exhibit the least occurrence, linked to various distinct clusters. Moreover, the timescale indicates that these keywords are more recent, suggesting a tendency towards novelty or recency.

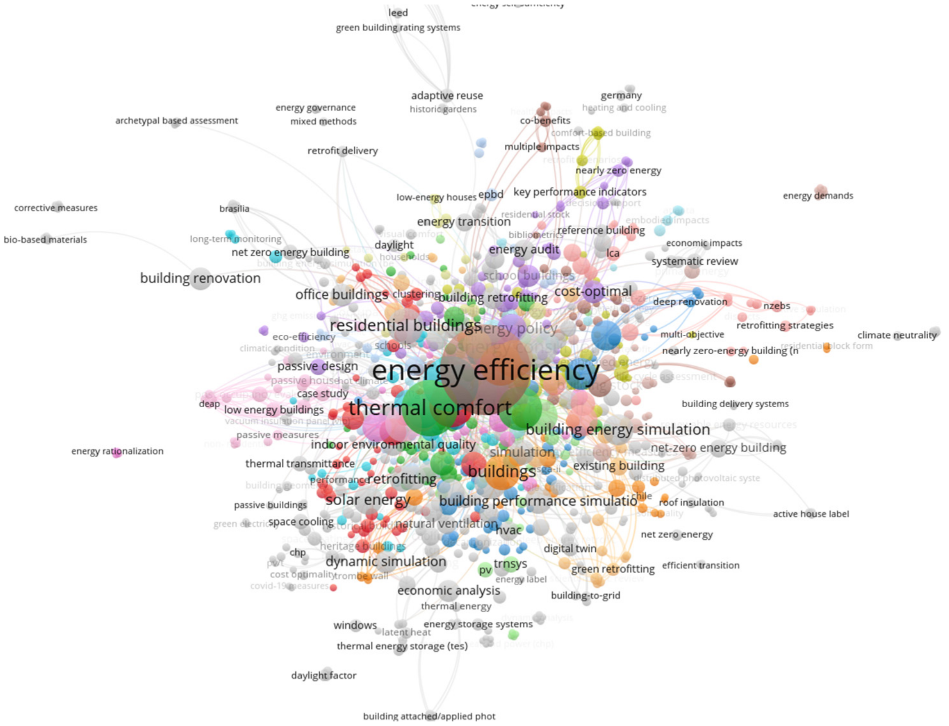


Figure 2. Network illustration for keywords used in the reviewed research.

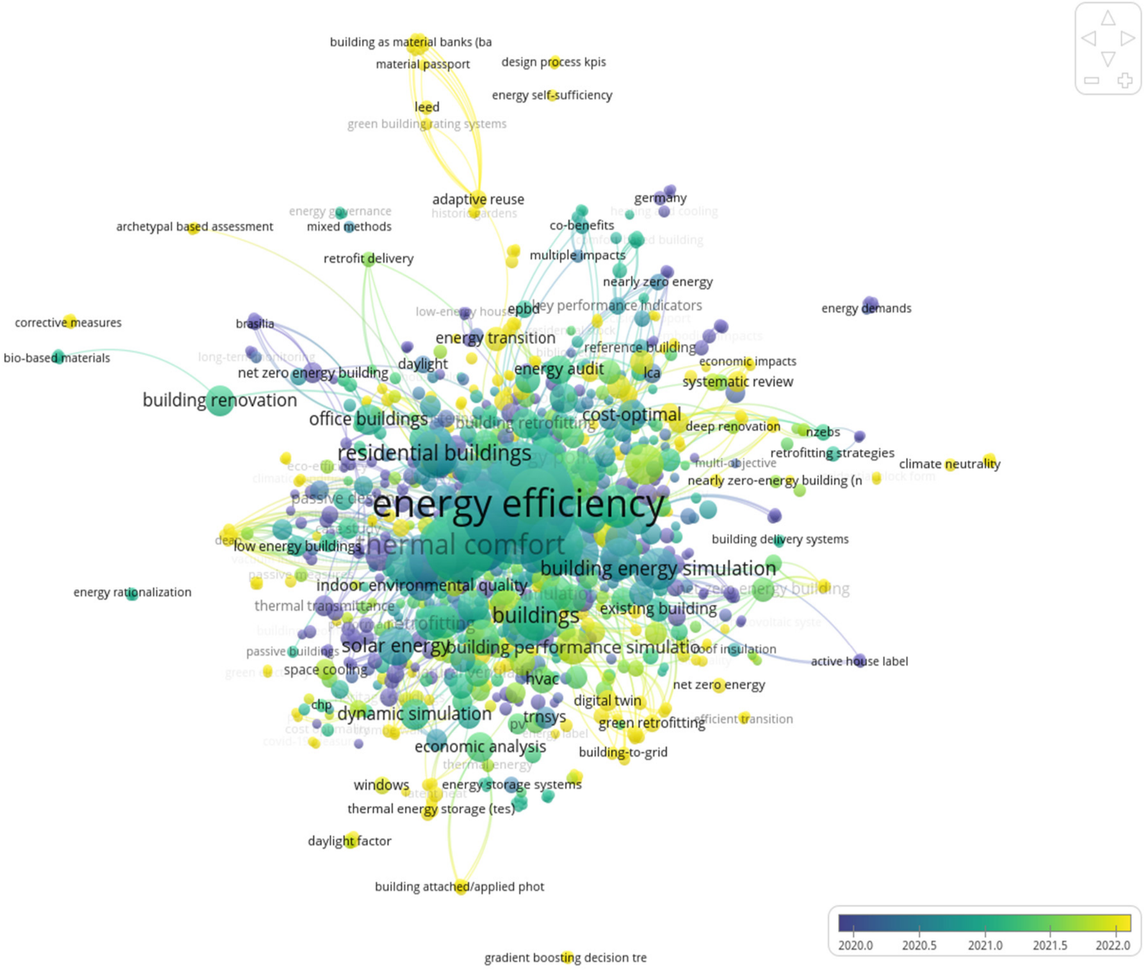
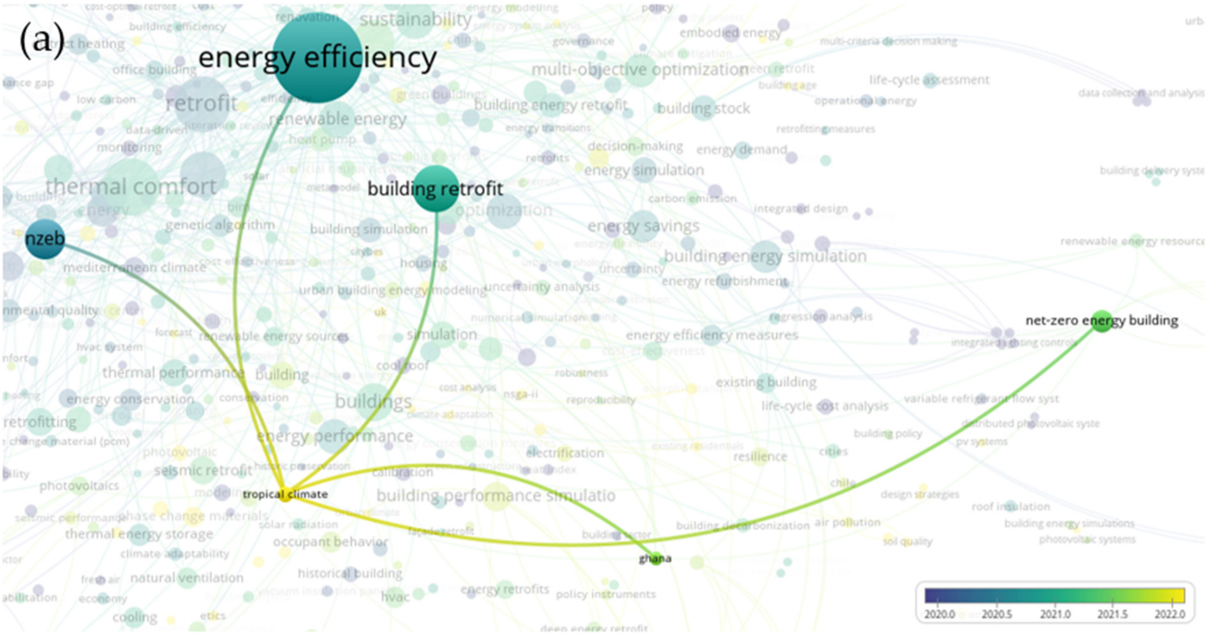


Figure 3. Network links and co-occurrences of the keywords on a timescale.



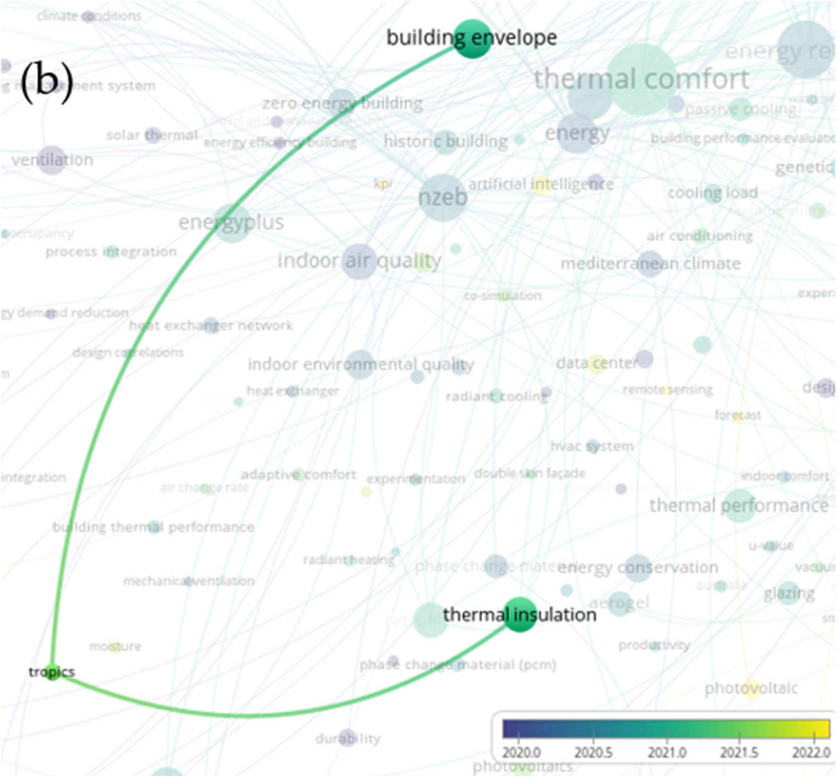


Figure 4. Co-occurrence of the links for the keywords (**a**) "tropical climate" and (**b**) "tropics".

As observed in the preliminary findings, various keywords derived from the highly co-occurring pairs in Table 3 were categorized under specific terms, as showcased in Table 4. This process is termed a thesaurus in Vosviewer and aims to standardize the data and enhance its practicality and realism for analysis. This approach yielded a new set of 6325 keywords, with only 123 meeting the defined threshold, thus generating 101 links.

Upon implementation, the resultant figures, Figures 5 and 6, depict the final representation, with "retrofit" emerging as the most prominent term. Additionally, Figure 7 groups keywords under "tropical climate." In Figure 7a, there is a prevailing trend indicating recent studies that are emphasizing tropical climates. Figure 7b illustrates the relationships between various domains such as retrofit, thermal comfort, nzeb, and energy efficiency.

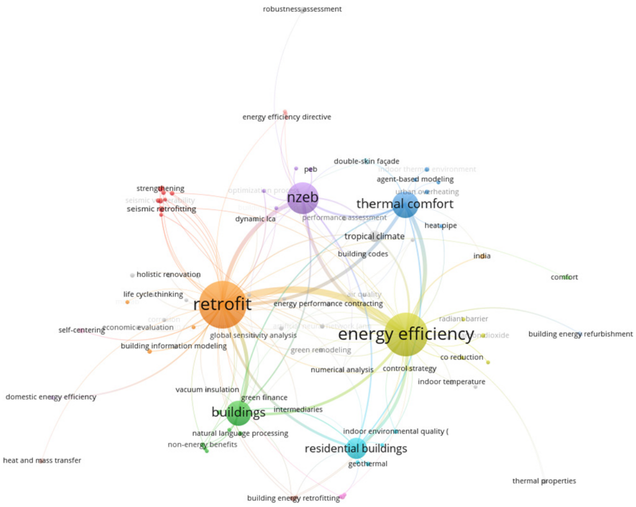


Figure 5. Network illustration for final keywords.

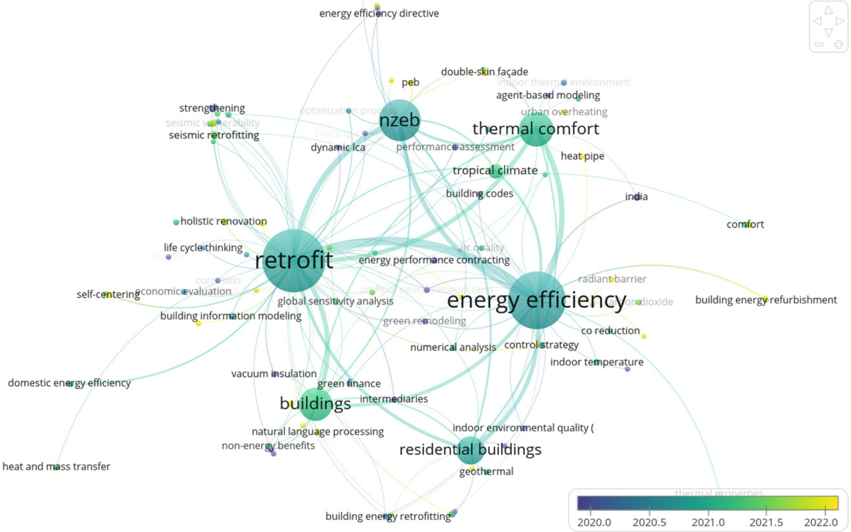


Figure 6. Networks links and co-occurrences for final keywords on timescale.

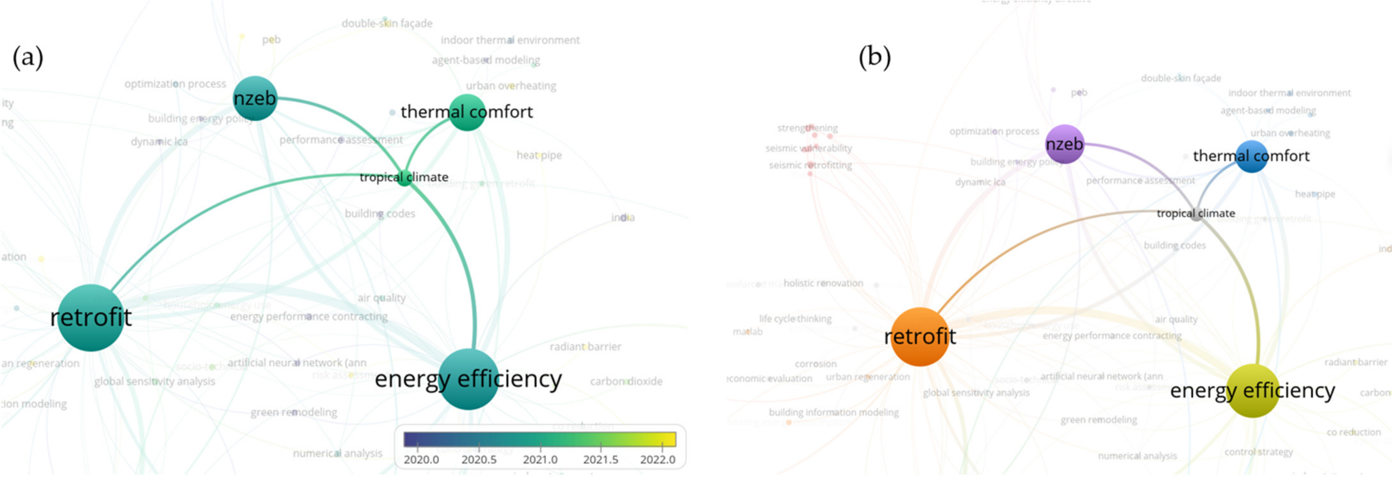


Figure 7. Keyword "tropical climate" (**a**) co-occurrence on a timescale and (**b**) co-occurrence of the link.

3.2. Systematic Analysis

Building energy efficiency retrofit entails optimizing technical, environmental, or economic parameters to identify the most suitable saving strategy. Although the analyzed methods may have different approaches, they must focus on meeting the established objective. An analysis of the literature revealed that enhanced comprehension can be categorized into techniques applied in retrofitting, studies involving economic metrics, performance metrics, and retrofit decision approaches.

Three subsections were developed regarding techniques applied in retrofitting. The first section focuses on building components (envelope). The second delves into utilizing systems or requirements for greater efficiency, while the third concentrates on renewable energy systems. The features of all the studies reviewed are summarized in Tables 5 and A1 (a follow-up of Table 5).

Economic metrics receive extensive evaluation because of their ability to determine the profitability of alternative approaches. Performance metrics are a crucial variable in energy-efficient assessments. Retrofit decision approaches reveal methods for identifying correct energy-saving approaches and play an essential role as tools to measure, monitor, and analyze the behavior of implemented strategies or technologies. The decision on which of these approaches to use depends on the specific objectives of the study.

3.2.1. Techniques Applied in Retrofitting

Building Component (Envelope)

A parametric analysis was carried out by Vidhya et al. [44], who investigated different saving strategies in their study focused on various methods to enhance thermal comfort in a school situated in Chennai, India. They concluded that natural ventilation, reducing infiltrations, and adding shading on windows can decrease the temperature by 3.2 °C in summer and 3.4 °C in winter. On the other hand, in the study developed by [45], natural ventilation was also implemented as an energy-saving strategy by changing the upper windows from fixed to pivot. They discovered that natural ventilation does not provide the best thermal comfort. For this reason, a cooling system was therefore incorporated. Then, the comfort hours were increased to 35%. Implementing a dynamic external shading device was also studied in [46], where a 24% cooling energy saving was achieved.

In the study presented by A. Shandilya [47], after comparing different saving strategies in a single-family house located in India, the results demonstrated that adding shading control and applying insulation to the walls and roof reduced the cooling energy demand by 70%, even when keeping single-glazed windows. The floor insulation was not included, as it decreased the comfort hours during the summer. Thus, it is important to consider the most possible parameters to determine the best strategies.

Replacing windows was an energy-saving strategy adopted in [48], where they evaluated different options to find the right type of window (louvered windows, plenum windows, or double-glazed and triple-glazed windows). According to the results, after evaluating life cycle cost, embodied energy, global warming potential (GWP), and energy use, the option with the best energy performance was triple-glazed windows. Nevertheless, considering the other indicators, the optimal choice was double-glazing windows because of their GWP and embodied energy values, 532 MJ kg/m^2 embodied energy and 101 kg/m^2 CO$_2$ embodied carbon, respectively. Equally, double-glazed windows reduced cooling energy consumption by 27%. In Sao Paulo, Brazil [49], researchers studied an office building and performed a sensitivity analysis to select the proper value for each of the following variables: the window opening effective area (WOEA), external shading angle, glazing thermal properties (U-value and heat gain), and wall absorptance solar radiation. They concluded that a double-glazed window with a U-value of 2.8 W/m^2 was preferred, employing a light color for the external walls with an absorptance (α) of 0.2, 93% WOEA, 45° for the external shading device vertical shadow angle (VSA), and 37% glazing solar heat gain. These improvements resulted in an energy saving from 8.7 kWh/m^2 per year to 21.4 kWh/m^2, depending on window orientation.

Window enhancement is important in achieving an efficient building. The authors of [50] demonstrated that an existing window could join a new one, becoming a double-glazed window. They developed a study in Singapore, where 8mm of sun energy grey glazing type and solar control film were adapted to 10 mm of clear glazing (the previous one installed). They were separated by 17 mm of air. This refurbishment reduced the U-value from 5.649 to 1.998 W m^{-2} K^{-1}, representing a 41.4% cooling energy saving. A study developed by S. Sebayang [51] revealed a window improvement in an educational building in Singapore. They implemented a combination of new glazing properties and vertical fins; the first reduced the overall thermal transfer value (OTTV) of the wall from 32.27 W/m^2 to 29 W/m^2, and the last produced 28.02 W/m^2, where the OTTV was 26.23 W/m^2. The results showed that the joint implementation of both strategies decreased the indoor air temperature by 0.835 °C.

Another investigation developed a similar study. Somasundaram et al. [52] adapted a second glazing to an existing glazing. Nevertheless, this system did not work the same way as the original double-glazed window; the authors suggested that this could be due to the Window-to-Wall Ratio (WWR), which was only 8%. Despite this, the cooling energy consumption was reduced by 5.9%. In [53], another study was carried out in which the WWR was established at 20%, where 3% and 7.5% were achieved as annual energy consumption savings of air conditioning and total energy saving, respectively. Based on these outcomes, a better result was achieved by implementing a greater WWR. In contrast, Chandrasekaran et al. [46] demonstrated that for larger percentages such as 40%, 50%, and 60%, energy savings are not positively correlated with the percentages. Their results showed that for 40%, more energy is saved than a WWR of 50% and 60%, which was because of a higher heat input. For this reason, it was recommended that the WWR be maintained between 20% and 40%. Alwi et al. [54] determined that a 30% WWR exhibited better performance, reducing solar gains by 6%. In [55], a parametric analysis found that having 32% of the façade as an opened surface was the optimal choice.

The window size or state (adapted to a shading system, opened, or closed) impacts natural ventilation and heat input and influences daylighting entry. Consequently, there must be a balance between all those variables to maintain an optimal comfort zone and low energy demands. One solution that was presented is daylighting control, which established a daylighting control to keep the illuminance level at 500 lux. This solution reduced artificial lighting use and limited heat gains, which positively influenced energy cooling demand and total energy consumption. Using these saving strategies, the first one resulted in a reduction of 20%, the second one in a decrease of 14.3%, and the WWRs remained in the initial percentages (from 23% to 38%). These outcomes were better than those provided by the other saving strategies studied, such as WWR in 20% (for all external windows), which only resulted in 5.6% reductions [56].

In another study, controlled systems, such as catching data from sunlight, were used to help achieve energy efficiency through dynamic façades, specifically, kinetic shading devices (louvers), to avoid incremental solar heat gain. A single-glazed blue-tinted device was used and was found to be the best case. The annual sunlight exposure decreased by 65% [57].

In the study by Gupta et al. [58], they added a green roof over an original roof, reflecting coating and bamboo-based shading systems. A parametric analysis was performed to find the best materials. The results indicated that by applying those technologies, cooling energy savings were achieved by 18.5% to 23%. In addition, bamboo-based shading devices helped to reduce greenhouse gas emissions because of their natural properties. It was demonstrated that these shading systems performed better than horizontal window shading in tropical climates.

Phase change material (PCM) technology is an alternative to building retrofitting. Based on [59], which analyzed different countries with tropical climates, PCMs are feasible for this climate type, given their influence on reducing energy consumption. The outcomes showed an energy savings from 16.58% to 68.63%. Also, the authors emphasized PCM layer thickness, which was positively correlated with energy saving. The investigation conducted in [60] proved this correlation through an analysis developed in a residential building located in Malaysia, in which they implemented Infinite R^{TM} as the PCM material. Three layers of thicknesses, 6 mm, 12 mm, and 18 mm, were tested and located in the inner part of the external and internal walls; each one was evaluated with different melting temperatures, from 27 °C to 30 °C, and solidification temperatures, in the range of 26 °C to 29 °C. After analyzing each possible solution, the outcomes illustrated that the best PCM combination corresponded to 27 °C for melting and 26 °C for the solidification process. Implementing 18mm as the thickness of the layer, given the enhancement in the thermal comfort, increased the thermal comfort time (TCT) to 78%. Furthermore, natural ventilation improved performance because of the capacity to remove heat inside the room on hot nights.

On the other hand, a study developed by M.J. Abden et al. [61] in Darwin, Australia, showed slightly different results from the investigation reported in [60]. First, the PCM was composed of form-stable PCM (FSPCM), implementing methyl stearate and diatomite. The thickness of FSPCM was 25 mm, and the melting temperature was 27 °C. The FSPCM was joined with thermal insulation called expanded polystyrene (EPS) with a thickness of 60 mm. These materials were incorporated below the wall and ceiling.

According to the outcomes, this combination represented a major decrease in total energy consumption by up to 10.3%, and the intensity of thermal discomfort was reduced by 22.1%. In this case, natural ventilation was ineffective because of tropical environmental conditions. The investigation developed by Kameni et al. [62] in an office building in Madagascar identified that adapting insulation below a wall improved thermal comfort; it also resulted in around 12% and up to 10% in CO_2 savings.

PCM was also studied in a residential building located in Darwin, Australia [63]. In this case, n-octadecane combined with gypsum was adopted as the PCM with a 2cm thickness. The result showed that the optimal melting temperature was 24 °C, achieving 7.6% cooling load reduction and 4.76% total energy consumption. These outcomes differ slightly from those of the previous study in Darwin, which may be due to the melting temperature and thickness selected, as both were inferior to the values in the other article. The authors also mentioned that an insulation material could help even more.

Most retrofit studies are developed through energy simulation software, and experimental studies are less common. However, some of them were found in the literature review. According to [64], a way to improve thermal comfort in tropical climates is employing roof covers with high-density polyethylene. Their results presented a reduction of 70–88% in the convective heat flux, but they also mentioned that the roof covers did not perform as well as a mechanical ventilation method. Different roof envelope materials, such as covers or insulators, can be used.

Adapting advanced technology to an existing installation to achieve energy efficiency was used in the study by [65], in which the indoor air quality was improved through a hybrid air treatment cooling system (HATCS). They developed an oxygen generation process implementing water-splitting methods using solar energy. Consequently, ozone-based treatment was produced to eliminate bacteria and viruses. Then, an air scrubbing mechanism was applied to the HVAC system. This air treatment helped to avoid outdoor air intake, thus reducing energy consumption by cooling load by 25%, which saved energy. Also, this strategy enhanced indoor air quality by up to 19%.

Use of Systems or Equipment with Greater Efficiency

According to Litardo et al. [56], considerable energy savings can be achieved by replacing obsolete equipment with more efficient equipment. In their investigation, it was concluded that using the HVAC system proposed by the Energy Star program, which meets the greatest efficiency standards, can provide 77.07 kWh/m^2y.

In the study performed in [66], appliance replacement, such as lighting, air conditioners, refrigerators, water heaters, clothes dryers, and washers, represented the most feasible saving strategy, considering the LCC. This could be due to the continual usage of these appliances, particularly the lighting and air conditioner, which achieved 83,640 kWh and 498,486 kWh in energy reductions during its lifetime.

Renewable Energy System

E. Ohene et al. [67] conducted a study through parametric analysis employing simulation software. Their study implemented retrofit strategies in a residential building located in Ghana to achieve a net-zero energy building (NZEB). The researchers found that passive strategies like taking advantage of daylight to reduce interior light, improving natural ventilation, applying window overhangs, and minimizing infiltration reduced heat gains effectively, and 48–58% energy savings were achieved. Those strategies helped to reduce energy consumption, which initially was 137 kWh/m^2y, whereas, after refurbishing, it was 68 kWh/m^2y, which turned the building into an NZEB. Daylight is often implemented as an energy-saving method; however, it is important to consider heat inputs. The study by Z. Amin et al. [60] achieved an NZEB after a building's refurbishment by implementing daylighting controls in an educational building in Ecuador. The photovoltaic (PV) system provided 66,590 kWh/y, and the energy consumption was only 48,498 kWh. The energy demand before refurbishment was 97,958 kWh/y. Thanks to the energy-saving strategies, an optimized PV system was installed. A similar method was also developed in a case study in Panama [68]. Nevertheless, the retrofit was performed after the photovoltaic system installation because of the necessity of achieving an NZEB.

In [69], an NZEB was achieved after establishing saving strategies to decrease energy consumption in an office building in India. Those strategies replaced the single-glazed type with the double-glazed type, and insulation was applied to the walls and roof. Thus, the U-value became 0.46. This photovoltaic system was installed on the rooftop and supplied the whole building's energy consumption.

Another application of PV systems is in replacing wall or roof envelopes; these technologies are called building-integrated photovoltaic (BIPV) curtain walls and BIPV membrane roofs. Jhumka et al. [70] studied an office building retrofit in Mauritius, where BIPV replaced the original roof and south façade. However, the study evaluated the heat transfer through the new envelopes and showed that both systems, including a curtain wall and membrane envelope, increased the heat transfer reverberating in the indoor air temperature. For that reason, the BIPV membrane roof was insulated; this system reduced the cooling load by 15% and represented 172% in energy savings, in contrast to the BIPV curtain wall, which did not generate a great decrease in energy consumption.

A photovoltaic system can be installed considering some adjustments, such as implementing plants beneath the system. This has been carried out to avoid rising temperatures, thus increasing efficiency. C. Kaewpraek et al. [71] performed this application in a residential building in Thailand. According to the results of their investigation, a green rooftop combined with a PV system improved the building's energy performance and helped reduce CO_2 emissions. According to the study developed by [72], combining photovoltaic systems with green roofs allowed a temperature reduction of the module, and this represented a module efficiency improvement of 3 to 11%.

Table 5. Retrofit strategies in tropical climates.

City, Country	Climate Type	Type of Strategy	Building Typology	Retrofit Purpose	Retrofit Strategies Studied	Retrofit Strategies with the Best Performance	Year	Ref.
Bangalore, India; Kolkata, India; Tanzania	Aw	Passive	Residential	Reduce energy consumption	Phase change material—thickness of 5 mm to 40 mm with an interval of 5 by 5 and melting temperature from 21 °C to 31 °C	Phase change material—thickness of 5 cm to 40 cm with an interval of 5 by 5 and melting temperature from 21 °C to 31 °C	2019	[59]
Bangalore, India	Aw	Passive	Office	NZEB	Wall insulation and photovoltaic system	Wall insulation and photovoltaic system	2023	[69]
Brasilia, Brazil	Aw	Passive	Office	Reduce energy consumption	Appliance improvement, natural ventilation, thermal mass	Appliance improvement, natural ventilation, thermal mass	2020	[73]
Chennai, India	Aw	Passive	Educational	Reduce indoor air temperature and energy consumption	Roof cover, light color painting, shading with trees, WWR increase, ceiling fan, reflective glass, double glazing	Roof cover, light color painting, WWR increase, ceiling fan, reflective glass, double glazing	2023	[44]
Chennai, India	Aw	Passive	Office	Reduce energy consumption	Fixed and dynamic external shading device	Dynamic external shading device	2022	[46]
Darwin, Australia	Aw	Passive	Residential	Reduce energy consumption	Phase change materials (form-stable PCM) and expanded polystyrene, separated and combined	FSPCM and EPS combined	2022	[61]
Darwin, Australia	Aw	Passive	Residential	Low cooling demands and improved thermal comfort	Phase change material (n-octadecane microencapsulated) 1cm and 2cm thickness	Phase change material (n-octadecane) 2 cm thickness	2022	[63]

Ecuador	Aw	Passive	Educational	Reduce energy consumption	Daylighting control, WWR reduction, solar shading, triple glazing, HVAC system replacement	Daylighting control	2021	[56]
Ghana	Aw	Passive	Residential	NZEB	Daylighting, envelope airtightness, sun shading, natural ventilation, building-applied photovoltaics	Photovoltaic system	2022	[67]
India	Aw	Passive	Residential	Reduce energy consumption and improve thermal comfort	Triple glazing, thermal envelope insulation (roof and walls)	Triple glazing, thermal envelope insulation (roof and walls)	2020	[47]
Indonesia	Af	Passive	Educational	Improve thermal comfort, reduce the indoor air temperature	New glazing properties and vertical fins	New glazing properties and vertical fins	2023	[51]
Indonesia	Af	Passive	Office	Low cooling demand	Double-glazed windows, WWR, temperature set point	Double-glazed windows, WWR, temperature set point	2023	[74]
Madagascar	Af	Passive	Office	Improve thermal comfort	Phase change material, adding insulation to walls and roof, solar protection, external shading	Insulation and external shading	2020	[62]
Malaysia	Af	Passive	Residential	Provide thermal comfort	Roof cover	Roof Cover	2020	[64]
Malaysia	Af	Passive	Residential	Provide thermal comfort	Phase change materials	Phase change material	2021	[60]
Malaysia	Af	Passive	Office	Apply multi-criteria decision-making to select a type of window	Louvered, plenum, double-glazed, and triple-glazed window	Double-glazed window	2022	[48]

Mauritius	Aw	Passive	Office	Low cooling demands	BIPV curtain wall and BIPV membrane roof	BIPV membrane roof	2023	[70]
Mumbai, India	Aw	Passive	Educational	Reduce energy consumption	Reflecting coating for external walls and green roof	Reflecting coating for external walls and green roof	2022	[67]
Mumbai, India	Aw	Passive	Educational	Low cooling demands	A green roof, reflecting coating, bamboo-based shading device	Green roof, reflecting coating, bamboo-based shading device	2022	[58]
Panama	Aw	Passive	Residential	NZEB	Temperature setpoint, cooling operation, occupancy, wall insulation	Temperature setpoint, cooling operation, occupancy, wall insulation	2022	[75]
Rio de Janeiro, Brazil	Aw	Passive	Office	Improve thermal comfort	Pivot windows	Pivot windows	2021	[45]
Rio de Janeiro, Brazil	Aw	Active	Residential	NZEB	Thermal energy storage for chiller and demand limiting	Thermal energy storage for chiller and demand limiting	2021	[76]
Sao Paulo, Brazil	Af	Passive	Office	Low cooling demands	Window opening area, shading, glazing properties (solar heat gain, U-value), wall absorptance	Overall, 93% of the opening area, 45° of external shading angle, light color for wall, 2.8 U-value	2020	[49]
Singapore	Af	Passive	Office	Low cooling demands and reduced energy consumption	Doble glazing	Double-glazed window	2019	[53]
Singapore	Af	Passive	Office	Low cooling demands	Doble glazing	Double-glazed window	2020	[52]
Singapore	Af	Passive	Office	Reduce energy consumption	Adding a secondary glazing (lowE, Sunenergy grey)	Adding a secondary glazing (lowE, Sunenergy grey)	2020	[50]
Singapore	Af	Active	Residential	Reduce energy consumption	Appliance replacement, window replacement, window and wall retrofit	Appliance replacement	2019	[66]

Singapore	Af	Active	Office	Reduce energy consumption	Hybrid air treatment cooling system	Hybrid air treatment cooling system	2019	[65]

3.2.2. Economic Metrics

Cost indicators are highly important in decision-making when evaluated based on existing weights at a specific decision-making moment. The most prevalent is the life cycle cost, defined in Section 3.2.4. On the other hand, based on the energy approach, an alternative method is to express the relationship between energy and cost. According to [66], the Dynamic Generation Cost (DGC) is adapted to study the energy saving generated by a specific strategy and consider its costs.

The DGC is calculated as shown in Equation (1):

$$DGC = \frac{\sum_{k=0}^{N} \frac{I_k + C_k}{(1+d)^k}}{\sum_{k=0}^{N} \frac{E_k}{(1+d)^k}} \quad (1)$$

where k represents the year evaluated, I is the investment cost, C is the lifetime cost, E corresponds to the energy saving, and d is the depreciation.

Equation (2) should be considered when evaluating the relationship between the life cycle cost and energy generation. The Levelized Cost of Energy considers $CAPEX$, which is the capital expenditure; OM, which is the annual operating maintenance cost; FC, which is the fuel cost; TC, which is the tax cost; and EG, which is the energy generation per year. This indicator is employed when a generation system, such as a photovoltaic system, is installed.

$$LCOE = \frac{CAPEX + OM + FC + TC}{EG} \quad (2)$$

3.2.3. Performance Metrics

Occupant behavior is an important variable to study in an energy-efficient assessment because it can interfere with a building's energy performance. Some occupants' actions are often related to the HVAC system since they can manipulate the set point temperature. In [56], the air conditioning temperature was fixed at 24 °C, after being 21–22 °C; this change helped to improve energy savings.

When thermal comfort impacts occupant behavior, this indicator should be assessed, similar to the study by Kameni et al. [62]. They found that integrating saving strategies could help to reduce thermal discomfort. According to their results, after employing the PCM strategy, the predicted mean vote (PMV) value was established from −0.21 to 1.08. In the study developed by [47], this indicator helped to choose the energy-saving strategies because thermal comfort was evaluated, and it was noticed that one strategy, which recorded a great energy performance, negatively impacted thermal comfort during the summer season. N. Ardiani et al. [74] showed that achieving low energy demand and ideal thermal comfort may require several different energy-saving techniques; for this reason, a thorough investigation is necessary.

After this literature review was developed, assessing the indicators employed by the researchers was appropriate. These indicators are an important tool for measuring, monitoring, and analyzing the behavior of the strategies or technologies applied. These depend on the objective of the study. As shown before, the studies are oriented to decrease cooling loads and energy consumption and increase thermal comfort. Thus, the main indicators are kWh/m^2 year and Energy Use Intensity (EUI).

Other variables need to be studied to achieve those objectives. Such is the case of heat transfer analysis through the building envelope to evaluate a building's thermal behavior, given its influence on energy performance. Based on these studies, decision-makers can take action accordingly. An important indicator is the Overall Thermal Transfer Variable (OTTV) employed in [51].

3.2.4. Retrofit Decision Approaches

Economic analyses are widely applied, given their ability to infer whether an alternative is profitable. LCC is an indicator implemented to evaluate each strategy available and find the most economically feasible. This includes the capital cost and the cost generated by operation, maintenance, and transportation; in other words, all the costs related to the project from its initial to its end.

LCC was analyzed in [48] and helped choose the correct option (type of window), where the most energetically viable was not selected because of its high cost. This action resulted in a 27% cost savings. LCC was also studied in the investigation by M.J. Abden [61], and the option selected (a combination of EPS and FSPCM) had the highest cost. Nevertheless, the payback period was appropriate (2.2 years), which is why, under this consideration, this option was chosen. Moreover, CO_2 savings were also considered in Australia because of the carbon pricing that must be paid. In this case, the strategy chosen represented 6.17 USD/m^2 in environmental savings and 380.5 kg/m^2 in the saving in $CO_{2\text{-eq}}$.

In [66], a cost analysis was performed focusing on cost–energy effectiveness through the Dynamic Generation Cost (DGC) indicator, which takes into account the cost and the energy-saving strategy in a respective year (USD/kWh). Thus, it was possible to recognize the most feasible strategy. This tool helped to identify that window and roof replacement resulted in cost-effectiveness that was greater than appliance replacement. A similar approach was developed in [67]. However, they considered energy generation through the Levelized Cost of Energy (LCOE), which was studied to define energy generation costs. The LCOE considers capital expenditure, operating maintenance costs, fuel costs, tax costs, and energy generation per year. They achieve 0.125 USD/kWh as the LCOE value, the lowest energy tariff established in Ghana. The payback period is an important indicator that refers to the time it takes to recover the investment. In the case of Ghana, it was 6 to 10 years. Based on the outcomes, it was found that installing PV systems was feasible.

Economic analysis is important since there are different ways to develop an energy-saving strategy. For example, a low-cost house can reduce its energy consumption, cooling demand, or internal heat gains with a low-cost strategy. In the case of [64], implementing a roof cover as a low-cost technology improved thermal comfort (acceptability of 80%).

Based on this literature review, there is a decision-making process in most cases to find the correct energy-saving method. An important comparison between every criterion must be made to carry out the decision-making process. A technique often used is parametric analysis. To perform such an analysis, different simulation software is required. One is the Grasshopper plugin in Rhinoceros software, which uses some plug-ins, such as Ladybug and Honeybee. The first deals with meteorological data and the second relates to different software and develops parametric analysis. Another often-used simulation tool is DesignBuilder simulation software, an EnergyPlus interface where parametric analysis is possible. In addition to performing a parametric analysis, a study of phase change material is also recommended [60].

There is an additional decision-making tool that requires a more involved procedure. This is multi-criteria decision-making, which corresponds to a method that evaluates more than two criteria, and the most significant variable is given priority in the decision process. Based on the results, the best energy-saving strategy is selected accordingly. This methodology was carried out in [48], where a survey was applied to define the priority order of the considered criteria, assigning a specific weight to each one. In this case, some professionals were considered for the task. The authors identified four factors to be evaluated as follows: GWP, which refers to the energy stored by a specific gas for long periods; LCC, which refers to embodied energy; and operational energy. According to the results, GWP took the first position, followed by LCC, and the operational and embodied energy were in third and fourth place. Finally, after considering all the criteria, the double-glazed windows performed the best. It is worth noting that, concerning the authors, academic professionals prioritize environmental aspects, and the economic field has greater importance for construction professionals.

Multi-criteria decision-making has a subcategory called multi-objective decision-making; the latter was considered in [75] to reduce energy consumption, meet an optimal thermal comfort level, and decrease energy and refurbishment costs. In that study, a sensitivity analysis was performed to identify the variables strongly associated with those objectives. After the analysis, the occupancy hours, external wall construction, and cooling set point temperature were identified as the most correlated variables. Those variables were studied and modified to reach the objectives.

An alternative to a decision-making process was used in [66], where a metamodel was developed that did not require a complex simulation. For this, a Bayesian model based on the Gaussian Process (GP) was performed. A Bayesian model and the GP work together because the latter generates a specific output, which usually depends on variables that can integrate an unknown value, which the Bayesian model will estimate. In this case, the GP was used to identify the energy consumption before and after a retrofit, which depended on air temperature and other variables that were considered. The Bayesian model was required to define the unknown variables and develop the calibration model, for instance, the infiltration rate. A cost-energy effectiveness analysis was integrated into this model to establish a saving strategy ranking given in USD/kWh. The lowest value generated in that analysis corresponded to the best strategy. In this case, the appliance was replaced over the roof, and the window and wall were substituted.

4. Discussion

This study aimed to focus on the tropical climate. According to the Köppen climate classification, this research revealed that Af (Tropical Rainforest Climate) and Aw (Tropical Savanna Climate) were the most prevalent categories. For Af climates, the primary focus of the reviewed studies was office buildings, followed by residential structures, with educational buildings being the least studied, as shown in Figure 8. In Aw climates, residential buildings were the primary focus, followed by office facilities and educational structures, which were also analyzed. This is important since different tropical climates exist, leading to the implementation of different strategies that may not be interchangeable. For instance, there are regions with high humidity with low temperatures and high humidity with high temperatures with the same solar radiation intensity. Thus, highlighting the climate type can help to choose better strategies.

This literature review focused on nations characterized by tropical and humid climates. Figure 9 illustrates the studies that discussed retrofit strategies in each region. The figure illustrates the frequency at which each study was presented in various countries. The leading region is the Asia continent (India, Singapore, Malaysia, and Indonesia), followed by Latin America (Brazil, Ecuador, and Panama), the African continent (Mauritius, Madagascar, and Ghana), and the Oceania continent (Australia). This helps us understand the efforts currently being made towards studying energy-based building retrofits.

In this study, it was determined that the country within the tropical sector with the most studies was India, specifically the cities of Bangalore, Chennai, and Mumbai. Next was Singapore. In the Americas region, the tropical countries found were Brazil, Panama, and Ecuador (Figure 9).

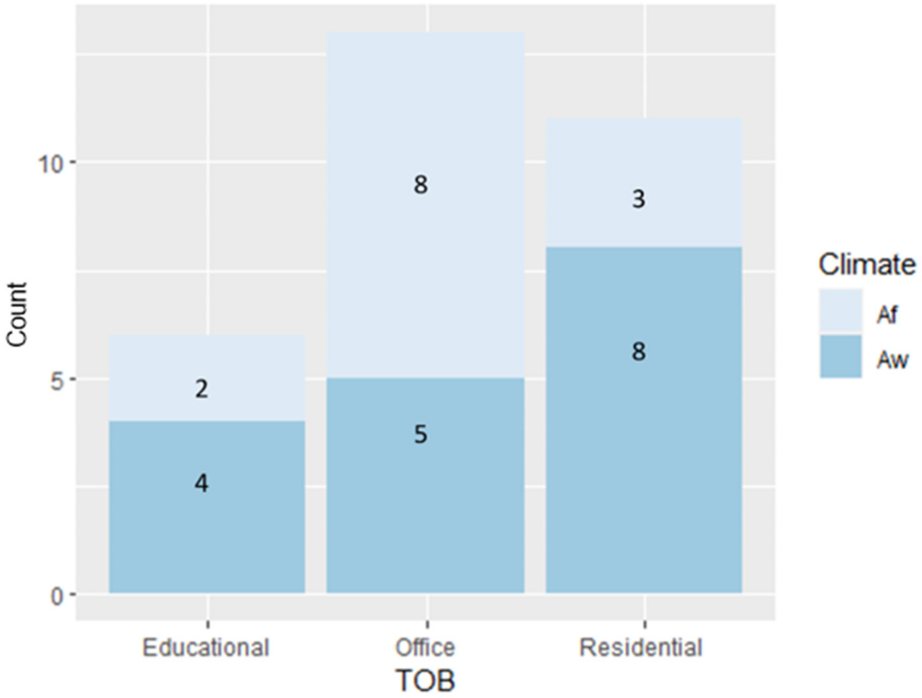


Figure 8. Building types presented in the studies found.

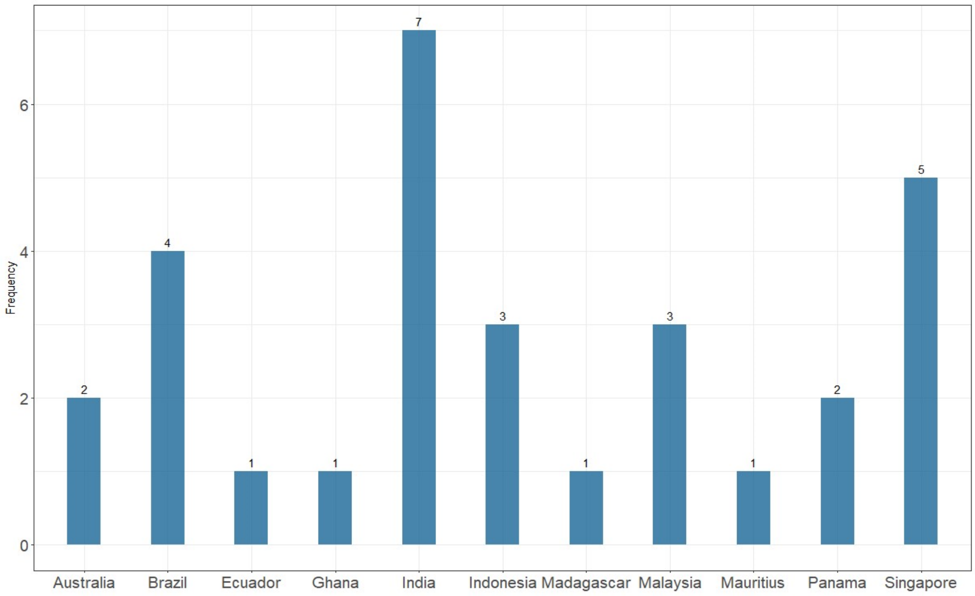


Figure 9. Countries represented in the studies found.

Different purposes were found for carrying out a retrofit analysis, and it was determined that the main reason was to achieve energy savings, followed by savings directly in cooling demand since it is widely used given climatic conditions. Some studies considered thermal comfort and achieving a net-zero energy building (NZEB) (Figure 10).

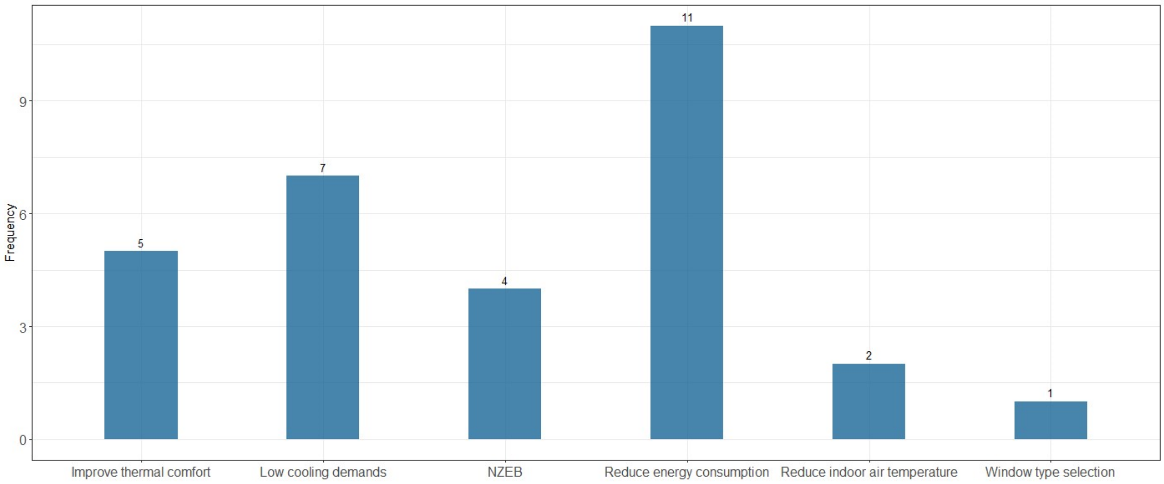


Figure 10. Purposes of energy retrofits.

Moreover, passive strategies remained crucial in office buildings within both climate types. Residential buildings implemented a mix of passive and active strategies, while educational buildings mostly relied on passive strategies and predominantly implemented passive approaches.

The reviewed research utilized three classification approaches including simulation, experimental, and in situ measures. Most studies utilized simulation approaches, especially for passive strategies. Some studies incorporated in situ measures, such as implementing changes to enhance building performance without structural alterations, while only one study used experimental approaches (Table A1).

Although the simulation approach was efficient in experimental validation and achieving better results, an emerging trend showed some studies applied in situ measures. This area presents a potential for further exploration, with resource availability influencing a shift towards more in situ approaches than experimental ones because it provides insights directly relevant to real-life situations and circumstances. Such insights are invaluable for guiding decision-making across industries, governments, and other practical domains and the impact of scientific research.

Various retrofit strategies were applied in residential and office buildings, including phase change materials, roof cover, daylight control, and WWR. Educational buildings did not implement phase change material strategies; instead, educational buildings focused on HVAC system replacement, shading devices, and shading with trees, while office buildings predominantly used wall insulation and photovoltaic strategies. Similarly, several strategies were applied in office buildings, including glazing enhancements, insulation additions, solar protection, shading devices, and advanced window technologies. Several authors [77] proposed solutions to reduce material consumption in residential buildings. However, there is a notable absence of retrofit strategies for office and educational buildings compared with other types of structures, indicating a potential area for application. Authors such as [78] advocate for an active strategy involving PV (photovoltaic), defined as bidirectional reflectance PV (BRPV), to address this gap. They evaluated its performance in a school building, which saw an increase in efficiency from 34.1% to 65.8%. Additionally, Historical or Heritage Buildings and institutional structures should be studied more.

Within the strategies with the best performance, the following were found: air conditioning (AC) set point, appliance replacement with more efficient ones, cooling operating schedule daylighting control and solar protection for windows, double and triple glazing, envelope insulation (which involves wall insulation, roof insulation), HVAC system improvement, natural ventilation, phase change material (PCMs), photovoltaic (PV) systems, and Window-to-Wall ratio improvement, keeping it in the optimal range (20–40%)

according to the literature [46]. According to the outcomes, envelope insulation (for windows, walls, or roofs) corresponds to the most common strategy with the best result in terms of energy saving, as shown in Figure 11. Natural ventilation was barely studied; however, the conclusion of the few investigations suggests that natural ventilation is not enough to provide optimal thermal comfort by itself. Despite passive strategies such as envelope insulation or ventilation, some authors pointed out that excessive envelope insulation combined with insufficient ventilation are primary factors contributing to fungal growth in energy-efficient buildings [79].

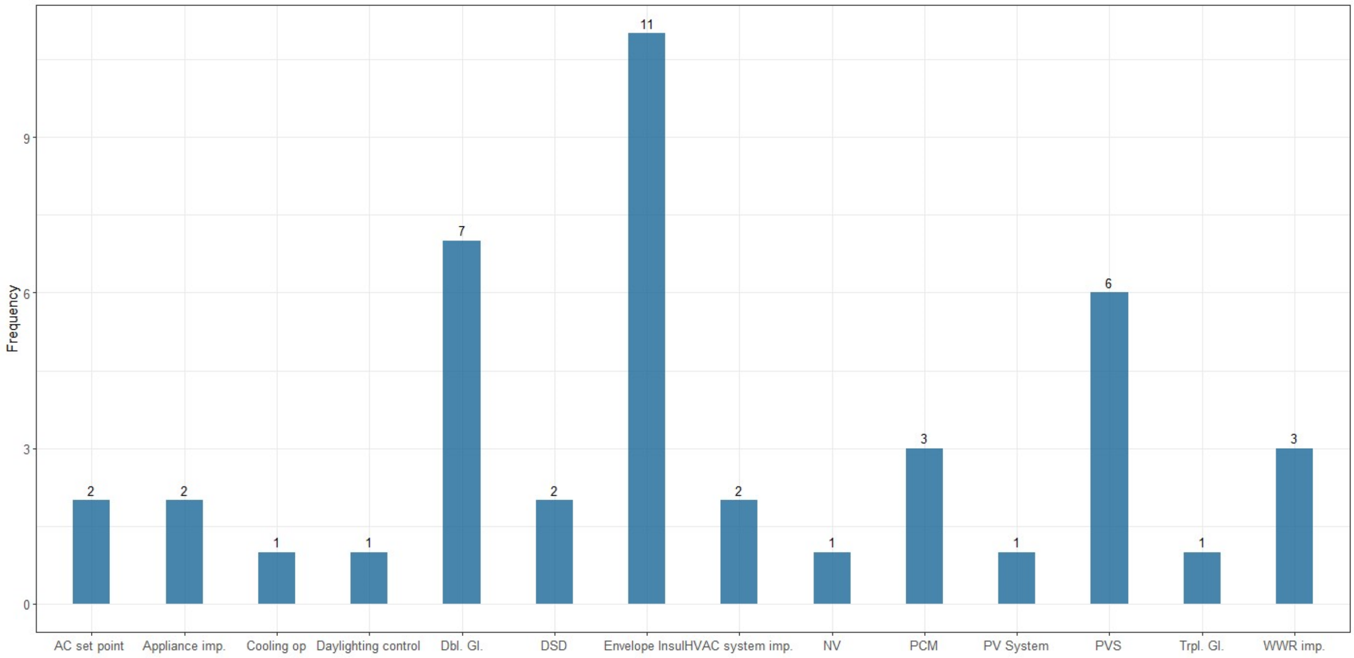


Figure 11. Strategies with the best performance within the studies found.

Most studies did not present specific cost analyses for retrofit strategies, with a few studies offering global value ranges, indicating a need for baseline values according to climate types. Higher upfront costs were highlighted as a challenge in retrofit techniques [77]. Additionally, the cost-optimal methodology should undergo cost-optimal calculations every five years to validate and subsequently revise existing national requirements. The examination of Member States' advancements in implementing this methodology suggests an overall positive trend in development [80].

Passive strategies have been widely used, yet it is evident that these strategies are not universally applicable across different building types. This highlights the opportunity to categorize and implement measures specific to each building type, thus improving strategies customized for specific building types. Educational and office buildings have yet to be studied, thus representing further research opportunities. Combined measures could enhance the cost-effectiveness of building energy retrofits. A study provided a practical framework for decision-making on energy retrofits, emphasizing the importance of comprehensive guidelines for city renewal, particularly in institutional buildings [81].

Compared with a wider range of retrofit studies and experiences in other climates, the literature indicated insufficient guidance and information on existing housing stock in the U.K. to support realistic plans for reducing carbon emissions [82]. Retrofit measures primarily focused on building envelopes, HVAC systems, lighting, and photovoltaic systems. Financial barriers, lack of standards, and regulatory support were key challenges in evaluating retrofit measures [83].

Other technical approaches to energy-efficient building retrofits included law regulation, financial incentives, and practical considerations (performance-based architectural design) [84]. The current mandatory building energy regulations in certain regions (e.g., the hot summer–cold winter region of China) were deemed insufficient to achieve significantly lower carbon emissions, suggesting the need for more ambitious regulations [85]. Opportunities for achieving nearly zero-energy buildings (nZEB) and enhancing energy efficiency in tropical climates were highlighted as part of the retrofit opportunities [86].

5. Conclusions

This research extensively reviewed and synthesized the existing literature on retrofitting strategies for buildings in tropical and humid climates. The main aim was to outline efficient approaches to improving energy efficiency, thermal comfort, and the overall performance of buildings in these geographic zones.

This study examined tropical climates, emphasizing Af (Tropical Rainforest Climate) and Aw (Tropical Savanna Climate) as the primary categories according to the Köppen climate classification. Across these classifications, this research highlighted varying focuses, revealing a bias towards office buildings in Af climates, whereas Aw climates strongly emphasized residential structures.

In office buildings in both climate types, passive strategies retained paramount importance. Conversely, a mix of passive and active approaches was employed in residential buildings, while the approaches in educational structures leaned towards passive strategies. This study reviewed three classification methodologies including simulation, experimental, and in situ measures, with simulation predominantly used, particularly for passive strategies. An intriguing emerging trend showed the budding application of in situ measures, hinting at potential exploration avenues.

Retrofit strategies varied significantly across building types, with offices leading in strategy implementation and residences and educational buildings, where strategies were relatively scant. Notably, educational structures lacked retrofit strategies compared with other building types, illuminating an area for extensive study and potential application. The absence of specific cost values for retrofit strategies underscored the need for baseline values, with high initial costs identified as a significant challenge in retrofit techniques.

In conclusion, research into retrofitting buildings in tropical and humid climates has primarily emphasized passive strategies. However, there is a noticeable gap in integrating active methods or blending both approaches, particularly in educational buildings. This highlights promising opportunities for further exploration and advancement. Utilizing a combination of measures could significantly enhance the cost-effectiveness of building energy retrofits, emphasizing the importance of comprehensive guidelines, especially in institutional buildings. The literature reveals significant shortcomings in guidance for reducing carbon emissions, indicating a pressing need for more ambitious regulations. This underscores the potential for achieving nearly zero-energy buildings and improving energy efficiency in tropical climates through retrofit opportunities.

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Abbreviations

Acronym	**Definition**
AC	air conditioning
Af	Tropical Rainforest Climate
Aw	Tropical Savanna Climate
BIPV	building-integrated photovoltaic
BRPV	bidirectional reflectance PV
CAPEX	capital expenditure
CBA	Cost–Benefit Analysis
DGC	Dynamic Generation Cost
EG	energy generation
EPBD	Energy Performance of Buildings Directive
EPS	expanded polystyrene
EUI	Energy Use Intensity
FC	fuel cost
FSPCM	form stable PCM
GHG	greenhouse gas
GP	Gaussian Process
GWP	global warming potential
HATCS	hybrid air treatment cooling system
HVAC	heating, ventilation, and air conditioning.
IEA	International Energy Agency
LCC	life cycle cost
LCOE	Levelized Cost of Energy
Mtoe	megatonne oil equivalent
NZEB	net-zero energy building
nZEB	nearly zero energy building
OM	operating maintenance
OTTV	overall thermal transfer value
PCMs	phase change materials
PMV	predicted mean vote
PV	photovoltaic
TC	tax cost
TCT	thermal comfort time
VSA	vertical shadow angle (VSA)
WOEA	window opening effective area
WWR	Window-to-Wall Ratio

Appendix A

Table A1 displays information on countries, climates, project types, building types, costs, energy generation, and U-values, particularly focusing on studies that applied retrofit strategies.

Table A1. Type of project and economics studies in tropical climate.

City, Country	Climate Type	Type of Strategy	Building Typology	Type of Project	Cost	Energy Generation kWh/m^2 y	U (W m^{-2} K^{-1}) Conventional or Original					U (W m^{-2} K^{-1}) Improved					Year	Ref.
							Walls	Windows	Titles	Roof	Glazing	Walls	Windows	Titles	Roof	Glazing		
Bamako, Mali; Bangalore, India; Kolkata, India; Dar es Salaam, Tanzania	Aw	Passive	Residential	Simulation	-	-	-	-	-	-	-	-	-	-	-	-	2019	[59]
Bangalore, India	Aw	Passive	Office	Simulation	-	108.02	0.46	-	-	-		0.46	-	-	-	-	2023	[69]
Chennai, India	Aw	Passive	Educational	Simulation	-	-	2.13	5.77	3.20	-	-	0.85	3	0.20	-	-	2023	[44]
Chennai, India	Aw	Passive	Office	Simulation	64 USD/m^2	-	-	-	-	-	-	-	-	-	-	-	2022	[46]
Darwin, Australia	Aw	Passive	Residential	Simulation	106 USD/m^2	-	-	-	-	-	-	-	-	-	-	-	2022	[61]
Darwin, Australia	Aw	Passive	Residential	Simulation	-	-	-	-	-	-	-	-	-	-	-	-	2022	[63]
Ecuador	Aw	Passive	Educational	Simulation	USD 3200	61.65	-	-	-	-	-	-	-	-	-	-	2021	[56]
Ghana	Aw	Passive	Residential	Simulation	USD 6,484.53	68.4-78.43	-	-	-	-	-	-	-	-	-	-	2022	[67]
Indonesia	Af	Passive	Educational	Simulation	-	-	3.56	5.6				-	-	-	-	-	2023	[51]
Indonesia	Af	Passive	Educational		-	-	-	-	-	-	-	-	-	-	-	-	2020	[55]
Madagascar	Af	Passive	Office	Simulation	-	-	2.62			2.01		-	-	-	-	-	2020	[62]
Malaysia	Af	Passive	Residential	In situ measures	3.6 USD/m^2	-	-	-	-	-	-	-	-	-	-	-	2020	[64]
Malaysia	Af	Passive	Residential	Simulation			1.3.				6.12	-	-	-	-	-	2021	[60]
Malaysia	Af	Passive	Office	Simulation	79.70 USD/m^2	-		7.3				-	2.1	-	-	-	2022	[48]
Mauritius	Aw	Passive	Office	Simulation						2.2.04		-	-	-	-	-	2023	[70]
Mumbai, India	Aw	Passive	Educational	Simulation	-	-	2.85	2.36		2.86		-	-	-	-	-	2022	[67]
Mumbai, India	Aw	Passive	Educational	Simulation	-	-	2.85	2.36		2.85		0.1	0.5	0.1		-	2022	[58]
Panamá		Passive	Residential	Simulation		330.87	-	-	-	-	-	-	-	-	-	-	2022	[68]
Rio de Janeiro, Brazil	Aw	Passive	Office	Simulation	-	-	-	-	-	-	-	-	-	-	-	-	2021	[45]

Sao Paulo, Brazil	Af	Active	Office	Simulation	-	-	2.38	5.8	-	-	-	2.8	2.8	-	-	-	2020	[49]
Singapore	Af	Passive	Office	Simulation			-	4.8	-	-	-	-	-	-	4.1	-	2019	[78]
Singapore	Af	Passive	Office	In situ measures	-	-	-	4.96	-	-	-	-	4.1	-	-	-	2020	[52]
Singapore	Af	Active	Office	Simulation and in situ measures	-	-	-	5.649	-	-	-	-	1.998	-	-	-	2020	[50]
Singapore	Af	Active	Residential	Simulation	-	-	-	-	-	-	-	-	-	-	-	-	2019	[66]
Singapore; Miami, USA; Darwin, Australia	Af	Active	Office	Experimental and simulation	-	-	-	-	-	-	-	-	-	-	-	-	2019	[65]

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