Tinjauan Literatur Sistematis Praktik Pendinginan Aktif Level Bangunan di Negara Iklim Tropis

A Systematized Literature Review On Building-Level Active Cooling Practices In Tropical Climate Countries

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Abstrak

Kajian analisis sistematis terhadap praktik dan inovasi teknologi pada sistem pendinginan aktif bangunan di kawasan tropis, dengan menekankan strategi integratif yang mendukung efisiensi energi dan keberlanjutan jangka panjang. Seleksi artikel dilakukan menggunakan protokol PRISMA pada basis data Scopus dengan kata kunci “air conditioning” dan “tropical,” menghasilkan 25 artikel terakreditasi yang diterbitkan antara tahun 2019 hingga 2025. Analisis tematik dilakukan untuk mengklasifikasikan temuan ke dalam empat domain strategis: peningkatan efisiensi sistem pendingin aktif, penerapan strategi desain pasif, substitusi teknologi konvensional dengan alternatif berenergi rendah, serta integrasi sumber energi terbarukan, khususnya sistem fotovoltaik. Sebagai sintesis dari keempat tema tersebut, studi ini mengusulkan Green Building Cooling Policy Model (GBCPM)—sebuah kerangka konseptual yang mengaitkan dimensi teknis, arsitektural, dan kebijakan dalam praktik pendinginan bangunan di iklim tropis. Model ini berfungsi sebagai alat perencanaan adaptif yang mendukung pencapaian target bangunan *net-zero energi* di wilayah dengan potensi iradiasi matahari yang tinggi. Tinjauan ini memberikan kontribusi teoritis dan aplikatif bagi pengembangan kebijakan pendinginan berkelanjutan di negara tropis dan kawasan beriklim serupa.

Kata kunci: bangunan tropis; efisiensi energi; integrasi fotovoltaik; kebijakan berkelanjutan; pendinginan aktif

Abstract

This review presents a systematic analysis of practices and technological innovations in active cooling systems for buildings in tropical regions, emphasizing integrative strategies that support energy efficiency and long-term sustainability. Article selection was conducted using the PRISMA protocol in the Scopus database with the keywords “air conditioning” and “tropical,” resulting in 25 peer-reviewed articles published between 2019 and 2025. A thematic analysis was applied to classify findings into four strategic domains: enhancing the efficiency of active cooling systems, applying passive design strategies, substituting conventional technologies with low-energy alternatives, and integrating renewable energy sources, particularly photovoltaic systems. As a synthesis of these themes, this study proposes the Green Building Cooling Policy Model (GBCPM)—a conceptual framework that links technical, architectural, and policy dimensions of building-level cooling practices in tropical climates. The model serves as an adaptive planning tool for achieving net-zero energy goals, especially in regions with high solar irradiation. This review contributes to the theoretical understanding and policy development of sustainable cooling systems in the Global South and similar climate zones.

***Keywords**: active cooling; energy efficiency; photovoltaic integration; sustainable policy; tropical building*

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Introduction

The significant rise in global temperatures over the past decade has intensified the demand for more reliable indoor cooling technologies, particularly in tropical countries. These regions experience inherently high baseline temperatures and face additional challenges due to climate change, which has increased the frequency and intensity of heatwaves (Byrne, 2021; Zhang et al., 2022). Consequently, the need for active cooling systems has become more urgent, especially to support thermal comfort in densely populated residential areas and public spaces.

Active cooling, which involves heat exchange mechanisms through external thermal systems such as compression-based air conditioning and heat pump systems, has emerged as the primary solution in this context (Gong et al., 2022; Suwal & Ramaswamy, 2022). While these technologies offer rapid and controllable cooling effects, their use presents special issues related to increased energy consumption and carbon emissions—particularly in tropical regions where cooling demand persists year-round (UNEP & IEA, 2020).

Various studies have investigated strategies to improve the efficiency of cooling systems, integrate active and passive approaches, and replace conventional systems with low-emission technologies to reduce energy impact (Nguyen et al., 2022; Khan et al., 2022). Enhancing air conditioning efficiency, for instance, has been achieved through the integration of thermal energy storage (TES) systems (Santos et al., 2024) and the application of IoT-based controls (Ali et al., 2019). On the other hand, passive design elements—such as optimal building orientation, the use of high-insulation materials, and façade vegetation—have proven effective in reducing thermal loads (Arminda et al., 2022; Tablada & Kosoriv, 2021).

Substitutive solutions such as seawater air conditioning (SWAC), ground source heat pumps (GSHP), and solar-powered cooling systems are also being developed as more sustainable long-term approaches (Sanjivy et al., 2023; Morais et al., 2020; Mat Wajid et al., 2021). Although these studies provide valuable technical insights, to date there has been no systematic literature review that comprehensively evaluates active cooling practices in tropical countries from technical, policy, and socio-ecological perspectives.

This study addresses that gap by presenting a systematic review of the 25 most relevant and up-to-date scholarly publications (2019–2025), identified through a Scopus database search using the keywords “air conditioning” and “tropical.” Articles were selected based on strict criteria, including study region, thematic relevance, and the contextual applicability to tropical buildings.

The uniqueness of this study lies in its integrative approach—not only synthesizing technical strategies for enhancing the efficiency of active cooling systems but also examining socio-economic contexts, such as disparities in technology adoption across social classes (Pavanello et al., 2021), and analyzing policies and regulations that influence the direction of environmentally friendly technology adoption (Gross et al., 2021; Cardenas-Rangel et al., 2022). As such, this research not only enriches the academic literature but also offers conceptual and practical contributions to the development of sustainable and inclusive active cooling strategies for tropical countries.

Methods

This study employed a systematic literature review (SLR) approach to identify and analyze current trends and practices in active cooling systems at the building level within tropical regions. The systematic procedure followed principles outlined by Fink (2019) and adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) reporting framework to enhance the transparency and reproducibility of the study selection process.

The literature search was conducted using the Scopus database by applying filters to titles, abstracts, and keywords with the phrase "air conditioning" AND "tropical." The term air conditioning was selected, as it represents the most commonly used concept for active cooling in global scientific literature. The inclusion criteria were defined as follows: (1) articles that are written in English, (2) articles published in peer-reviewed journals between 2019 and February 17, 2025, and (3) articles that explicitly examine active cooling practices in buildings located in tropical climate regions.

Exclusion criteria included (1) studies conducted outside the tropical climate context, (2) research focused on non-building domains (e.g., vehicles or transportation systems), (3) duplicate articles, and (4) publications that did not provide relevant technical or policy-related information concerning active cooling systems.

An initial search yielded 167 articles that met the basic inclusion criteria. Through a multi-stage screening process involving abstract and full-text evaluations, 142 articles were excluded due to lack of relevance to tropical contexts or building-related focus. This rigorous filtering resulted in 25 articles deemed most relevant and informative for in-depth analysis. The article selection process is illustrated in the PRISMA flow diagram below (Figure 1). The use of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework enhances the transparency and reproducibility of the review methodology, in line with established standards for systematic literature reviews (Page et al., 2021).

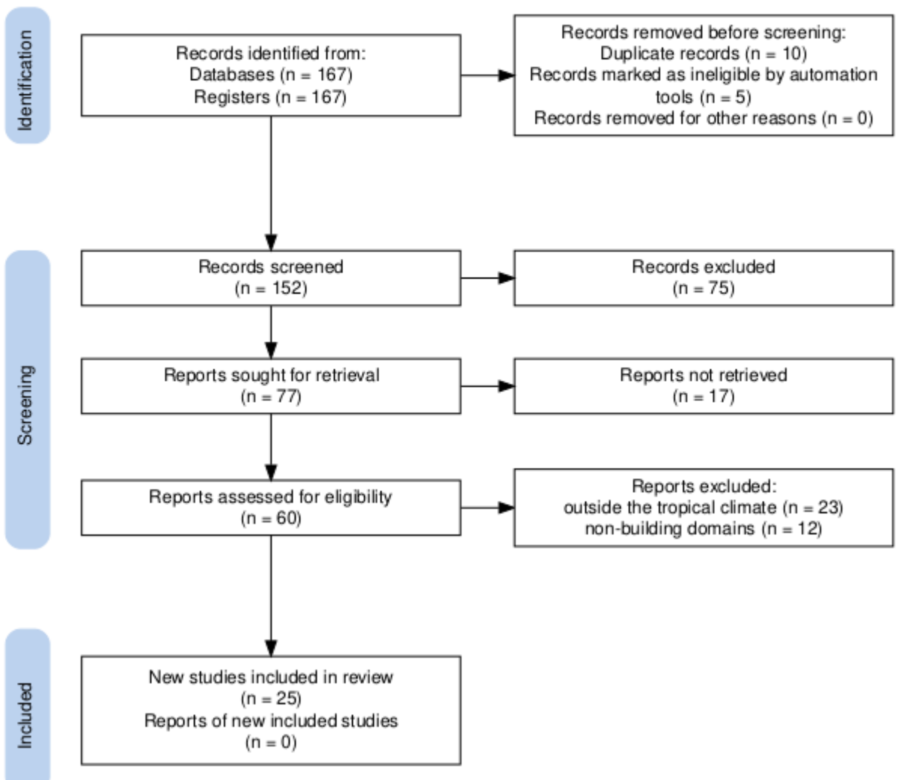

Figure 1. PRISMA Flow Diagram of Study Selection Process

The analysis was conducted using a thematic approach to identify patterns, strategies, and challenges in the implementation of active cooling in tropical buildings. Each article was examined based on its contribution to three key aspects: (1) the efficiency of active cooling systems, (2) the integration of passive approaches to reduce active load, and (3) the policy and socio-ecological implications of cooling technologies. Given the selective number of articles included, this study prioritizes analytical depth and topical relevance over the sheer quantity of publications reviewed.

Results and Discussion

A total of 25 selected articles were thematically analyzed, resulting in four main categories in the development of active cooling systems in tropical regions: (1) Efficiency of Active Systems, (2) Passive Cooling Strategies, (3) Substitution of Conventional Technologies, and (4) Social and Policy Implications. These categories were derived based on the patterns of approaches, technical outcomes, and policy contributions identified across the studies. Table 1 summarizes the reviewed articles.

Table 1. Review of Literature on Active Cooling Studies in Tropical Regions

No.	Author(s) & Year	Study Location	Topic	Policy Implications / Key Findings
1	Sanjivy et al. (2023)	French Polynesia	SWAC system performance	CO_2 emissions limited to 225 tons/year; 30× more efficient than conventional AC.
2	Pavanello et al. (2021)	Brazil, India, Indonesia, Mexico	Income and AC adoption	Projected 16× increase in AC adoption by 2040; persistent inequality in thermal comfort access.
3	Santos et al. (2024)	Brazil	TES and cooling system integration	Up to 10.6% energy savings; policy incentives needed for adoption of energy-efficient technologies.
4	Mat Wajid et al. (2021)	Malaysia	Solar adsorption cooling system (SADCS)	Potential alternative to compression AC; achieves 20°C and 60% RH.
5	Carpino et al. (2024)	Panama	NZEB simulation in tropics	PV sizing, cooling schedules, and set-point temperatures are critical success factors.
6	Nguyen et al. (2022)	Vietnam	Eutectic PCM for buildings	PCM + drop ceiling delays peak temperature by 4 hours; efficient in humid climates.
7	Li et al. (2024)	Singapore	Radiant cooling systems	Saves up to 34% energy compared to air-based systems; suitable for tropical conditions.
8	Lucchi (2024)	Malaysia	Museum energy efficiency	Lighting and cooling design are vital for energy performance and conservation.
9	Chung-Camargo et al. (2024)	Panama	Tropical retrofit strategies	Different strategies required for rainforest vs. savannah zones.
10	Byrne et al. (2020)	Indonesia	PCM for solar-powered AC	Coconut oil-based PCM with 16°C fusion temp suitable for net-zero energy AC systems.

No.	Author(s) & Year	Study Location	Topic	Policy Implications / Key Findings
11	Nyembwe et al. (2023)	Africa, Asia, South America	Thermal quality in tropical hospitals	Tropical hospitals require regulatory design standards for comfort and health.
12	Ramirez-Leon et al. (2023)	Caribbean	Fan speed control in AC	Fan speed modulation leads to 10% energy savings.
13	De Leon et al. (2023)	Panama	Net-zero energy districts	Active-passive integration essential in NZED design.
14	Tsai & Tsai (2022)	Taiwan	Green building materials	Mandatory regulation needed for high-insulation products.
15	Haida et al. (2021)	Tropical (unspecified)	R744 vapor compression with ejector	Efficient, but requires pressure control strategies to prevent instability.
16	Veanti et al. (2022)	Indonesia	Future AC energy demand	Significant demand increase projected due to climate change.
17	Arminda et al. (2022)	Malaysia	POFA-based alternative concrete	Indoor temp reduced by up to 5.69°C; 32.8% energy savings.
18	Ramapragada et al. (2022)	India	Residential AC energy consumption	Night-time AC use increases household energy by 650 kWh annually.
19	Karthick et al. (2023)	Chennai, India	Orientation and shading design	Cooling loads reduced by up to 35.9% using passive strategies.
20	Rawat & Singh (2022)	Tropical Asia (review)	Cool roof effectiveness	Cooling load reduction ranges from 7.5% to 54%.
21	Izadpanah et al. (2023)	Iran (dry-tropical)	Active-passive façade combination	Significant cooling load reduction in dry tropical climates.
22	Tablada & Kosoriv (2021)	Singapore	Vertical façade farming	Reduces AC demand while enhancing urban food resilience.
23	Cruz & Cunha (2022)	Brazil	Wall systems under global warming	Increased AC needs for SCIP and ICF wall systems.
24	Widiatmojo et al. (2021)	Thailand & Vietnam	Ground-source heat pumps (GSHP)	GSHP outperforms ASHP with 33% energy savings.
25	Morais et al. (2020)	Brasília, Brazil	Shallow geothermal energy	Effectiveness highly dependent on local soil thermal properties.

(Source : writer's analyses study, 2025)

1. Efficiency of Active Systems

Eight studies focused on enhancing the efficiency of active cooling systems in tropical contexts. Santos et al. (2024) integrated thermal energy storage (TES) into cooling systems in Brazil, achieving energy savings of up to 10.6%. Ramirez-Leon et al. (2023) emphasized fan speed regulation as an energy-saving strategy in the Caribbean. Haida et al. (2021) evaluated a two-phase ejector R744 vapor compression system, which showed high efficiency but remains challenged by pressure control instability.

Li et al. (2024) developed a radiative cooling system in Singapore, reporting energy savings of up to 34% compared to air-based systems. In Malaysia, Mat Wajid et al. (2021) explored the potential of a solar adsorption cooling system (SADCS), capable of maintaining thermal comfort without direct emissions. Byrne et al. (2020) assessed the use of coconut oil-based phase change materials (PCM) for solar-powered air conditioning in Indonesia. Both Widiatmojo et al. (2021) and Morais et al. (2020) demonstrated that ground-source heat pump (GSHP) systems significantly outperform air-source heat pumps (ASHP) and conventional AC units in terms of energy efficiency.

2. Passive Cooling Strategies

Seven studies explored passive cooling strategies aimed at reducing the load on active systems. Karthick et al. (2023) assessed the effectiveness of building orientation and shading techniques in India, achieving up to a 35.9% reduction in cooling loads. Arminda et al. (2022) evaluated the use of concrete incorporating palm oil fuel ash (POFA), which reduced indoor temperatures by as much as 5.69°C and saved up to 32.8% in energy consumption.

Nguyen et al. (2022) demonstrated that the application of eutectic phase change materials (PCM) in roofing could delay peak temperatures by four hours in humid climates. Rawat and Singh (2022) synthesized findings across tropical Asia, reporting cooling load reductions ranging from 7.5% to 54% through the use of cool roofs. Izadpanah et al. (2023) showed that combining active and passive façade systems was particularly effective in dry tropical climates.

Tablada and Kosoriv (2021) introduced a vertical façade farming concept, which reduced air conditioning demand and contributed to urban food resilience. Lucchi (2024) emphasized the importance of efficient lighting and cooling systems in enhancing energy conservation in museum buildings.

3. Substituting conventional technologies

Five studies investigated the replacement of conventional air conditioning systems with low-energy alternative technologies. Sanjivy et al. (2023) tested a seawater air conditioning (SWAC) system in French Polynesia, demonstrating an efficiency up to 30 times higher than traditional AC units, with significantly lower CO_2 emissions. Mat Wajid et al. (2021) evaluated solar adsorption cooling systems (SADCS) as a non-compression-based solution suitable for tropical applications.

Li et al. (2024) and Byrne et al. (2020) also contributed to this category by developing alternative low-carbon cooling systems—radiative cooling and solar-powered phase change material (PCM)-based air conditioning, respectively. Furthermore, Widiatmojo et al. (2021) and Morais et al. (2020) point out the potential of ground-source heat pumps (GSHP) to replace conventional systems, particularly in regions where soil thermal properties are favorable.

4. Social and Policy Implications

Five studies explicitly addressed policy-related issues and social disparities in the adoption of cooling systems. Pavanello et al. (2021) demonstrated that income levels and geographic location significantly influence access to thermal comfort, projecting up to a 16-fold increase in air conditioner adoption by 2040, with persistent inequality in access. Nyembwe et al. (2023) pointed out the importance of regulatory frameworks in tropical hospital design to ensure compliance with thermal comfort and health standards.

Tsai and Tsai (2022) advocated for mandatory regulations on the use of high-insulation building materials. De Leon et al. (2023) and Carpino et al. (2024) examined net-zero energy district designs, stressing the importance of integrating active-passive strategies and self-sufficient energy systems based on photovoltaic (PV) generation.

Among the 25 studies analyzed in this review, eight focused on improving the efficiency of active systems, seven discussed passive cooling strategies, five explored the substitution of conventional technologies, and five examined the social and policy dimensions of cooling adoption. This distribution indicates that approaches to active cooling in tropical regions are inherently multidimensional, reflecting the interconnection between technology, building design, and socio-economic context.

Figure 2 visualizes the proportion of studies in each thematic category. The graph shows that research on active system efficiency dominates the discourse, followed by passive strategies, with the other two categories represented more evenly. This trend reflects the growing tendency in recent literature to adopt an integrative perspective, combining technical and non-technical dimensions to support the development of sustainable and climate-resilient buildings in tropical regions.

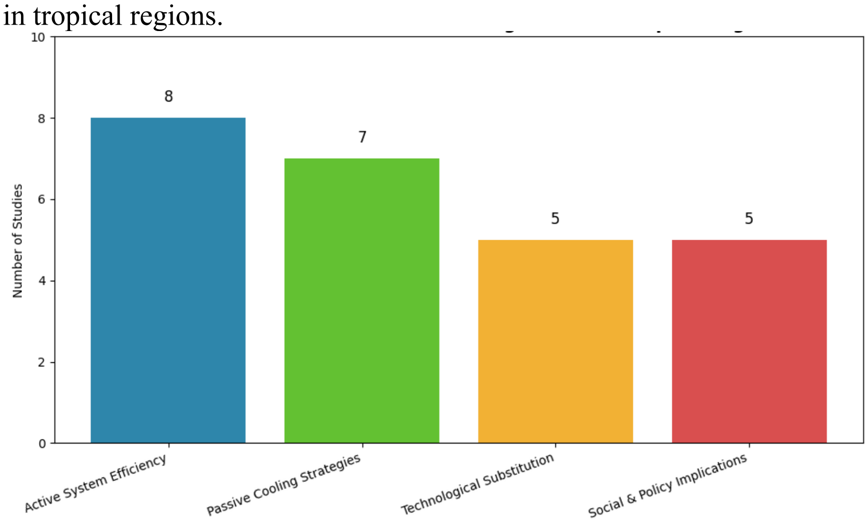

Figure 2. Thematic Distribution of Reviewed Studies on Active Cooling in Tropical Buildings

5. Green Building Cooling Policy Model (GBCPM)

As a synthesis of 25 thematically analyzed articles, this study proposes the Green Building Cooling Policy Model (GBCPM) as a comprehensive conceptual framework to support the management of cooling systems in buildings located in tropical regions. The model is designed to bridge technical findings and policy discourse to establish adaptive, efficient, and renewable energy–based cooling systems. GBCPM integrates a range of strategies identified in previous studies, including the enhancement of active system efficiency, application of passive design strategies, substitution of conventional technologies, and integration of renewable energy sources to support the achievement of net-zero carbon buildings.

The model begins with the identification of thermal conditions in buildings, which includes heat load mapping, space-use intensity analysis, indoor air quality assessment, and thermal comfort evaluation. This stage is essential for determining specific and context-sensitive cooling requirements. Based on this information, strategies for improving active system efficiency can be implemented using technologies such as thermal energy storage, inverter-based thermostats, R744 ejector refrigeration systems, and comfort surveys to guide operational adjustments.

Subsequently, passive elements such as building orientation, high-insulation materials, natural ventilation systems, cool roofs, vernacular design principles, and vertical vegetation play a crucial role in significantly reducing active cooling loads. These approaches are reinforced through the substitution of conventional cooling systems with low-energy, environmentally friendly technologies, including ground source heat pumps (GSHP), seawater air conditioning (SWAC), solar adsorption cooling systems (SADCS), and radiant cooling systems. Geographic conditions, local resource availability, and building typologies tailor the deployment of these technologies.

As a final component, GBCPM emphasizes the importance of integrating photovoltaic (PV)-based energy systems as autonomous energy sources. This strategy aims to achieve net-zero energy buildings in tropical areas with high solar irradiation potential. In this way, GBCPM serves as an adaptive framework that is not only technical in nature but also considers social, ecological, and policy dimensions in supporting the transition toward sustainable cooling systems. A visual representation of the model is provided in Figure 2, illustrating the interconnection between thermal condition assessment, technical interventions, and the achievement of PV-based energy autonomy as a unified system.

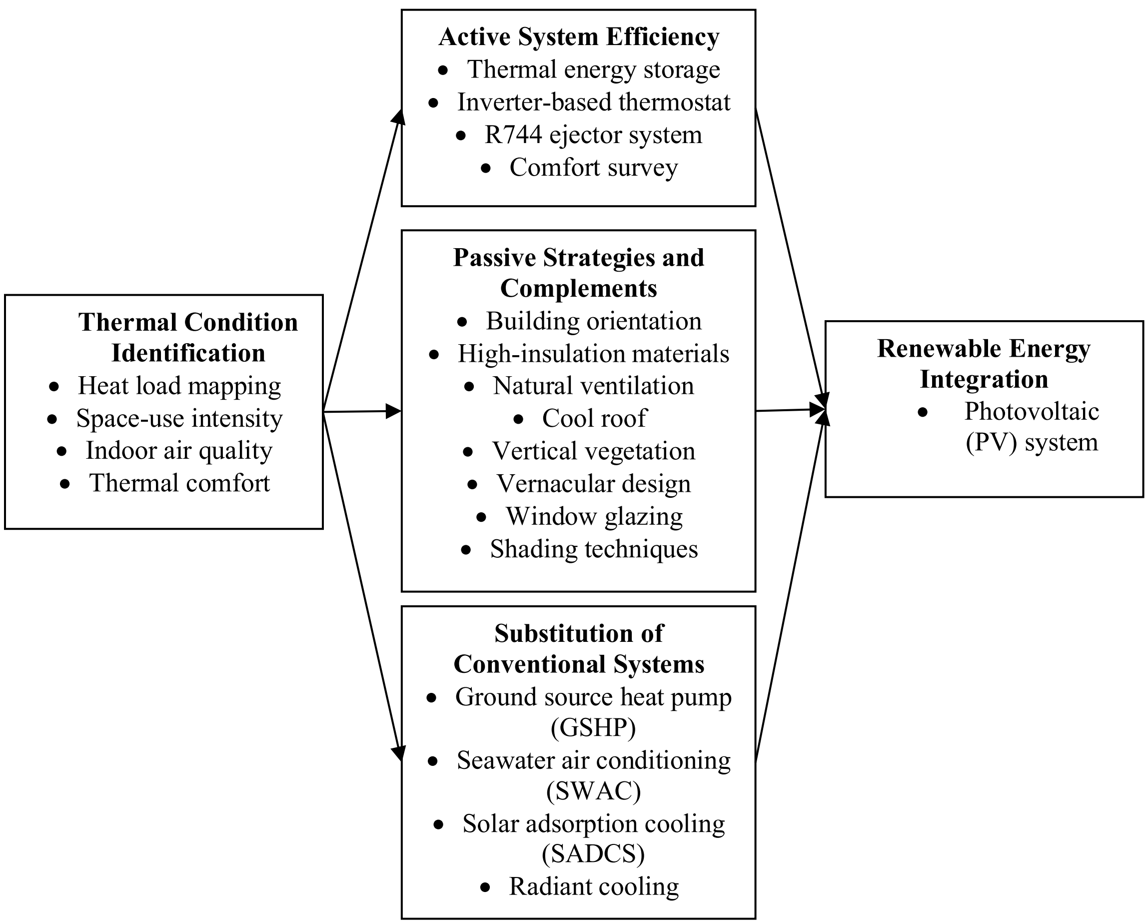

Figure 3. The Green Building Cooling Policy Model (GBCPM)

Conclusion

This study presents a systematic literature review on active cooling technologies and strategies in tropical regions, following a PRISMA-based protocol to ensure contextual relevance to building-level applications. The review maps the current landscape of research across four thematic areas: the efficiency of active cooling systems, passive cooling strategies, substitution of conventional technologies with low-energy alternatives, and the integration of renewable energy sources to support thermal comfort and sustainability in tropical buildings.

Through thematic synthesis, the study proposes the Green Building Cooling Policy Model (GBCPM), a comprehensive conceptual framework that integrates technical, environmental, and policy insights into an adaptive model for planning and managing sustainable cooling systems. GBCPM outlines a four-stage process: identifying building-specific thermal conditions, enhancing the performance of active cooling systems, implementing passive and substitution-based strategies, and integrating photovoltaic energy systems to support the realization of net-zero energy buildings in tropical contexts. This model emphasizes not only technological solutions but also the alignment of cooling interventions with socio-climatic realities, urban typologies, and long-term sustainability goals.

The findings contribute to the theoretical and practical discourse on sustainable building practices in tropical regions by highlighting how different strategies such as technological, architectural, and policy-driven can be synergistically combined. Furthermore, the model offers guidance for policymakers, architects, and energy planners to develop targeted interventions, technical standards, and incentive frameworks that promote efficient and inclusive cooling infrastructure.

However, the study acknowledges two key limitations. First, the use of limited search terms may have excluded relevant studies that used different terminology for active cooling. Second, by focusing exclusively on English-language peer-reviewed journals, the review may have omitted significant findings from local publications or grey literature. Future research is recommended to broaden both linguistic and database coverage and to further validate the GBCPM framework through empirical studies and regional case applications across diverse tropical settings.

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