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Envelope design for low-energy buildings in the tropics: A review

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ABSTRACT

The building sector accounts for over one-third of global energy consumption and a significant share of carbon emissions. Improving building energy efficiency, particularly in the tropics, where most of the future development is foreseen, is thus crucial. One of the main factors that determine building energy performance is the building envelope. This paper presents a comprehensive review of the impact of several envelope design variables, such as thermal, optical, physical, and geometrical, on the energy performance of buildings in the tropics.

A correlational analysis that elaborates on the effectiveness of each of these measures is discussed in detail. The findings indicate that insulation, glazing properties, and Window-to-wall ratio (WWR) are promising solutions for improving energy efficiency in tropical buildings. Among these, insulating the building envelope has the most significant impact on energy savings. The variables of building orientation and the thermal mass of building materials have the least influence on total energy consumption. The latter exhibits complex effects in regions characterized by hot-humid climates. An optimized design in cooling-dominated climates should have a large aspect ratio, a higher WWR in the north and south facades, and an ideal shading system. With all variables combined and appropriate ventilation, a building can save 35% of annual energy and up to 60% in some cases. This study further reveals that available research on the effect of building shape and the context of surrounding built environment on energy consumption remains limited.

1. Introduction

According to the United Nations Framework Convention on Climate Change (UNFCC), addressing building energy efficiency for emission reductions is essential to attaining the goals of the Paris Agreement [1]. COP 26 (2021 United Nations Climate Change Conference) also emphasizes that buildings play a critical role in climate action, stressing the need to reduce emissions by 50% by 2030 and recommending that new buildings be net-zero in terms of operations by 2030 [2]. The recently launched Intergovernmental Panel on Climate Change (IPCC) report also underscores the buildings' potential to achieve Sustainable Development Goals [3].

All of this is in agreement with the assessment that buildings account for more than one-third of global energy demand and more than three-quarters of global greenhouse gas emissions related to energy [1]. Building operations alone are responsible for more than 55% of global electricity [4]. The International Energy Agency (IEA) indicates that if more energy-efficient solutions are not found, the building sector will generate an increased energy demand of 30% by 2060. Substantial economic and environmental advantages could be realized by improving the sector's energy efficiency.

In the context of rising global average temperatures and growing reliance on electro-mechanical systems for space cooling, the potential for reducing energy demand lies in improving the upcoming building stock in the expanding hot regions [3,5]. Given the region's rapidly emerging building sector, improving building energy efficiency in the tropics is becoming increasingly important.

According to the literature, a variety of variables contribute to the dynamic rise of energy consumption in buildings [6]. The building envelope is critical in determining energy efficiency in buildings [7–9]. It is the shell of the building that acts as a barrier between the conditioned indoor and outside environment. It accounts for 50–60% of heat exchange and can result in 26% of the total building load due to heat gain and 36% of the peak cooling loads in cooling-dominated climates like India [10–12]. The energy performance of different envelope components-walls, floors, roof, ceilings, windows, etc., affects the energy required for building heating and cooling, indoor comfort, ventilation, and natural lighting [13]. Its design variables, such as geometry, insulation, reflectance, thermal mass, shading, etc., affect energy

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List of abbreviations:

Acronyms

ECC	Eta Correlation Coefficient
ECM	Energy Conservation Measures
EMM	Energy Modulation Measures
HVAC	Heating, Ventilation, and Air Conditioning
Low - E	Low Emissivity
OE	Operational Energy
PCM	Phase Change Material
PVR	Passive Volume Ratio
R-value	Thermal Resistance (m^2K/W)
SC	Shape Coefficient
SP	Shape Proportion
SHGC	Solar Heat Gain Coefficient
UAE	United Arab Emirates
U-value	Thermal Transmittance (W/m^2K)
W/L	Aspect Ratio or width-to-length ratio
WWR	Window Wall Ratio

Measures

$\mathcal{E}$	Emittance
μ	Reflectance
α	Absorptance
Q	Heat (J)
m	Mass (Kg)
c	Specific Heat Capacity (J/Kg-K)
C	Thermal Capacity (J/K)
ΔT	Temperature Change (K)
Φ	Heat flow rate (W)
λ	Thermal Conductivity (W/mk)
A	Cross-sectional Area (m^2)
d	Thickness (m)
R	Thermal Resistance (m^2K/W)
k	Thermal Transmittance (W/m^2K)
U	Thermal Transmittance of window assembly (W/m^2K)
R_{se}	External Surface Resistance (m^2K/W)
τ	Direct Transmittance

performance. Improving these design factors can result in a 46.8% reduction in yearly space-cooling energy consumption in hot climates [14].

Several researchers worldwide have analyzed building envelope variables for improvements in building energy consumption. Thermal and optical properties like thermal capacity, insulation, color, and reflectance can reduce the yearly cooling loads by up to 38% in tropical regions [15–17]. A study for a semi-arid climate reported more than 50% annual energy savings through insulation, reflective paint, low-emissivity (low-E) glazing, and shading [18,19]. Improvements in these measures offer the ability to enhance indoor comfort levels by moderating indoor temperatures [20,21]. Optimizing the building envelope also affects HVAC systems, energy loads, and associated costs [22]. Many review studies assemble optimization of the energy performance of the new or existing buildings. Nonetheless, no comprehensive overview of strategies for enhancing energy efficiency in tropical buildings exists. The following section overviews past studies on building envelope design in the tropics.

1.1. Summary and gaps

1.1.1. Advances in research

A wealth of studies have investigated building energy performance based on several envelope design considerations. The most examined variables include insulation, reflectance, window wall ratio (WWR), glazing types, shading devices, type of walls and roof assembly, ventilation mode, and orientation [14–17,22–32]. While some authors limit their analysis to a few roof or wall, others consider the whole building to produce a more realistic view [33]. The authors have presented methodologies and optimization approaches and highlighted the importance of active and passive design strategies to minimize cooling loads across climatic regions.

In recent times, an increasing body of research has focused on investigating the energy efficiency of buildings situated in tropical regions [17,22,23,31,34–39]. A handful of novel inquiries have sought to evaluate energy efficiency based on building shape [40–43,43–45]. Fig. 1 demonstrates the growing interest in improving the building envelope in the tropics. The trend highlights the rising importance of this issue post-2000. Fig. 2 provides an interesting peak into the type of building envelopes investigated in the tropics. As masonry and concrete remained the most popular envelope types over the years, glazing has received increasing attention over the past decade only, particularly for double-skin facades [39,46–49]. Even within masonry, brick and concrete blocks continue to receive the most attention (79%), followed by stones (4.52%), compressed earth blocks (3.95%), and hollow bricks (3.39%), as illustrated in Fig. 3. It is interesting to note that studies on sustainable envelopes like adobe, timber, and bamboo and conventional systems like semi-transparent photovoltaics have become prevalent in recent years [50–56]. As shown in Fig. 4, more attention has been given to residential buildings (49.2%), followed by offices (28.8%) and educational (11%). However, the literature reviews on building envelope in the tropics are less numerous.

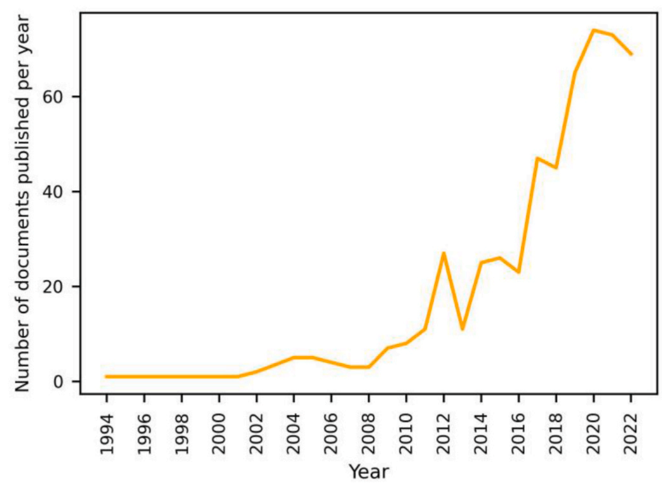


Fig. 1. Number of documents published per year.

1.1.2. Previous reviews

The reviews to date have ascertained the impact of varying envelope design variables for heating and cooling-dominated climates and captured energy improvements in buildings through the lens of retrofit measures [29,57]. Sarihi et al. reviewed different façade retrofit measures, such as energy conservation measures (ECM) and energy modulation measures (EMM), for minimizing energy demand in both cooling and heating-dominated climates [29]. While ECMs prevent excessive heat transfer through insulation, WWR, and infiltration, EMMs alter energy usage through design strategies like shading, coatings, etc. [29,58]. Reviews discuss decision-making models for energy performance

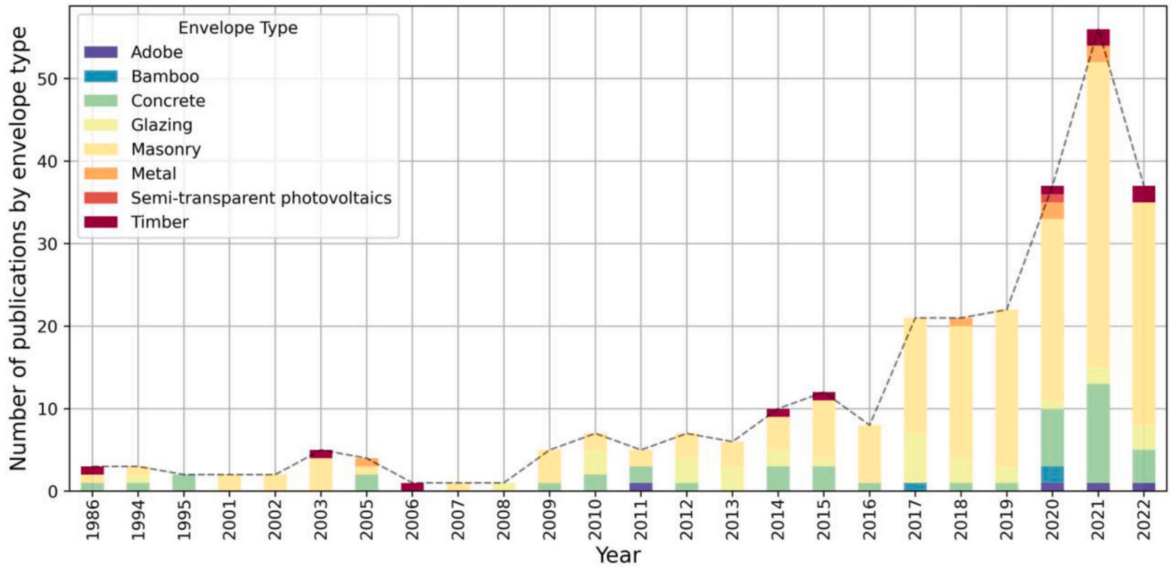


Fig. 2. Number of publications in the tropics based on the type of building envelope.

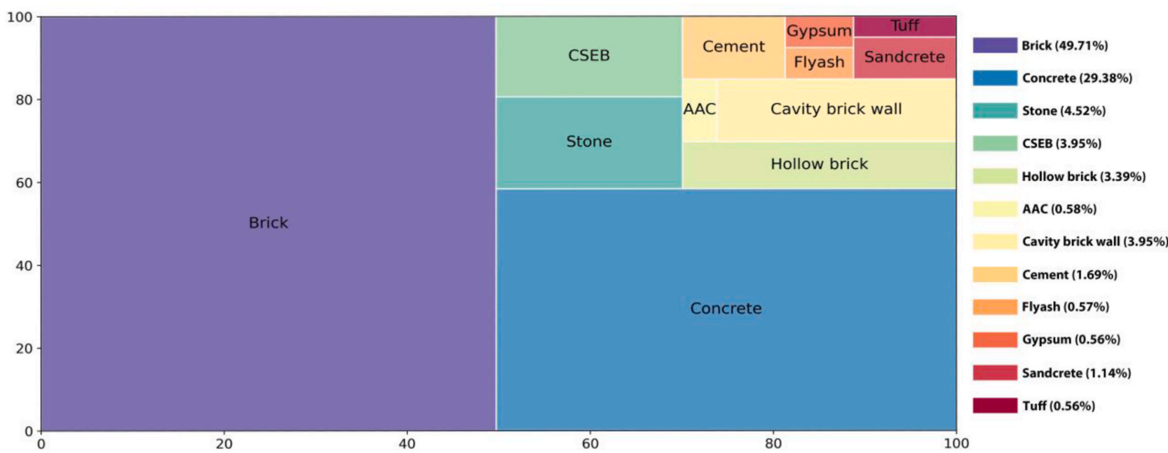


Fig. 3. Distribution of the types of masonry-based envelopes investigated in the tropics. The numerical values on x and y axis are to be used to measure the area of the rectangle for a particular material. The percentage share of each envelope material can consequently be obtained as follows- (area of rectangle/100)
Notes: The labels cement, flyash, gypsum, concrete and tuff in the figure refer to masonry blocks. AAC- Autoclaved Aerated Concrete block; CSEB- Compressed Stabilized Earth Block.

optimization in buildings and software tools for energy simulation [59–61]. Kheiri provided an extensive overview of state-of-the-art methods for optimizing building energy through envelope design [60].

A recent string of review studies underscores the importance of several physical and thermal factors for improving energy efficiency. An exhaustive set of these variables reviewed in cold, warm, and hot climate conditions include building orientation, shape, envelope systems, insulation, heat capacity, and thermal mass [12,33,61–63]. For example, Sadineni et al. covered advancements in fenestration, walls, and roof types for cold regions in the United States and the United Kingdom and hot climates of South Asia and the Middle East [61].

With the growing interest in net zero energy buildings, the design strategies in terms of renewable energy and other technologies and EEMs have also started gaining traction [36]. Feng et al. put together the energy performance in net-zero energy buildings in hot and humid regions [64]. The study found intensive use of passive design technologies for net zero buildings.

Additionally, several other reviews focus on region-specific and contextual climate studies. Friess & Rakhshan focused primarily on United Arab Emirates (UAE) and confirmed the effect of the passive envelope design on the energy required [65]. Ma & Wang reviewed research on building energy efforts in Hong Kong [66]. It highlights energy-saving measures, including policy, design, and renewable energy systems. The effects of building form and factors like roof and wall type and WWR have also been reviewed for the tropical climate of Malaysia [48]. Other reviews include studies focusing on specific variables. These include shading devices, ventilation strategies, and building insulation materials for varying climate zones [12,20,21,67,68].

The collective findings of these studies offer valuable perspectives on enhancing energy efficiency in buildings through optimizing envelope design parameters across various climatic scenarios or through the proposition of retrofit strategies for pre-existing structures.

1.2. *Novelty of the review*

A variety of reviews examining building envelope design strategies and variables, along with retrofit measures for minimizing energy use, exist in the literature [21,29,36,59,61,63,67,69–71]. The reviews documented the effect of measures like ECMs, EMMs, passive and active design techniques, natural ventilation, PCM, shading systems,

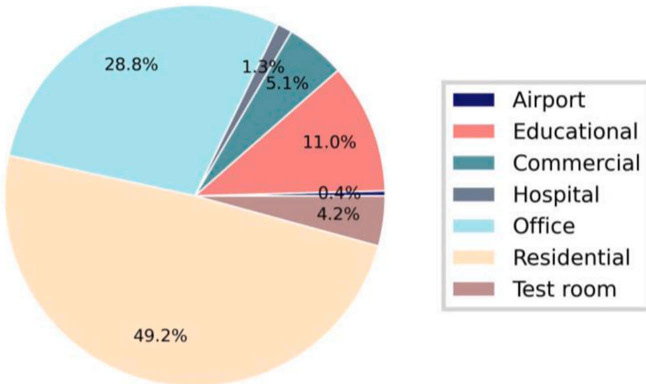


Fig. 4. Distribution of types of buildings analyzed in the studies conducted in the tropics.

insulation, thermal inertia, facade types, etc., on energy consumption in a particular country (or region) or climate or for different climatic types [20,33,48,58,65,66,70,72]. Some reviews also focus on the climatic design and indoor thermal comfort, however, they do not discuss the effect of envelope design [73,74].

It is to be noted that since the previous reviews, many authors have started investigating the impact of a larger number of envelope design variables on building energy performance in several countries across the tropics [11,18,20,23,47,75–80]. However, prior reviews have not provided a comprehensive and detailed discussion of the studies that investigate the effect of the building envelope in countries across the tropics as a whole. Additionally, no attempt has been made to review the existing literature on the impact of building shape on energy performance.

To enhance our understanding of the tropics, it is imperative to comprehend the historical evolution of trends influencing energy consumption in buildings in these areas. This review paper summarizes and assesses the current body of knowledge that discusses the effect of building envelope on energy consumption in the tropics. It will provide an improved understanding of the variables and building components that are most effective in improving energy performance in such a climate.

The tropics are defined as areas located between the northern latitude of the Tropic of Cancer (about 23°26′ North) and the southern latitude of the Tropic of Capricorn (approximately 23°26′ South). Its major climatic types as per the Köppen-Geiger classification (Fig. 5) include Tropical rainforest climate (Af), Tropical monsoon climate (Am), Tropical wet and dry or savanna climate (Aw), tropical and subtropical desert climate (BWh, part of BWk) and Mid-latitude steppe and desert climate (BSh) [81]. There are also patches of Type C climate-Humid subtropical climate (Cfa) and Monsoon-influenced humid subtropical climate (Cwa). While type A climate is characterized by a mean monthly temperature of more than 18 °C throughout the year and large amounts of direct solar radiation, type C climate in the tropics exhibits warm and moist conditions with mean daily temperatures ranging from 30 °C to 38 °C. Type B climate shows low precipitation and intense solar radiation [82,83].

The research further suggests that the shape of a building plays a crucial role in determining energy savings. However, this factor has only begun to gain attention in the last decade. With the advent of several capable advanced computational building energy modeling and simulation tools, studies have suggested methodological approaches for determining thermal performance and energy consumption for different building shapes. With this backdrop, the review also proposes collating the state-of-the-art developments on shape in hot and cold climates, representing a further novel contribution of the study.

2. Literature review

A comprehensive literature study was done using three databases- Scopus, Google Scholar, and ScienceDirect without limitation of the year of publication. However, the literature shows that related studies were published majorly between 1998 and 2021. The search was based on the existing studies' title, abstract, and keywords. A combination of the following keywords was used- 'building envelope', 'tropics', 'hot climate', 'thermal performance', 'comfort', 'façade', 'building energy', 'cooling loads', 'shape', 'geometry', 'energy efficiency' and 'energy consumption/demand'. The identified papers were screened based on the relevance of the title, followed by the abstract and area of study or climatic zone. Following this, papers found appropriate for this paper's scope were identified. Additionally, the relevant references mentioned in these papers were also checked based on the criteria mentioned earlier.

Several conditions were applied during the screening process. The studies had to be based in the tropics and assess more than one envelope design variable. The prime objective included building energy performance/demand/consumption or indoor comfort. The search methodology for identifying the relevant literature is demonstrated in Fig. 6.

The content in the following sections is organized as follows. Sections 2.2, 2.3, 2.4, and 2.5 comprehensively review recent studies on different envelope properties and associated design variables. Section 3 summarizes the entire literature and assesses key envelop design variables, followed by the conclusion in section 4.

2.1. Building envelope

The effectiveness of the building envelope is determined by the thermal, physical, and optical characteristics of its components in addition to building geometry [29,41,48]. These properties significantly affect indoor thermal comfort and building energy consumption [58,84]. Insulation, window properties, and air exchange are critical in cold climates [6]. Optimizing these properties in tropical climates can be difficult due to high daytime temperatures [23,48,85]. Determining their appropriate significance in the tropics influences energy savings [86,87].

The study in the following section summarizes several façade and envelope design variables into four categories, as shown in Fig. 7. Detailed consideration is given to building shape and related metrics. The derived categories include 1) Thermal properties, 2) Optical properties, 3) Physical properties, and 4) Geometry.

2.2. Thermal properties

The building energy loads and temperature of indoor air and envelope surface depend on factors like the outdoor air temperature, solar radiation, and optical and thermal properties of the envelope [88]. Thermal properties are characterized by insulation and thermal mass [18,33,63]. Insulation is determined by the thermal resistance or R-value (m^2K/W), thermal conductivity (W/mK), and thermal transmittance or U-value (W/m^2K) [89]. Suitable insulating materials can reduce energy consumption by slowing down the rate of heat flow into building mass by conduction [90]. They exhibit low thermal conductivity compared to commonly used construction materials.

Thermal mass is the total mass of all building elements and affects the energy storage capacity of the material. It depends on thickness, density, and specific heat of wall, roof, and floor [33,90]. There is no significant reduction in the overall thermal gain per day, however, it causes a time lag and a reduction in peak heat flow as a result. High thermal mass helps delay and reduce indoor peak air temperature and reduces the energy consumed in the tropics. The impact is pronounced in a substantial diurnal fluctuation in air temperature [33,61]. It depends on material properties, orientation, and ventilation [91].

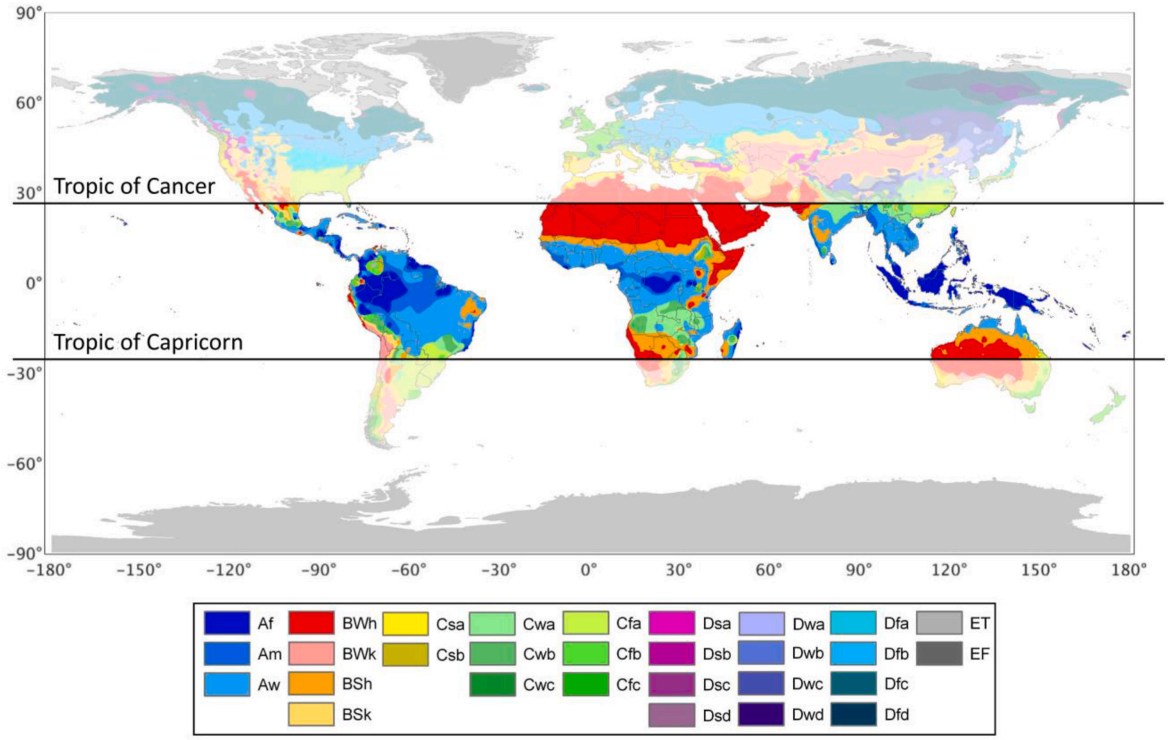


Fig. 5. World Map highlighting the different climate types as per Koppen-Geiger climate classification dominant in the Tropics-the areas between the Tropic of Cancer in the Northern Hemisphere and the Tropic of Capricorn in the Southern Hemisphere. The map and color scheme were adopted from Ref. [83].

2.2.1. *Thermal transmittance (U-value)*

The basic physical mechanisms that facilitate heat transfer in buildings include conduction, convection, and radiation. Fourier's law, or the law of thermal conduction, governs heat transfer by conduction. It states that heat flow rate (Φ) through a solid slab in steady state is always proportional to the cross-sectional area *(A)* and temperature difference *(ΔT)* and inversely proportional to the thickness *(d)* as shown in Eq. (1), where λ is called thermal conductivity. It depends on the slab material and is measured in W/mK [92].

$$\Phi = \lambda \frac{A(\Delta T)}{d} \tag{1}$$

The different layers of materials used in building components like wall, roof etc., are usually characterized by thermal resistance *(R)*. It is the ratio of slab thickness to thermal conductivity as expressed in Eq. (2). It is the inverse of thermal transmittance. Thus, good thermal insulators have low thermal conductivity.

$$R = \frac{d}{\lambda} \tag{2}$$

While the total resistance is the sum of the resistances of the individual material layers ($\sum \frac{d}{\lambda}$), the U-value *(k)* for such a multilayered body is calculated as per Eq. (3). A low U-value for a material assembly would imply high resistance and thus good thermal insulation.

$$k = \frac{1}{\sum \frac{d}{\lambda}} \tag{3}$$

The application of thermal insulation to reduce the U-value of the building envelope has been studied widely for both hot and cold climates [12,93]. It is the crucial factor impacting the demand for building energy [6,94]. Insulation in tropical regions, such as China, can reduce the annual cooling burden by up to 38% [16,95]. External wall insulation alone can produce considerable energy savings in hot regions [88]. For example, using insulation in Dubai can deliver annual energy savings ranging from 23 to 35% [96].

It appears, however, that using insulation in hot regions has complicated effects [14]. Although insulation can lower the maximum daily daytime temperature by 6 °C, it should be noted that in tropical areas, the indoor air temperature at night may experience a rise of up to 2.8 °C [91,93,97]. Highly insulated and airtight envelopes can increase the overheating risk [9,98–100]. While increasing thickness can be effective in heating-dominated buildings, it does not influence energy loads much in warmer climates [24,25,36]. A low U-value is not inherently associated with low energy consumption in such climates [101–104]. According to a recent study, high U-values in cooling-dominated climates produce more significant operational energy (OE) savings [12].

Meanwhile, in the arid desert climate of UAE, a decrease in U-values can result in a 2.6–19.3% reduction in cooling energy use [105,106]. Similarly, in Indian cities, lower U-values can lead to substantial energy savings of up to 50% [30]. Cooling loads decrease with a lower U-value and vice versa [89]. While increased insulation can curtail heat gain or loss through conduction, it is essential to note that over-insulation[1] may inadvertently result in higher energy consumption [36]. Sen et al. report that higher insulation prevents direct solar gains from radiating back into the atmosphere at night [38]. Nevertheless, natural ventilation can counter the reverse effects of insulation and ensure comfortable night-time conditions [91].

Such inconsistencies in energy consumption with an increase/decrease in U-value in the tropics are associated with the type of glazing, mode of ventilation, the position of insulation relative to thermal mass, and the local climatic context [19,90]. For instance, combining double glazing with high insulation can cause overheating in the tropics, but the effect is more pronounced in desert and semi-arid climates [98,107].

[1] The thickness of insulation after which any further insulation would be counter-productive, i.e., could result in an overall increase in cooling loads is referred to as the point of thermal inflexion.

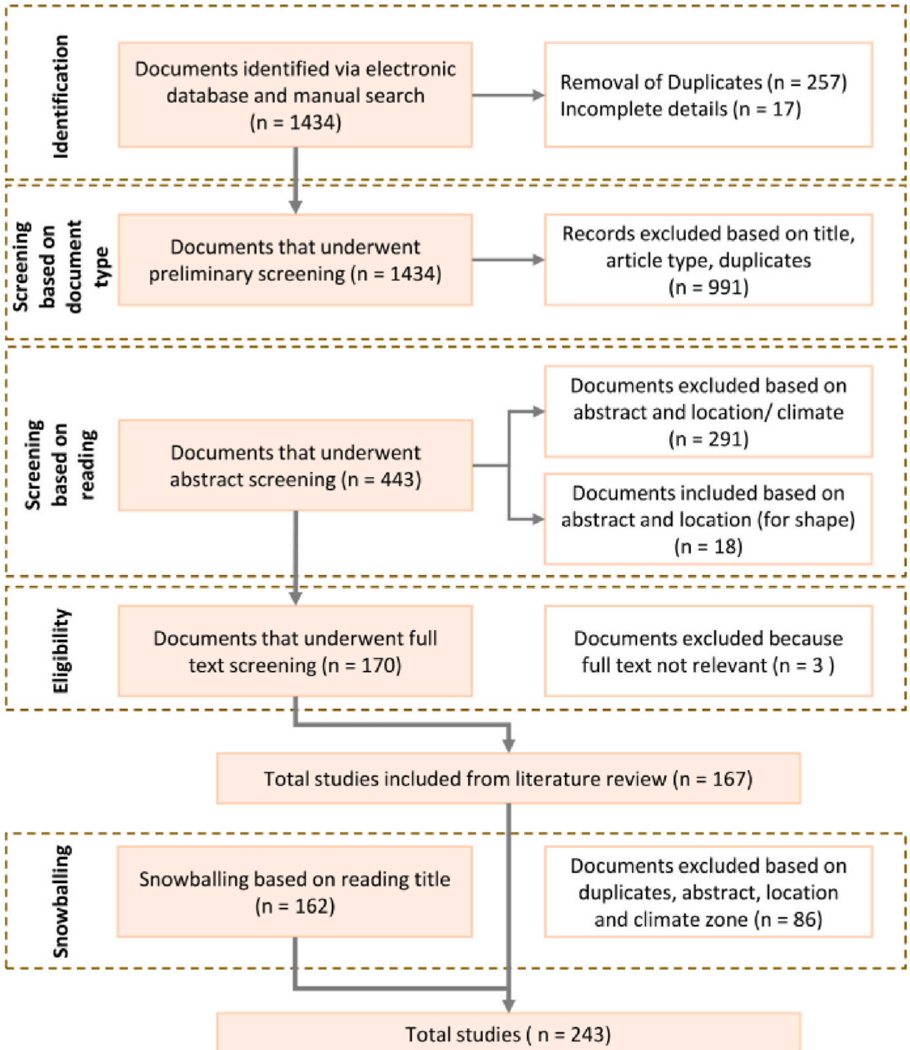


Fig. 6. Schematic illustrating the literature search process. The process started with the identification of studies based on the listed criteria, followed by screening and snowballing to shortlist studies appropriate to the scope of this review. The search results presented around 250 papers, forming the basis for the present research work.

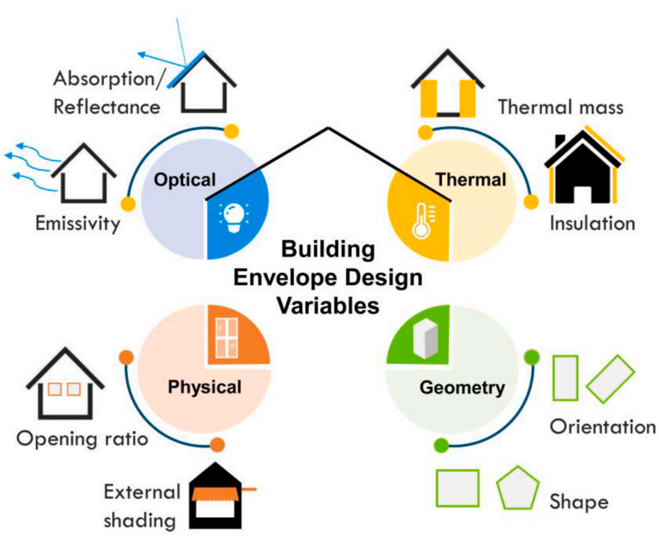


Fig. 7. The four major properties of the building envelope and their design variables reviewed in the study.

2.2.1.1. U-values and solar heat gain coefficient (SHGC). Windows considerably affect the thermal performance of the building envelope [108,109]. Heat exchange via glazing depends on properties like U-value, SHGC, and visual transmittance. The negligible thermal resistance offered by the glass and the direct solar radiation affect the total energy a building consumes [7,110]. It is the sum of solar radiation absorbed by the glazing and then re-radiated indoors and the directly transmitted radiation (τ) as shown in Eq. (4), where U is the U-value of window assembly, α is the absorptance of glazing, and R_{se} is the resistance offered by the external glazing surface [92].

$$SHGC = U\alpha\, R_{se} + \tau \tag{4}$$

The transmitted gains form a significant share of indoor heat gains [111]. A high SHGC can result in overheating even with a low U-value opaque envelope [27]. SHGC[2] is crucial in reducing cooling energy demand in the tropics [30,58]. Enhancing these characteristics also proves advantageous when considering structures with a high WWR

[2] It is the fraction of the solar radiation that is absorbed by the building component and then transferred (re-radiated) to the internal environment and the solar radiation that is directly transmitted with respect to total incident solar radiation.

[92]. For a small WWR, however, even a well-insulated envelope can yield energy savings because of reduced solar gains [112].

For example, for a well-insulated envelope with a WWR of 20%, savings reduce as the window U-value changes from 1.95 to 0.68 W/m^2K, and SHGC increases from 0.1 to 1.68 [30]. While lowering the U-value for a WWR by more than 50% increases the cooling demand, reducing the SHGC decreases the total energy required by 18.4–29.7% [113]. A reduction in SHGC can also reduce peak indoor temperatures by up to 4.9 °C, reducing the daily cooling load by 34%. The higher the SHGC, the greater the increase in total energy use as a function of WWR for cooling-dominated climates [114]. Poorly insulated buildings, however, may show irregular patterns [113].

Many researchers have also examined the effect of U-value and SHGC under varying climatic conditions and shading types [113]. Friess & Rakhshan suggest a maximum window U-value of 1.9 W/m^2K and a shading coefficient of 0.25 in the hot climate of UAE for WWR higher than 60% [65]. SHGC and shading are the most influential factors, with a 39% greater impact than other parameters. When supplemented with Low-E glazing, 10–20% energy savings can be achieved [65].

The literature thus ascertains that SHGC is more effective in decreasing the space cooling demand in well-insulated buildings, irrespective of window size [115]. The effect is, however, more pronounced for larger WWR. Lower U-values prove beneficial for low WWR. It influences heat gains, mainly when solar gains through windows occur during a minor part of the occupied hours [15]. It is worthwhile to point out that a lower SHGC reduces building energy consumption in hot summer regions but increases it in colder regions [116]. Empirical evidence suggests that glazing for hot climates is Low-E, characterized by low values for both SHGC and U-values [52,117]. Table 1 discusses the variations in observed energy savings for different combinations of SHGC and U-value.

2.2.2. Thermal mass

Thermal mass is the ability of a material to absorb and store heat and progressively release it later. In addition to material density, it is ruled by the thermal capacity *(C),* that depends on mass (or thickness) and specific heat *(c),* as shown in Eq. (5) [33,90,118]. The amount of heat added *(Q)* is proportional to the mass of matter *(m)*, specific heat capacity *(c)*, and temperature change *(ΔT)* as shown in Eq. (6) [92]. The ability to absorb and store heat thus increases with an increase in mass and specific heat.

$$C = m \times c \tag{5}$$

$$Q = mc\Delta T \tag{6}$$

Further, as the thickness increases, the rate of heat flow reduces, resulting in a more significant time lag, as explained by Fourier's law [92]. The greater thickness helps control indoor air temperatures by causing the internal surface temperature to change slowly and with less magnitude [89,90,119]. Most studies report that thermal mass improves indoor thermal comfort for most buildings and climate types [33,99,

Table 1
Effect of changing U-value, SHGC, and WWR on energy savings in the tropics as understood from [30,31,113].

WWR	SHGC	Window U-Value	Wall and Roof Insulation	Savings in Cooling Loads
>50% or <50%	Low		High/Low	High
>50% or <50%	High		High/Low	Low
<50%		Low		High
>50%		Low		Low
>50%		High	High	Low
<50%		Low	High	Low/High
>50% or <50%	Irregular	Low	Poor	High

120–122]. As per Olsthoorn et al. it is associated with high-temperature cooling or low-temperature heating, implying that cooling/heating time extends over a longer duration [123].

However, it is essential to note that the effects of adding thermal mass are not straightforward. Though it appears to be more pronounced in warm and humid climates, a typical characteristic of the tropics, the literature reveals some discrepancies [124]. For the semi-humid climate of Brazil, high thermal mass can improve indoor thermal comfort and provide savings in cooling energy consumption [125]. The maximum indoor temperature reduces considerably with increased thermal mass [49,126,127]. Similar findings have been reported from studies conducted in Kenya, Cairo, and Israel [128,129]. It can curtail the hours of discomfort caused by overheating by up to 7% in tropical regions like Cairo, Myanmar, and Thailand [99,130]. Reduction in indoor air temperature by up to 4 °C and fluctuations by up to 0.9 °C is possible in hot and dry climates [91,131]. Increasing thermal mass can reduce energy consumption by 13.4% in UAE and peak cooling demand in Hong Kong by up to 60% [105,106].

In contrast, Leccese et al. argue that lighter construction with insulation performs better [132]. Ren and Chen suggest that a lightweight envelope performs better only when the comfort criteria is lowered in tropical regions [133]. According to a study conducted in Thailand, thermally massive walls can reduce air-conditioning loads during the day. It can, however, be counterproductive at night [134]. While the indoor air temperature reduces with rising wall thickness, the mean temperature rises by 1.3 °C during nighttime [91]. Ralegaonkar et al. propose that humid climates with a limited diurnal range should avoid heavy mass construction. Lightweight construction performs better as it can be quickly cooled down [135]. The relatively low time lag reduces indoor nighttime temperature [136]. Similar findings have been reported by studies conducted in regions like Cyprus (Köppen climate classification: BSh), Las Vegas (Köppen climate classification: BWh), Miami, and Phoenix (Köppen climate classification: Aw) that have similar climate characteristics as tropics. Increasing thermal inertia may result in a slight rise in cooling energy demand due to high indoor air temperatures. Authors attribute these observations to night-time ventilation and the use and position of insulation layer [137–139].

In a separate investigation, the researchers suggest that while employing lighter mass may reduce nocturnal cooling, an increase in the thickness of insulation could yield favorable outcomes [31]. Here, the impact of insulation overtakes the effect of thermal mass. However, beyond a certain thickness, the indoor environment remains uninfluenced by the outdoor thermal flux through building mass. Greater thicknesses may thus become less attractive due to less impact and higher costs [91]. High thermal mass can also create overheating when coupled with high insulation [140]. For instance, an increase in the thermal mass of an insulated wall in a sub-tropical climate can lower the demand for heating energy but require more cooling [138].

The inconsistencies are also linked to the level of thermal mass and placement of the insulation layer. The cooling loads can increase by up to 19% or reduce by 16%, depending on the thermal mass and the position of the insulation. Evidence suggests that insulation should be placed on the hotter side to maximize efficiency by minimizing heating of the thermal mass [89,106]. A peak cooling load reduction of 1.8% is possible by moving the layer to outside, irrespective of the thickness [17]. Insulation above the slab can take up to three times longer to transmit the same amount of heat [90]. Several studies confirm that the influence of insulation holds greater significance in tropical areas than thermal mass [33,49,91,120,124,132,137,141,142]. It is important to note that irrespective of the position of thermal mass, shading is crucial to block solar gains in the tropics [99].

The type of climate also influences the effect of thermal mass. For instance, in hot-arid desert climates subjected to high ambient temperatures and intense sunlight, thermal mass stores more heat than it can transfer back outside at night, resulting in discomfort in airtight buildings [138]. For mechanically cooled buildings, internal thermal mass can result in greater energy consumption due to heat transfer from/to the interiors [120]. On the contrary, it can reduce fluctuations in indoor temperatures in hot climate of Jeddah, Saudi Arabia and composite climate of Jaipur, India [127].

Thus, it can be summarized that the effect of thermal mass is complex in the tropics and its application should consider the design of other envelope variables. The discordance can be attributed to factors such as the level of thermal mass, construction material, insulation and its placement, shading, diurnal variations in temperature, climate type, night-time ventilation and air change rate [33,137–139,143,144]. Ventilation and greater air exchanges can increase indoor thermal comfort in the tropical hot-humid climate [143]. Using thermal mass on the interior side with outside insulation appears more beneficial [33].

2.3. Optical properties

The radiant solar energy reaching an external surface is partially reflected and absorbed depending on the surface characteristics. These characteristics can be defined in terms of three optical properties-color, solar absorptance, and emissivity with the effect of the latter two being more prominent [90,145]. Unlike color, which responds to radiation in the visible range, absorptance affects the heating of the surface in both visible and infrared regions. However, the surface's solar absorptance or reflectance is related to the type and color of the external finish [88]. While solar reflectance is the dominant factor affecting thermal performance during the daytime, emissivity is prominent at night [146].

2.3.1. Absorptance or reflection

In accordance with the law of energy conservation, solar radiation falling on an opaque surface can either be absorbed or reflected. As per Eq. (7), the total sum, where μ is the reflectance and α is the absorptance, should be 1.

$$\alpha + \mu = 1 \tag{7}$$

As reflectance increases *(μ)*, absorption *(α)* reduces. The effectiveness of reflection depends on the color and material texture. Light-colored and smooth surfaces offer greater reflectance or low absorption [136,147]. They serve by reflecting the energetic short waves. The cooling energy requirement increases with the solar absorptance of the external surfaces in hot climates [18,88,148–150]. The annual electricity consumption for a building in China reduced by 8.93%, with a drop in absorptance from 0.6 to 0.2. However, the energy needed for heating increased by 4.02% [151]. A 30% reduction in solar absorption can reduce annual cooling burdens in Singapore by 12.6% [17].

The surfaces with high solar reflectance offer the potential to decrease both surface and indoor air temperatures [152]. Plummeting solar absorptance from 0.65 to 0.1 in Mediterranean climates can reduce indoor air temperature by up to 80% [140]. Reflective paints report up to 7% energy savings [153]. The surface temperatures can drop from 38.9 °C to 9.8 °C with a change in reflectance from 0.1 to 0.9 [145].

2.3.2. Emissivity

As per Kirchhoff's law, the amount of radiation absorbed is equal to the amount emitted, as shown in Eq. (8), where Ɛ is the emittance [154]. This is, however, true for the same wavelengths. The wavelength of emitted radiation depends on the temperature of the emitter [90].

$$\varepsilon = \alpha \tag{8}$$

High solar reflectance and emissivity can enhance energy efficiency in tropical and subtropical climates [155]. The use of high-emissivity coatings reduces cooling energy consumption by lowering surface temperature. As an example, for a constant value of solar absorptance, the temperature of the external surface at peak can be 39.6 °C for an emissivity of 0.1 and 31.3 °C for an emissivity of 0.9. Koenigsberger et al. state that for two materials with the same solar absorption, the one with higher emissivity will re-emit much of the absorbed heat and attain a lower temperature [90]. As anticipated, higher emissivity allows heat to escape rapidly [145]. Malz et al. observed a 2.27% reduction in the heat flux through the external wall for a dip in the emissivity from 0.8 to 0.5. A further decrease to about 5.30% was observed as emissivity reduced to 0.2 [1,2].

Certain coatings, like white color, offer high solar reflectance (surface albedo ≥65%) and thermal emittance [156]. The two properties together make a surface cooler when exposed to solar radiation. The applicability of such cool materials has been extensively investigated, particularly for roofs. As the primary contributor to solar gains in the tropics, cool roofs can significantly reduce cooling burdens and indoor air temperatures [8,93,157]. For instance, Pisello et al. notice that while using a cool roof can reduce the indoor operative temperature by up to 2.6 °C, the application combined with white paint leads to a temperature reduction of 3.1 °C. Covering the whole envelope with a cool coating produces an improvement of 4.4 °C compared to the base case [158].

2.3.2.1. Cool roofs. Cool roofs, also known as white or reflective roofs, are the best-performing technology compared to other passive techniques like roof insulation, green roof, night ventilation, and external shading. While the latter reduces energy consumption by 30%, applying a cool roof alone can save 18–93% in tropical climates [88,150,159,160]. It can reduce the heat flow into the building by 49% and produce greater savings compared to phase change materials (PCM) and green roofs in India [34,161]. One can achieve an annual savings of 10–19% by applying high albedo coating to all uncoated roofs in arid climates [162].

Combining cool roofs with other measures can result in energy savings of up to 78% [163]. Using reflective coatings with PCM can produce savings from 5 to 12% monthly in Singapore [79]. Mousavi et al. however, prefer insulation and reflective paint over PCM, as the former combination is not only thermally effective but results in cost savings too. The coatings can generate more than 50% savings in annual energy consumption in a semi-arid climate [18]. A reflective barrier on an insulated external roof surface can improve its thermal performance by reducing the insulation temperature by up to 4 K during the daytime [164]. Despite its effectiveness in lowering radiation transfer from the outer surface to the insulation layer, this may yield counterproductive results during nighttime due to restricted radiative cooling.

2.3.3. White color coating

The application of color, a strategy used to adapt buildings to the local climate in traditional times, has been identified as an inexpensive approach for reducing summer space cooling demand. As an example, the use of white plaster and clear (cool) paints are capable of reflecting up to 95% of solar radiation and emitting a significant portion of it (infrared emissivity up to 90%) into the surroundings [90,165,166]. While thermally insulated and shaded roofs offer a maximum temperature reduction of 9.9 °C and 8.9 °C respectively, the application of white color can reduce surface temperature by up to 13 °C and indoor air temperatures by 1.2–3.3 °C in hot and arid climates. Applying white paint and glazed tiles can reduce discomfort hours by 100% [149,159,167]. A light-colored roof also results in 30% lesser total heat gain (via conduction and radiation) than a dark-colored roof [168]. An annual reduction of 14–26% in air conditioning is possible by converting dark roofs to white roofs [162]. However, the effect of color on external surfaces reduces with increased insulation. For highly insulated and shaded envelopes, the paint's effect is minor compared to a completely exposed envelope [169].

Overall, the literature determines that exterior surface finishes with light color, high solar reflectance, and emissivity can result in considerable energy savings in the tropics [140]. The measures yield better results when applied on roofs than walls. Increasing reflectance and emissivity can reduce energy consumption in cooling-dominated climates, especially in orientations with significant solar irradiance [153, 170]. Yet, the impact of altering the reflectance and, consequently, its absorption is more significant compared to modifying emissivity [145, 148].

2.4. Physical properties

2.4.1. Opening ratio

The window-to-wall ratio or the opening ratio determines the amount of incident solar radiation that enters indoors. WWR affects the operational carbon from the cooling loads and contributes about 47.4% [26,108]. In cooling-dominated climates, a low WWR is advantageous in façades with a low U-value [29,171]. Higher ratios can produce overheating and, thus, greater cooling energy consumption. Reducing WWR from 1 to 0.4 can reduce indoor air temperature and enhance thermal comfort while ensuring natural ventilation in the tropics, like in China and Malaysia [19,78]. Adjusting window areas can reduce cooling loads by 17.82% in India and 39% in hot and humid regions of the United States [14,172]. A small WWR reduces solar heat gains and enhances comfort levels. However, large windows may be suitable for cooling-dominated climates in the south and north orientation [75,173].

A WWR of 20% in all directions except the south can result in optimum thermal comfort and cooling loads. In the south, a WWR of 60% can provide greater indoor comfort due to the steep angle of incoming solar radiation [42]. For the hot climate of Dubai, Green Building Regulations recommend at least 50% of the glazed areas in the north [65]. It is crucial to determine the appropriate WWR for energy efficiency and thermal comfort and to increase natural ventilation and daylight, particularly in hot and humid climates.

2.4.2. Shading systems

Shading, particularly in external systems, is the most effective measure for blocking solar radiation [23,58]. Different shading typologies can reduce the cooling energy demand in South Africa and Egypt by 25–50% [174,175]. An egg-crate shading device can decrease indoor air temperature and extend indoor comfort hours by 26% in Malaysia's hot–humid climate [23].

Optimal shading achieved by increasing the depth on the east and west facades can reduce cooling burdens by up to 10% in Singapore and Hong Kong [32,151]. The shading of opaque façades in the west and the southwest directions report maximum savings with horizontal and vertical shading types [176].

Heat transfer can also be lessened by installing vertical greenery on external walls. The layers of creeping plants reduce solar radiation by about 40–80% [177,178]. The shading from green façades can reduce indoor temperatures by 8.4 °C in Hong Kong and minimize the external surface temperature of a wall from 18.7 °C to 9.8 °C in Riyadh [29,179]. Analogously, it can substantially reduce roof surface temperatures that otherwise experience high solar irradiation. The daytime average roof temperature in Riyadh can drop by 12.8 °C; Mumbai's greatest maximum reduction is 26.1 °C [179]. The green facades are suitable insulation mechanisms [180,181]. Double-skin green façade on tall structures can reduce cooling energy requirements by 20% and air conditioning loads by 76% in tropical countries like Indonesia, Brazil and Malaysia [39,182–184].

Despite its ability to reduce cooling demands, shading reduces daylight and might be counterproductive during winter due to the reduced solar radiation. It is thus essential to balance WWR, shading, and glazing properties according to the building's orientation [185]. It is worth noting that exterior shading screens should be designed based on the city's solar geometry, building orientation, and climate to provide shading while ensuring daylight ingress and ventilation [27,37]. These may include external movable shading devices or perforated screens that limit solar gains and ensure ventilation and daylighting [24,44]. Findings reveal that such screens can increase the daylight area by 50% and reduce the total transmitted solar radiation by 63%. It can provide 55% savings in annual energy consumption [186].

2.5. Geometry

Apart from the several envelope properties discussed above, other factors contributing to building energy performance include climatic conditions, building shape, and orientation. These factors need to be critically assessed during the building design phase. However, the literature indicates a paucity of studies on building geometry in tropical nations [55,88,131,187]. The following section thus reviews the current literature on building shapes for all climatic zones without limitation to the tropics.

2.5.1. Building shape

Increasing interest in examining the effect of building shape on building energy efficiency is recent. Of the 30-plus shape-centric articles reviewed, 75% have been published in the last decade, as illustrated in Fig. 8.

The building shape impacts the total surface area exposed to the external environment and thus affects the energy losses [188]. A suitable shape and orientation can minimize energy loads by up to 40% without additional costs [189]. The selection of the best-performing shape is linked to variables like compactness index, shape coefficient, and shape proportion [41,63]. Shape proportion (SP) involves changing the proportion of the shape while keeping the volume fixed. Shape coefficient (SC), also called shape factor, refers to the ratio of outer surface area in contact with the exterior surroundings, ground or adjacent non-heated spaces, and internal volume of the building [40,190]. The compactness factor is like the shape coefficient and refers to the ratio of the building volume and its outer surface area [191].

2.5.1.1. Compactness and shape coefficient (SC). Several researchers relate building energy demand with the shape coefficient of buildings. Oral & Yilmaz used SC and other design variables to determine maximum U-values in Turkey [192]. Depecker et al. conceived fourteen parallelepiped buildings for France's cold and mild Mediterranean climate [193]. Observations show that energy consumption is proportional to the SC in a cold climate. In the case of a mild climate with long sunny periods, the heat transmitted via walls is less significant, and thus the correlation with shape is absent. For the tropics, characterized by high solar potential and consequently low transmittance losses, the effect of the increasing SC on the energy demand is low [45].

A very compact building will have a high volume-to-surface ratio, exposing the small building surface to heat transmission. Similar to SC, the compactness index affects a building's capacity to store heat and, consequently, its heat loss [63]. For the hot summers of Athens, more compact shapes (or low SC) resulted in the lowest cooling loads due to lesser surface area. A square-shaped building reported the highest energy performance compared to a rectangular, octagon, or elongated square [42]. Though a low SC is preferred in hot climates, rectangular buildings can also provide significant savings when properly orientated [88]. Studies note that compact buildings are also actively cooled, with indoor air temperatures often below outdoor [194].

Leo Samuel et al. show that dome-shaped roofs in solar-intensive regions like India minimize solar heat gains due to a lower SC and self-shading ability [131]. An inverted U-shape room can further reduce air temperature due to a lesser sun-exposed area [187]. Tang et al. on the contrary, suggest that vaulted roofs result in lower indoor air temperatures due to a larger surface area which permits more heat to be dissipated by convection and thermal radiation at night [55].

Overall, it is seen that a small exposed surface area and a low surface-to-volume ratio (or more compactness) allow buildings to heat up slowly and thus generate reduced energy consumption [194]. The yearly

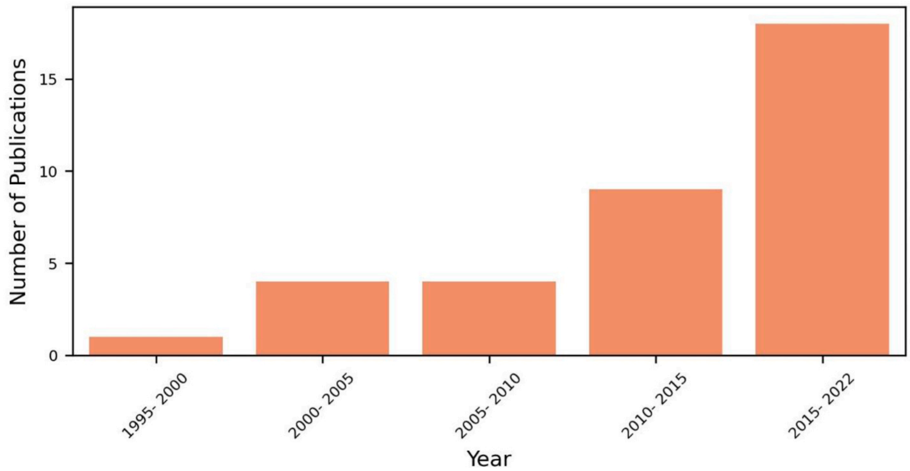


Fig. 8. Number of papers published on the shape of the building envelope.

energy use for any building form increases as relative compactness[3] decreases [114].

2.5.1.2. Indices other than SC and compactness. Ciardiello et al. used shape proportion before calculating SC to adhere to more realistic geometries [41]. They considered eight different building shapes based on the common shapes used in residential buildings. These included linear shape (I), L-shaped (L), court (O) and C-shaped (C) buildings, and some rare shapes like T-shaped (T), H-shaped (H), cross (X) and Y-shaped (Y). After examining four different shape proportions of each shape, the authors identified O, T, H, X, and Y as the best-performing shapes. The findings reveal that optimizing SC and WWR can result in more energy savings Amraoui et al. suggest that though compact forms reduce cooling loads, a hyper-compact building is undesirable [195]. Literature thus argues that though a low SC assures low energy consumption in cold climates, a direct relation cannot be derived for the tropics. Some researchers recommend using passive volume, the product of the façade's perimetric area (m^2) for every 6 m depth or twice the thermal zone's height, as an efficiency indicator [40]. The compact shapes balanced with high passive volume are preferred for the temperate climate.

The SC or surface area to volume ratio of a building is influenced by its aspect ratio (building width/building length or depth). The building shapes with a higher aspect ratio or W/L correspond to lower values for SC [196]. W/L also impacts the amount of solar radiation hitting any surface. For example, a circular shape with a W/L ratio of 1:1, has the lowest SC and receives the least annual solar radiation. Adamski found buildings with oval shape bases rather than circular and square to offer better thermal performance in heating periods [197]. Research suggests acceptable W/L ratios for hot and humid climates to range between 1.7:1 and 3:1, with 1.7:1 being the optimum shape [75,198].

In addition to conventional building shapes, as discussed above, the performance of free-form building shapes on a building's thermal performance has also been investigated. Determining thermal load characteristics and developing approaches for these shapes has received wide attention. Jin & Jeong used selected physical design and thermal behavior parameters to create different free-form buildings [199]. The authors subsequently demonstrate an optimization process for an energy-efficient design through parametric modeling in Rhinoceros/-Grasshopper [43].

Thus, several studies have focused on optimizing building envelopes to improve energy efficiency through a list of thermal and optical variables but with a narrow focus on optimizing the building shape and surrounding built context [200]. The studies investigating building shapes have been primarily done regarding SC and shape proportion. Appendix A illustrates the building shapes investigated in the reviewed studies.

2.5.1.3. Building orientation. The major factors that govern the association between building shape and incident solar radiation include the W/L ratio and building orientation [196]. Orientation affects insolation and is maximum for geometric shapes with a lower W/L ratio, particularly for east-west elongated shapes [27,196]. Appropriate orientation can limit the heat absorption from surroundings and moderate indoor temperatures [20]. It also impacts the solar reflectance of the external walls, which varies between 0.1 in the south to 0.9 in the east and west [41].

A building oriented north and south results in the slightest heat gain and cooling needs. This is followed by the northwest and the southeast directions, particularly in the tropics [22,90,201]. Longer facades should be made to face the north and south [42]. Changing the building orientation from north/south to east/west can reduce cooling loads between 8.57 and 11.54% for buildings in Singapore [32]. It is seen that the west and southwest-facing orientations perform worst regarding the total number of hours with comfortable indoor air temperatures [202]. Preventing windows in east and west directions can create more acceptable indoor conditions; windows in these directions receive the highest radiation due to a steep angle of incidence [23,203]. A typically solar-controlled north window in a hot-arid climate can provide up to 9% savings in energy consumption. The same can result in 15% savings in the other three directions [30]. The solar gains for different building orientations are illustrated in Fig. 9 [42].

The building orientation also affects the potential for ventilation. Changing orientation to enable natural ventilation can elevate annual indoor thermal hours by 16% in the hot-humid climate of Malaysia [202]. It is wise to orient buildings in a way that permits natural ventilation [166].

The literature thus evidences the importance of orienting the longer building facade in the south or north and the direction of prevailing winds in the tropics. Greater southern exposure limits solar gains due to the nearly vertical angle of incoming solar radiation, preventing sunlight from reaching deep within the floor, as depicted in Fig. 9 [22].

3. Literature summary

According to the literature, the use of studied design variables began in the late 20th century. Building insulation, shading, glazing properties,

[3] The relative compactness of a building is defined as the ratio of the volume to the exterior wall area of the building divided by the ratio of a reference building.

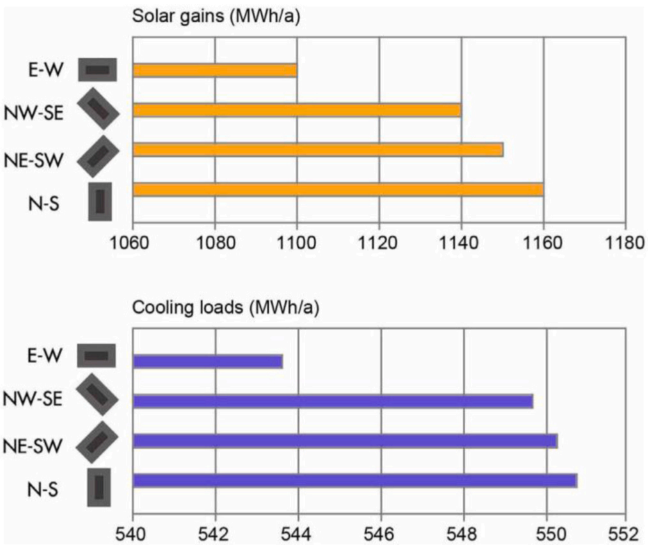


Fig. 9. Annual solar gain and cooling loads for different orientations in the Mediterranean climate. E– W means that the building is oriented, with the longer side facing North-South. Reprinted from Ref. [42], with permission from Elsevier.

and reflective coatings have particularly received greater interest. These measures have been majorly used to enhance the thermal properties of the façade by preventing excessive heat transmission. It is seen that using both roof and wall insulation can result in higher savings of up to 35% compared to insulating either of the components. Thermal insulation remains an attractive solution for reducing energy consumption in the tropics. It also dominates the impact of thermal mass.

Several studies also report using low-emissivity coatings for glazing and reflective coatings like cool materials for external surfaces to minimize solar heat gains. In studies published after 2000, variables such as geometry, glazing, SHGC, and thermal mass have been utilized frequently. More research is needed on the effect of shape and adjacent built context on cooling energy consumption, particularly in hot regions. A summary of the energy savings obtained through combinations of different envelope design measures in the tropics is presented in Table 2. If applied in combination, these variables can result in an annual average savings of 35%.

A sensitivity analysis, based on the collated literature, was performed to examine the influence of each envelope design variable on building energy savings. A total of 75 cases that represent a combination of different design variables, as depicted in Table 2, were selected. The analysis was done by examining the Eta coefficient, which measures the strength of association between a scale-dependent variable (maximum energy savings) and the categorical explanatory variables [216]. The Pearson correlation test was then used to determine the significance values (or p-value). The explanatory variables included thermal insulation, shading, WWR, coatings, glazing type, SHGC, and thermal mass. All other variables, like infiltration, ventilation, set point temperatures, etc., were included under the category 'others'.

The chi-square test of independence was further employed to determine the relationship between each pair of design variables in terms of their investigation in the studied literature. The test compared the frequency of each category for one nominal variable to the second nominal variable. Cramér's V, an effect size measurement for the chi-square test, was also obtained to measure the strength of association between the design variables [217].

The sensitivity analysis (Table 3) reveals that insulation, glazing type, and WWR have a statistically significant relationship with building energy savings ($p < 0.1$). The insulation has a medium correlation (ECC>0.4) but the largest effect compared to other variables, as shown in Fig. 10. The type of glazing and WWR are also significant in effecting energy savings in the tropics. The strength of association is however weak (0.2 < ECC<0.4).

This observation is in concurrence with Fig. 11 which discusses the percentage savings produced by the statistically significant variables. As indicated in the figure, the hatched yellow and black lines represent the mean and median, respectively. It illustrates the estimated energy savings possible by using several envelope design measures in the absence or presence of insulation, and by considering modifications in glazing type and WWR in the tropics. The presence of outliers, represented as diamonds, are data points lying significantly outside the range of most observations. These outliers provide insights into the extreme cases of energy savings observed in the literature.

As shown by the yellow line, glazing type, and insulation provide a mean savings of 30% and can save up to 60% when combined with other measures. Without insulation, the average savings are below 20% for a majority of observations. WWR has a considerable impact and can increase average savings by over 10% in combination with other variables. Similar observations have been reported by several studies conducted in the tropics [15,29,101,108,218–220].

The type of glazing can also significantly affect energy savings in the tropics as illustrated in Figs. 10 and 11. Average savings can drop by 10% without appropriate glazing design [15,18,26,30,221,222]. Insulation, however, has a greater maximum savings potential as also observed from sensitivity analysis in Table 3. The use of external insulation can provide substantial savings in energy consumption [34,99,115,117,126,205,223–225]. This alone can yield energy savings of 23–35% [33,93,96,226]. Literature suggests that more savings are observed in hot climates like Oman, Riyadh, Qatar, Delhi, UAE, etc. [16,34,65,93,115,116,183,205]. Roof and wall insulation along with appropriate window-wall ratio can contribute significantly to energy savings in hot climate as also evident from Table 2 [19,69,113,221,227,228].

A moderate correlation (ECC>0.4) between energy savings and others highlights that factors like set-point temperature, ventilation rate, type of HVAC system, etc., also have a comparable effect on energy savings. Literature reports that infiltration, and natural ventilation play a crucial role in hot and humid climate [20,61,77,144,229–231]. Significant energy savings are possible from a relatively higher cooling setpoint temperature across tropical countries [84,232–235]. Thermal mass and orientation were found to be non-significant with the least ECC value (ECC<0.2).

Fig. 12 shows the results from the chi-square test. It demonstrates whether or not a relationship exists between two variables (on the vertical and horizontal axis). A low p-value ($p < 0.1$) indicates that the considered literature provides sufficient evidence to support the existence of a significant relation between a pair of variables, whether they are examined together or not. Findings reveal that in most of the studies conducted in the tropics, the use of insulation has a statistically significant relationship with building orientation ($p < 0.01$). Analogously, a significant chi-square value for glazing with SHGC and WWR ($p < 0.05$), highlighted in black shows that the three envelope variables are also significantly linked (considered/not considered together) in the reviewed literature. A low p-value for shading systems with the external coating ($p < 0.1$) and WWR ($p < 0.05$) also indicates a relationship between the two variables.

The values from the Cramér's V test, as shown in Fig. 13, illustrate the strength of association between a pair of variables on the two axes. For instance, Cramer's V value of 0.3 between WWR and shading indicates a strong positive association between the two variables. A large V value along with a low p-value suggests that the two variables are often examined together to evaluate building energy performance in the tropics [14,19,28,75,78,117,208–210,236]. However, the figure also suggests that though insulation and building orientation are statistically related ($p < 0.09$), the variables are weekly associated (Cramér's V = 0.2). Studies that examine insulation rarely consider the effect of

Table 2
A summary of the annual savings (%) obtained by applying combinations of different envelope design solutions. The studies are arranged in descending order of their resulting energy savings [206,207,211,212,214].

Source	Insulation	Exterior coating orcolor	Glazing Type	Shading	WWR	SHGC	Orientation	Thermal mass	Others	Maximum savings in annual energy consumption (%)
[206]	■		■	■		■				86
[98]	■	■	■						■	66
[183]	■			■						57.7
[207]	■	■	■						■	53
[28]			■	■	■				■	50
[117]	■		■	■	■	■		■		47.3
[14]	■	■	■	■	■					46.81
[208]	■	■								42.34
[209]			■							39.5
[15]	■									38
[207]	■	■	■							35.6
[117]	■									35
[18]	■	■								34
[175]				■						33
[18]	■									32
[17]	■	■	■	■						31.4
[207]	■									31.2
[207]	■		■							30
[210]	■		■	■	■				■	28
[207]	■									27
[175]	■		■	■						26.7
[211]	■		■	■	■					26.35
[212]	■		■	■	■					25.92
[93]	■	■		■						25.4
[145]		■								25
[18]		■								25
[194]	■		■							24
[18]			■	■		■				22
[30]	■		■			■	■			22
[209]							■			22
[213]			■							21.3
[214]	■	■								21
[215]	■		■	■						20.5
[209]					■					20.4
[14]			■							20.26
[17]	■							■		19.4
[194]	■			■						19
[117]								■		18

changing building orientation as demonstrated in Table 2 [12,18,49,70,91,95,120,124,132,140,175,204,213,215,237,238].

The results show that type of glazing has a moderate level of association with SHGC and WWR. For instance, almost all studies that examine SHGC, consider the effect of the kinds of glazing [18,75,93,110,112,117,204,239]. The same holds for studies examining glazing type and WWR as also shown in Table 2. However, comparatively more research has been conducted on the combined effects of glazing type and WWR than on SHGC and WWR in the tropics [19,26,28,65,97,185,208,209,232,240–245]. Notably, glazing, WWR, and insulation all contribute substantially to energy savings, as discussed in Figs. 10 and 11. It is evident from Fig. 12 and Table 2 that insulation with glazing type and insulation with other variables have received equal attention [26,29,31,36,95,102,120,144,219,221,238,242,246].

Despite a significant relationship of shading with coating and WWR as discussed in Fig. 12, the latter has a stronger association. This suggests a growing interest in examining the impact of shading and WWR on building energy performance in tropical regions [14,19,117,175,

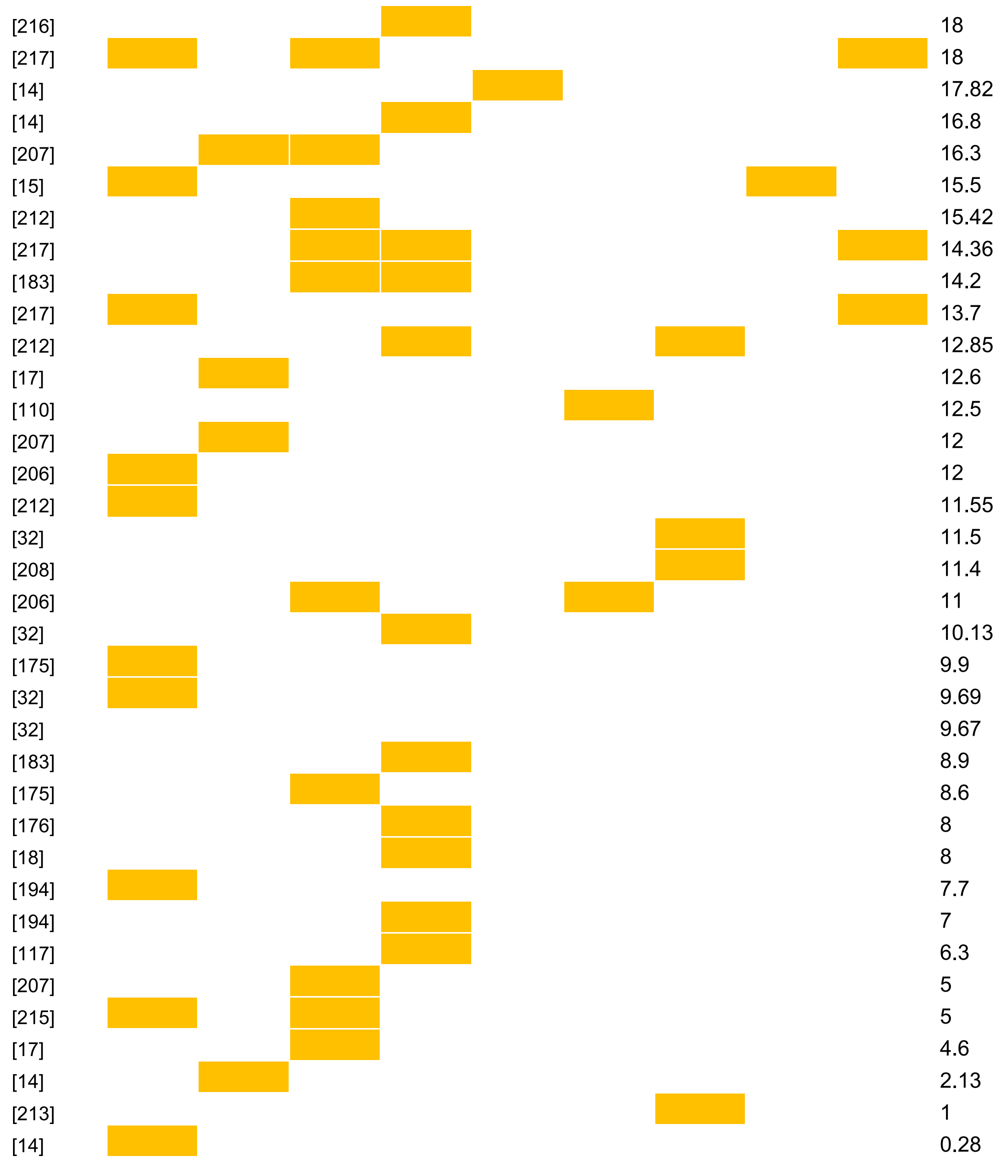


Table 3
Comparison of the importance of studied envelope variables.

Variables	Eta correlation coefficient (ECC)
Insulation	0.419***
Shading	0.204
Coating	0.271
Glazing type	0.314**
WWR	0.244*
SHGC	0.220
Orientation	0.162
Thermal mass	0.047
Others	0.430**

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

208–210,242,247,248]. It is evident from Table 2 that only a limited number of studies have assessed shading and coating together [14,17].

Attempts have also been made to examine shading, glazing, and WWR simultaneously [19,242,244,247]. Almost all studies that evaluate the impact of WWR also consider shading and glazing. An insignificant relation between insulation and thermal mass indicates a paucity of literature assessing the combined effect of these variables on energy savings in the tropics. Most existing studies examine their impact on indoor thermal comfort [91,128,129,131,249,250].

4. Conclusion

Buildings account for a considerable share of total energy consumption for space cooling, specifically in tropical regions. Thus, the relationship between building envelope design and energy consumption has received growing attention in recent years. The present review provides a comprehensive discussion of the studies that investigate the effect of several envelope design variables in countries across the tropics as a whole. It summarizes their impact on building energy consumption and thermal performance. The reviewed literature confirms that energy consumption can be reduced by making cautious modifications to the thermal, physical, and optical design variables of the building envelope and its geometry.

Building envelope design variables such as insulation or U-value, glazing properties, and WWR have primarily been recognized as promising solutions for improving energy efficiency in tropical buildings. The

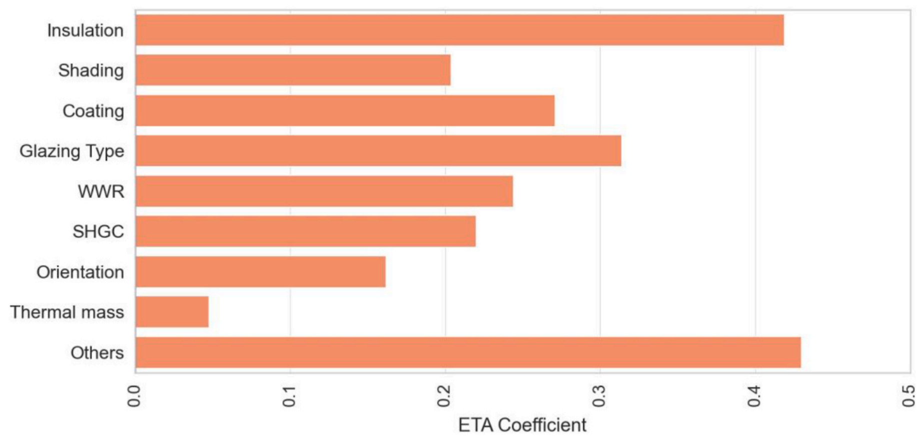


Fig. 10. The importance of building envelope variables for savings in annual energy consumption.

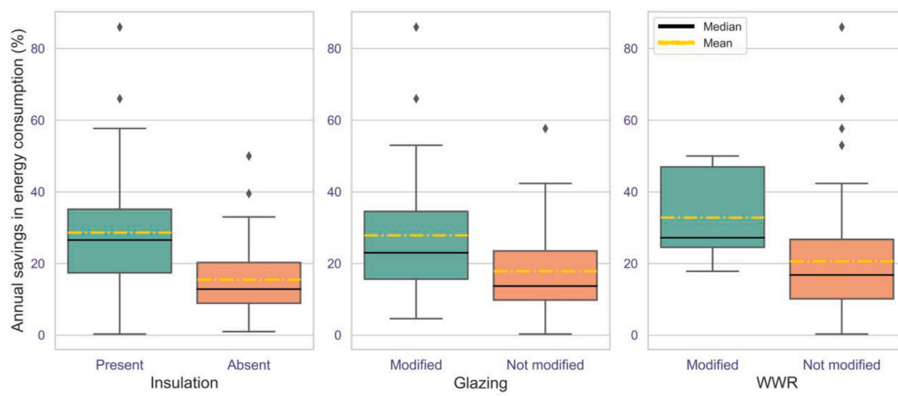


Fig. 11. Annual savings in energy consumption with/without the use of insulation, WWR, and glazing type.

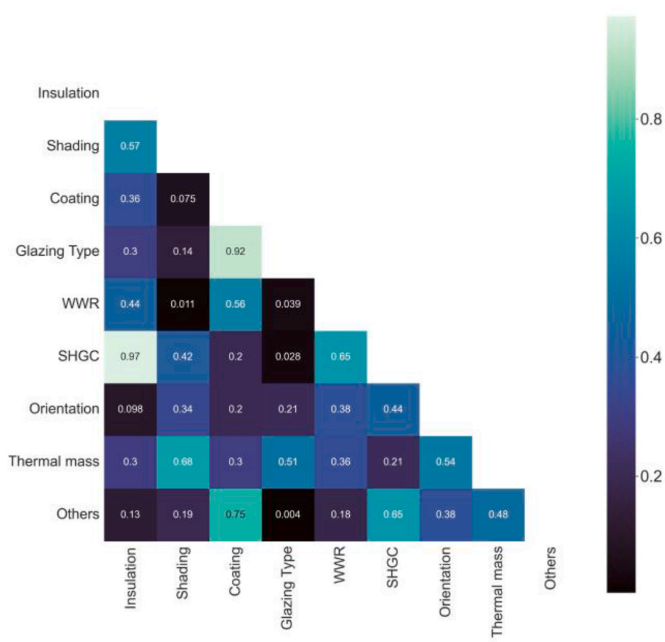


Fig. 12. The statistical significance of association between pairs of building design variables-p-value (2-tailed sig.) for the chi-square test. A low p-value ($p < 0.1$) indicates a significant relationship.

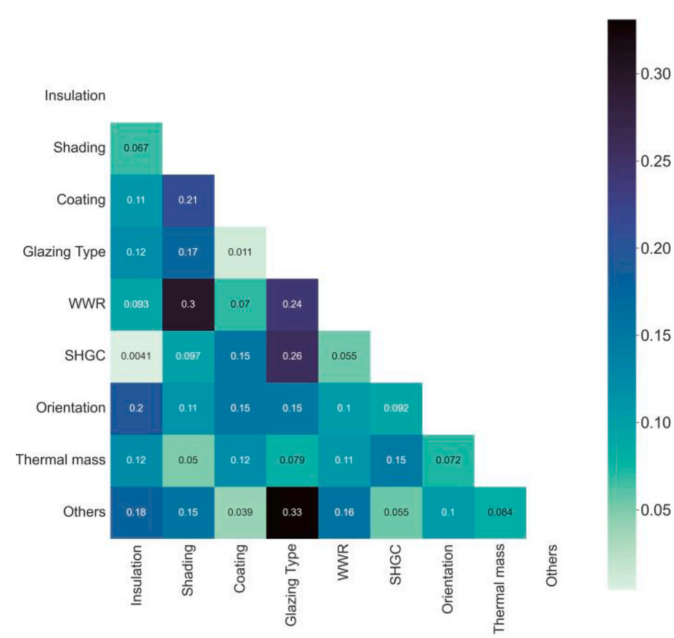


Fig. 13. Comparing the strength of association between pairs of building design variables- Cramér's V for the chi-square test. A large value indicates a stronger relationship.

use of thermal mass and orientation have a minimal influence on total energy consumption. An optimized design in hot climates should have a large aspect ratio, higher WWR in the north and south, and an ideal shading system with low-E coating glazing. External shading in the form of green vegetation or perforated screens designed per the city's solar geometry can be effective in cooling-dominated climates. Increasing reflectance and emissivity can reduce energy consumption, especially in orientations with significant solar irradiance. Factors like set-point temperature, ventilation rate, type of HVAC system, etc., also have a substantial effect on energy savings in hot and humid climates. While some variables have a direct link with savings, others are found to be more complicated in the tropics.

In general, there is the potential to save 35% of building energy annually and up to 60% when all variables are taken into account. The annual average can, however, fall below 20% without insulation. Roof and wall insulation along with an appropriate window-wall ratio can contribute significantly to energy savings in hot climate. It is important to note that insulation does not offer similar benefits for all configurations. While it can be effective for a low WWR and glazing with a low SHGC, it can be detrimental for large WWR in the west and east. Insulation should be applied considering factors like WWR, thermal mass, and glazing properties. While these variables effectively reduce conductive and convective heat gains, SHGC helps control direct heat transmission. However, fewer studies have been conducted on the combined effects of glazing type, WWR, and SHGC in the tropical countries.

The literature reports contradictions when considering thermal mass in hot-humid climates. The impacts of adding thermal mass are not straightforward in hot-humid climates. While thermally massive walls can reduce indoor air temperature during the day, they can be counterproductive at night. Additionally, it can result in greater energy consumption in hot-arid climate. The discrepancy can be attributed to factors like construction material, level of insulation, diurnal variations in temperature, outdoor climate type, night-time ventilation etc. In order to account for the variations, the use of thermal mass in the tropics should employ tools that capture its dynamic behavior. The studies should consider the holistic effect of other design variables and varying micro-climate. Interventions should be adapted to local climate and characteristics of the building.

Many existing studies have examined the effect of thermal, optical and physical properties of building envelope components on energy use and thermal comfort in tropical countries. However, there is a disconnect between the studies examining the combined effect of envelope variables and factors like occupants, equipment and appliances, HVAC systems etc. There needs to be more literature trying to assess the combined effects of envelope design properties along with variations in occupancy pattern, ventilation type, equipment schedule and efficiency, setpoint temperatures, etc. Furthermore, although precise information on such characteristics might potentially reveal causative links and a common platform for a more logical comparison, such details are often lacking in the available research.

Further examination shows that building shape can significantly affect thermal comfort by impacting solar gains in the hot-humid climate. Lately, few attempts have been made to determine the thermal characteristics of free-form structures. However, there is limited research on the effect of changing building shape on energy consumption, particularly in the tropics. Additionally, more research is needed to investigate the combined impact of envelope design variables and urban form on indoor thermal comfort and energy consumption in the tropics.

Lastly, further research is required to investigate the link between envelope design, occupant behavior, urban form and appliance activity use in the context of potential for renewable energy, target users, and accessibility. A more comprehensive understanding is vital to identify critical parameters required to enhance energy efficiency in buildings and address issues related to sustainable development.

Declaration of competing interest

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

Data availability

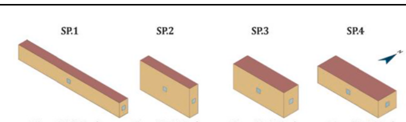
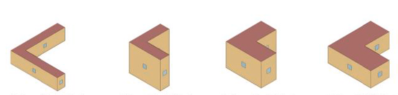
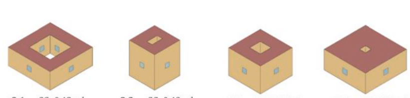
Data will be made available on request.

Acknowledgments

The authors would like to thank the journals that permitted the use of Figs. 5 and 9, and other Figures used in Appendix A.

Appendix A

Building shapes and façade types investigated in cited literature work. Reprinted from Refs. [40,41,43,45,114], with permission from Elsevier.

Source	The figure of scheme/case study	Elements and techniques established in literature
[41]		**Shape I-** shape proportions (SP) and corresponding shape coefficients (SC)
		**Shape L-** SC for SP 1, SP 2, SP 3, SP 4 respectively
		**Shape O–** SC for SP 1, SP 2, SP 3, SP 4 respectively

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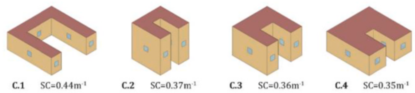
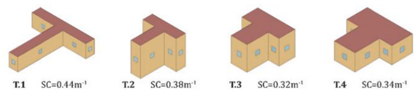
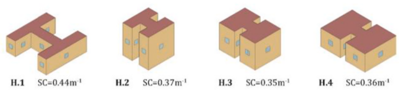
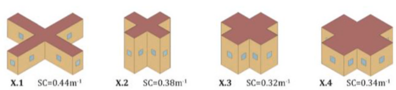
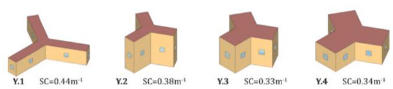
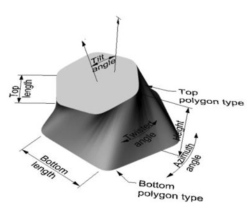
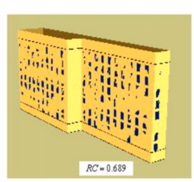
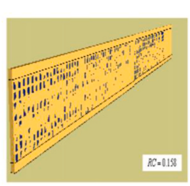
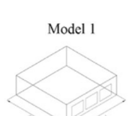
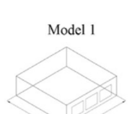
Source	The figure of scheme/case study	Elements and techniques established in literature
		**Shape C–** SC for SP 1, SP 2, SP 3, SP 4 respectively
		**Shape T-** SC for SP 1, SP 2, SP 3, SP 4 respectively
		**Shape H–** SC for SP 1, SP 2, SP 3, SP 4 respectively
		**Shape X–**SC for SP 1, SP 2, SP 3, SP 4 respectively
		**Shape Y–** SC for SP 1, SP 2, SP 3, SP 4 respectively
[43]		Free-form building type
[114]		Buildings with relative compactness = 0.689
		Buildings with relative compactness = 0.158
[45]		Building geometry with SC = 1.472
		Building geometry with SC = 1.476

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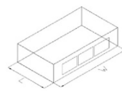
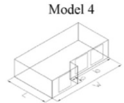
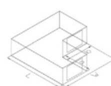
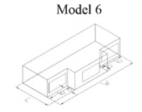
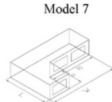
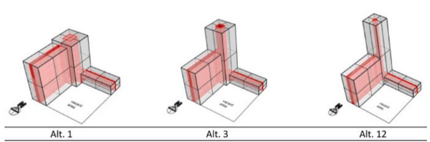
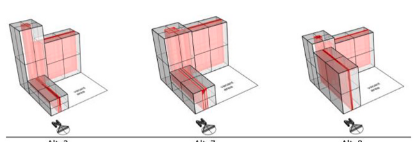
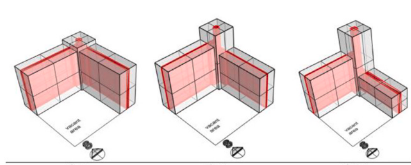
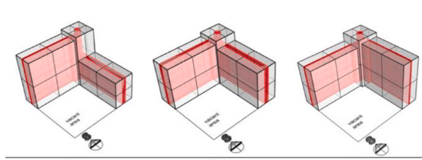
Source	The figure of scheme/case study	Elements and techniques established in literature
	Model 3 	Building geometry with SC = 1.503
	Model 4 	Building geometry with SC = 1.553
	Model 5 	Building geometry with SC = 1.578
	Model 6 	Building geometry with SC = 1.589
	Model 7 	Building geometry with SC = 1.656
[40]		Passive Volume Ratio (PVR) for Alt 1 = 0.77 Alt 3 = 0.83 Alt 12 = 0.87
		PVR for Alt 2 = 0.85 Alt 7 = 0.79 Alt 8 = 0.82
		PVR for Alt 5 = 0.85 Alt 7 = 0.90 Alt 15 = 0.89
		PVR for Alt 5 = 0.87 Alt 7 = 0.83 Alt 15 = 0.90

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