

Article

Energy Efficiency in Subtropical Homes: Replacing Asbestos–Cement Roofs with Sustainable Alternatives

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Abstract: This study evaluates the impact of building orientation, typology, and envelope characteristics on energy efficiency and CO₂ emissions in urban dwellings in subtropical climate, with a focus on Cartagena, Colombia. North-facing dwellings consistently demonstrate superior energy performance, achieving an average efficiency increase of $4.27 \pm 1.77\%$ compared to south-facing counterparts. This trend is less pronounced near the equator due to the sun's high zenith angle. Semi-detached homes exhibit $23.17 \pm 9.83\%$ greater energy efficiency than corner houses, attributed to reduced exterior wall exposure, which lowers energy demand and CO₂ emissions by 2.16 ± 0.74 kg CO₂/m² annually. Significant disparities in emissions are observed across socioeconomic strata; homes in strata 3 and 4 show the lowest emissions (6.69 ± 1.42 kg CO₂/m² per year), while strata 5 and 6 have the highest (10.48 ± 1.42 kg CO₂/m² per year), due to differences in construction quality and glazing ratios. Roofing materials also play a key role, with thermoacoustic (TAC) roofs reducing emissions by up to 5.80% in lower strata compared to asbestos–cement roofs. Furthermore, sandwich panels demonstrate substantial potential, achieving CO₂ emissions reductions of up to 51.6% in strata 1 and 2 south-facing median homes and a minimum saving of 9.4% in strata 5 and 6. These findings underscore the importance of integrating energy performance criteria into public housing policies, promoting construction practices that enhance sustainability and reduce greenhouse gas emissions while improving occupant comfort and property value.



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Keywords: subtropical climate; building energy modelling; sustainable construction; carbon footprint reduction

1. Introduction

Energy efficiency in residential buildings plays a pivotal role in addressing global challenges related to sustainability and public health [1,2]. Residential structures significantly contribute to energy consumption and greenhouse gas (GHG) emissions [3], emphasizing the need for innovative approaches to enhance their thermal performance. While much of the existing research has focused on temperate and extreme climates, subtropical regions remain underexplored.

Roof materials significantly influence a building's thermal performance, particularly in climates with high cooling demands. Asbestos–cement (AC) [4] is a worldwide roofing material, once widely used for its affordability, durability, and thermal resistance. Nevertheless, it has been identified as a severe health hazard [5,6]. The International Agency for Research on Cancer (IARC) classifies asbestos as a Group 1 carcinogen, directly linking its fibers to fatal illnesses such as mesothelioma [7], lung cancer [8] and asbestosis [9]. More than 70 countries around the world have forbidden asbestos, including Colombia [10], with Law 1968 of 2019 [11]. However, financial and regulatory challenges have delayed its replacement in low- and middle-income housing, where AC roofs remain prevalent [12]. These roofs not only perpetuate health risks but also represent an opportunity to improve energy

efficiency in a region characterized by high temperatures, humidity, and socioeconomic vulnerability.

On the other hand, the evaluation of energy retrofitting measures has been extensively studied in temperate and extreme climates [13–15], with insights highlighting their transformative potential. For instance, the retrofitting of the Juan XXIII neighborhood in Alicante, Spain [16] demonstrated dual benefits: improved energy efficiency and the revitalization of vulnerable communities. The study outlined comprehensive retrofitting stages and emphasized how such interventions can enhance quality of life from environmental, social, and economic perspectives. Similarly, other studies in Spain have explored the benefits of envelope renovations, renewable energy integration, and compliance with nearly zero-energy building (NZEB) standards [17]. These interventions have achieved significant reductions in energy consumption, GHG emissions, and energy bills, illustrating the effectiveness of targeted retrofits in temperate climates. However, the methodologies developed in these contexts are often ill-suited to subtropical climates, where energy dynamics, construction materials, and socioeconomic realities differ significantly.

In extreme climates, such as Iraq, research has emphasized the role of material properties in reducing heat flux [18]. Studies have shown how specific combinations of wall and roof materials can optimize insulation performance, mitigating cooling demand [19]. Additionally, analyses of heating and cooling demands [20,21] across Spain's climatic zones have highlighted the influence of climate evolution, with warmer regions like Almería experiencing substantial increases in cooling requirements [22]. These findings underscore the importance of adapting building regulations and material selection to evolving climatic and regional contexts. Sustainable alternatives [23,24] have demonstrated potential for improving thermal efficiency while reducing environmental impacts. These materials often incorporate advanced synthetic or natural fibers, such as polyester or mineral wool, to balance durability, cost-effectiveness, and energy performance. However, material selection must also account for safety and sustainability. Historical lessons, such as the health risks of refractory ceramic fibers, underscore the need for rigorous evaluations to ensure that replacements for asbestos-containing materials are both effective and safe.

Despite a robust body of global research, explicit studies addressing energy efficiency in subtropical homes, particularly in South America, remain rare. Subtropical climates present unique challenges, including the interplay of roof materials, building orientation, and placement on thermal performance. These factors are further influenced by socioeconomic dimensions, which determine material accessibility and affordability. Most existing research oversimplifies or overlooks these complexities, focusing instead on temperate or extreme climates [25]. The Caribbean exemplifies the urgent need for region-specific studies. This region's climatic, architectural, and socioeconomic characteristics present distinct challenges and opportunities for energy efficiency interventions. The widespread presence of AC roofs, combined with local climate dynamics and construction practices, necessitates a comprehensive approach to evaluate sustainable alternatives.

This study addresses the aforementioned research gaps by evaluating the energy performance of replacing AC roofs with alternatives like thermoacoustic (TAC) roofs [26] and sandwich panel roofs [27] in the Colombian Caribbean. It integrates multiple variables, including roof material, building orientation, and placement, to offer a nuanced understanding of their combined effects on energy consumption and CO₂ emissions. The findings aim to inform sustainable construction practices, contribute to public policy, and provide actionable insights applicable to subtropical climates worldwide. By expanding the discourse on energy efficiency to subtropical regions, this study contributes to bridging critical knowledge gaps and advancing global efforts toward sustainable and energy-efficient residential buildings.

2. Materials and Methods

This section presents the methodology and results of a modeling study assessing the impact of replacing asbestos–cement roofing with alternative materials in Colombian homes,

specifically in the Caribbean region. The analysis considered factors such as socioeconomic status, building orientation, and position. Figure 1 shows a flowchart of the methodology.

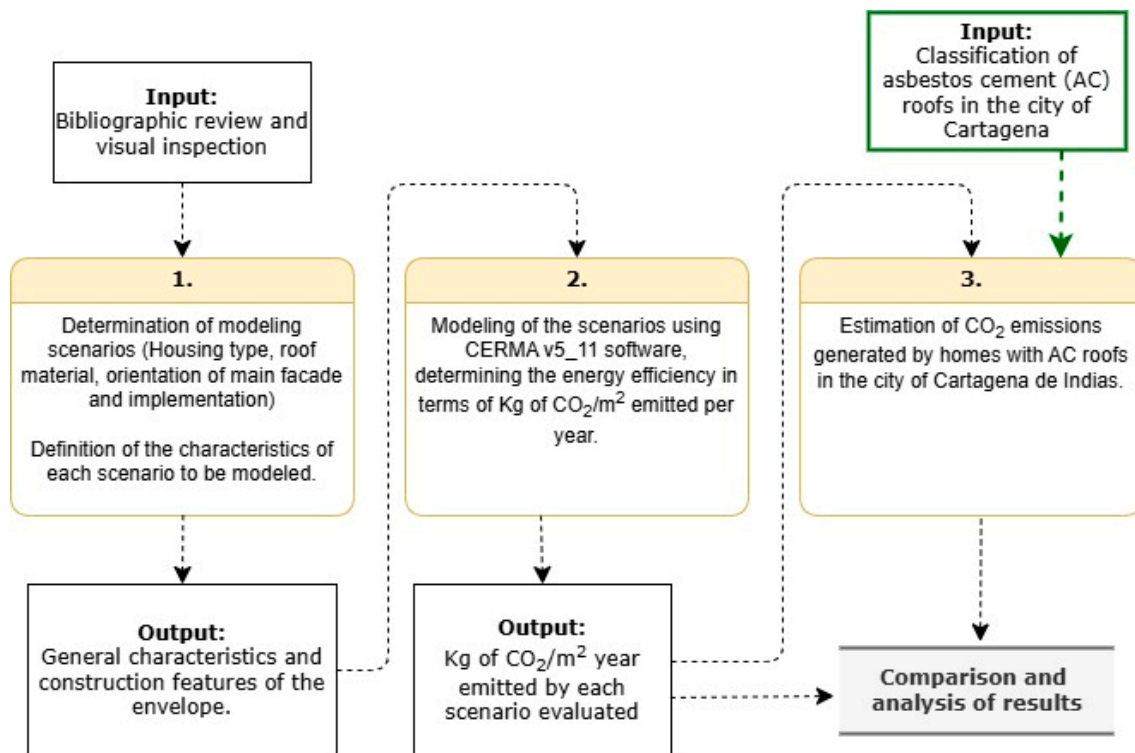


Figure 1. Flowchart of the methodology.

To model energy efficiency, 36 different combinations of variables were evaluated, as detailed in Table 1. These combinations, shown in Figure 2, included three socioeconomic strata (1–2, 3–4, and 5–6), three roofing materials (asbestos–cement [28–30], thermoacoustic tile [26], and sandwich panel [31]), and two building orientations, south-facing and north-facing, according to Figure 3a,b, with two building positions (corner and middle).

Table 1. Housing combinations modeled to assess their energy efficiency in Cartagena.

Socioeconomic Stratum (E)	Combination	Roof Material Orientation			Orientation Main Facade		Implementation	
		Asbestos–Cement (AC)	Thermoacoustic (TAC)	Sandwich (SAN)	South (S)	North (NOR)	Corner (COR)	Median (MED)
E1–2	E1&2-AC-SOUTH-COR	X			X		X	
	E1&2-AC-SOUTH-MED	X			X			X
	E1&2-AC-NOR-COR	X				X	X	
	E1&2-AC-NOR-MED	X				X		X
	E1&2-TAC-SOUTH-COR		X		X		X	
	E1&2-TAC-SOUTH-MED		X		X			X
	E1&2-TAC-NOR-COR		X			X	X	
	E1&2-TAC-NOR-MED		X			X		X
	E1&2-SAN-SOUTH-COR			X	X		X	
	E1&2-SAN-SOUTH-MED			X	X			X
	E1&2-SAN-NOR-COR			X		X	X	
	E1&2-SAN-NOR-MED			X		X		X

Table 1. Cont.

Socioeconomic Stratum (E)	Combination	Roof Material Orientation			Orientation Main Facade		Implementation	
		Asbestos–Cement (AC)	Thermoacoustic (TAC)	Sandwich (SAN)	South (S)	North (NOR)	Corner (COR)	Median (MED)
E3–4	E3&4-AC-SOUTH-COR	X			X		X	
	E3&4-AC-SOUTH-MED	X			X			X
	E3&4-AC-NOR-COR	X				X	X	
	E3&4-AC-NOR-MED	X				X		X
	E3&4-TAC-SOUTH-COR		X		X		X	
	E3&4-TAC-SOUTH-MED		X		X			X
	E3&4-TAC-NOR-COR		X			X	X	
	E3&4-TAC-NOR-MED		X			X		X
	E3&4-SAN-SOUTH-COR			X	X		X	
	E3&4-SAN-SOUTH-MED			X	X			X
	E3&4-SAN-NOR-COR			X		X	X	
	E3&4-SAN-NOR-MED			X		X		X
E5–6	E5&6-AC-SOUTH-COR	X			X		X	
	E5&6-AC-SOUTH-MED	X			X			X
	E5&6-AC-NOR-COR	X				X	X	
	E5&6-AC-NOR-MED	X				X		X
	E5&6-TAC-SOUTH-COR		X		X		X	
	E5&6-TAC-SOUTH-MED		X		X			X
	E5&6-TAC-NOR-COR		X			X	X	
	E5&6-TAC-NOR-MED		X			X		X
	E5&6-SAN-SOUTH-COR			X	X		X	
	E5&6-SAN-SOUTH-MED			X	X			X
	E5&6-SAN-NOR-COR			X		X	X	
	E5&6-SAN-NOR-MED			X		X		X

E = Socioeconomic stratum; AC = asbestos–cement roof; TAC = thermoacoustic roof; SAN = sandwich roof; NOR = north; MED = median; COR = corner. X = indicates the Roof Material Orientation, Main Facade Orientation and Implementation of the combination selected.

Annual CO₂ emissions (kg CO₂/m² year), a key indicator of a building’s environmental impact [32], were calculated for each of the 36 combinations using the Residential Energy Rating Abbreviated Method (CERMA, for its initials in Spanish), which is a building energy simulation software, following Spanish building regulations [6]. CERMA V5.11 is a software application designed for the energy performance certification of residential buildings, mainly in Spain. It serves as a versatile tool for assessing both new constructions and retrofitting projects, in compliance with the Building Technical Code of Spain [33–36]. Developed by the Fredsol Group at the Polytechnic University of Valencia in collaboration with the Valencia Institute of Buildings. The software uses the Abridged Residential Energy Rating Method to calculate energy demand, consumption, and associated CO₂ emissions integrating regional climatic data, including those of southern Spain and the Canary Islands. Given its development with these diverse climatic zones in mind, CERMA’s methodology and datasets make it highly applicable to regions with similar warm and humid conditions, such as the Caribbean. These applications highlight its reliability and adaptability to different climatic zones and regulatory requirements, making it an essential tool for promoting energy efficiency and sustainability in residential buildings [37].



Figure 2. Representative Google Street View images of dwellings in Cartagena de Indias for socioeconomic strata: (a) E1&2; (b) E3&4 and (c) E5&6.

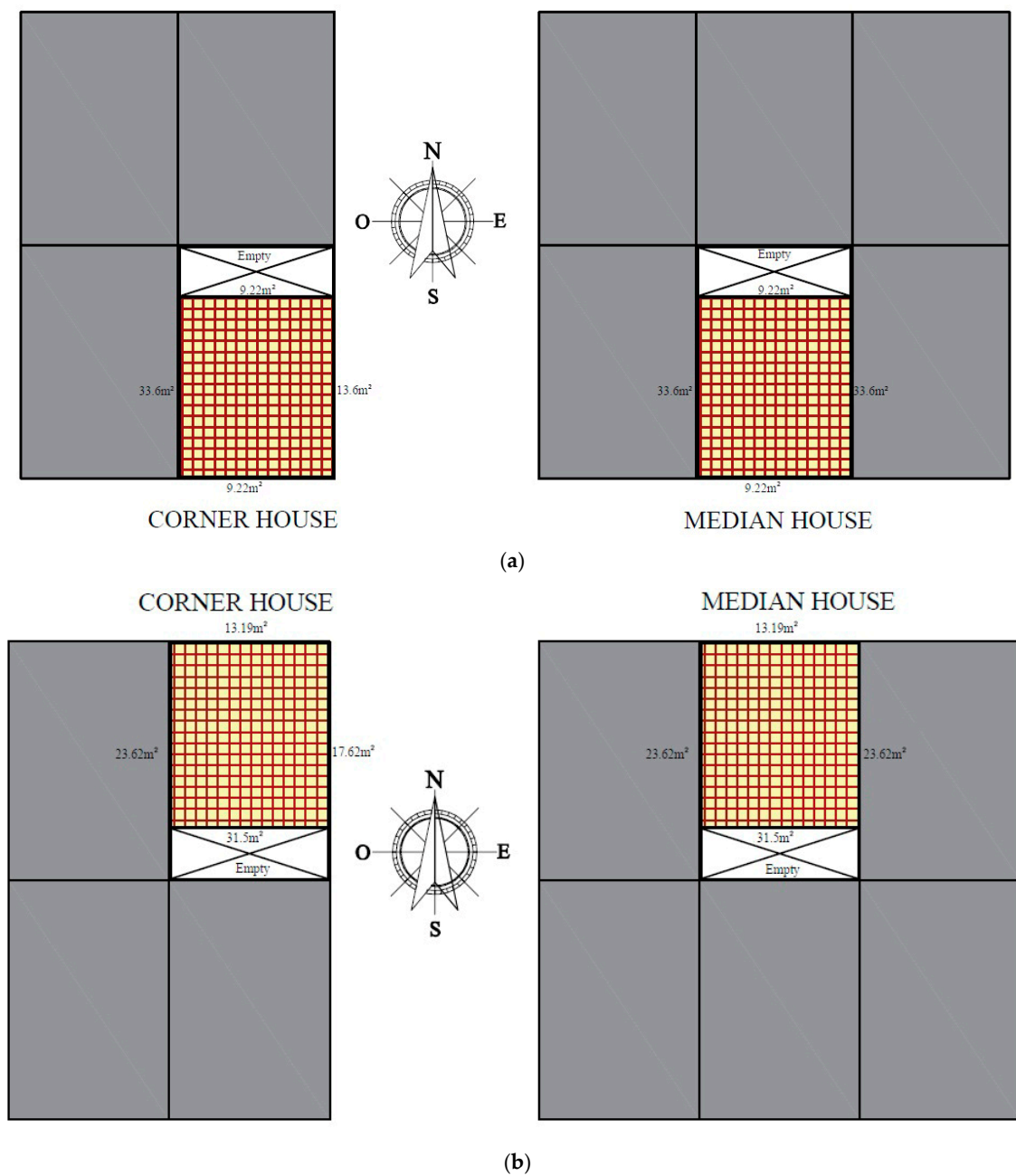
Considering the predominantly hot and arid climate of the Colombian Caribbean, characterized by an average annual temperature of 28 °C, the analysis focused exclusively on cooling loads. Heating and domestic hot water systems were excluded from consideration, as these systems are culturally uncommon and virtually nonexistent in the region, even in higher socioeconomic strata such as strata 5 and 6. This omission reflects the minimal relevance of such systems within the local context, where cooling demands dominate energy consumption patterns [38]. To account for the region's socioeconomic diversity, three socioeconomic strata were defined (1–2, 3–4, and 5–6), as shown in Figure 2, each associated with distinct building characteristics. These characteristics, including geometry, materials, and construction techniques, were based on a comprehensive survey of existing buildings in the region. Table 2 presents the detailed parameters for each building typology. It is important to note that this study assumes steady-state conditions and does not account for occupant behavior or equipment efficiency variations.

For each of the 36 combinations, the CO₂ emissions (kg of CO₂/m² year) were calculated using the CERMA software, according to the Spanish standard [32]. Considering the south-tropical desert climate zone, the present study will only focus on the cooling system, neglecting the heating and domestic hot water system.

By estimating the average CO₂ emissions of dwellings across various socioeconomic strata in Cartagena, it was possible to calculate the annual CO₂ emissions directly attributable to asbestos–cement (AC) roofing. This calculation utilized the total AC roof area identified in previous studies [12,39], which amounted to 9.1 square kilometers.

Table 2. Geometric parameters for each dwelling type and material in each scenario.

General Parameters	Socioeconomic Stratum (E)		
	E 1 & 2	E 3 & 4	E 5 & 6
Type of building	Single-story, single-family home		
Volume (m ³)	140	196	252
Habitable Land (m ²)	50	70	90
Average height (m)	2.8	2.8	2.8
No. of bedrooms	2	2	3
No. of living-dining spaces	1	1	2
No. of wet spaces (bathrooms + kitchen)	2	3	4
Average number of inhabitants	3	3	2

**Figure 3.** Orientation and implementation scheme of the homes considered. (a) South orientation; (b) north orientation.

It is important to note that this calculation offers an approximate estimate, providing a general order of magnitude for the CO₂ emissions generated solely by the presence of AC roofs in Cartagena. A more precise analysis would require detailed data on specific building characteristics, energy consumption patterns, and regional climate conditions.

3. Results and Discussion

The modeling results presented here (Figure 4) provide diverse and highly significant findings that illuminate emission dynamics in the Colombian Caribbean region, as well as in similar desert and subtropical areas.

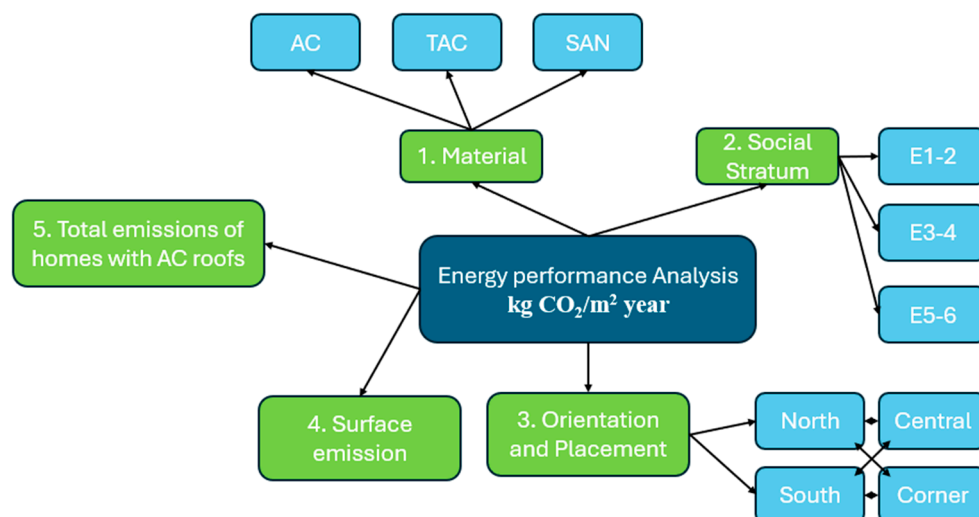


Figure 4. Steps of the analysis.

Figure 5 reveals that north-facing dwellings consistently exhibit superior energy performance across all scenarios compared to their south-facing counterparts, with an average efficiency increase of $4.27 \pm 1.77\%$. This difference, while noteworthy, is less pronounced due to Cartagena's proximity to the equator, where the sun's high angle relative to the zenith minimizes the impact of orientation. These results align with findings in other climatic and geographic contexts, underscoring the critical role of building orientation in optimizing energy performance. For instance, studies on Sizhai traditional dwellings in Zhejiang Province demonstrated a significant variation in energy consumption based on building azimuth, with optimal orientations achieving annual electricity cost reductions of approximately 150 kWh [40]. Similar trends have been observed in traditional Najd courtyard houses [41], where north-facing zones exhibited reduced heating demands in winter due to their lower exposure to direct sunlight, underscoring the broader applicability of our findings.

The observed energy efficiency advantages of north-facing dwellings are further supported by research highlighting the influence of solar exposure on indoor temperature regulation [42]. In high-altitude, hot-climate cities, south-facing rooms have been found to experience indoor temperatures up to 3 °C higher than north-facing ones, emphasizing the substantial thermal load resulting from direct solar radiation. Additionally, shading devices and adjustments to window-to-wall ratios (WWRs) have been shown to significantly mitigate heat gain and enhance energy performance. For example, horizontal overhangs optimized for north and south orientations reduced solar radiation on windows by over 80%, leading to cooling energy savings of up to 22% with appropriately scaled overhang ratios. These findings underscore the importance of integrating passive design strategies, such as orientation, shading, and material selection, into urban planning and architectural design to achieve energy-efficient solutions tailored to specific regional and climatic conditions.

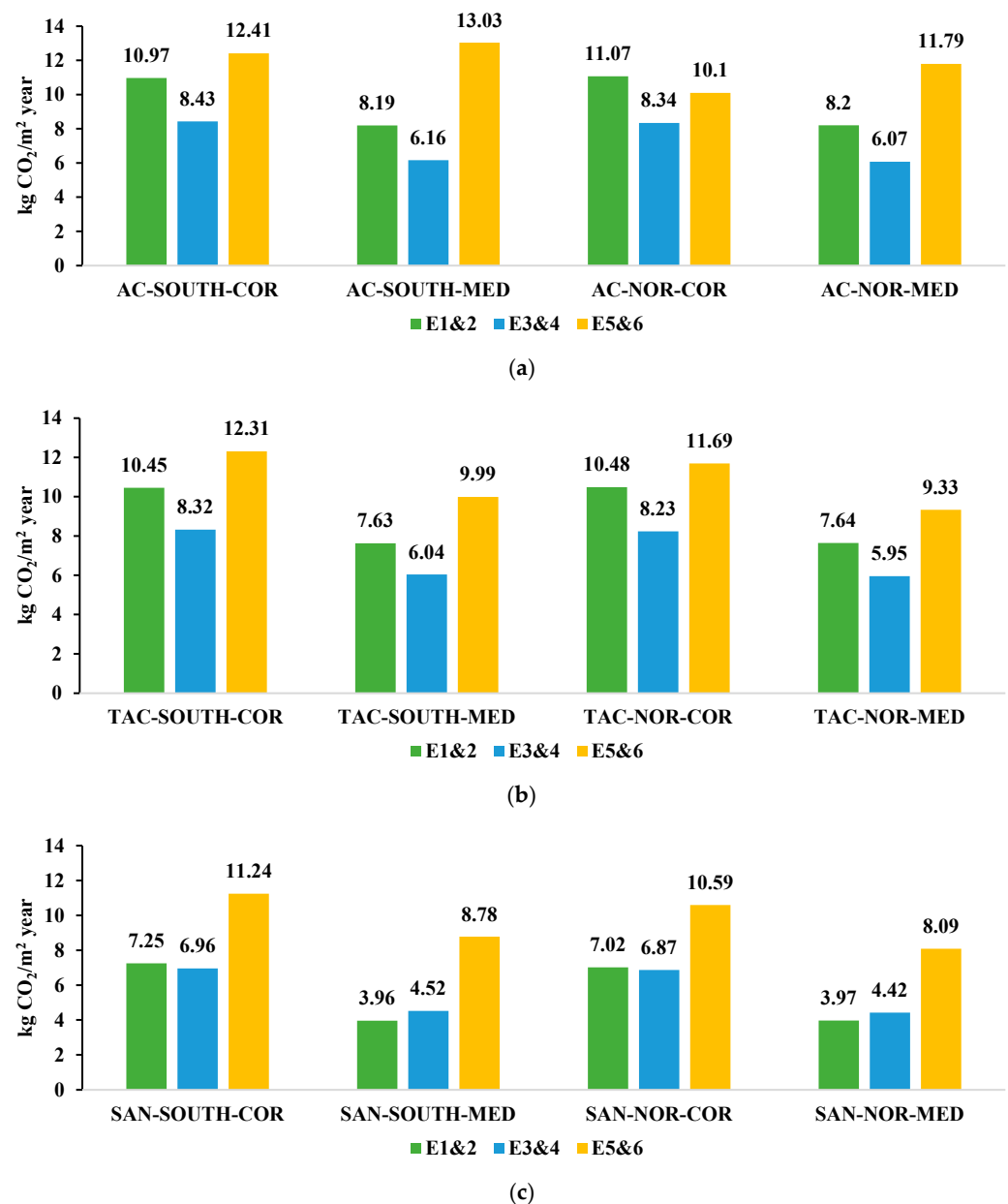


Figure 5. Emissions of the studied housing typologies by socioeconomic stratum. (a) AC = asbestos-cement roof; (b) TAC = thermoacoustic roof; (c) SAN = sandwich roof; NOR = north; MED = median; COR = corner.

Semi-detached homes exhibited an average reduction of 2.16 kg CO₂/m² year compared to corner homes, highlighting the importance of building typology in mitigating emissions. This is attributed to the reduced exterior wall surface area in semi-detached dwellings, resulting in lower sensible energy demand and consequently lower CO₂ emissions. This trend was consistent across all roof types and socioeconomic strata. These findings underscore the importance of building orientation and typology in mitigating carbon emissions in urban environments, particularly in regions with high solar radiation [43,44]. According to the literature [45–47], by promoting building designs that optimize energy performance, it is possible to reduce greenhouse gas emissions and improve overall environmental sustainability.

Figure 6 presents a comparative analysis of CO₂ emissions per square meter per year for different housing typologies and socioeconomic strata.

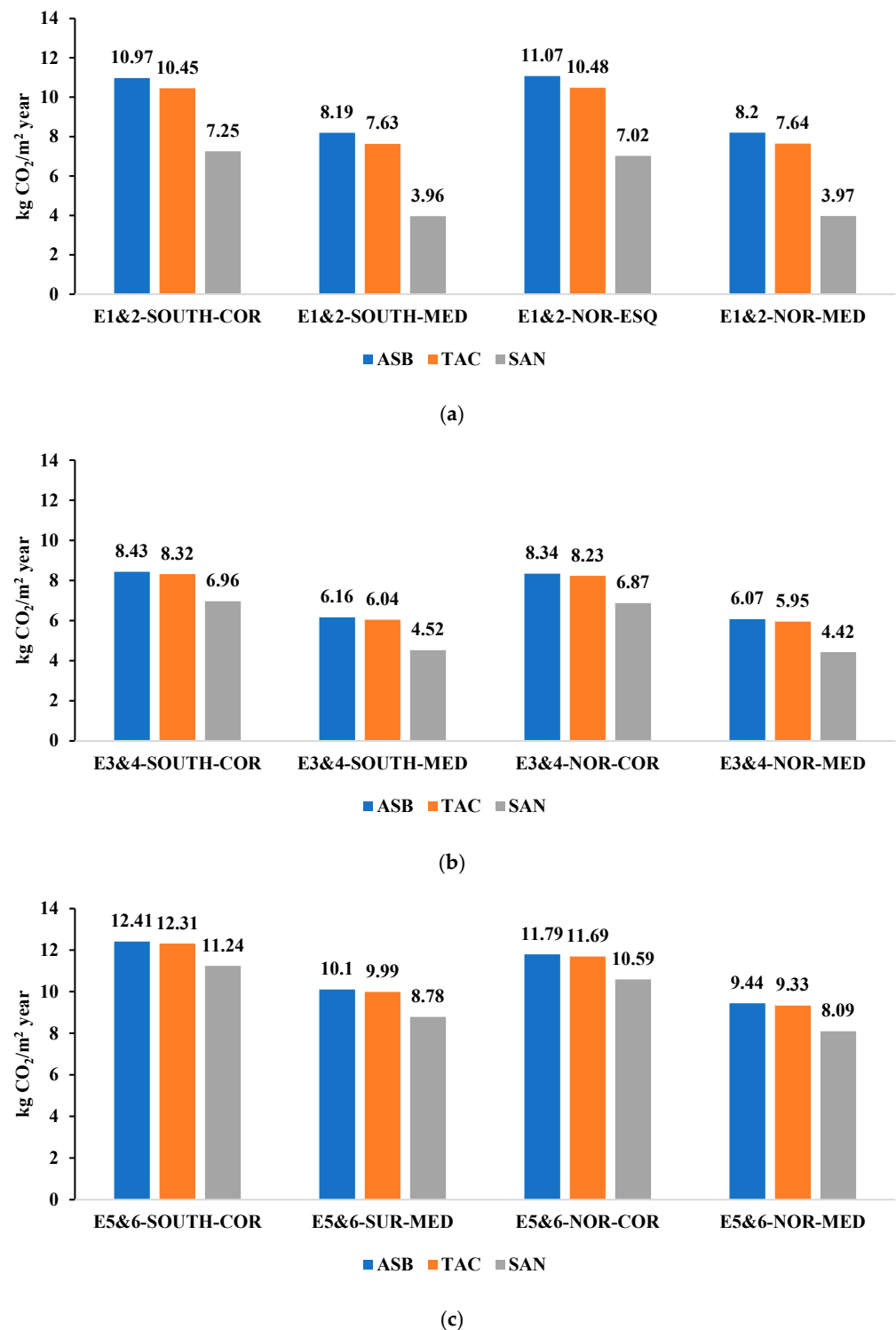


Figure 6. Emissions of the housing typologies studied according to roof material. (a) E1&2 = socioeconomic strata 1 and 2; (b) E3&4 = socioeconomic strata 3 and 4; (c) E5&6 = socioeconomic strata 5 and 6. AC = asbestos–cement roof; TAC = thermoacoustic roof; SAN = sandwich roof; NOR = north; MED = median; COR = corner.

Homes in strata 3 and 4 showed the lowest average CO₂ emissions, which is attributed to better building envelope quality, including more energy-efficient walls, roofs, floors, and windows.

The observed patterns in energy efficiency and CO₂ emissions across different housing strata in Colombia highlight the critical impact of construction practices and material selection. For all types of roofs, orientations, and implementations, it is evident that the superior construction characteristics of homes in higher strata significantly influence their performance. In strata 3 and 4, homes are slightly larger, averaging 70 m² compared to the 50 m² of strata 1 and 2. However, the construction quality of the envelope—encompassing walls, roofs, floors, and windows—is notably better in strata 3 and 4, which contributes to improved thermal performance and lower energy demands [43,46].

A key distinction lies in the proportion of glazed surfaces relative to total wall area [48–50]. In strata 1 and 2, glazing accounts for just 6%, whereas in strata 3 and 4, it increases to 15%. This higher proportion of glazing improves natural lighting and reduces reliance on artificial illumination but may also introduce greater solar heat gains, particularly if shading or insulation measures are inadequate. Meanwhile, homes in strata 5 and 6, which average 90 m² in size, feature an even more significant glazing ratio, exceeding 60%. While the glazing materials—aluminum frames and monolithic glass—are similar to those in strata 3 and 4, the large window areas lead to increased solar heat gain and higher emissions, especially in regions with intense sunlight. Interestingly, despite the larger size of these homes, the quality and thickness of other envelope materials, such as walls, floors, and roofs, do not improve substantially beyond those of strata 3 and 4.

This analysis underscores a critical gap in Colombia's social stratification system, which has yet to incorporate energy efficiency considerations into housing policies. Introducing energy performance criteria into public policy could be a transformative step toward sustainability. Promoting energy-efficient construction would not only reduce greenhouse gas emissions but also enhance thermal comfort for occupants and lower energy consumption from the national grid. These measures would have the added benefit of increasing the economic value of properties, aligning environmental and economic incentives.

Additional insights reveal that roofing materials also play a pivotal role in emissions. Asbestos–cement roofs show CO₂ emissions comparable to thermoacoustic (TAC) roofs, with TAC roofs demonstrating a modest advantage. The emissions reduction achieved with TAC roofs averages 5.80% for strata 1 and 2, 1.59% for strata 3 and 4, and 0.96% for strata 5 and 6 (Figure 6). This trend indicates that in lower strata, roofs contribute more significantly to overall emissions, while in higher strata, the emphasis shifts toward the influence of large glazed surfaces (Figures 7 and 8). This shift highlights the need for the targeted interventions based on stratum-specific energy profiles, ensuring that improvements are both equitable and effective in reducing emissions across all housing categories.

The finding that the use of drywall can be counterproductive in high-performance systems such as sandwich panels underscores the importance of careful selection of materials and construction techniques to optimize energy efficiency. The widespread adoption of asbestos–cement (AC) roofing globally can be attributed to its competitive thermal performance, which remains comparable to that of newer materials like thermoacoustic (TAC) roofs. However, asbestos poses severe health risks as a carcinogenic material [51,52], necessitating its phased elimination as a priority for public health and environmental authorities. Alternatives such as sandwich panels provide a promising solution, offering superior thermal efficiency. These panels yield thermal performance improvements of 42.2%, 21.5%, and 11.5% for housing strata 1–2, 3–4, and 5–6, respectively. This translates to substantial emission reductions of 4.05 kg CO₂/m², 1.55 kg CO₂/m², and 1.26 kg CO₂/m², making them an environmentally and thermally advantageous option. This aligns with findings from life cycle assessment (LCA) studies, such as one conducted in Western Australia [53], which showed that the carbon footprint of roofing materials could be substantially reduced through strategic material selection and recycling efforts. For instance, the integration of cradle-to-cradle material reuse with sheet-metal roofing reduced its carbon footprint by 71–73%, highlighting the potential of material innovations to achieve both thermal and environmental objectives.

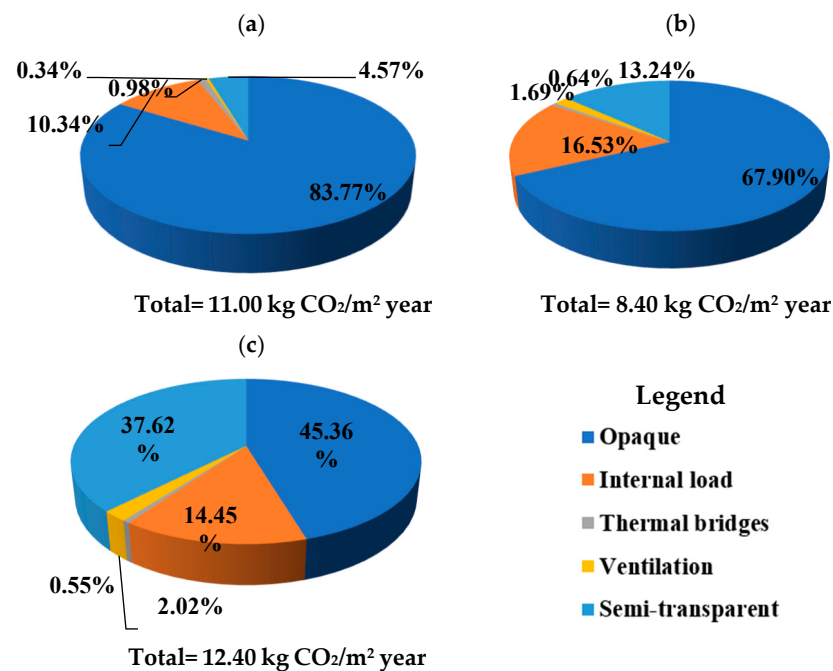


Figure 7. CO₂ emissions by socioeconomic stratum, by component for an AC-SOUTH-COR dwelling. (a) E1&2 = socioeconomic strata 1 and 2; (b) E3&4 = socioeconomic strata 3 and 4; (c) E5&6 = socioeconomic strata 5 and 6. AC = asbestos–cement roof; TAC = thermoacoustic roof; SAN = sandwich roof. NOR = north; MED = median; COR = corner. The “Opaque” category includes walls, ceilings and floors of the home. The “Semi-transparent” category includes doors and windows. Thermal bridges = In energy efficiency, thermal bridges refer to areas in a building’s envelope where heat transfer is significantly higher than in surrounding areas.

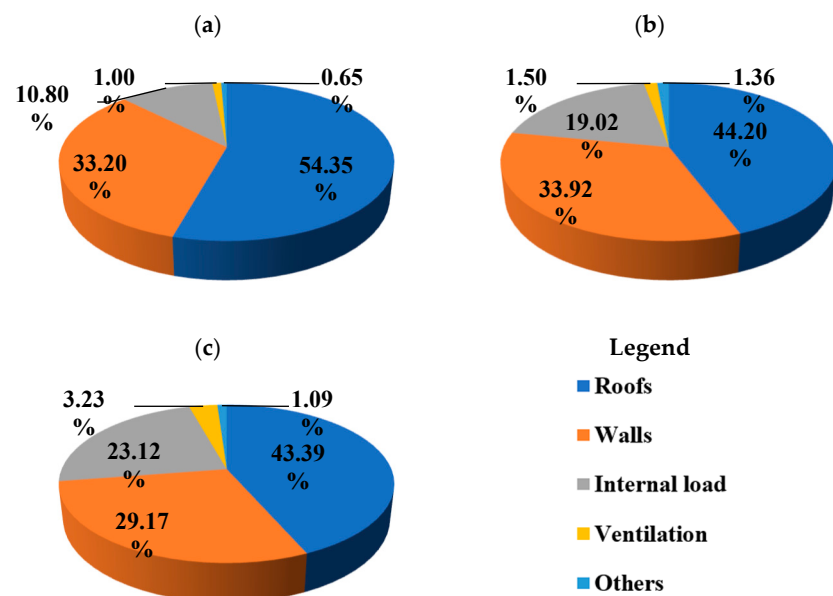


Figure 8. CO₂ emissions by socioeconomic stratum, by groups for an AC-SOUTH-COR dwelling. (a) E1&2 = socioeconomic strata 1 and 2; (b) E3&4 = socioeconomic strata 3 and 4; (c) E5&6 = socioeconomic strata 5 and 6. AC = asbestos–cement roof; TAC = thermoacoustic roof; SAN = sandwich roof. NOR = north; MED = median; COR = corner.

When roofing systems combine multiple materials, such as sandwich panels paired with drywall, the thermal transmittance of the entire assembly (U_{Cover} , see Table A1) is treated as a single value, reflecting the combined properties of all layers. Figure 9 illustrates a comparative analysis of various configurations using sandwich panels across different housing strata. Interestingly, although the same sandwich panel type is employed universally, thermal transmittance (U_{Cover}) is lower in strata 1–2 compared to strata 3–4 and 5–6, where drywall is incorporated.

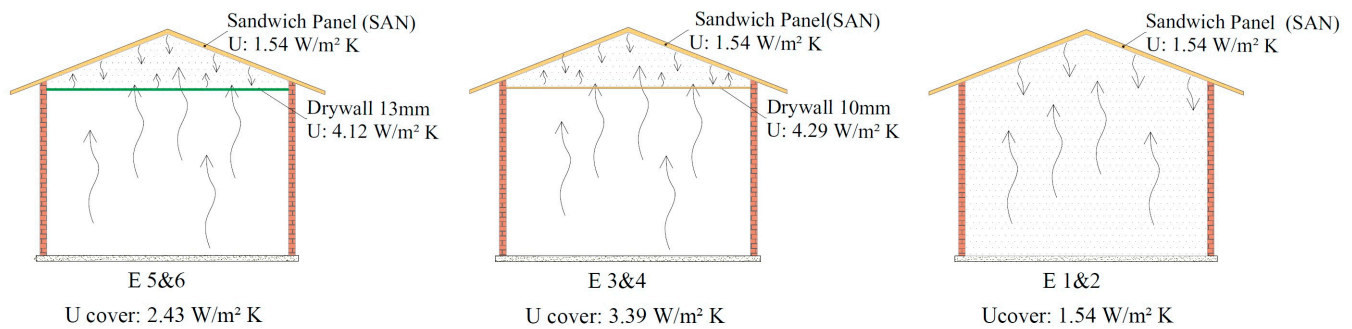


Figure 9. Comparison of housing configurations across socioeconomic strata to highlight the superior thermal performance of sandwich panel-clad dwellings in lower socioeconomic levels.

The interaction between material properties in composite roofing systems provides further insight into optimizing energy performance. For instance, while sandwich panels universally enhance thermal efficiency, the incorporation of drywall in strata 3–4 and 5–6 homes introduces inefficiencies (Table 3). This arises from the high thermal transmittance of drywall, which allows cooled air to penetrate and become trapped between it and the sandwich panel, leading to uneven air distribution and reduced cooling efficiency. As a result, while drywall serves an aesthetic function, its inclusion compromises the energy performance of mid- and high-income housing.

Table 3. Results of emissions generated by homes with asbestos–cement roofs in the city of Cartagena.

Social Stratum (E)	Total Area in the City (km ²)	Area Covered by AC (km ²)	Emissions (Ton CO ₂ /km ² per Year)	Total Emissions (Ton CO ₂ per Year)
1–2	59.68 (73.73%)	6.01	8070	48,500.70
3–4	16.44 (20.31%)	2.83	6690	18,942.76
5–6	4.82 (5.96%)	0.25	10,480	2639.28
Total	80.94 (100.00%)	9.09	-	70,082.74

The literature supports this phenomenon, as studies on building design reveal that inappropriate material layering can compromise energy performance [54]. For example, research on shading devices and window-to-wall ratios (WWRs) has shown that while these elements can significantly reduce heat gain, improper configurations may inadvertently increase reliance on artificial lighting or cooling systems [55]. Similarly, the current study underscores that while drywall can enhance energy efficiency when paired with low-performing roofing materials like AC or TAC, its use alongside advanced systems like sandwich panels is counterproductive.

In contrast, in homes with roofs composed of materials with higher thermal transmittance, such as AC or TAC, the addition of drywall enhances overall energy efficiency. This improvement occurs because drywall's thermal transmittance is lower than that of the external roofing material. Therefore, for roofing systems with inherently low thermal efficiency, the integration of drywall is both technically and economically beneficial. However, in cases where the roofing material already exhibits superior thermal performance

(e.g., sandwich panels), the addition of drywall undermines energy efficiency and should be reconsidered.

These findings emphasize the necessity of context-specific material selection to optimize thermal performance and minimize environmental impact. Public policies should not only promote the adoption of advanced roofing materials but also guide against practices that diminish energy efficiency, such as the indiscriminate use of drywall in high-performing systems. By integrating these insights into design and construction practices, residential buildings can achieve improved energy performance and reduced CO₂ emissions. Furthermore, studies like those conducted in Western Australia highlight the importance of expanding recycling infrastructure, enabling the cradle-to-cradle reuse of materials and fostering sustainability across diverse roofing contexts.

The primary aim of this activity is to encourage readers to understand the environmental impact of residential buildings on the environment. In this specific context, the authors have focused exclusively on emissions, expressed in annual tons of CO₂, originating from homes with asbestos–cement roofs. The findings highlight the need for further research to replicate the hyperspectral classification approach and expand the calculation of emissions across various roof types throughout the city. Such efforts would provide a more comprehensive understanding of the total emissions generated by residential buildings, paving the way for the development of effective strategies to monitor and reduce the negative environmental impacts of housing.

To enhance the environmental sustainability of our surroundings and the planet as a whole, it is crucial to make informed decisions about the materials used in constructing our homes. These decisions should go beyond economic considerations to include the environmental sustainability of the chosen materials. Embracing this perspective would contribute significantly to mitigating the negative impacts of human activity on the environment. By promoting more responsible and sustainable construction practices, a collective effort can be fostered to reduce emissions and ensure a more sustainable future.

Incorporating an environmental lens into construction choices is not merely an idealistic goal but a practical necessity. By understanding the emissions associated with specific construction materials and roof types, stakeholders—including policymakers, urban planners, and residents—can prioritize interventions that yield the greatest environmental benefits. These actions would not only support local and global climate goals but also enhance the long-term value and resilience of the built environment.

4. Conclusions

This study assessed the energy efficiency of buildings with asbestos–cement (AC) roofs in Cartagena de Indias, focusing on the influence of orientation, placement, and socioeconomic strata while exploring alternative roofing materials. The results provide both quantitative and contextual insights into sustainable building practices in the Colombian Caribbean and beyond.

- **Impact of Orientation and Placement:** The findings demonstrate that orientation and placement are critical determinants of energy efficiency. North-facing dwellings consistently outperformed their south-facing counterparts, with a $4.27 \pm 1.77\%$ improvement in energy performance. Similarly, semi-detached (median) configurations exhibited a $23.17 \pm 9.83\%$ advantage over corner placements, corresponding to a reduction of 2.16 ± 0.74 kg CO₂/m² annually. These results highlight the importance of passive design strategies, such as optimal orientation and compact placement, to minimize cooling demands and emissions.

- **Role of Socioeconomic Strata:** Socioeconomic stratification strongly influenced energy efficiency outcomes. Homes in strata 3 and 4 displayed the best thermal performance (6.69 ± 1.42 kg CO₂/m² annually), compared to higher emissions in strata 1 and 2 (8.07 ± 2.42 kg CO₂/m²) and strata 5 and 6 (10.48 ± 1.42 kg CO₂/m²). This difference is attributed to disparities in construction quality, particularly insulation and glazing ratios, which ranged from 6% in lower strata to over 60% in strata 5 and 6. These findings suggest the urgent need for policies that integrate energy efficiency into housing standards, addressing both equity and environmental goals.
- **Evaluation of Roofing Alternatives:** Among roofing materials, sandwich panels demonstrated the highest potential for emissions reduction, with savings of up to 51.6% in strata 1 and 2 south-facing median homes and a minimum of 9.4% in strata 5 and 6. Thermoacoustic (TAC) roofs also performed favorably, particularly in lower strata, reducing emissions by up to 5.80%. However, the environmental benefits of roofing alternatives varied significantly depending on socioeconomic conditions and building configurations, emphasizing the importance of tailored interventions.
- **Policy and Practical Implications:** The research underscores a critical gap in Colombian housing policies, which currently overlook energy efficiency criteria. Implementing these considerations could reduce national energy consumption, improve thermal comfort, and enhance property value. Internationally, the findings provide valuable lessons for regions with similar climates and challenges, particularly those transitioning away from asbestos-based construction. Practical recommendations include promoting the adoption of high-performance roofing materials like sandwich panels, optimizing building orientation and placement in urban planning, and establishing incentives for energy-efficient construction across all socioeconomic strata.
- **Research Limitations and Future Directions:** This study is limited by its focus on cooling loads, reflecting the cultural and climatic realities of the Caribbean, where heating and domestic hot water systems are largely absent. Future research should address the long-term durability and lifecycle costs of alternative roofing materials, explore more granular impacts of glazing ratios and shading devices, and validate findings through real-world case studies. Expanding this framework to other climatic zones would enhance the applicability and robustness of the conclusions.

These results offer actionable insights for policymakers, architects, and urban planners, emphasizing the potential of integrated energy-efficient design strategies to reduce emissions, enhance occupant comfort, and support global sustainability objectives.

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Appendix A

Table A1. Building envelope: constructive and thermal properties for each dwelling type in each scenario.

Characteristic	E 1 & 2		E 3 & 4		E 5 & 6	
	Description	Thermal Transmittance	Description	Thermal Transmittance	Description	Thermal Transmittance
Exterior Wall Main Facade	OUTER SPACE Paint * 1. Cement mortar 0.015 m thick 2. Conventional concrete block de 0.100 m thick 3. Cement mortar 0.015 m thick INTERIOR SPACE	$U = 2.82 \text{ W/m}^2\text{K}$	OUTER SPACE Paint * 1. Cement mortar 0.015 m thick 2. Clay brick with horizontal perforation of 0.100 m thick 3. Cement mortar 0.015 m thick Paint * INTERIOR SPACE	$U = 2.35 \text{ W/m}^2\text{K}$	OUTER SPACE Paint * 1. Stucco layer 3 mm thick 2. Cement mortar 0.015 m thick 3. Clay brick with horizontal perforation 0.100 m thick 4. Cement mortar 0.015 m thick Paint * INTERIOR SPACE	$U = 2.33 \text{ W/m}^2\text{K}$
Exterior Wall Side/Rear Facade	OUTER SPACE 1. Conventional concrete block 0.100 m thick 2. Cement mortar 0.015 m thick INTERIOR SPACE	$U = 2.92 \text{ W/m}^2\text{K}$	OUTER SPACE Paint * 1. Cement mortar 0.015 m thick 2. Clay brick with horizontal perforation 0.100 m thick 3. Cement mortar 0.015 m thick Paint * INTERIOR SPACE	$U = 2.35 \text{ W/m}^2\text{K}$	OUTER SPACE Paint * 1. Stucco layer 3 mm thick 2. Cement mortar 0.015 m thick 3. Clay brick with horizontal perforation 0.100 m thick 4. Cement mortar 0.015 m thick Paint * INTERIOR SPACE	$U = 2.33 \text{ W/m}^2\text{K}$
Median Wall	NEIGHBORING WALL 1. Conventional concrete block 0.100 m thick 2. Cement mortar 0.015 m thick INTERIOR SPACE	$U = 2.07 \text{ W/m}^2\text{K}$	NEIGHBORING WALL 1. Clay brick with horizontal perforation 0.100 m thick 2. Cement mortar 0.015 m thick Paint * INTERIOR SPACE	$U = 1.99 \text{ W/m}^2\text{K}$	NEIGHBORING WALL 1. Clay brick with horizontal perforation 0.100 m thick 2. Cement mortar 0.015 m thick Paint * INTERIOR SPACE	$U = 1.94 \text{ W/m}^2\text{K}$
Cover	SCENARIO No. 1 (AC) OUTER SPACE 1. AC cover of 6 mm INTERIOR SPACE	$U = 6.37 \text{ W/m}^2\text{K}$	SCENARIO No. 1 (AC) OUTER SPACE 1. AC cover of 6 mm 2. Plasterboard or drywall sheet 10 mm thick INTERIOR SPACE	$U = 4.16 \text{ W/m}^2\text{K}$	SCENARIO No. 1 (AC) OUTER SPACE 1. AC cover of 6 mm 2. Plasterboard or drywall sheet 13 mm thick INTERIOR SPACE	$U = 3.87 \text{ W/m}^2\text{K}$
	SCENARIO No. 2 (TAC) OUTER SPACE 1. Thermoacoustic plastic cover (Ref: ECOROOF Residencial 2 mm thick—Arkos brand, see table footer) INTERIOR SPACE	$U = 5.62 \text{ W/m}^2\text{K}$	SCENARIO No. 2 (TAC) OUTER SPACE 1. Thermoacoustic plastic cover (Ref: ECOROOF Residencial de 2 mm thick—Arkos brand, see table footer) 2. Plasterboard or drywall sheet 10 mm thick INTERIOR SPACE	$U = 4.16 \text{ W/m}^2\text{K}$	SCENARIO No. 2 (TAC) OUTER SPACE 1. Thermoacoustic plastic cover (Ref: ECOROOF Residencial de 2 mm thick—Arkos brand, see table footer) 2. Plasterboard or drywall sheet 13 mm thick INTERIOR SPACE	$U = 3.87 \text{ W/m}^2\text{K}$
	SCENARIO No. 3 (SAN) OUTER SPACE 1. Sandwich type cover (Ref: SKYDECK 10 mm thick—ABACOL brand, see table footer) INTERIOR SPACE	$U = 1.54 \text{ W/m}^2\text{K}$	SCENARIO No. 3 (SAN) OUTER SPACE 1. Sandwich type cover (Ref: SKYDECK de 10 mm thick—ABACOL brand, see table footer) 2. Plasterboard or drywall sheet 10 mm thick INTERIOR SPACE	$U = 3.39 \text{ W/m}^2\text{K}$	SCENARIO No. 3 (SAN) OUTER SPACE 1. Sandwich type cover (Ref: SKYDECK de 10 mm thick—ABACOL brand, see table footer) 2. Plasterboard or drywall sheet 13 mm thick INTERIOR SPACE	$U = 2.43 \text{ W/m}^2\text{K}$

Table A1. Cont.

Characteristic	E 1 & 2		E 3 & 4		E 5 & 6	
	Description	Thermal Transmittance	Description	Thermal Transmittance	Description	Thermal Transmittance
Ground (floor)	INTERIOR SPACE 1. Polished concrete 2. Rammed earth (0.1 m) NATURAL GROUND	U = 2.99 W/m ² K	AIRE INTERIOR 1. >Ceramic floor 6 mm thick 2. Adhesive mortar (0.01 m) 2. Concrete (0.1 m) 3. Rammed earth (0.1 m) NATURAL GROUND	U = 2.94 W/m ² K	INTERIOR SPACE 1. Ceramic floor 9 mm thick 2. Adhesive mortar (0.01 m) 2. Concrete (0.1 m) 3. Rammed earth (0.1 m) NATURAL GROUND	U = 2.91 W/m ² K
External doors	Metal door	U = 5.70 W/m ² K	Medium/low density wood door, 2.1 m high and 0.9 m wide	U = 2.00 W/m ² K	Wooden door—medium/low density, 2.4 m high and 1.0 m wide.	U = 2.00 W/m ² K
External windows	Metal frame 4 mm monolithic glass	U = 5.70 W/m ² K	Metal frame 4 mm monolithic glass	U = 5.70 W/m ² K	Metal frame 6 mm monolithic glass	U = 5.70 W/m ² K

* Paint: The paint layer is not considered to contribute to the thermal resistance of the building element (wall). Covering layers 3 and 4: The space between the drywall and the ceiling is assumed to have poor airtightness due to open joints or the presence of permanent ventilation openings. Covering layers 5 and 6: All components are assumed to be well-sealed, with only small ventilation openings. Thermal properties: The thermal properties of walls, doors, windows, and floors were obtained from the Construction Elements Catalog of the Spanish Technical Building Code, which is integrated into the CERMA software [32]. Asbestos–cement sheet: The thermal transmittance of asbestos–cement sheets was taken as the average of these values found in the following 3 sources [28–30]. ECOROOF thermoacoustic tiles: The thermal conductivity of ECOROOF thermoacoustic tiles was taken from [31]. Sandwich tiles: The thermal conductivity of sandwich tiles was taken from [26].

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