Article

Techno-Environmental Assessment of Insulation Materials in Saudi Arabia: Integrating Thermal Performance and LCA

Yazeed Alsaqabi [1], Abdulbasit Almhafdy [1,*], Husnain Haider [2], Amirhosein Ghaffarianhoseini [3], Ali Ghaffarianhoseini [3] and Ahmed AbdelMonteleb M. Ali [1,4]

[1] Department of Architecture, College of Architecture and Planning, Qassim University, Buraydah 52571, Saudi Arabia; y.alsaqabi@qu.edu.sa (Y.A.); ahm.ali@qu.edu.sa (A.A.M.A.)
[2] Department of Civil Engineering, College of Engineering, Qassim University, Buraydah 52571, Saudi Arabia; h.hussain@qu.edu.sa
[3] Department of Built Environment Engineering, School of Future Environments, Auckland University of Technology, Auckland 1010, New Zealand; amirhosein.ghaffarianhoseini@aut.ac.nz (A.G.); ali.ghaffarianhoseini@aut.ac.nz (A.G.)
[4] Department of Architectural Engineering, Faculty of Engineering, Assiut University, Assiut 71515, Egypt; ahmed.abdelmonteleb@aun.edu.eg
* Correspondence: a.almhafdy@qu.edu.sa

Abstract: Arid and hot regions, like Saudi Arabia, utilize up to 60% of the country's energy to regulate buildings' indoor comfort. Energy efficiency is a long-term sustainability measure that is part of the government's Vision 2030 strategy. A standard method of improving the thermal performance of buildings is through the use of insulation materials. Considering the cooling loads' requirement and the Global Warming Potential (GWP), the present research evaluated the effectiveness of insulation materials, including extruded polystyrene, expanded polystyrene, rock wool, and glass wool in the hot, arid climate. For this case study, four similar villas facing the cardinal directions were selected from the residential project at Qassim University. HOBO data loggers were used to collect indoor temperature data. Thermal performance and Life Cycle Assessment (LCA) were conducted in accordance with Saudi Building Code-602 (SBC-602). Simulation outputs based on the four cardinal directions were used for assessing the thermal performance and LCA of the different thicknesses and densities of insulation materials. This was done using IESVE and SimaPro, IMPACR2002+, to assess their cooling load and GWP, respectively. The results suggest the potential for using lower insulation thickness for the northern and western façades without violating the SBC. The results obtained the actual thicknesses of the three insulation materials for achieving indoor temperatures in the four cardinal directions and the selection of materials and their densities along with associated GWP. The outputs of the study have been generalized in the form of a performance-based flowchart as a tool for selecting the type and thickness of thermal and environmental insulation in residential buildings in the Qassim region of Saudi Arabia.

Keywords: thermal performance; wall insulation; orientation; life cycle assessment; energy efficiency
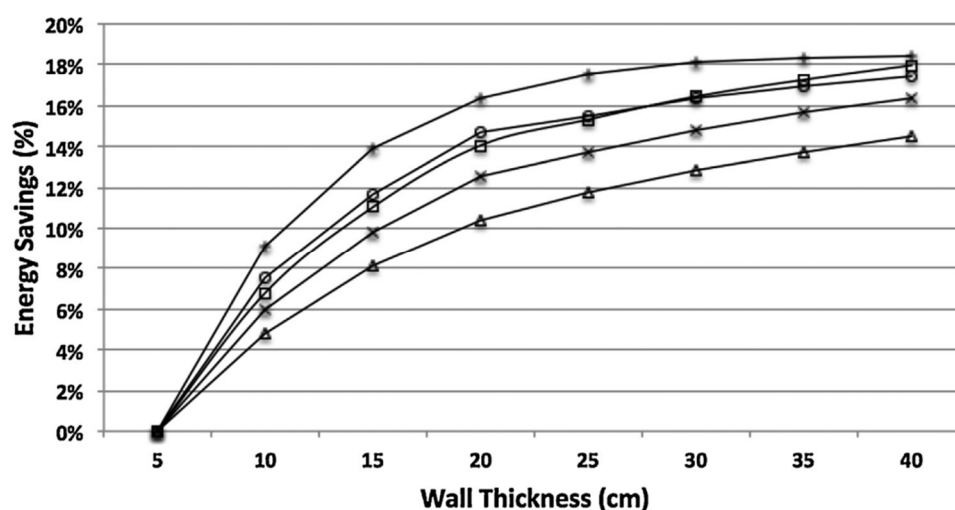
1. Introduction

Globally, the building sector consumes 40% of primary energy for cooling and heating [1], which is consumed primarily by the building envelope (including the wall, windows, roof, and infiltration rate) [2]. Wall insulation plays a vital role in improving energy efficiency and reducing carbon emissions in residential buildings, with increased wall thickness being an acknowledged solution [3,4]. Increased insulation thickness, however, has an adverse impact on the Life Cycle Assessment (LCA) of energy consumption and emissions since it also includes these parameters from the manufacturing processes [5,6]. Hence, the evaluation of insulation materials from the life cycle perspective for region-specific

suitability is essential as a sustainability measure. Additionally, it will enhance the overall thermal efficiency of the entire building structure as a wall envelope.

According to Krarti et al., [7], over 65% of the annual energy consumption of a non-insulated villa in a hot, arid climate (e.g., Qassim region) is used for air-conditioning, which accounts for a significant portion of the electricity consumption by Saudi households. With 50% of the building sector's energy consumption coming from the residential sector, improving its energy efficiency is critical. While previous efforts have focused on the energy efficiency of electrical appliances, these need to be supplemented by the evaluation of potential improvements in thermal performance and the envelope design of residential buildings [8].

Alaidroos and Krarti [9] investigated the impact of building envelopes on the energy performance of residential houses in Saudi Arabia using the EnergyPlus package, reporting energy savings between 22.7% and 39.5% for cities with different climatic conditions (Figure 1). Based on the results, the study found that adding wall thermal mass saves energy in Abha, a city with a mild climate, while the lowest energy savings were found in Jeddah, which has an extremely hot climate. A large temperature difference between daytime and nighttime allows heat to be stored during a day cycle and then released during a night cycle. This energy exchange is why thermal mass is most effective in climates with a high diurnal temperature range. A simulation of the impacts of five sequential building envelope energy retrofits on the cooling load in residential buildings in Qatar pointed to circa 53% reduction in cooling demand, with a moderately short payback period [10].

Figure 1. Total annual energy consumption, space cooling and space heating for a villa located in five KSA cities [9].

As summarized in Table 1, the impact of the wall envelope on energy consumption and the life cycle cost estimation was the focus of many research projects. Sobhy et al. [11] compared the outer walls of a traditional brickwork residential building with single and double walls (with a cavity) along the western and northern façades. The study found a reduction in cooling/heating energy demand between 5% and 13% as a result of thermal insulation and a conducive climate. Al-Sanea et al. [12] evaluated the thermal resistance capacity of four types of walls (concrete bricks with an insulation layer, double concrete with an insulation layer, clay bricks with an insulation layer, and double clay bricks with an insulation layer) in three different climatic regions of KSA, Riyadh, Jeddah, and Abha. While the wall structure (layering arrangement) did not impact the load transmission, over-all cost, or thermal resistance, insulation and environmental conditions greatly impacted thermal resistance. For polystyrene, polyurethane, and rock fiber, the average thermal resistance values for Riyadh were found to be 2.84, 2.05, and 2.40 $m^2k/watt$, respectively. A combination of polystyrene and double walls was found to be the most cost-effective,

with quick investment recovery, while the following average thermal resistance values were obtained, polystyrene (1.92 m^2k/watt), polyurethane (1.46 m^2k/watt), and rock fiber (1.66 m^2k/watt).

Recently, Al-Naghi et al. [13] compared lightweight concrete bricks with conventional concrete bricks using the DesignBuilder platform. Lightweight concrete bricks demonstrated five-fold higher thermal resistance than standard concrete bricks, transferring 82% more heat than standard bricks and saving 58% in energy consumption. Pourghorban et al. [14] found wall insulation to be the most effective way to reduce heat loss from a building's exterior as well as energy consumption for hot environmental conditions based on a performance evaluation of hollow walls (reflective insulation systems) with 20-cm air separation. The study also evaluated the effectiveness of reflective, mass, suction, and nanosystems of the thermal insulation of buildings, considering materials such as glass wool (GW), rock wool (RW), expanded polystyrene (EPS), and extruded polystyrene (XPS) as part of the mass scheme, which considers the limitations of the wall envelope. RW, GW, EPS, and XPS are the materials of choice for residential thermal insulation [15].

Several studies have investigated the optimal thickness of thermal insulation based on the building's position and climatic factors [16–19]. Some studies pertaining to the impact of energy sources on the insulation thicknesses for typical buildings in different climate zones of Turkey found an optimum thickness between 2.0–17 cm [20,21]. Yu et al. [22] investigated typical residential external walls in five Chinese cities, including Shanghai, Changsha, Shaoguan, and Chengdu, and found that the effect of orientation on the optimum insulation cannot be ignored. The optimum thickness ranged between 5.3 cm and 23.6 m in these five cases, with over 79% energy savings. Another study by Ucar and Balo [23] investigated the optimum thicknesses for four climate zones of Turkey and found that the optimum insulation thicknesses varied between 1.06 and 7.64 cm, depending on the city and the heating fuel used. Derradji et al. [24] investigated the insulation thickness of expanded polystyrene in different regions of Algeria and found an optimal range between 1 cm and 2.5 cm, with 0.5 and 1.5 $/m^2$ energy savings, depending on the type and the percentage of the windows.

Table 1. Relevant past studies on wall envelope design impact on energy consumption and the LCA of wall insulation materials.

Reference	Parameters Included	Methods Used	Outcomes
[13]	AAC Blocks, Insulating Plaster, and Reflective Coating	Infrared cameras, temperature/relative humidity sensors, U-value equipment	— ACC walls perform better than HCB walls. — Thermal transmittance was reduced by 82% with the ACC walls. — Insulation plaster and reflective coating achieved a 58% reduction.
[25]	WWR	Experimental measurement, TAS EDSL	— Given attention to the heat gain, South and East orientation are the worst in all the cities. — 10% of WWR is recommended.
[26]	Environment, energy, economy c	Experimental measurement	— Polyurethane 8 cm, EPS 20 cm, and Rockwool 7 cm are optimum energy, economy, and environment states.
[9]	Wall insulation, Roof insulation, WWR, window Shading，and thermal mass	Costs of life cycle Analysis Energy cost savings	— During the life of each residential house, the Saudi government would spare up to 36% on subventions.

Table 1. *Cont.*

Reference	Parameters Included	Methods Used	Outcomes
[27]	Masonry bricks	Experimental measurement	— Compared to standard concrete brick, the insulated red clay brick sample (insulating mortar) had the highest percentage upsurge in thermal resistance — Body-mixing or filling the holes with insulation to bricks improved thermal resistance. — Analyzing insulating mortar vs. standard concrete mortar, the thermal resistance significantly increased.
[28]	External Walls R-Value	Thermal and economic analyses	— Wall design has the most negligible impact on transmission loads, total expense, and optimum R-values, while insulation form and environment have the most impact. — In both walls and climates, polystyrene has the lowest overall cost — Polystyrene was found to be furthermost remunerative and showed the fastest payback time.
[29]	EPS Wood fibre Rockwool GW	Simulation, TRNSYS	— EPS, GW, Rockwool, and wood fibre were tested.
[30]	Walls installations Roof installations Window GHG emissions EE consumption	AccuRate V2.0.2.13SP2	— In terms of life cycle GHG emissions, built-in sandwich walls with PET foam cores, double-glazed windows, and concrete roof tiles produce the lowest.
[31]	thermal admittance, steady thermal transmittance, surface mass, thickness	MatLab rel. 7.0 FRONTIER rel. 4.3	— Pre-cast walls were found highly efficient when they are in ultra-thin or thin thicknesses
[32]	thermal resistance thermal transmittance two exterior reinforced pre-cast concrete walls	Experimental measurement	— N and E walls have thermal mean transmittance (air to air) of 1.803 and 1.459 W/m^2 K. — Mean thermal resistance for the surface to surface) at N and E walls are 0.352 and 0.355 W/m^2 K. — Thermal transmittance is affected by external weather conditions and wall orientation, but thermal resistance is not.

Table 1. *Cont.*

Reference	Parameters Included	Methods Used	Outcomes
[33]	pre-cast concrete sandwich panels	Lab Experimentation "hot plate apparatus"	− The U-value of a thin sample sandwich panel (150 mm thick) is 0.324 W m2 K1, which is 16% lesser than a standard 315 mm wide sandwich panel (With polystyrene foam 100 mm). − The thin sandwich panel scores 71% thermal transmittance from the overall thermal transmittance. − The percentage of regular walls was less than 20%. In an optimized panel configuration, the U-value was reduced by 59 percent to 0.13 W m2 K1.

The literature also presents certain investigations that have evaluated the impact of insulation position. Al-Sanea and Zedan [34] found 7.8 cm an optimum figure for liquid polystyrene wall insulation for Riyadh and suggested separating the insulation into three layers (2.6 cm each) to save 1.6% cooling and 3.2% heating energy. Ozel [17] studied the effect of insulation location (inside, outside, and middle) and found that the insulation outside gives the smallest fluctuation; however, the location did not affect the optimum insulation thickness. Ahmed et al. [32] studied the effect of orientations on the thermal transmission of external pre-cast hollow walls through experimental measurements on-site for a residential house in Dhahran. Their study found around 25% higher thermal permeability on the northern wall in comparison to the eastern wall with an average thermal resistance of 0.35 K/s. The study concluded that the orientation of the wall does not affect thermal resistance, but the direction and external weather conditions impact thermal permeability. Ozel [35] determined the ideal polystyrene insulation thickness for Elazig, Turkey's four directions and found that the south was the most energy-efficient direction, requiring a 5.5 cm-thick southern outer wall, while the northern, eastern, and western walls should be 6 cm thick.

Certain studies integrate energy performance with LCA. Stazi et al. [36] used an optimization approach for solar wall systems and found a potential to reduce cumulative energy demand and CO_2 emissions by up to 55%, for the production and use phases of LCA, compared to traditional methods. Earlier, Kim [37] used eQuest and SimaPro to examine the differences between glass curtain walls and transparent composite façades over the life cycle. They assessed that 93% of the life cycle energy uses and 89% of equivalent CO_2 emissions of glass curtain walls were needed for transparent composite façades, with the potential further improvement that can be made by enhancing energy performance, durability, and recycling materials.

Babaizadeh et al. [38] used TRACI-based BEES, SimaPro, and EnergyPlus to investigate energy consumption and LCA of five window-shading devise configurations of different materials, i.e., aluminum, wood, and polyvinyl chloride, for buildings in the USA. The study found that the horizontal form of shading is more efficient than others in all climatic conditions and recommended a solar shading system for mixed humid and hot-humid climate zones. The benefits of reduced energy consumption outperformed depleted emissions during different life cycle phases. Wood-based materials were highlighted as the most environmentally friendly, followed by aluminum.

Increasing interest in external walls and their continuous development is evidenced through literature reviews and practical and laboratory experiments about external walls of buildings. Using thermal insulators in external walls is an established methodology; however, determining the optimal type of insulation and the optimum thickness in terms
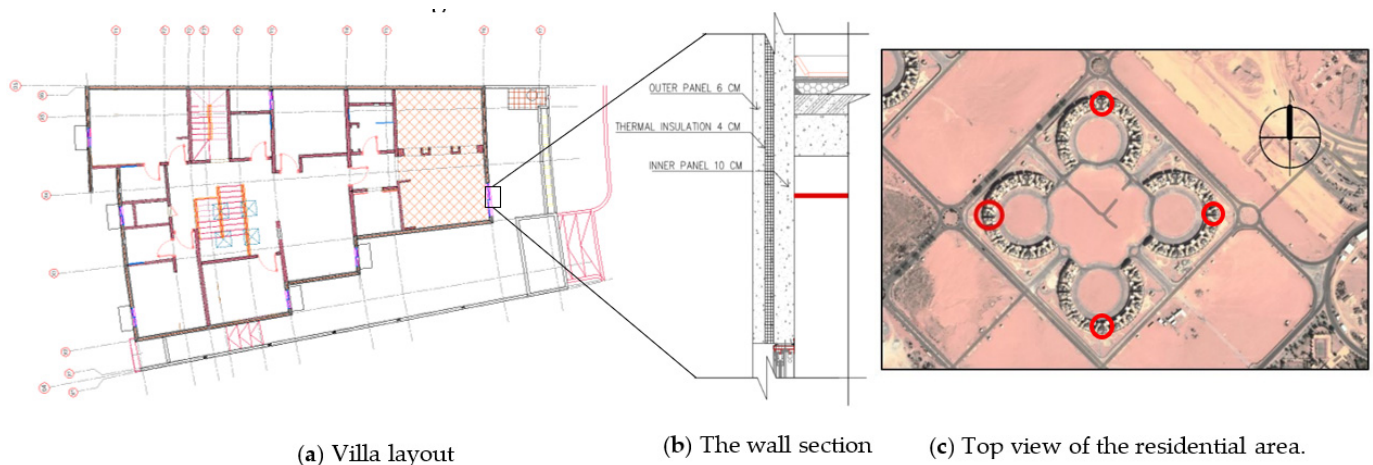
of thermal and environmental performance (evaluation life cycle of a substance) is the key challenge.

The lack of research on optimal insulation thickness relevant to Saudi Arabia, as opposed to a large quantum of research globally, is likely due to the low per-unit electricity cost in KSA. However, environmental concerns in the Kingdom's Vision 2030 (through stated environmental conservation through higher energy costs) demonstrate a focus on research in this domain. Within KSA, there is a void of research for determining the appropriate insulation materials and thickness specifically for the Qassim region. This provides the opportunity to combine thermal performance and LCA-based environmental impact assessment for determining optimum insulation. The research reported in this paper has two primary objectives: i) To evaluate four frequently used insulation materials (with different specifications) and assess the optimal properties of these systems, and ii) To conduct an integrated analysis of energy performance and LCA of the optimal insulation materials specific to the Qassim region in KSA.
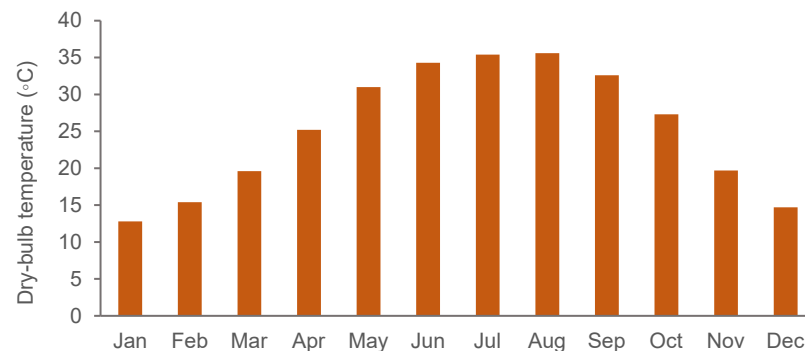
2. Methods

2.1. Study Area

The area identified for undertaking the study was faculty housing at Qassim University, consisting of consists of 288 residential villas of similar design, illustrated in Figure 2. The geometric layout of the villas provided an opportunity to investigate various factors affecting their thermal performance. The climate of the Qassim Region is generally hot and dry with wide temperature variations ranging from 46 °C (July) to below freezing during winter (nights) (Figure 3). The significant seasonal temperature variation is accompanied by high intensity of solar radiation due to clear skies and low cloud cover—approximately 1000 watts/m^2 h (General Authority of Meteorology and Environmental Protection (GAMEP), 2016) which increases the severity of environmental conditions.

(**a**) Villa layout   (**b**) The wall section   (**c**) Top view of the residential area.

Figure 2. Location of an experimental study in Qassim University, (**a**) Villa layout, (**b**) The wall section, (**c**) Top view of the residential area.

The field study was conducted to simulate the thermal performance using IESVE by creating sequential modifications in the building's (insulation) design to assess thermal performance. The measuring instruments were selected from HOBO. In order to examine the energy consumption for cooling the residential buildings, the air temperature was monitored over 24 h (28 July 2021) in the center of the western room (Figure 2) at a height of 1.5 m. The air conditioners were turned off, while all doors and windows were closed. The simulation models provided an accurate and detailed analysis of the building's thermal performance, electricity consumption, and microclimate. The boundary conditions of the wall configurations (49.8 m^2 wall area for the simulated room), indoor temperature, and

outdoor temperature (for the whole year) were calculated in IESVE based on the given characteristics shown in Tables 2 and 3.

Figure 3. Average monthly temperatures for Qassim region (Source: GAMEP met. Station, 2016).

Table 2. Material properties of building construction.

Element	Construction	U-Value (W/m^2.k)
External wall with XPS Insulation	Pre-cast Concrete 20 cm: Outer panel 6 cm Insulation 4 cm Inner panel 10 cm	0.2780
Internal Wall	Concrete Brick wall	2.63
Roof	Tile finish Waterproof membrane Concrete deck Insulation Plasterboard	0.202
Glazing (Aluminum Frame)	Double Glazing Outer pane 6 mm Cavity 12 mm Inner pane 6 mm	2.032 SHGC 0.25
Ceiling/Flooring	Porcelain tile finish Reinforced concrete Plasterboard	0.397

2.2. Energy Analysis

The energy analysis simulation model focused on cooling energy loads. As shown in Figure 4, the base model was modeled on the actual house design, with the exterior windows and construction used with their original specifications (Table 2) through the simulation. Prior to undertaking the parametric analysis, the model was calibrated to ensure consistency and accuracy of simulation results using ambient air temperature as the variable of interest. Further, as done by Zhang et al. [39], the Pearson correlation coefficient was used to obtain the correlation between the field data and the simulated results, as a measure of the error between the two datasets.

Table 3. Energy and LCA parameters for the insulation properties.

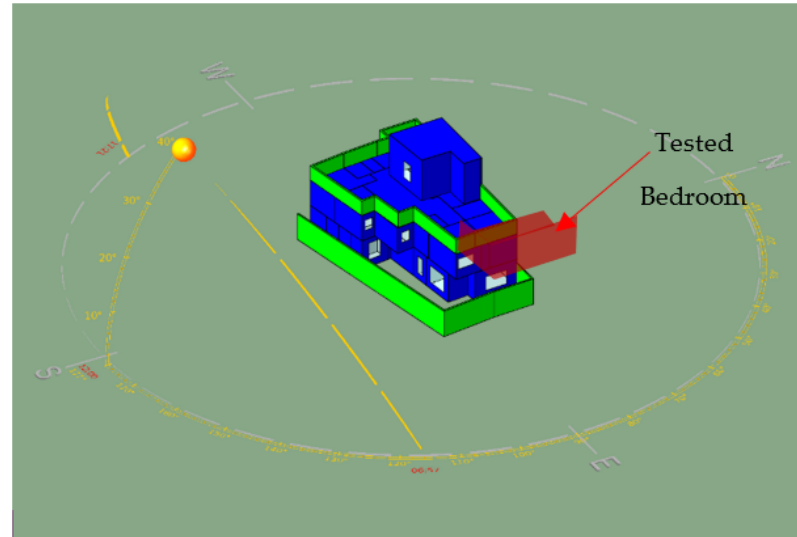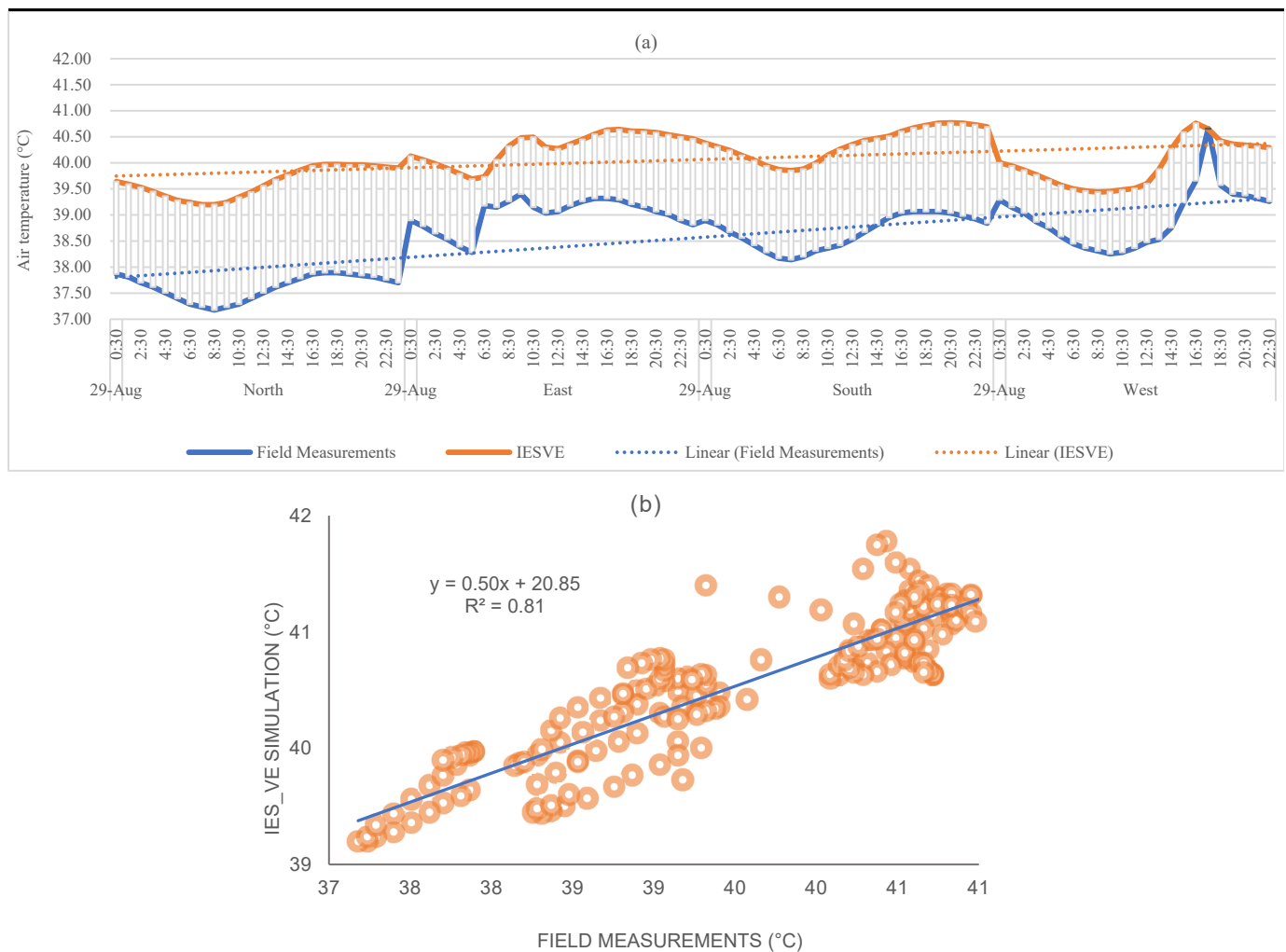| Wall	Wall Insulation		U-Value (W/m². k)	Orientation	Required U-Value by SBC-602
	Type	Thickness (mm)			
Outer Pane: 60 mm Inner Pane: 100 mm	EXP—5.28 Kg Co2 eq.	50	0.5107	N E S W	**0.342**
		60	0.4364		
		70	0.3810		
		80	**0.3381**		
		90	0.3038		
	GW—3.2 Kg Co2 eq.	80	0.4364		
		90	0.3935		
		100	0.3582		
		110	**0.3288**		
		120	0.3038		
	EPS—2.9 Kg Co2 eq.	70	0.4364		
		80	0.3880		
		90	0.3493		
		100	**0.3176**		
		110	0.2912		
	RW—1.3 Kg Co2 eq.	65	0.4769		
		75	0.4211		
		85	0.3770		
		95	**0.3413**		
		105	0.3117		

Figure 4. The Baseline Model built in IESVE.

Figure 5a,b presents the relationship between the simulated indoor air temperature results and the collected field measurement as a line chart and scatter plot, illustrating a positive correlation ($R^2 = 0.81$) between them. This substantially validates the robustness of the model used, as well as the selection of the variable of interest to drive the simulation model. While considering the four main orientations, north, east, south, and west, 48 parametric simulations were undertaken to examine the impact of four wall insulation materials (XPS, GW, EPS, and RW with different thicknesses) on the building's energy performance.

Figure 5. Filed measurements data (**a**) for whole day in all orientations, and the scatter plot (**b**) represents the correlation coefficient between Field data and simulation result.

The minimum U-value specified in SBC-602 for residential buildings (0.342 W/m^{2}K) was applied to all insulation materials to simulate the least cooling load. Thus, in accordance with the code, the cooling load was used as a benchmark to compare and analyze the other scenarios. The impact of orientations of the buildings on the simulation results creates a benchmark for simulation models with other variables of interest.

2.3. Life Cycle Assessment (LCA)

LCA is a tool used to assess the expected effects of a product or process on nature by determining the evaluation system's limits, whether for the manufacturing stage, the operational stage, the depreciation, the recycling stage, or for all phases according to the study's system.

There were many LCA standards; in 1994. The Canadian Standards Association released the first global LCA standard. However, Figure 6 shows that the International Standards Organization ISO had the most acknowledged standards, with many series such as follows:

- ISO 14040: Environmental management, LCA, Principles, and framework [40].
- ISO 14041: Environmental management, LCA, Goal definition, and inventory analysis [41].
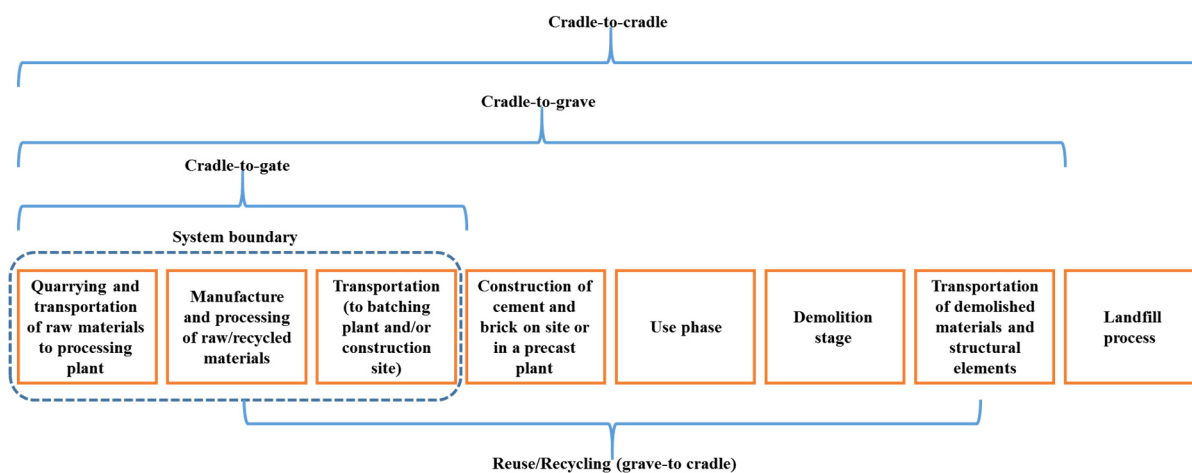- ISO 14042: Environmental management, LCA, Life-cycle impact assessment [42].

- ISO 14043: Environemental management, LCA, Life-cycle interpretation [43].

Figure 6. Life-cycle assessment framework [40–43].

2.3.1. Goal and Scope

To determine the environmental impacts of four wall insulation materials, including XPS, GW, EPS, and RW with different thicknesses, The scope of the study highlights the cradle-to-gate phase of the product life cycle (Figure 7), which comprises the production stage. The functional unit is one kilogram per unit, i.e., standardization of the mass for each material in all scenarios. SimaPro licensed software (V.9.1.1.1) performed LCA stage outlines by ISO 14040.
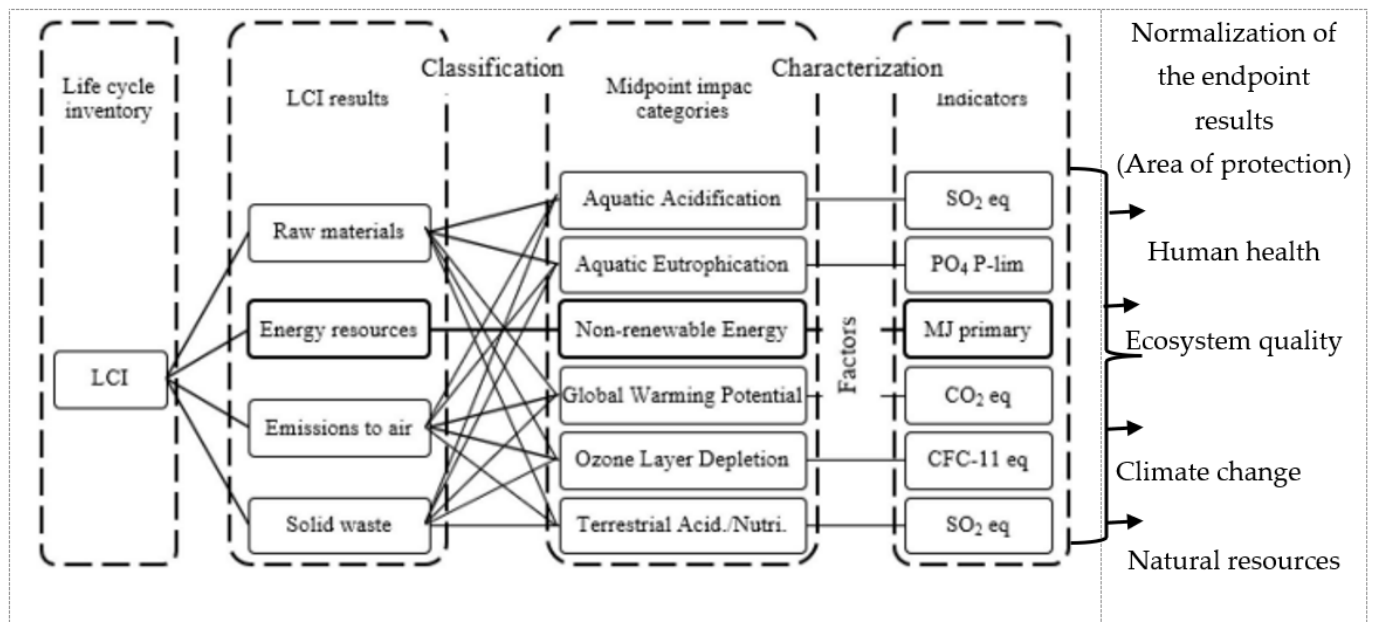

Figure 7. Process-based LCA method [41–44].

2.3.2. Life Cycle Inventory (LCI)

Based on the availability of the processes involved, LCI calculations were obtained using Ecoinvent database (a global data source) [45]. The overall parameters for energy and LCA simulation are summarized in Table 3, with scenarios that achieved the SBC-602 requirement highlighted in red.

2.3.3. Life Cycle Impact Assessment (LCIA)

LCIA calculations were performed using EN ISO 14040 and EN ISO 14044 standards. According to IMPACT 2002 + v.2.15, 2.3.3, LCIA results were categorized into midpoint categories, including parameters, types, and characterizations of possible impacts (Figure 8). 75 impact categories are defined by SimaPro under 21 classifications for LCIA. The IMPACT 2002+ has two main categories: midpoint and endpoint methods. This study focused on midpoint, method as shown in (Figure 8), focusing on the Kg CO_2 eq environmental impacts results.

Figure 8. The framework of midpoint analysis, as one of the Impacts 2002+ methods (derived from [45]).

After the energy analysis, all scenarios within the range of SBC limitations were compared based on carbon dioxide emissions for the selected insulation materials (Table 4), by selecting the governing function as "comparison" using the IMPACT 2002+ methodology and database. The present study highlights options with less thickness that can be adopted with less cooling load and carbon emission.

Table 4. The highest value of cooling loads for XPS, GW, EPS, and RW insulation materials facing the South.

Thickness	Benchmark is 151 kWh/m^2			
	North	**East**	**South**	**West**
The highest value of cooling loads for XPS insulation materials facing the South, benchmark = 151 kWh/m^2				
XPS 50 mm	160	171	175	164
XPS 60 mm	155	166	169	159
XPS 70 mm	140	153	155	145
XPS 80 mm	136	149	**151**	141
XPS 90 mm	133	147	148	138
The highest value of cooling loads for GW insulation materials facing the South. Benchmark = 150 kWh/m^2				
GW 80 mm	155	166	169	159
GW 90 mm	151	163	165	156
GW 100 mm	138	151	153	143
GW 110 mm	136	149	**150**	141
GW 120 mm	133	147	148	138

Table 4. *Cont.*

Thickness	Benchmark is 151 kWh/m^2			
	North	**East**	**South**	**West**
The highest value of cooling loads for EPS insulation materials facing the South, Benchmark = 149 kWh/m^2				
EPS 70 mm	155	166	169	159
EPS 80 mm	151	163	165	155
EPS 90 mm	137	150	152	142
EPS 100 mm	135	148	**149**	140
EPS 110 mm	132	146	147	137
The highest value of cooling loads for RW insulation materials facing the South, Benchmark = 151 kWh/m^2				
RW 65 mm	157	168	172	161
RW 75 mm	143	155	158	148
RW 85 mm	140	152	154	144
RW 95 mm	136	149	**151**	141
RW 105 mm	134	147	148	139

3. Results and Discussion

3.1. Thermal Simulation

The parametric simulation results of all the materials revealed variations in orientation and application of different thicknesses of the insulation materials, resulting in fluctuation of cooling loads. In practice, the relation between the material insulation thicknesses and thermal capacity (U-Value) is linear. A lower U-value represents a thicker insulation material and an inversely proportional impact on cooling loads. As highlighted in Section 2.2, 0.342 W/m^{2}K is the minimum U-value for a wall in any residential building, Therefore, considering an established benchmark of 151 kWh/m^2 and the SBC recommendation of 80 mm of XPS insulation as a reference, Table 4 presents the cooling loads for five different thicknesses of XPS for orientation along the four cardinal directions.

The cooling loads of GW insulation of thicknesses 80, 90, 100, 110, and 120 mm also present similar performance patterns. In this case, SBC recommends GW insulation material thickness of 110 mm (Table 4), wherein the highest cooling load of 150 kWh/m^2 was obtained along the southerly orientation.

An analysis of the parametric simulation results of EPS insulation material for the thicknesses of 70, 80, 90, 100, and 110 mm (Table 4) reveals that the highest cooling load of the recommended SBC (EPS 100 mm) is 149 kWh/m^2. Considering this value, a benchmark value of 90 mm along the north, east, and west orientations results in lower or similar cooling loads. Similarly, RW insulation of thickness 95 mm, the southerly orientation demonstrates the highest cooling load of 151 kWh/m^2. Table 4 presents similar trends for all insulation materials and validates the lower cooling loads for higher thicknesses of insulation materials.
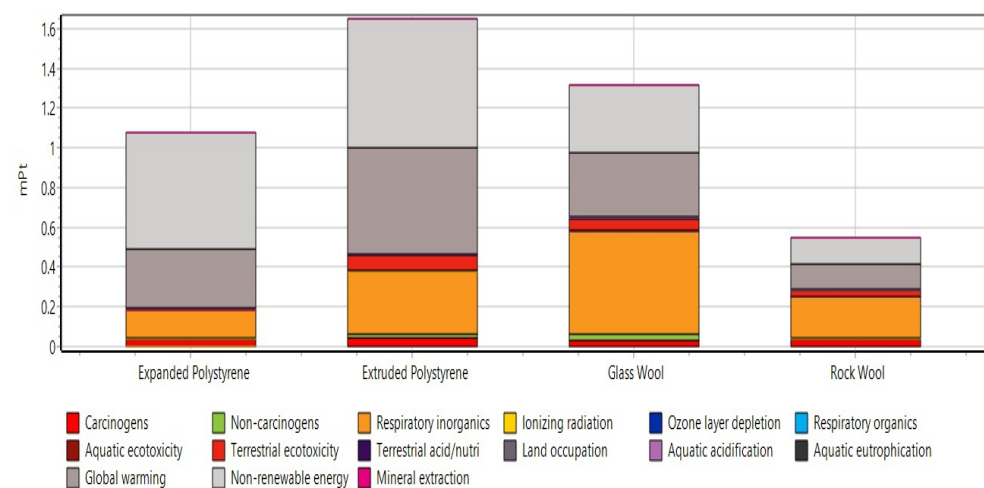
The simulation results in Table 4 also present the impact of orientation on the cooling loads, as illustrated in Figure 9. EPS 110 mm imposes the lowest cooling loads out of all materials, while XPS 50 mm sets the highest cooling loads compared to the other materials. It can also be interpreted that materials with different thicknesses could be logically allocated to specific orientations to achieve an optimum cooling load. E.g., XPS 70 mm, GW 100 mm, GW 90 mm, EPS 90 mm, EPS 80 mm, RW 85 mm, and RW 75 mm, could all be applied to the north and west orientations, while the recommended SBC thicknesses could be applied to the east and south orientations. The manipulation of different thicknesses and their allocation to a specific orientation façade could significantly reduce cooling loads. Hence, the impact of insulation materials and their thicknesses, in conjunction with building orientation, should be considered to evaluate the cooling load instead of applying the recommended thickness of insulation materials.

Figure 9. Impact of orientation on cooling loads for different insulation material thicknesses.

3.2. Life Cycle Assessment

As mentioned in the standard, all scenarios within the range of SBC limitations were compared based on carbon dioxide emissions. Figure 10 shows the results using the midpoint method, considering Kg CO_2 eq as the metric for each thermal insulation material. The results of the preliminary analysis of the thermal insulation materials specified in the study showed varying values of emissions and environmental impacts, demonstrating RW as the least emitting material among the four materials investigated.

Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Single score
Comparing 1 p 'Expanded Polystyrene', 1 p 'Extruded Polystyrene', 1 p 'Glass Wool' and 1 p 'Rock Wool';

Figure 10. Midpoint environmental impact results.

The results of the LCA of the thermal insulation materials at the manufacturing stage illustrated that RW had the minimum GWP (Figure 11). The results show the following

ranking based on GWP or emission values: XPS was ranked highest (5.28 kg CO_2 eq), GW ranked second (3.2 kg CO_2 eq), 63% less than XPS, EPS ranked third (2.9 kg CO_2 eq), 10% less than GW, while RW was ranked with the least GWP at 1.3 kg CO_2 eq, 123% less than GW, with an absolute difference of circa 300% between it and XPS.
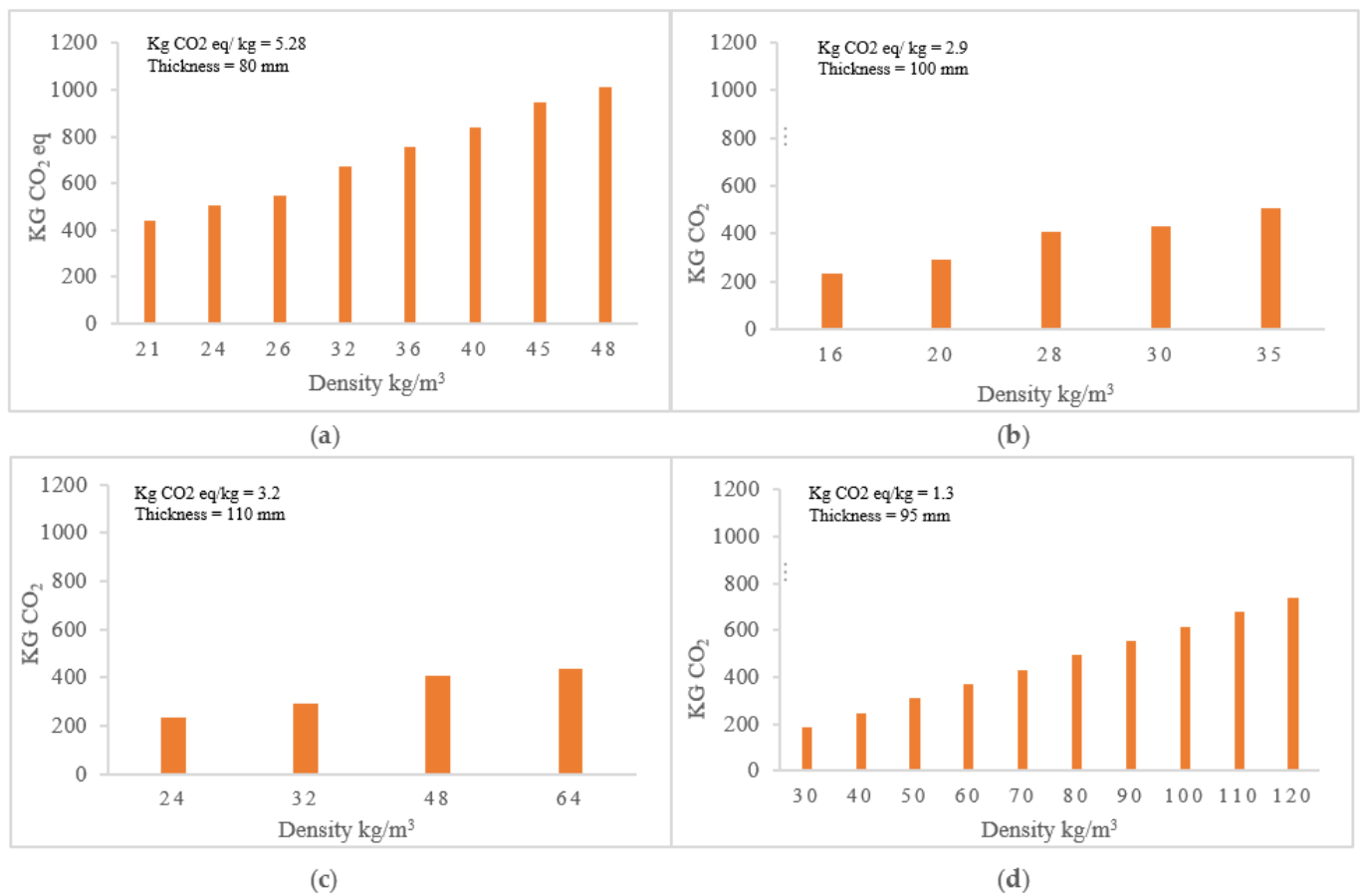
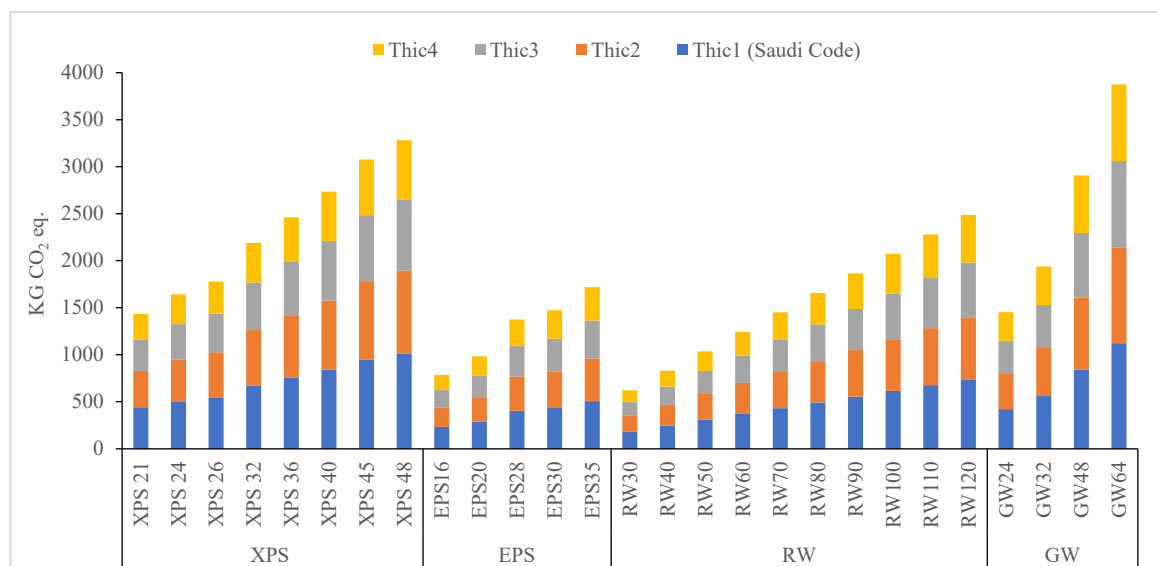

Figure 11. Global warming (Kg CO_2 eq emissions).

The reasons for the significant differences in these values are the material composition and manufacturing processes used. For example, XPS presents the highest GWP due to use of the use of harmful gases and their condensation inside the insulation body during its manufacture, as compared to EPS, with fewer emissions than XPS due to the use of water vapor instead of harmful gases in the manufacturing processes, as evidenced from literature.

As seen in Figure 12a, emissions from the manufacture of XPS of 21 kg/m^3 to insulate the room of 49.8 m^2 wall area with the SBC specified thickness (80 mm) showed the least value of 442 Kg CO_2 eq, while it showed the highest value of 1010 of Kg CO_2 eq with a density of 48 kg/m^3, a variation of 129% over the minimum value. In Figure 12b, the GWP of EPS for the room considered with the SBC specified thickness of 100 mm demonstrated a minimum value of 231.1 Kg CO_2 eq at a density of 16 kg/m^3, while a density of 35 kg/m^3 demonstrated GWP of 505 Kg CO_2 eq, a difference of 119%. In Figure 12c, the SBC's recommended thickness of 110 mm demonstrates the least GWP of 420.7 Kg CO_2 eq at a density of 24 kg/m^3 and the highest GWP of 1122 Kg CO_2 eq for a density of 64 kg/m^3. For manufacturers of RW, Figure 12d demonstrates the highest GWP of 738 Kg CO_2 eq at a density of 120 kg/m^3, while a density of 30 kg/m^3 demonstrates the minimum GWP of 185 Kg CO_2 eq. Overall, RW demonstrated the lowest GWP out of the four materials considered for the study. Figure 13 illustrates the effect of density on GWP in terms of Kg CO_2 eq for each material, which evidences the significance of this parameter in the application of insulation in buildings.

Figure 12. Global warming potential impact with wall area of 49.8 m^2 (kg CO$_2$ eq emissions), (**a**) manufacturing XPS, (**b**) manufacturing EPS, (**c**) manufacture of GW, (**d**) manufacture of RW.

Figure 13. Comparison of total carbon dioxide KG CO$_2$ eq values.

3.3. Optimization of Thermal and Environmental Analysis Results

The thermal performance analysis of the four orientations according to the requirements of the SBC showed a variation in the cooling loads, with the highest cooling loads along the southward orientation. Considering this as a reference, Figure 14a shows the

differences up to 2.0 cm among other orientations. Figure 14b illustrates a combination of different types of insulation and thicknesses of the specified SBC range (dotted line). For instance, the western façade of the minimum insulation thickness (the lowest in the study) achieved the acceptable code limit in RW materials. For the GW, XPS, and EPS, it exceeded the required limit in the SBC code. Hence, the SBC code can be achieved with the minimum thickness of the RW. The north and west orientations could use XPS 70 mm, GW 100 mm, GW 90 mm, EPS 90 mm, EPS 80 mm, RW 85 mm, and RW 75 mm, while the east and south orientations could use the recommended SBC code thicknesses. Manipulating different thicknesses and their allocation to specific orientation can potentially result in significant cooling load reduction. As a consequence, in order to assess the cooling loads imposed by different material thicknesses for different orientations, instead of relying exclusively on a thickness specified by the SBC, it would be best to evaluate the cooling loads imposed by differing thicknesses.
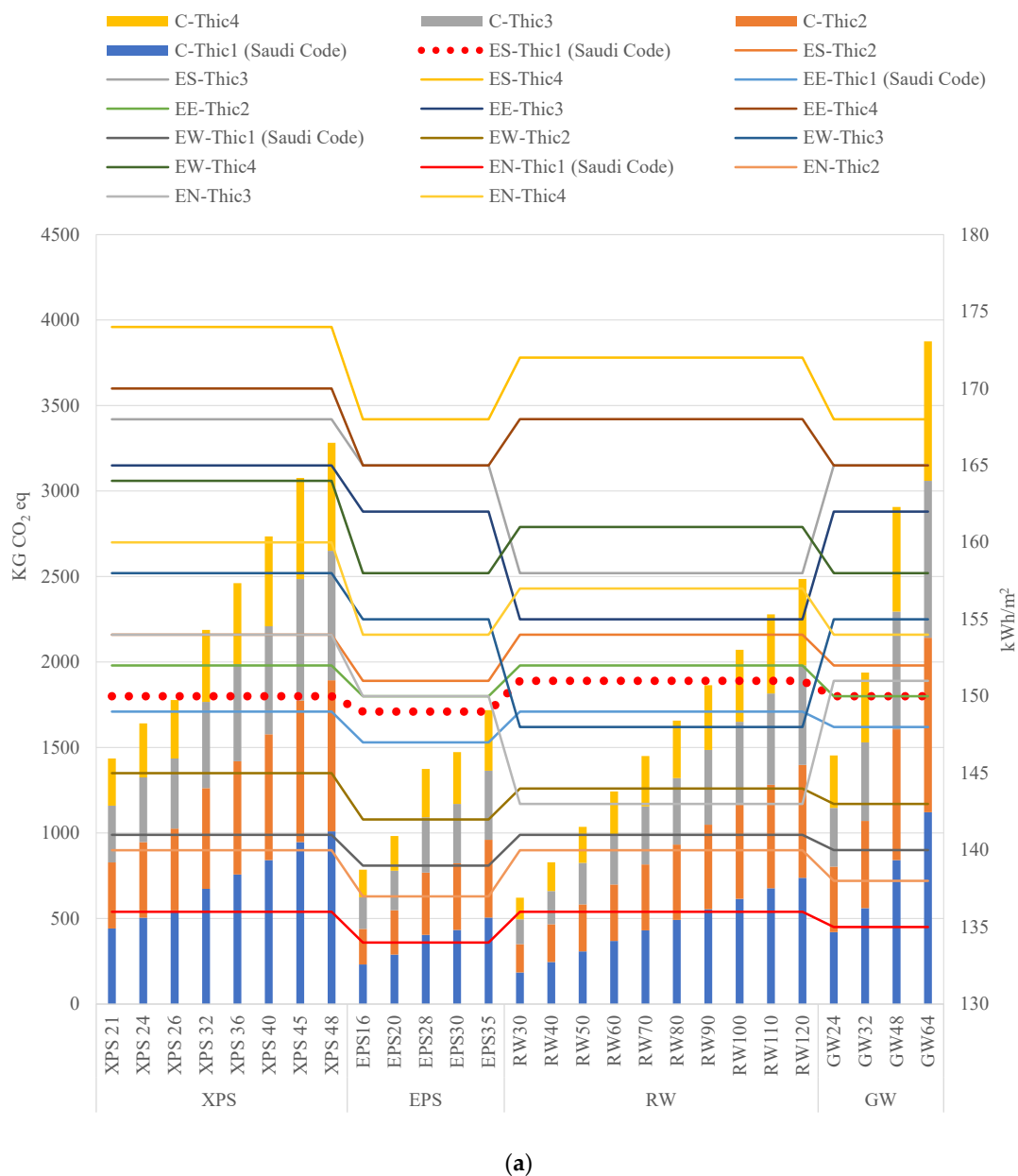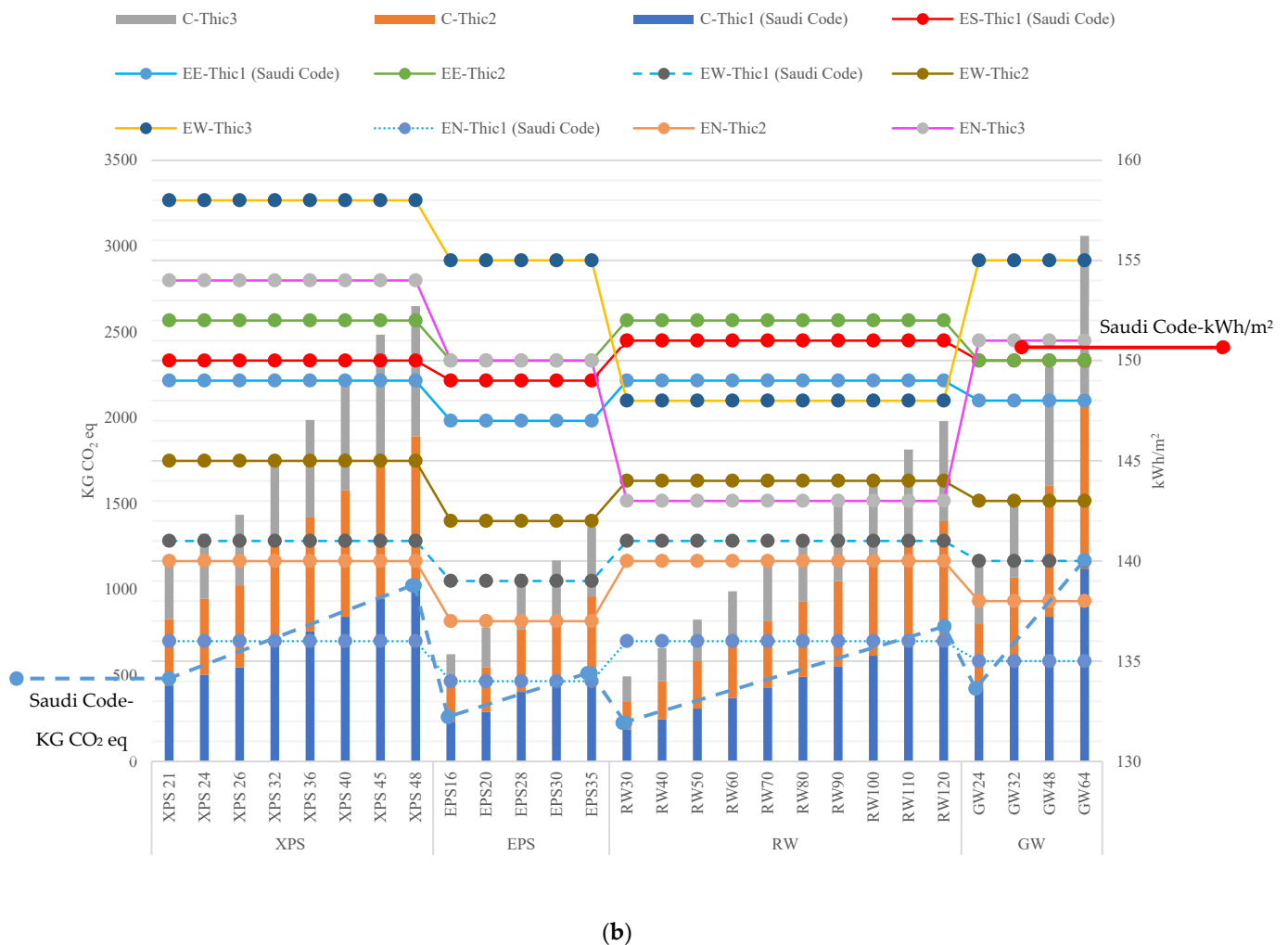

(a)

Figure 14. *Cont.*

(**b**)

Figure 14. Optimization chart for all thermal and environmental aspects based on (**a**) Overall kWh\m² and kg CO₂ eq respectively, (**b**) Based on SBC.

Further, environmental performance assessment using LCA (cradle-to-grave) of insulation materials also demonstrated a difference in their GWP, and for different thicknesses within the same material. This provides a tool for the material selection of insulation, using these results in conjunction with the cooling loads to optimize the material types and thicknesses for application in a given climatic region and achieving sustainability benefits from energy savings and emissions reduction.

4. Conclusions

The evaluation of the thermal performance and the environmental impact assessment of the insulation materials showed varying values for the types of insulation specified in the study. The thermal performance was affected by the material, its thickness, and the orientation of the building. A comparison with the SBC determined the specific thicknesses along different orientations to achieve requisite cooling loads, as opposed to standardized thicknesses mentioned in SBC. The lowest cooling loads are caused by EPS 110 mm, while the highest cooling loads are caused by XPS 50 mm. Different thickness materials can also be logically oriented to achieve optimal cooling loads. The recommended SBC thicknesses could be applied to the east and south orientations. Alternatively, XPS 70 mm, GW 100 mm, GW 90 mm, EPS 90 mm, EPS 80 mm, RW 85 mm, and RW 75 mm could be applied to the north and west orientations. For the LCA, on the western façade of the minimum insulation thickness, the RW is compliant with SBC. For the GW, XPS, and

EPS, it exceeded the required limit in the SBC. XPS 70 mm, GW 100 mm, GW 90 mm, EPS 90 mm, EPS 80 mm, RW 85 mm, and RW 75 mm can be used for the North and West orientations. The East and South orientations could use the recommended SBC thicknesses. Similarly, the material density was analyzed as the primary parameter affecting the GWP of the insulation material. Considering the application of insulation materials as a combination of thermal and environmental performance parameters provides a powerful tool for the customized application of insulation materials in various climatic conditions. Future studies are recommended to monitor the temperature variations inside the wall for different combinations of load-bearing walls and insulation types. It also provides a tool for achieving sustainability benefits through energy savings as well as minimized LCA costs.

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