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Integrated life cycle assessment of passive house envelope alternatives in a hot-arid climate: The case of the Gaziantep ecological house

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Abstract

The growing demand for energy-efficient buildings has led to the widespread adoption of Passive House (PH) standards, emphasizing operational energy reduction through optimized insulation and airtight construction. However, the embodied environmental impacts of building materials remain a critical concern. This study presents a Life Cycle Assessment of the Gaziantep Ecological House, Turkey's first PH-certified building, focusing on both operational and embodied carbon emissions across its construction phases. The study evaluates the A1-A3 (material extraction, processing, and manufacturing) and A4 (transportation) stages, incorporating various wall construction scenarios to assess their environmental trade-offs. The results reveal that while high-performance insulation materials contribute to energy efficiency, their embodied carbon emissions can significantly impact sustainability. Among alternative wall materials, brick-based scenarios exhibited the highest global warming, acidification, and eutrophication potentials due to high-temperature kiln-firing and fossil fuel dependency. Conversely, adobe (earthen) walls demonstrated the lowest environmental impact across multiple categories, reinforcing their viability as a low-carbon construction material. However, challenges related to moisture resistance and structural performance require further investigation. Additionally, hempcrete, often perceived as an environmentally friendly material, showed higher-than-expected ozone depletion potential due to its cementitious binder content, highlighting the trade-offs between carbon sequestration benefits and secondary environmental burdens. The study also underscores the critical role of transportation emissions (A4 phase), where locally sourced materials such as adobe and autoclaved aerated concrete significantly reduced transport-related carbon emissions compared to imported alternatives. Overall, this research emphasizes the need for a balanced approach to sustainable construction, integrating both operational energy efficiency and embodied carbon reduction. Future studies should explore hybrid material strategies, bio-based insulation alternatives, and circular economy principles to further minimize lifecycle environmental impacts. By integrating LCA-driven decision-making into early-stage building design, policymakers, architects, and engineers can optimize passive house construction for long-term environmental sustainability.

1. Introduction

The climate crisis has become one of the most pressing environmental challenges of the 21st century, with its consequences increasingly evident through rising global temperatures and extreme weather events. According to the Intergovernmental Panel on Climate Change [1] anthropogenic greenhouse gas (GHG) emissions, primarily from fossil fuel combustion, industrial activities, and deforestation, are the main contributors to global warming. The rapid increase in GHG concentrations, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), has intensified the greenhouse effect, accelerating climate change [2]. The Global Carbon Budget 2023 report highlights that CO_2 emissions reached an all-time high of 40.6 gigatons (Gt) in 2022, underscoring the urgent need for decarbonization strategies [3].

Among various industrial sectors, the building and construction industry is one of the largest contributors to global GHG emissions, accounting for nearly 37% of total energy-related CO_2 emissions [4]. Buildings consume substantial amounts of energy for heating, cooling, lighting, and operational functions, making energy efficiency a critical factor in reducing environmental impacts [5]. As urbanization accelerates and housing demand rises, the construction sector remains highly energy-intensive, exacerbating climate-related pressures [6]. Consequently, enhancing building energy performance through innovative design strategies has become a cornerstone of sustainable development efforts.

The Passive House (Passivhaus) standard has emerged as an effective strategy for reducing building energy consumption. Passive houses minimize heating and cooling demands through high-performance insulation, airtight building envelopes, and energy-efficient ventilation systems [7, 8]. Studies indicate that passive houses consume up to 90% less heating energy compared to conventional buildings, making them a key solution for reducing energy-related emissions [9]. However, while passive houses are widely recognized for their operational energy efficiency, emerging research suggests that the environmental footprint of building materials is also a critical factor in overall sustainability [10].

Traditional sustainability assessments have focused primarily on operational energy consumption, often overlooking the environmental impacts of material extraction, production, transportation, and disposal of which contribute to embodied carbon emissions [11]. Life Cycle Assessment (LCA) methodologies reveal that construction materials can contribute up to 50% of a building's total carbon footprint, particularly in highly energy-efficient structures, where operational energy demand is significantly reduced. These findings underscore the necessity for a holistic approach that evaluates both operational and embodied carbon emissions [12].

Despite the growing body of passive house research, several critical gaps remain. First, while many studies highlight operational energy savings, few comprehensively assess embodied carbon emissions in passive house construction [13, 14]. Second, passive house research is predominantly focused on temperate and cold climates, particularly in Europe and North America, whereas hot-arid regions remain underrepresented in the literature [15]. Given that climate conditions significantly influence passive house performance, there is a need to examine how passive design strategies function under extreme temperature conditions. Finally, passive house construction often relies on high-performance insulation materials, which may have substantial embodied carbon footprints. While these materials enhance operational energy efficiency, their long-term sustainability depends on optimizing the trade-off between initial environmental costs and energy savings [16]. Accordingly, this study aims to optimize passive house envelope design in a hot-arid climate by integrating operational energy performance and embodied carbon assessment within a comprehensive Life Cycle Assessment (LCA) framework.

This study aims to address these research gaps by conducting a holistic assessment of a certified passive house—Gaziantep Ecological House (Turkey's first PH-certified building)—considering both operational and embodied energy metrics. Unlike most passive house research, which prioritizes operational energy savings, this study integrates Life Cycle Assessment (LCA) to evaluate the embodied carbon footprint of construction materials. This approach ensures that high-performance insulation materials and airtight building envelopes are assessed not only for their energy efficiency but also for their long-term environmental impact. In doing so, this research builds upon Arbulu et al. and Norouzi et al., extending their analyses into a fully integrated LCA-based framework [13, 14].

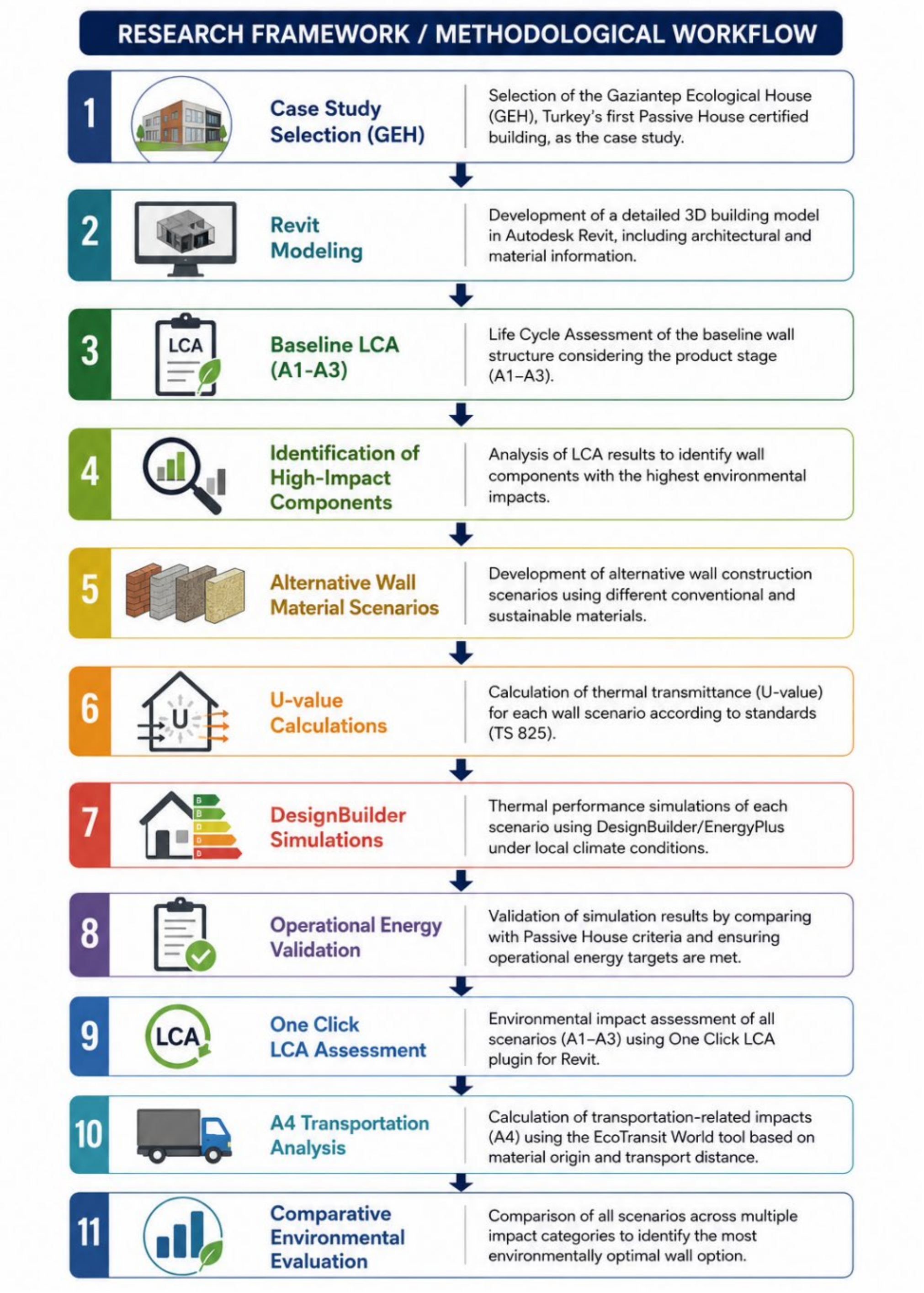
Furthermore, this study evaluates passive house adaptation in hot-arid climates, addressing a geographic gap in passive house literature. The Gaziantep Ecological House serves as a novel case study to assess passive design strategies under extreme temperature conditions, expanding upon Peng & Wang, who emphasized the need for climate-adapted designs, but did not conduct full lifecycle energy and emissions analysis [15].

Beyond technical advancements, this study provides actionable insights for architects, engineers, and policymakers on balancing energy efficiency with embodied carbon reductions in passive house construction. As governments push for decarbonization in the building sector, ensuring that passive house standards incorporate embodied carbon assessments is crucial for long-term climate alignment [16]. While Jørgensen & Ma advocate for digital tools in energy-efficient buildings, this study enhances their framework by integrating LCA-driven sustainable design principles [17]. By addressing both energy efficiency and lifecycle sustainability, this research advances passive house standards as a comprehensive decarbonization strategy, aligning with international climate mitigation efforts.

2. Materials and Methods

This study employed an integrated methodological framework to evaluate the environmental performance of alternative passive house envelope scenarios under hot-arid climate conditions. The methodology combines operational energy analysis and embodied environmental impact assessment within a comprehensive Life Cycle Assessment (LCA) approach. The overall research framework and methodological workflow adopted in the study are presented in Fig. 1.

The research process began with the selection of the Gaziantep Ecological House (GEH), Türkiye's first certified Passive House building, as the case study. A detailed three-dimensional building model was developed using Autodesk Revit, including architectural geometry, material layers, and envelope properties. Following the creation of the baseline building model, a cradle-to-gate life cycle assessment (A1–A3) was conducted to identify the building components with the highest environmental impacts.



Selection of the Gaziantep Ecological House (GEH), Turkey's first Passive House certified building, as the case study.

Development of a detailed 3D building model in Autodesk Revit, including architectural and material information.

Life Cycle Assessment of the baseline wall structure considering the product stage (A1–A3).

Analysis of LCA results to identify wall components with the highest environmental impacts.

Development of alternative wall construction scenarios using different conventional and sustainable materials.

Calculation of thermal transmittance (U-value) for each wall scenario according to standards (TS 825).

Thermal performance simulations of each scenario using DesignBuilder/EnergyPlus under local climate conditions.

Validation of simulation results by comparing with Passive House criteria and ensuring operational energy targets are met.

Environmental impact assessment of all scenarios (A1–A3) using One Click LCA plugin for Revit.

Calculation of transportation-related impacts (A4) using the EcoTransit World tool based on material origin and transport distance.

Comparison of all scenarios across multiple impact categories to identify the most environmentally optimal wall option.

Fig. 1. Overall methodological workflow of the study

Based on the preliminary LCA findings, alternative wall material scenarios were developed using both conventional and low-carbon construction materials, including adobe, pumice block, hempcrete, and expanded clay aggregate systems. Thermal transmittance (U-value) calculations for each wall configuration were performed in accordance with TS 825 standards to ensure thermal compatibility with Passive House requirements.

The thermal performance of each wall scenario was subsequently analyzed using DesignBuilder/EnergyPlus simulation tools under local climatic conditions. Operational energy performance was evaluated through annual heating and cooling demand simulations, and the results were assessed according to Passive House performance criteria. The simulation outputs were then integrated into the environmental assessment process.

Embodied environmental impacts of all scenarios were calculated using the One Click LCA platform. In addition to material production stages (A1–A3), transportation-related impacts (A4 phase) were evaluated using transport distance and material origin data. Finally, all wall scenarios were comparatively analyzed across multiple environmental impact categories to determine the most environmentally sustainable envelope alternative for passive house applications in hot-arid climates.

2.1. Case study

The Gaziantep Ecological House (GEH), located in the Şehitkamil District of Gaziantep, Turkey, is situated within a warm-temperate climate zone and represents a significant milestone in sustainable architecture as Turkey's first certified passive house. Given its unique status as the first and only passive house in Turkey within the new building category, it has been selected as the case study for this research. The construction of this building was completed in 2013, and in 2015, it was awarded LEED Platinum certification, demonstrating its high level of environmental performance and energy efficiency [18].

The building, with a construction area of 320 m², has been designed with a compact architectural approach, as illustrated in Fig. 2. This design strategy aims to minimize waste generation and resource loss during construction while also reducing excessive energy consumption during operation [19]. Currently, the building serves as an information center and includes a 60-seat mini auditorium, along with a foyer and workspace areas. Additionally, the interior features a technical room, while the north façade accommodates restrooms.

The GEH is recognized as a "plus-energy" building, as it achieves 90% higher energy efficiency compared to conventional buildings through the systems and detailed solutions implemented. It not only meets its own energy demand but also generates excess energy from renewable sources. The building is certified under both the Passive House (Passivhaus) standard and the LEED Platinum certification, demonstrating its high-performance energy efficiency and sustainability credentials. The building envelope is designed to be airtight, thermal bridge-free, and highly insulated, effectively minimizing heat loss. In line with this design principle, the exterior walls consist of a 30 cm thick reinforced concrete layer combined with an uninterrupted 40 cm layer of glass wool insulation to ensure optimal thermal performance. The wall layer composition used in the GEH is detailed in Table 1.

The total thermal transmittance coefficient (U-value) of the existing wall, as presented in Table 1, is reported to be 0.112 W/m²K (Fig. 3). Gaziantep is classified within the second-degree heating region, where the recommended U-value for walls is 0.57 W/m²K [20]. However, in accordance with Passive House standards, the U-value for external walls should be below 0.15 W/m²K [21]. The high insulation performance of the GEH exceeds both national and Passive House requirements, demonstrating its exceptional thermal efficiency.

Fig. 2. Exterior view and floor plan of the study building

Table 1. Wall layers of the GEH

Wall Material	Thickness (cm)	Thermal Conductivity Coefficient (W/mK)
Reinforced Concrete Wall	30	2.1
Glass Wool	40	0.035
Cement-Bonded Wood Chipboard	1.4	0.15
Plaster + Paint	1	0.87

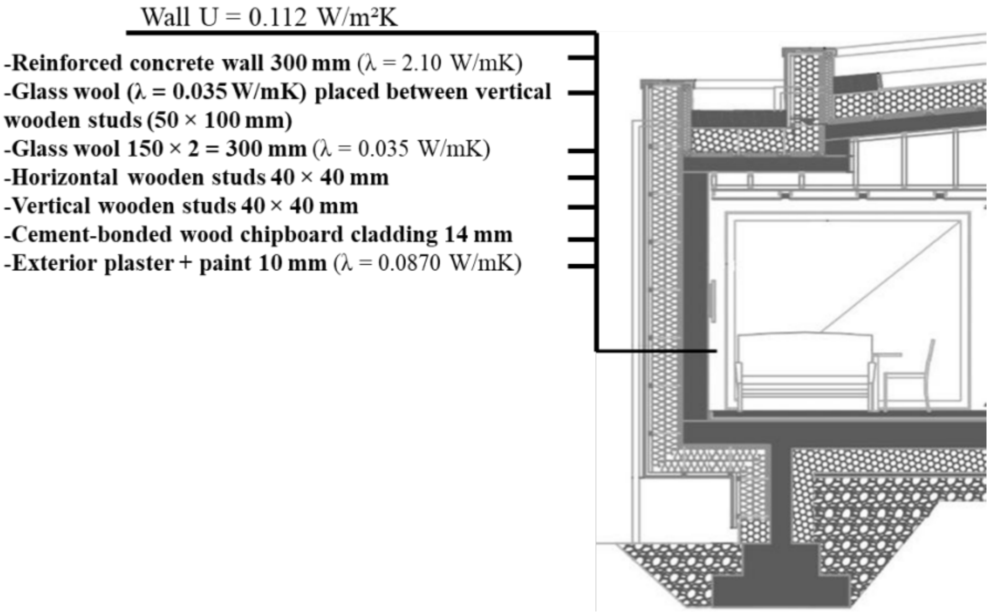


Fig. 3. A detailed section of the GEH wall

2.1.1. Simulation software

The Life Cycle Assessment (LCA) method was employed to evaluate the environmental impacts of the Gaziantep Ecological House. To conduct LCA-based environmental impact assessments, the One Click LCA plug-in for Autodesk Revit was utilized. One Click LCA is a life cycle assessment tool that integrates with Autodesk Revit and enables the calculation of carbon emissions per square meter, building energy classification, material carbon footprint, and the percentage distribution of carbon emissions across different structural components [22]. Prior to the environmental impact assessment in One Click LCA, the building was modeled in Autodesk Revit (Fig. 4). The One Click LCA plug-in identifies the materials used in the Revit building model and recommends Environmental Product Declarations (EPDs) for those materials. In addition to utilizing external databases, One Click LCA also incorporates its own proprietary database for material assessments [23]. The environmental impacts of the A1-A3 life cycle stages of the Gaziantep Ecological House, as modeled in Autodesk Revit, were calculated using the One Click LCA plug-in. To evaluate the A4 phase, the EcoTransit World (Ecological Transport Information Tool for Worldwide Transports) online calculation tool was utilized [24]. EcoTransit World is an ISO 14083-compliant tool that calculates energy consumption, greenhouse gas emissions, air pollutants, and CO_2 equivalents for transport distances [25].

To ensure that a material substitution in the passive house does not negatively impact the building's energy performance, both the proposed new material layers and the existing condition of the building were modeled in the Design Builder simulation software, allowing for an energy performance assessment (Fig. 4). Design Builder is a building simulation tool that facilitates the modeling of energy, carbon, lighting, and occupant comfort, while also enabling comparative analysis of alternative designs [26]. Although EnergyPlus, a simulation program developed by the U.S. Department of Energy, is widely used for modeling heating, cooling, lighting, ventilation, and other energy flows in buildings, it lacks a user-friendly interface. Design Builder operates on the EnergyPlus framework while providing a more accessible and user-friendly interface, making it an effective tool for comprehensive building energy simulations [27].

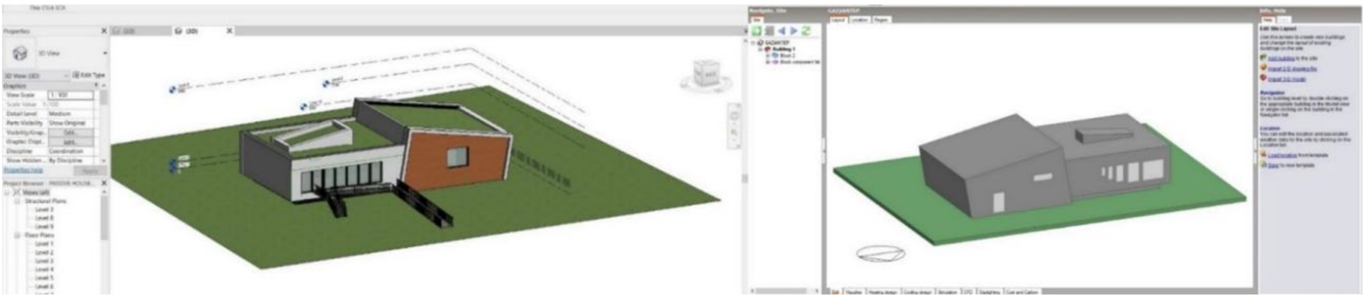


Fig. 4. Autodesk Revit and DesignBuilder models of the GEH

2.2. Assessment of the environmental impact of the GEH and identification of high environmental impact building envelope components

The Life Cycle Assessment (LCA) method was employed to determine the environmental impacts of the passive house. In this study, the A1-A3 life cycle stages, which encompass the raw material extraction, manufacturing, and transportation to the construction site, as well as the A4 phase, which includes the transportation of materials to the construction site, were considered for evaluating the building's environmental performance (Fig. 5).

The inclusion of the A4 phase in the Life Cycle Assessment (LCA) is intended to account for the significant emissions generated during the transportation of construction materials to the site, which should not be overlooked [28]. The functional unit was defined as 1 m² of conditioned gross floor area over a 50-year building service life.

Using the One Click LCA plug-in, the environmental impact values of the Gaziantep Ecological House were determined, and the material layer contributing the most to environmental impact was identified. Additionally, percentage-based impact values were calculated. Building components that had a significant share in the building's overall environmental impact were identified, and alternative material layers were proposed to mitigate these impacts.

In this study, the environmental impact assessment was conducted following the TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) impact classification, which includes global warming, acidification, eutrophication, ozone depletion, and photochemical ozone formation potential [29]. Among these, global warming potential (GWP) was prioritized in determining the impact ratios of building components, and recommendations were made based on this category. The global warming potential (GWP) of the GEH was calculated to be 211 tons CO_2e. The percentage contribution of building components to this environmental impact is illustrated in Fig. 6.

As shown in Fig. 6, the building components contributing the most to the global warming potential (GWP) of the GEH are exterior walls and other façade cladding materials, accounting for 46.3% of the total impact. The floor and roof structures also have a significant contribution of 45.3%, making them another major factor in the overall environmental footprint of the building. In contrast, doors and windows were found to have the lowest contribution to the global warming potential.

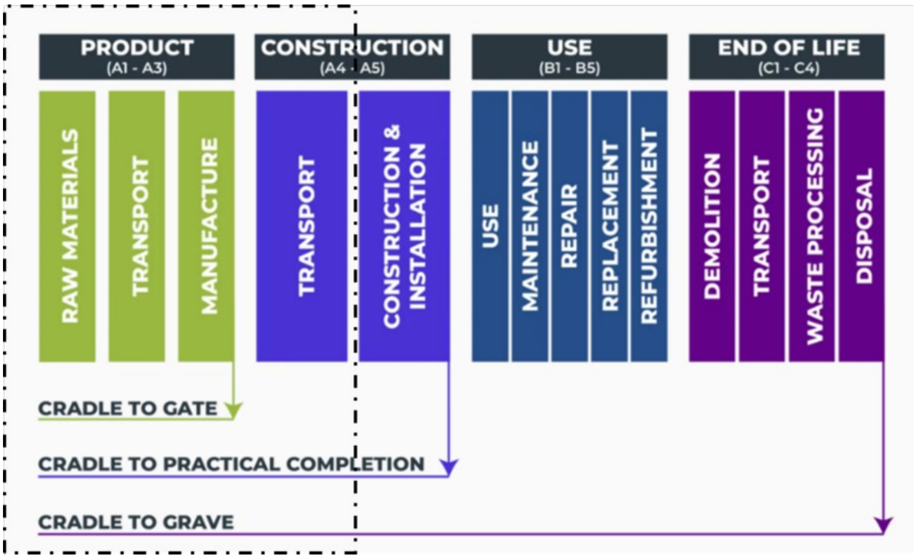


Fig. 5. System boundaries of the study

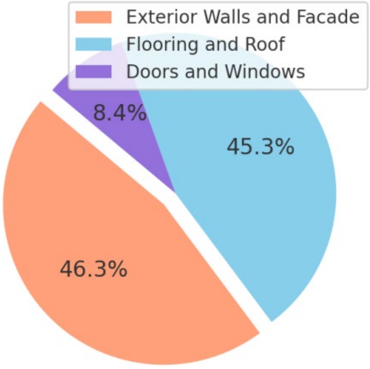


Fig. 6. GWP contribution of GEH building components

To effectively reduce environmental impact, it is crucial that improvement proposals focus on materials that can be easily replaced within the building and can be widely applicable to similar structures. In determining which building materials should be prioritized for improvement, both the percentage contribution of building components and the proportional environmental impact of individual materials were analyzed. The construction materials contributing the most to the environmental impact of the GEH are presented in Fig. 7.

Among the construction materials used in the GEH, ready-mix concrete, which is utilized in walls, roofs, and floors, was identified as the primary contributor to global warming potential (GWP). The composition of ready-mix concrete consists of 75% aggregate (sand, gravel, crushed stone), 10% cement, and 15% water by volume [30]. According to the Turkish Construction Sector Statistics, 105 million cubic meters of ready-mix concrete were produced in Turkey in 2022. Additionally, these statistics indicate that 300 million tons of aggregate and 73.7 million tons of cement were produced for concrete manufacturing in the same year [31]. Cement production is responsible for 5% to 10% of global anthropogenic CO_2 emissions [32]. Studies have demonstrated that a significant portion of CO_2 emissions in cement production originates from the calcination of clinker, the primary raw material in cement manufacturing [33].

Furthermore, the extraction of aggregates, another key component of ready-mix concrete, has severe environmental consequences, including habitat destruction for plant and animal species, erosion leading to the depletion of fertile soil layers, dust emissions, and water pollution. Given these environmental challenges, reducing the use of ready-mix concrete and cement-based materials is crucial for minimizing the overall environmental impact of buildings.

In the GEH, ready-mix concrete was utilized in the floors, foundation, and walls. To mitigate the environmental impact of the building, ready-mix concrete used in the walls was selected for material substitution.

However, no modifications were proposed for the foundation and floors, as reinforced concrete structural systems are widely used in Türkiye, especially for high-rise tunnel-form buildings in seismically active regions due to their safety and applicability [34].

A comparative Life Cycle Assessment (LCA) study on the embedded carbon values of reinforced concrete, wood, and steel structural systems has identified wood as the most environmentally friendly construction material, followed by reinforced concrete and steel, respectively. Despite its lower environmental impact, wooden structural systems are not as commonly used for multi-story buildings as traditional materials and present certain design and implementation challenges [35], which is why the foundation and floors were not modified in this study.

Instead, alternative material scenarios were developed for the reinforced concrete wall components by proposing commonly used materials such as brick, autoclaved aerated concrete (AAC), and pumice blocks, as well as sustainable construction materials such as adobe and hempcrete. The selection of alternative wall materials was conducted according to a multi-criteria evaluation framework considering thermal performance, embodied carbon reduction potential, regional material availability, compatibility with passive house principles, applicability within Türkiye's construction practices, and their documented use in previous scientific studies. Accordingly, both conventional and alternative low-carbon materials were comparatively assessed to determine their suitability for sustainable passive house envelope applications in hot-arid climates.

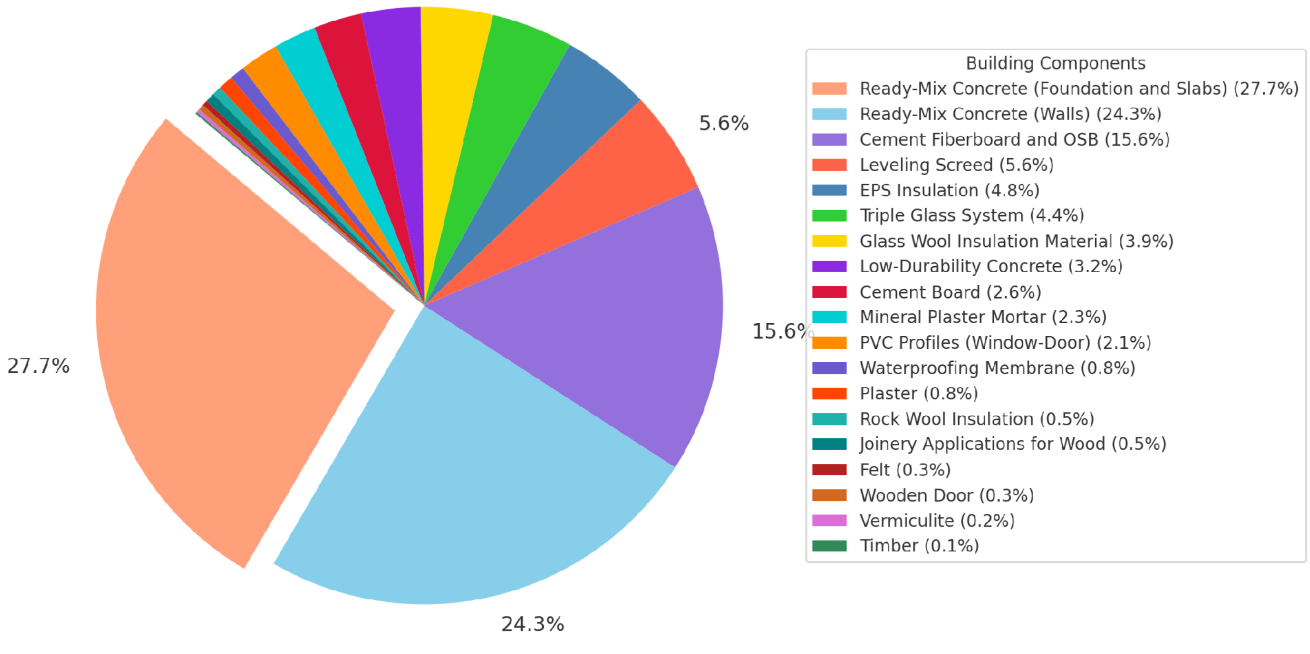


Fig. 7. Building materials' share in GEH's GWP

As shown in Fig. 7, cement-bonded wood chipboard ranks third in global warming potential contribution, with a 15.6% CO_2e impact. Cement-bonded wood chipboard typically includes Portland cement and wood chips, and may also contain aggregate, fly ash, and chemical additives [36, 37]. In comparison, fiber cement board consists of 18-30% Portland cement, 35-65% silica, 5-10% fly ash, and 4-7% cellulose fibers [38]. Given the environmental impacts of cement-bonded wood chipboard, this study proposes replacing it with fiber cement board to reduce the environmental footprint of the building envelope. Fiber cement board is a durable material suitable for exterior facades, resistant to atmospheric conditions, and does not emit harmful emissions into the environment [39]. When comparing material compositions, fiber cement board emerges as a more environmentally friendly alternative, particularly due to the presence of cellulose fibers, which are natural, recyclable, and ecological [40, 41]. The alternative materials proposed for the existing building envelope are presented in Table 2, while the construction scenarios incorporating these materials are detailed in Table 3. To ensure that the building's energy performance remains unchanged with the proposed material replacements, the existing energy performance was first determined, and based on these findings, the thicknesses of the newly proposed material layers were calculated accordingly.

2.2.1. Preservation of the energy performance of the GEH and determination of the thickness of the proposed building envelope components

The existing building was modeled using the Design Builder simulation software, and its annual heating and cooling load per square meter was calculated to determine its energy performance. Since climate data for Gaziantep was not available in the Design Builder database, the necessary climate data was downloaded as an EPW file and imported into the software. In the simulation, the heat recovery heating and cooling system in the building was activated, whereas other active systems could not be simulated. The proposed materials were also modeled under the same environmental conditions and system settings as the existing building. Due to the lack of monitored operational energy data, validation was performed through compliance with certified Passive House performance criteria and comparative simulation consistency.

When proposing new construction materials to reduce the environmental impact of the existing structure, it is crucial to preserve the building's energy performance and ensure compliance with Passive House standards. Accordingly, the thermal transmittance coefficient (U-value) of the building envelope was designed to be equal to or lower than that of the existing structure, and the thickness of alternative material layers was calculated accordingly. The U-value was determined in accordance with TS 825, using Eqs. 1 and 2.

Table 2. Proposed alternatives for building envelope materials

Existing Building Envelope	Alternative Material Layers Proposed for the New Building Envelope
Reinforced Concrete Wall	Brick Autoclaved Aerated Concrete (AAC) Pumice Block Adobe Hempcrete Block
Glass Wool Insulation Material	Glass Wool Insulation Material (Different Thickness)
Cement-Bonded Wood Particle Board	Fiber Cement Board
Exterior Plaster	Exterior Plaster
Paint	Paint

Table 3. Alternative building envelope scenarios

Building Envelope Layers	Scenarios
30 cm Reinforced Concrete Wall + 40 cm Glass Wool Insulation + 14 mm Cement-Bonded Wood Chipboard + Plaster + Paint	Existing Condition
20 cm Brick Wall + 52 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 1
30 cm Brick Wall + 43 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 2
20 cm Autoclaved Aerated Concrete (AAC) Wall + 55 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 3
30 cm Autoclaved Aerated Concrete (AAC) Wall + 48 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 4
20 cm Pumice Wall + 56 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 5
30 cm Pumice Wall + 48 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 6
35 cm Adobe Wall + 40 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 7
30 cm Hempcrete Block + 58 cm Glass Wool Insulation + 14 mm Fiber Cement Board + Plaster + Paint	Scenario 8

$$R = (\frac{d_1}{\lambda_{h1}}) + (\frac{d_2}{\lambda_{h2}}) + (\frac{d_3}{\lambda_{h3}}) + \cdots + (\frac{d_n}{\lambda_{hn}}) \quad (1)$$

In this equation:

R = Thermal resistance of multilayer building components (m²K/W)

$d_1, d_2, \ldots d_n$ = Thickness of the building materials (m)

$\lambda_1, \lambda_2, \ldots \lambda_n$ = Thermal conductivity values of the building materials (W/mK)

$$U = \frac{1}{R} \quad (2)$$

In this equation:

U = Total thermal transmittance coefficient of the building component (W/m²K)

R = Thermal resistance of multilayer building components (m²K/W)

The following steps were followed in the development of alternative material layers in this study:

1. The environmental impact values of the existing construction materials used in the GEH were calculated, and the percentage contributions of building components to the overall environmental impact were determined. This analysis identified the building components and materials with the highest environmental impact, allowing for the development of alternative material scenarios for improvement.
2. Upon reviewing the environmental impact values of the existing building, it was determined that walls contributed the most to the overall environmental impact. Based on these findings, the building envelope was selected as the focus for improvement strategies.
3. Further analysis of the wall layers revealed that reinforced concrete was the primary contributor to environmental impact among wall materials. Conversely, the glass wool insulation used in the wall system was found to have a significantly lower environmental impact. Therefore, in the alternative scenarios, reinforced concrete walls were replaced with brick, autoclaved aerated concrete (AAC), pumice, adobe, and hempcrete block walls to explore their potential for reducing environmental impact.
4. Since the insulation material exhibited a low environmental impact, the thickness of the insulation layer was increased in cases where the wall construction material was modified, ensuring that the wall's U-value met the required standards. The thickness of the newly proposed wall and insulation materials for the building envelope was calculated using Eqs. 1 and 2. Glass wool insulation, which was already used in the existing wall system, was retained, with only its thickness adjusted accordingly. The technical specifications of the selected wall construction materials, obtained from manufacturing facilities, are presented in Table 4.

In the newly proposed scenarios, aimed at reducing the environmental impact of the GEH, the material thicknesses were determined to ensure that the wall U-value and heating-cooling loads of the existing building were maintained. The specified thicknesses for each scenario are presented in Table 5. The U-values, heating and cooling loads of the alternative building envelope scenarios, developed using the alternative materials listed in Table 2, are presented in Figs. 8-10.

Table 4. Properties of proposed wall materials

Proposed Wall Materials	Density (kg/m³)	Thermal Conductivity (W/mK)
Brick	1810	0.304
Autoclaved Aerated Concrete (AAC)	400	0.130
Pumice Block	360.41	0.105
Adobe	1200	0.400
Hempcrete Block	450	0.236

Table 5. Required insulation thickness to preserve U-Value

Proposed Wall Materials	Current Thickness (cm)	Required Insulation Thickness to Preserve U-Value
Brick	20	40 + 12
	30	40 + 3
Autoclaved Aerated Concrete (AAC)	20	40 + 15
	30	40 + 8
Pumice Block	20	40 + 16
	30	40 + 8
Adobe	35	40 + 0
Hempcrete Block	30	40+18

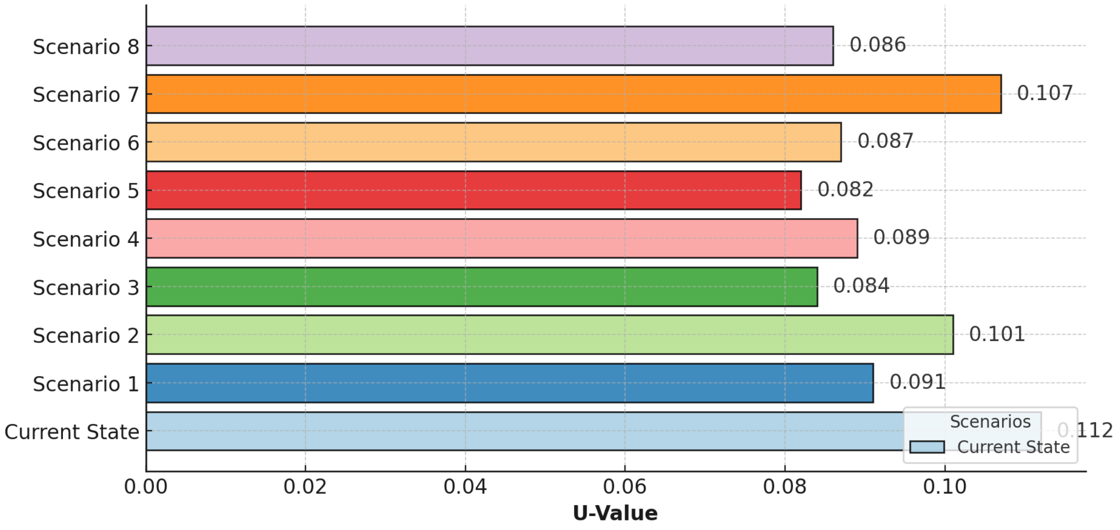


Fig. 8. U-Values of existing and alternative building envelopes

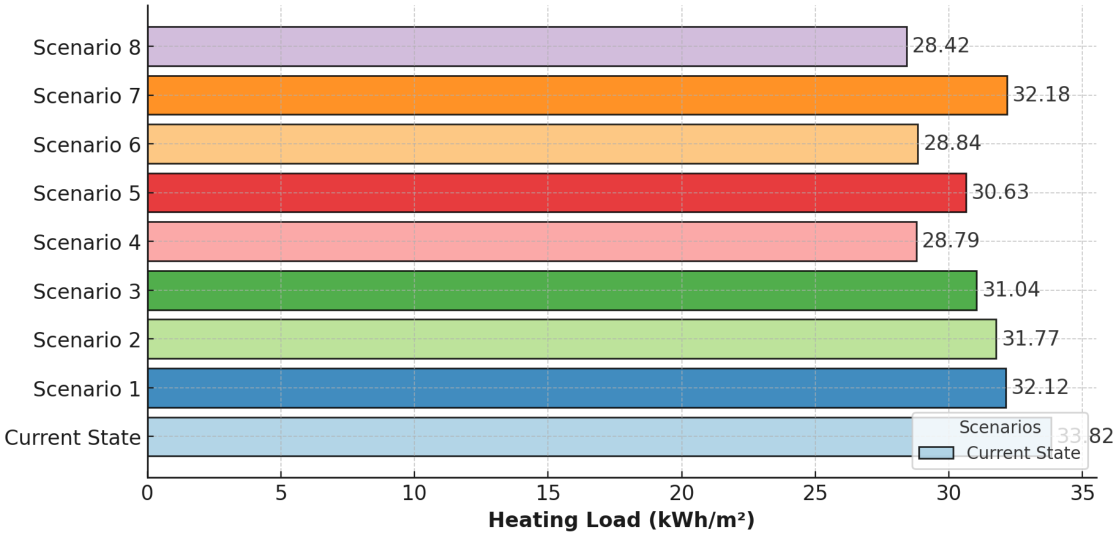


Fig. 9. Annual heating load for existing and alternative building envelope scenarios

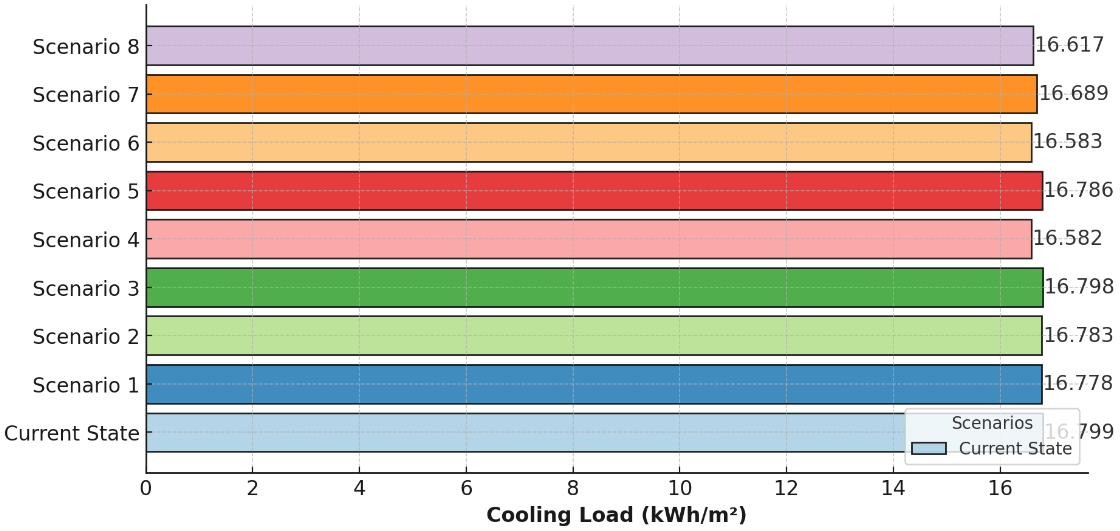


Fig. 10. Annual cooling load for existing and alternative building envelope scenarios

2.2.2. Determination of the environmental impacts of the proposed material layers

The environmental impacts of the proposed material layers were assessed using the same methodology applied to determine the environmental impacts of the existing building, utilizing the One Click LCA plug-in for Autodesk Revit. To calculate the environmental impact values for the A4 phase, the nearest manufacturing facilities capable of supplying the construction materials to Gaziantep were identified (Table 6). Attention was given to ensuring that the materials selected from the One Click LCA database had Environmental Product Declarations (EPDs) with technical specifications matching those of the materials produced at these facilities. Regarding adobe, the primary production location was identified as Oğuzeli, a district of Gaziantep. Consequently, it was assumed that the adobe used in the GEH was sourced from a facility located 39.9 km away in Oğuzeli. Hempcrete was retained in the A1-A3 comparison to evaluate its theoretical environmental potential as a bio-based material. However, it was excluded from A4 transportation analysis due to the absence of domestic production in Türkiye, which would result in unrealistic transport-related emissions.

3. Results

3.1. Global warming potential assessment of the GEH and alternative scenarios

The Global Warming Potential (GWP) of GEH has been calculated as 211 tons CO_2e, with the percentage contribution of each building component has already illustrated in Fig. 7. Among the materials used, ready-mix concrete, which is employed in the walls, roof, and floors, has been identified as the largest contributor to the building's GWP. This finding aligns with Bahmani & Mostofinejad, 2025, who demonstrated that cement-based materials have a significant GWP due to clinker production, which accounts for nearly 8% of global CO_2 emissions [42].

Following concrete, the cement-bonded wood particleboard used in the structure accounts for 15.6% of the total GWP. The screed flooring, which has a high cement content, contributes 5.6% to the overall GWP. Expanded polystyrene (EPS), used in the roof insulation, adds 4.8%, whereas glass wool, used in the wall insulation, contributes 3.9% to the building's total GWP. These findings highlight that the choice of insulation material has a direct impact on embodied emissions, which is consistent with research by Maeijer, 2025, who found that using alternative low-carbon insulation materials can reduce embodied emissions by up to 25% [43]. To enhance the sustainability of GEH while maintaining its energy efficiency, alternative wall scenarios have been proposed. The GWP values for these scenarios are presented in Fig. 11.

Table 6. Assumed Material Supply Locations and Transport Distances

Material	City	Company	Distance (km)
Ready-Mix Concrete	Gaziantep	KÇS Concrete	11.2 km
Brick	Hatay	Artuğ Brick	193 km
Autoclaved Aerated Concrete (AAC)	Gaziantep	Gaziantep Ytong	20.3 km
Pumice	Kayseri	Ponce Block	305 km
Adobe	Gaziantep Dörtyol	-	39.9 km
Glass Wool	Mersin	İzocam	261 km

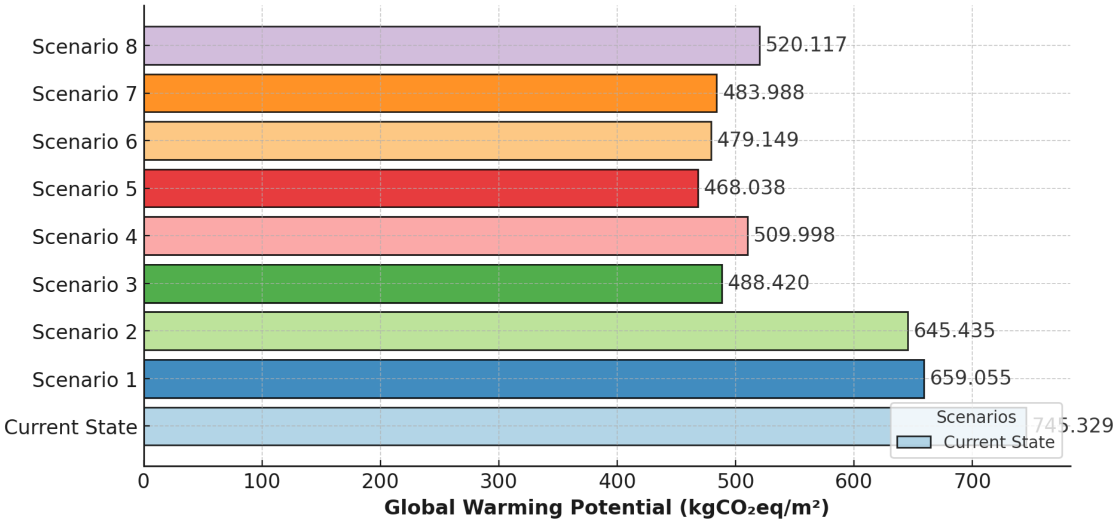


Fig. 11. GWP comparison of current and alternative envelope scenarios

The contribution of brick wall material to global warming potential (GWP) is notably higher than that of insulation, suggesting that increasing insulation thickness is a more effective GWP reduction strategy.The brick production, especially the high-temperature sintering process, leads to substantial CO_2 emissions [44]. Alternatives like unfired clay or geopolymer bricks offer lower emissions while maintaining structural integrity [45]. Scenario 2 (30 cm brick wall) had the highest GWP, exceeding the current concrete wall. Conversely, Scenario 1 (20 cm brick wall) showed lower GWP, reinforcing the advantage of thicker insulation over thicker masonry. Scenario 8 (hempcrete) ranked second highest in GWP. Although hempcrete sequesters carbon during plant growth, its cement binder increases emissions, consistent with [46]. AAC walls (Scenarios 3 and 4) showed GWP increased with thickness due to the higher cement content and energy-intensive autoclaving process [28]. AAC's embodied energy is offset by its long-term thermal benefits [47]. Scenario 5 (20 cm pumice block) yielded the lowest GWP, contributing just 7.2% of total emissions. Scenario 6 (30 cm pumice) also performed well. These results align with Sankarasubramanian, 2025, who emphasized the low processing needs and natural origin of pumice [48]. Adobe walls (Scenario 7) also showed favorable performance, but pumice-based solutions proved the most sustainable in balancing carbon footprint and thermal efficiency.

3.2. Acidification potential assessment of the GEH and alternative scenarios

The acidification potential (AP) values of the alternative material scenarios proposed for the GEH are presented in Fig. 12. The results highlight the significant role of cement-based materials, such as ready-mix concrete and cementitious boards, in acidification emissions, mainly due to their high SO_2 and NO_x outputs during production [49]. The acidification potential (AP) of the GEH has been calculated as 576 kg SO_2e, with the percentage contributions of building components. Among the materials used in the structure, the highest contribution to acidification potential was recorded for reinforced concrete, which was utilized in the foundation and floor slabs, accounting for 24.1% of total acidification emissions.

The wall materials contributed 20.5%, while glass wool insulation had a 6.1% share of the total AP. Additionally, cement-bonded wood chipboard contributed 12.8% to the acidification impact. These findings align with studies showing that cement-based materials significantly contribute to acidification due to sulfur and nitrogen oxides (SO_2 and NO_x) emitted during clinker production [50]. The high impact of concrete is particularly linked to the use of Portland cement, which has been identified as a major source of acidification emissions in the construction sector. Research also suggests that alternative binders, such as alkali-activated materials or low-clinker cement formulations, could substantially reduce the acidification footprint of concrete-based components [51, 52].

The acidification potential (AP) analysis revealed that brick-based scenarios had the highest impact, with Scenario 2 (30 cm brick wall) showing brick contributing 46.72% of total AP emissions. This stems from the energy-intensive sintering process and fossil fuel use in brick production [53]. Studies confirm that traditional clay bricks emit more SO_2 and NO_x than concrete blocks, primarily due to firing temperatures above 900°C [54]. Interestingly, brick-based scenarios exhibited higher AP than the existing ready-mix concrete wall, challenging the assumption that brick is always more sustainable. This underscores the need to include AP and eutrophication in LCA evaluations [55]. Scenario 8 (hempcrete) showed AP values comparable to the concrete baseline, suggesting that hempcrete's carbon benefits may not extend to acidification due to its cement binder. Pumice-based walls (Scenarios 5 and 6) had lower AP than autoclaved aerated concrete (AAC). In both cases, increasing insulation rather than wall thickness resulted in reduced acidification, showing this as a preferable strategy for preserving U-values sustainably. The lowest AP was recorded in Scenario 7 (adobe walls), with only a 2% contribution.

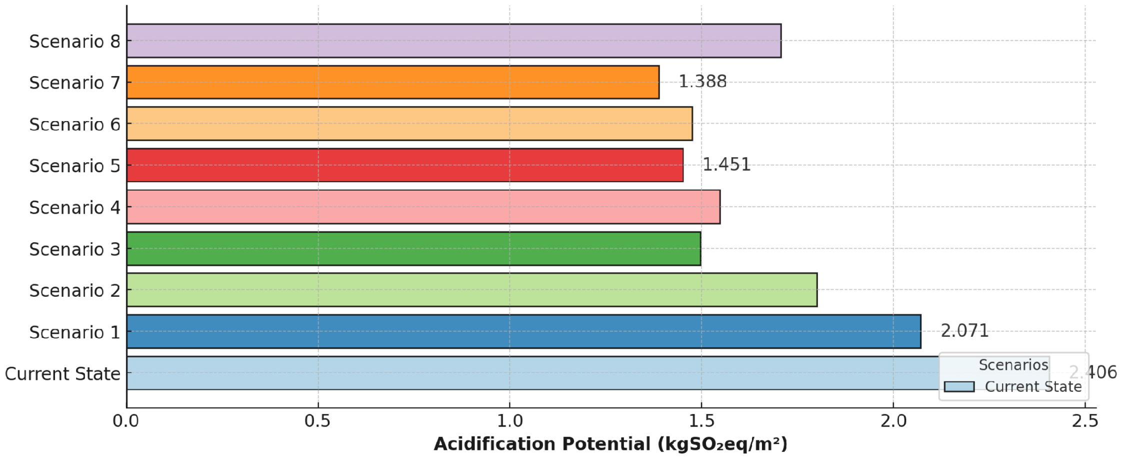


Fig. 12. AP comparison of current and alternative envelope scenarios

This supports previous findings that earth-based materials have significantly lower acidification and eutrophication impacts than cement- or kiln-based materials [56].

3.3. Eutrophication potential assessment of the GEH and alternative scenarios

The eutrophication potential (EP) of the GEH has been calculated as 322 kg Ne, with the highest contribution (44.5%) originating from mineral plaster used in the exterior wall layers. Concrete, which has been widely recognized for its durability and structural efficiency, also contributes significantly to eutrophication due to the leaching of nitrates and phosphates from its cementitious components [57]. In this study, the eutrophication impact of the ready-mix concrete used in the walls of the GEH was found to be 10.8%, whereas the insulation materials contributed only 1.5%. Additionally, cement-bonded particle boards contributed 3.7% to the total eutrophication potential. These findings align with previous research indicating that the production of cement-based materials, particularly clinker in Portland cement, is responsible for nitrogen oxide (NOx) emissions, which are precursors to eutrophication in aquatic systems [58].

The eutrophication potential (EP) values of the alternative material scenarios proposed for the GEH are presented in Fig. 13. The brick-based alternatives (Scenario 1 and 2) exhibited higher eutrophication potential compared to the current building materials, similar to their impact in the acidification category. The highest eutrophication impact was observed in Scenario 2, which used 30 cm-thick bricks, resulting in a 20.71% contribution to total eutrophication emissions. Studies have shown that brick production, particularly during the high-temperature sintering process, emits substantial amounts of NOx and sulfur dioxide (SO_2), both of which contribute to acidification and eutrophication [59].

Interestingly, the hempcrete-based Scenario 8 had a lower impact than the existing design but still ranked among the higher impact scenarios. While hempcrete has been promoted as a low-carbon material due to its carbon sequestration potential, its reliance on lime-based binders and cementitious additives increases its eutrophication potential, as observed in other life cycle assessment (LCA) studies [60].

Among the lightweight concrete alternatives, pumice block (pumice-based blocks) and autoclaved aerated concrete (AAC, also known as gas concrete) were evaluated, with pumice block-based alternatives (Scenario 5 and 6) exhibiting lower eutrophication potential than gas concrete. The lowest eutrophication impact was observed in Scenario 7, which used adobe as the primary structural material, with a mere 1% contribution. Adobe's significantly lower impact is attributed to its natural composition and the fact that it is sun-dried rather than kiln-fired, eliminating the need for fossil-fuel-intensive production processes [61]. This confirms previous findings that adobe and other earthen materials have considerably lower embodied emissions and eutrophication potential compared to cementitious materials [62].

The proposed alternative material scenarios also included adjustments to insulation materials and fiber-cement board replacements. In the adobe-based Scenario 7, the glass wool insulation layer contributed 2.11% to the eutrophication potential, while the fiber-cement board replacing cement-bonded particle board had a lower impact of 1.57%. Fiber-cement board, despite containing cement, incorporates higher proportions of renewable cellulose fibers, making it a more sustainable alternative to traditional cementitious boards [63].

Overall, these findings highlight the need for a holistic environmental assessment of construction materials. While energy efficiency is often the primary focus in sustainable building design, the environmental burdens of material choices, particularly their eutrophication impact, should also be a key consideration. Future studies should explore the use of bio-based and geopolymer-based alternatives, which have shown promise in reducing both carbon footprint and aquatic toxicity effects [64].

3.4. Photochemical ozone formation potential assessment of the GEH and alternative scenarios

The total photochemical ozone formation potential (POFP) of the GEH has been calculated as 117 kg O_3e. Among the building materials, the highest contribution (64%) came from expanded polystyrene (EPS) insulation, which was used in the roof system.

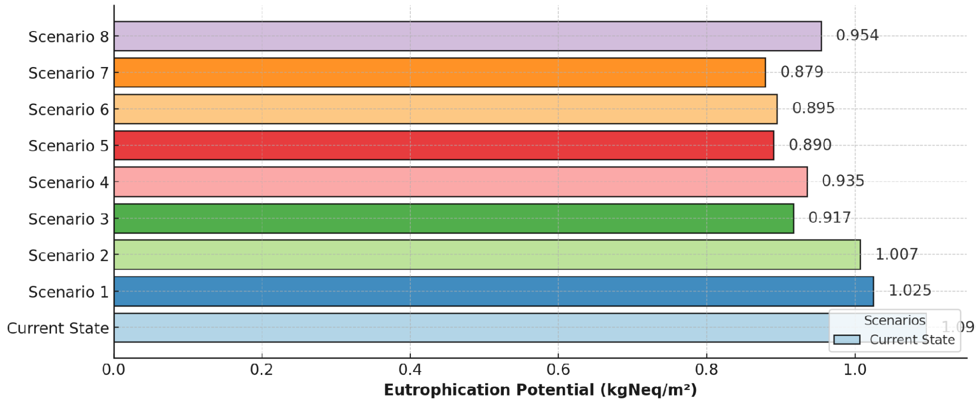


Fig. 13. EP comparison of current and alternative envelope scenarios

EPS is known to have a high impact on photochemical ozone formation due to its petroleum-based composition and emissions of VOCs during production and disposal [65]. Other key contributors to POFP included:

- Glass wool insulation (used in the wall system) with 1.3% contribution,
- Ready-mix concrete (used in wall structures) contributing 3.9%, and
- Cement-bonded particle boards account for 2.8% of total photochemical ozone emissions.

As in previous categories (acidification and eutrophication), brick-based scenarios (Scenarios 1 and 2) showed the highest photochemical ozone formation potential (Fig. 14). Brick manufacturing, especially the kiln-firing process, emits significant nitrogen oxides (NO_x), a primary contributor to ozone formation [58]. Scenario 8, which included hempcrete, ranked second. While hempcrete is known for carbon sequestration, its production, especially involving cement-based binders and chemical treatments, may contribute to VOC emissions, potentially raising its ozone formation potential [58]. Among lightweight alternatives, AAC and pumice-based blocks followed, with pumice performing slightly better. This supports Gursel et al. (2014), who found AAC to produce more NO_x emissions due to autoclaving compared to natural pumice-based concrete [58]. The lowest ozone formation impact was found in Scenario 7 (adobe), contributing only 1%. As a sun-dried material, adobe avoids fossil fuel use, minimizing NO_x and VOC emissions. This is consistent with research showing that earthen materials outperform cement-based ones in air pollution metrics. Overall, the results highlight the need to consider smog-related impacts when selecting materials. Though EPS insulation offers high thermal efficiency, its life cycle VOC emissions contribute significantly to ozone formation and poor air quality [64]. Future studies should focus on low-emission insulation options like bio-based fibers and aerogels, which combine environmental benefits with energy performance [60].

3.5. Ozone Depletion Potential (ODP) assessment of the GEH and alternative scenarios

The total ozone depletion potential (ODP) of the GEH was calculated as 8.64E-03 kg CFC-11e. Among all building materials, the highest contribution to ODP (60.6%) originated from ready-mix concrete, commonly used in structural elements such as walls, floors, and foundations. Within this category, the contribution of concrete used in the wall system alone accounted for 26.1%. The glass wool insulation material, used in the wall system, was responsible for 8.4% of the total ODP impact. Similar findings have been reported in previous studies, highlighting those certain types of insulation materials, particularly those containing halogenated blowing agents—can significantly contribute to ozone layer depletion [65].

Scenario 8, which incorporated hempcrete blocks, exhibited the highest ODP, contributing 31.79% of the total, surpassing the existing concrete-based design (Fig. 15). Although hempcrete is often viewed as eco-friendly for its carbon sequestration properties, its reliance on cement-based binders increases its ODP impact. In contrast to categories like acidification and eutrophication, where brick had the highest impact, autoclaved aerated concrete (AAC) scenarios (3 and 4) ranked second in ODP. AAC production processes, including the use of aluminum powder and autoclaving, may release halogenated compounds [58].

Pumice and brick scenarios showed moderate ODP impacts. Notably, in Scenario 5 (20 cm pumice) and Scenario 1 (20 cm brick), insulation materials had a higher ODP contribution than the structural components, highlighting the significant impact of CFC-containing insulation. The lowest ODP was found in Scenario 7 (adobe), where adobe contributed only 1%, while insulation accounted for 12.78%. This underscores the sustainability of earthen materials and the need to focus on low-impact insulation. These findings emphasize the importance of reducing synthetic insulation use and suggest future exploration of bio-based alternatives like sheep wool, cellulose, or aerogels that offer low ODP.

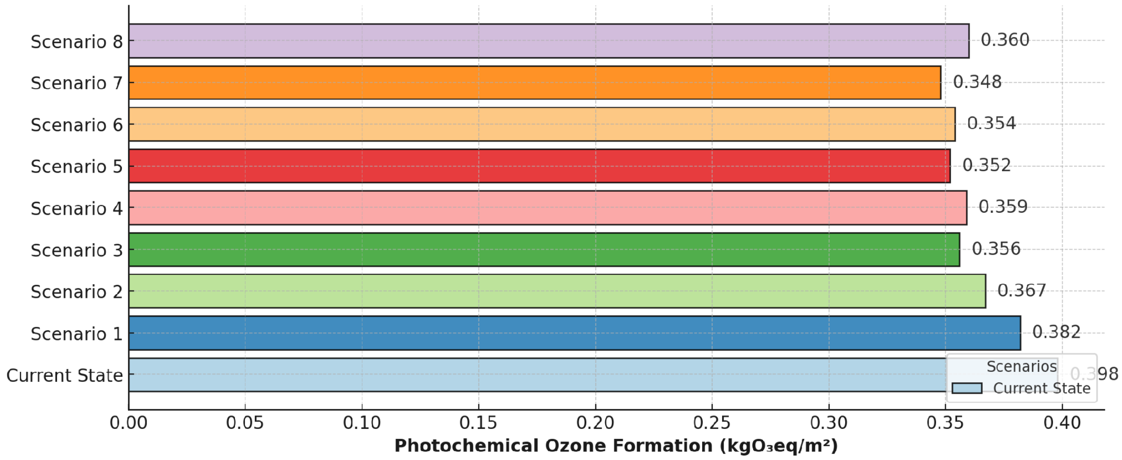


Fig. 14. POFP comparison of current and alternative envelope scenarios

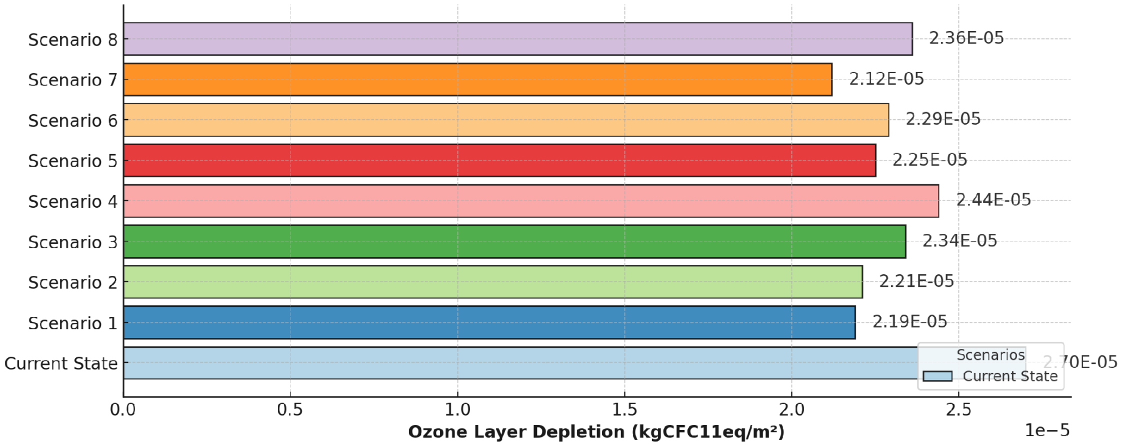


Fig. 15. ODP comparison of current and alternative envelope scenarios

Fig. 16 compares the environmental performance of alternative wall materials for the Gaziantep Ecological House across five categories (GWP, AP, EP, POFP, ODP). Scenario 2 (S-2) showed the highest global warming potential, over 130% of the current situation (C.S.), primarily due to the high embodied carbon in brick, which aligns with studies linking brick production to significant CO_2 emissions from high-temperature sintering [68]. Additionally, acidification and eutrophication potentials show significant increases in Scenario 2, reinforcing that brick-based alternatives contribute more to environmental degradation than other proposed materials. In contrast, Scenario 7 (S-7), which incorporates adobe as the primary wall material, demonstrates the lowest impact across most categories, particularly in photochemical ozone formation (POFP) and ozone depletion potential (ODP). Interestingly, Scenario 8 (S-8), which utilizes hempcrete blocks, exhibits higher ozone depletion potential than other alternatives, likely due to the cementitious binder content. Moreover, despite its lower GWP, hempcrete's reliance on cement-based components increases its contribution to ozone depletion, highlighting the trade-offs between embodied carbon and other environmental impacts.

Overall, this analysis suggests that reducing environmental impacts in passive house design requires a balanced selection of materials that optimize energy performance while minimizing embodied emissions and secondary environmental burdens [58]. Future studies should focus on refining bio-based insulation materials to further improve sustainability outcomes without compromising thermal efficiency.

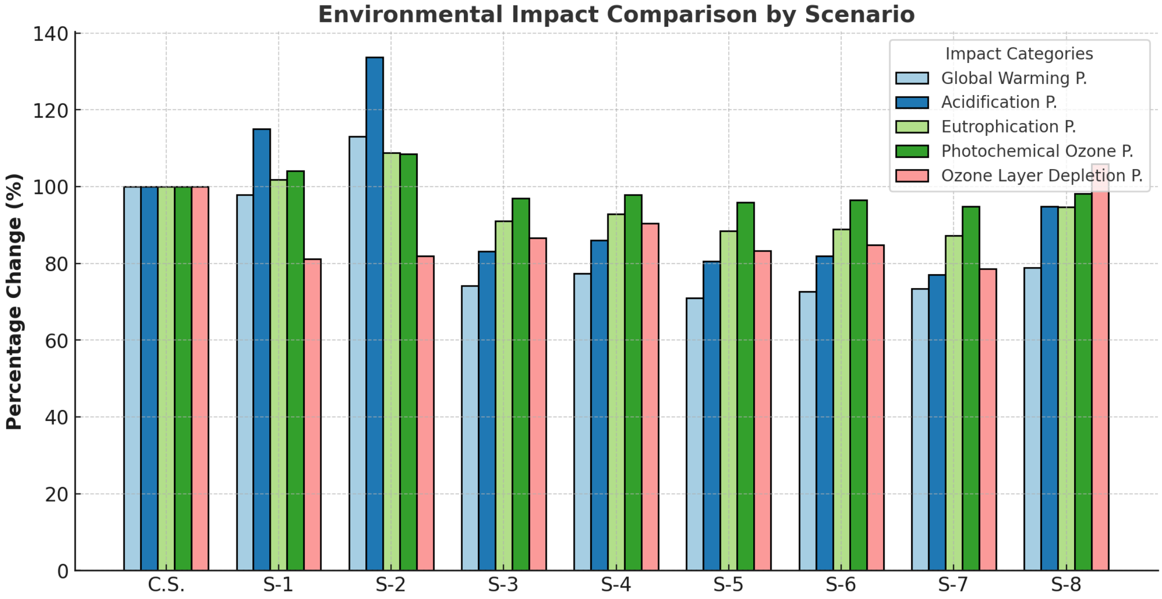


Fig. 16. Comparative environmental assessment of building envelope scenarios

3.6. LCA A4 phase evaluation: Transport-related carbon emissions

In the Life Cycle Assessment (LCA) of the A4 phase, carbon emissions from transporting materials to the Gaziantep Ecological House (GEH) site were analyzed. This included emissions from the transport of reinforced concrete from the KÇS Ready-Mix Concrete Plant and 40 cm thick glass wool insulation from the Mersin İzocam factory. The results showed that ready-mix concrete transport caused 0.18 tons of

CO_2 emissions, while insulation transport contributed 0.28 tons. Emissions were calculated based on distances listed in Table 6. Hempcrete was excluded due to two reasons: its lack of domestic production in Turkey would lead to high transport emissions, and its overall environmental performance in the A4 phase was insufficient to justify inclusion. Fibercement boards, used in equal quantities across all scenarios, were excluded from A4 impact calculations to maintain consistency in comparative analysis. In contrast, glass wool insulation was applied in varying thicknesses, so its emissions were individually calculated per scenario. Fig. 17 presents a comparative overview of A4 emissions across material alternatives. These results underscore the importance of using locally sourced materials and highlight how transportation distances significantly influence the environmental impact of sustainable construction [66].

In the A4 phase, transportation-related emissions are directly proportional to the distance materials travel. For this assessment, primary manufacturing sites were used instead of intermediary suppliers. As shown in Fig. 17, pumice block (Scenarios 5 and 6) caused the highest transport emissions. Similarly, aerated concrete used in Scenarios 3 and 4 accounted for nearly 90% of emissions due to its 305 km transport from the Ponce Blok factory in Kayseri. Brick-based Scenarios 1 and 2 also had high emissions, sourced from the Artuğ Brick Factory (193 km). In contrast, materials produced within Gaziantep, such as aerated concrete and adobe, showed the lowest impacts. For instance, in Scenario 7, adobe transport accounted for 87% of emissions, while glass wool insulation from Mersin contributed 13% a difference explained by material quantity. Scenario 3, using 20 cm aerated concrete, had the lowest total emissions in A4. As shown in Fig. 17, aerated concrete contributed 45% in Scenario 3 and 54.1% in Scenario 4 (30 cm wall). These findings suggest that heavier and thicker wall materials increase transport trips and CO_2 emissions. Scenarios that increased insulation rather than wall thickness—while maintaining the same U-value—proved more environmentally efficient in transport.

4. Discussion

4.1. Trade-off between operational energy efficiency and embodied carbon

The results of this study clearly demonstrate that optimizing passive house envelope systems requires a balanced evaluation of both operational energy performance and embodied environmental impacts. While passive house principles primarily aim to minimize operational heating and cooling demands through highly insulated building envelopes, the environmental burdens associated with material production may significantly influence the overall sustainability performance of the building lifecycle. Therefore, selecting appropriate wall materials involves complex trade-offs between thermal efficiency, embodied carbon, durability, structural applicability, and long-term environmental performance.

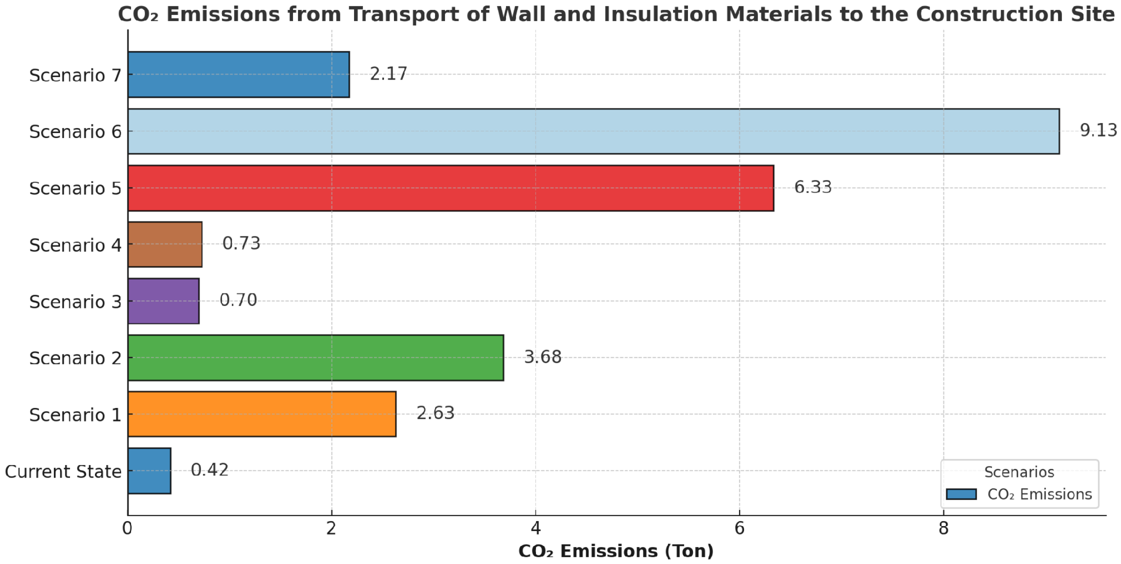


Fig. 17. Transport-related CO_2 emissions of wall and insulation materials (ton CO_2eq)

Brick-based wall systems exhibited relatively high durability, widespread applicability, and structural reliability within contemporary construction practices [67, 68]. Their long service life and compatibility with existing construction standards make them favorable from a practical and engineering perspective. However, the results revealed that brick scenarios generated the highest embodied environmental impacts across several categories, particularly global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). These elevated impacts are primarily associated with the energy-intensive firing process and fossil fuel consumption required during brick manufacturing [69]. Consequently, although brick systems provide robust structural performance and durability, their high embodied carbon burden limits their environmental sustainability within low-carbon passive house applications.

In contrast, adobe-based wall systems demonstrated the lowest embodied environmental impacts among all evaluated scenarios. The environmental advantages of adobe are largely attributed to its natural composition, low processing requirements, and the possibility of utilizing locally sourced raw materials with minimal industrial energy consumption [70, 71]. These findings highlight the considerable potential of earthen materials in reducing lifecycle carbon emissions in sustainable building applications. Nevertheless, adobe materials also present several practical limitations, including reduced structural capacity, sensitivity to moisture exposure, and limited suitability in seismic regions [72, 73]. Considering Türkiye's high seismic risk profile, the widespread implementation of adobe in multi-story passive house applications may require additional structural reinforcement systems, which could partially offset its environmental benefits.

Hempcrete-based wall systems represented another notable trade-off scenario. Due to its bio-based composition, hempcrete offers significant carbon sequestration potential and contributes positively to embodied carbon reduction strategies [74, 75]. However, the analysis revealed comparatively high ozone depletion potential (ODP) values associated with the cementitious binders used in hempcrete formulations. Furthermore, hempcrete is generally classified as a non-load-bearing material, requiring supplementary structural framing systems that may increase additional material consumption and associated environmental impacts [75, 76]. These findings indicate that bio-based materials should be evaluated comprehensively across multiple environmental impact categories rather than solely through carbon reduction potential.

Among the evaluated alternatives, pumice-based wall systems demonstrated a comparatively balanced environmental performance by combining moderate embodied carbon values with favorable thermal insulation characteristics and practical applicability within regional construction practices. The local availability of pumice materials in Türkiye also contributes to reduced transportation-related emissions during the A4 lifecycle stage. In this respect, pumice-based systems may represent a more feasible compromise between environmental sustainability, structural applicability, and operational energy efficiency for passive house construction in hot-arid climate regions.

Overall, the findings emphasize that no single material can simultaneously optimize all environmental, thermal, structural, and practical performance criteria. Therefore, sustainable passive house envelope design should adopt a multi-criteria decision-making approach that carefully balances operational energy savings with embodied environmental impacts, material durability, local availability, and long-term building performance.

4.2. Structural and practical limitations of alternative materials

Although adobe exhibited the lowest environmental impacts among the evaluated wall alternatives, several structural and practical limitations restrict its widespread application in contemporary passive house construction. Adobe materials are generally more suitable for low-rise buildings and may present significant structural challenges under seismic loading conditions [72]. Given that Türkiye is located in a highly active seismic region, the applicability of adobe in multi-story or earthquake-prone areas requires careful structural assessment in accordance with Turkish seismic regulations.

In addition to seismic limitations, adobe materials are highly sensitive to moisture exposure and require adequate protection against water penetration and long-term weathering effects [72]. Without proper detailing and maintenance strategies, durability problems such as cracking, erosion, and loss of structural integrity may occur over time.

Similarly, hempcrete-based systems also present practical limitations despite their bio-based composition and carbon sequestration potential. Hempcrete is generally considered a non-load-bearing material and therefore requires an independent structural frame system, which may increase additional material consumption and embodied emissions [56, 75]. Furthermore, the absence of domestic hempcrete production in Türkiye currently limits its practical applicability and increases transportation-related environmental burdens.

These findings suggest that material selection for passive house envelopes should not rely solely on environmental indicators but should also consider structural safety, durability, regional applicability, and compliance with local construction standards.

4.3. Implications for sustainable passive house design in hot-arid climates

This study contributes to the growing body of literature emphasizing the importance of integrating embodied carbon assessment into passive house design decision-making. Most existing passive house studies primarily focus on operational energy reductions [77], whereas the present findings demonstrate that embodied impacts may represent a substantial proportion of total lifecycle environmental burdens in highly energy-efficient buildings.

The results further highlight the environmental benefits of locally sourced construction materials. Transportation-related emissions evaluated in the A4 phase revealed that locally available materials such as adobe and AAC significantly reduced transport-associated carbon emissions compared to imported or regionally distant alternatives. This finding reinforces the importance of regional material sourcing strategies within sustainable construction practices.

For hot-arid climate regions such as Gaziantep, passive house optimization should therefore involve a balanced evaluation of thermal performance, embodied carbon, transportation impacts, material durability, and structural feasibility. Integrating these criteria into early-stage design decisions may support the development of more environmentally sustainable passive house standards adapted to local climatic and construction conditions.

5. Conclusions

This study presented a comprehensive Life Cycle Assessment (LCA) of the Gaziantep Ecological House (GEH), Türkiye’s first certified passive house, by integrating both operational energy performance and embodied environmental impacts. The findings demonstrated that material selection plays a critical role in the overall sustainability of passive house applications. Although passive house principles significantly reduce operational energy demand [78], the environmental burden associated with construction materials may substantially influence total lifecycle impacts. The results further revealed that exterior wall systems constituted one of the major contributors to the building’s embodied environmental impacts, emphasizing the importance of envelope optimization in sustainable building design.

Among the evaluated alternatives, brick-based wall scenarios exhibited the highest environmental impacts across several categories, including global warming, acidification, and eutrophication potentials, primarily due to energy-intensive production processes and fossil fuel dependency during manufacturing. In contrast, adobe-based wall systems demonstrated the lowest environmental impacts in most categories, highlighting the environmental advantages of low-processed natural materials. However, the study also identified important trade-offs between environmental performance and practical applicability. Despite their favorable embodied carbon performance, adobe materials present limitations related to structural capacity, seismic resistance, moisture sensitivity, and long-term durability [72]. Similarly, although hempcrete exhibited carbon sequestration potential, its cementitious binder content increased ozone depletion impacts, illustrating that materials performing well in one impact category may generate secondary environmental burdens in others.

The findings of this study provide important implications for sustainable construction practices and passive house policies, particularly in hot-arid climate regions. The results emphasize that achieving truly sustainable passive house design requires an integrated evaluation of operational energy efficiency, embodied carbon, transportation-related emissions, structural feasibility, and local material availability. In this context, the use of locally sourced and low-processed construction materials can significantly reduce transportation emissions [79, 80] and improve overall environmental performance. Therefore, policymakers, architects, and engineers should incorporate LCA-based decision-making into early-stage building design processes to support low-carbon and climate-responsive construction strategies aligned with international decarbonization goals.

Future research should focus on optimizing bio-based and low-carbon construction materials with improved structural durability and moisture resistance while maintaining high thermal performance. Further studies are also needed to investigate hybrid wall systems combining conventional and alternative materials to balance structural safety, energy efficiency, and embodied carbon reduction. Additionally, the development of region-specific LCA databases and the integration of circular economy principles, such as material reuse, recycling, and design for disassembly, would contribute to more accurate environmental assessments and more sustainable passive house applications in different climatic regions.

Declarations

Conflict of Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author Contributions

F. Ç. Kara Dülger: Investigation, Data curation, Original draft preparation, Validation, Methodology, Software, Visualization. M. Tuna Kayılı: Conceptualization, Writing, Methodology, Supervision.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

Not applicable.

Use of Generative AI and AI-assisted Technologies

The authors used ChatGPT for grammar and formatting and have reviewed and take full responsibility for the final content.

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