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Environmental Impacts of Reinforced Concrete Buildings: Comparing Common and Sustainable Materials: A Case Study

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Abstract: The world is currently grappling with the two critical issues of global warming and climate change, which are primarily caused by the emission of greenhouse gases. The construction industry and buildings significantly contribute to these emissions, accounting for roughly 40% of the total greenhouse gas emissions. In response to this pressing issue, environmental organizations and governments have pushed the construction industry to adopt environmentally friendly practices to reduce their carbon footprint. This has led to a greater emphasis on designing and planning sustainable buildings that are in line with the principles of sustainable development. Hence, it is imperative to evaluate buildings in terms of their greenhouse gas emissions and explore ways to reduce them. This research examines the impact of material selection on the carbon footprint of reinforced concrete buildings, aiming to reduce embodied carbon. For this purpose, two reinforced concrete buildings are designed for their embodied carbon to quantify their environmental impact. The first building employs commonly used materials such as ceramics, clay bricks, stone, and plaster. In contrast, the second building incorporates sustainable materials such as cork, plywood, and rockwool. According to the findings, using sustainable materials in the second building leads to a 41.0% reduction in the carbon footprint of the construction process. Additionally, using sustainable materials can mitigate pollution levels in the three categories of endangerment to human health, ecosystem pollution, and resource consumption by 31.4%, 23.7%, and 33.3%, respectively.

Keywords: life cycle assessment (LCA); carbon footprint analysis (CFA); reinforced concrete buildings; sustainable construction; SimaPro

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1. Introduction

Nowadays, global warming is considered a major problem that needs immediate attention [1]. It is primarily caused by human activities, such as burning fossil fuels and deforestation, which release greenhouse gases (GHGs) into the atmosphere and trap heat from the sun [2]. These gases form a blanket around the Earth, preventing heat from escaping and causing the planet to warm. This temperature rise is causing several adverse impacts on the planet, including rising sea levels, more frequent and intense heat waves, more severe weather events, and changes to ecosystems and wildlife habitats. If people do not take steps to reduce their GHG emissions and slow the pace of global warming, these impacts are likely to get worse in the coming years and decades [3].

In addition, the impacts of global warming are likely to be felt most acutely by people and communities who are already facing challenges, such as low-income communities, indigenous peoples, and small island nations. This makes it even more important for all of us to take action to address this problem. Addressing global warming will require reducing GHG emissions, transitioning to renewable energy sources, and taking other measures to reduce our carbon footprint and protect the planet [4].

The construction industry is a major contributor to global warming and carbon footprint due to various factors, including energy consumption, deforestation, material production and building operation [5]. It is noteworthy that the production of building materials, transportation of workers and materials to construction sites, and the operation of construction equipment all require energy and release GHGs into the atmosphere [6]. Clearing land for construction can result in the loss of forests, which play a crucial role in carbon sequestration [7]. Also, the production of building materials, such as cement, steel, and brick, generates significant GHG emissions [8,9]. Finally, once constructed, buildings consume energy for heating, cooling, lighting, and other purposes, contributing to emissions. Figure 1 displays the embodied carbon in every stage of a building's life cycle, excluding the operational phase.

Figure 1. The embodied carbon in every stage of a building's life cycle.

However, there are steps that can be taken to reduce the impact of construction activities on global warming and carbon footprint. Some of these include the use of sustainable building materials, energy-efficient design, renewable energy sources, etc. Overall, reducing the impact of building construction on global warming and carbon footprint requires a multi-disciplinary approach that involves collaboration between architects, engineers, contractors, building owners, and policymakers [2,6–8].

Life Cycle Assessment (LCA), a systematic and standardized method governed by ISO 14,040 [10] and ISO 14,044 [11], evaluates the environmental impact of a product or service throughout its entire lifecycle, from the extraction of raw materials to production, use, and disposal [12]. The main goal of LCA in the construction industry is to reduce the environmental impact of construction activities by identifying opportunities for improvement at each stage of the lifecycle [13]. This information can be used to make informed decisions about materials selection, design, construction methods, and building operations. Therefore, LCA can be a valuable tool for the construction industry, as it can help to minimize the environmental impact of construction activities, promote the use of environmentally friendly materials and construction methods, and ultimately contribute to a more sustainable built environment [14]. Therefore, a lot of studies have been performed to examine the environmental impacts of buildings [15]. Such studies focusing on the LCA of structures have been reviewed in the following sections

Gan et al. found that a considerable portion of GHG emissions in buildings stems from the embodied carbon generated by the production and transportation of building materials. This has made reducing embodied carbon in construction a crucial aspect of efforts to curb the release of GHGs into the atmosphere in recent years [16].

Most research focuses on mitigating the emission of GHGs in indoor environments, neglecting the embodied carbon footprint [17,18]. This emphasis is directed towards reducing the production of GHGs during the construction and operation phases, rather than addressing embodied carbon footprint. Timber buildings constructed from sustainable sources have a lower embodied carbon compared to conventional steel and concrete structures. However, the significant variation in embodied carbon among different mass timber structures is not being taken into consideration. A lifecycle assessment to determine the total carbon footprint of nine different wood designs for an eight-story mixed-use building was investigated by Jensen et al. [19]. This assessment considered the structural, acoustic, thermal, and fire-resistant properties of each design. Their results revealed a significant difference in the carbon footprint of different wood plank designs, with a reduction ranging from 14 to 52% for non-structural uses in comparison to concrete and steel base structures, and a reduction of 31–73% when considering the structural system alone.

Webster demonstrated that by optimizing design, it's possible to mitigate 10–25% of GHG emissions compared to current practices [20]. Strategies for reducing these emissions include minimizing overdesign, implementing topology optimization, and utilizing the performance-based design. Furthermore, it is estimated that the proper selection of building materials and components can result in a 10–25% decrease in carbon emissions.

In 2020, Chen et al. conducted a comprehensive cradle-to-grave LCA of a 12-story building constructed with either laminated wood or reinforced concrete [21]. The results showed that the building made of reinforced concrete emitted 6.11 kg of embodied carbon footprint, while the equivalent building made of laminated wood emitted only 2.16 kg, a reduction of 70%. Additionally, the wooden building stored 1.84 kg of CO_2eq in the wood materials used over its lifetime. The choice of building materials has significant implications for mitigating the effects of global climate change and should be carefully considered.

Moreover, the environmental impact of four low-carbon design approaches, including the utilization of recycled materials, the creation of components with longer lifespans, design compatibility with the natural environment, and the reduction in energy demand and carbon footprint through design was studied by Rasmussen et al. [22]. Their results indicated that the strategy of recycling and reuse was successful in reducing embodied carbon, while the incorporation of wood into the design of structures was also identified as a low-carbon approach. When combined, these two strategies resulted in savings of approximately 40% in the embodied carbon life cycle compared to the benchmark. Furthermore, the use of sustainable materials was shown to have a 30% lower carbon footprint compared to the reference, and the implementation of designs that adapt to the environment resulted in a 17% reduction in carbon footprint.

Based on the authors' review of the literature, no existing work has investigated the consequences of using sustainable materials in both structural and non-structural parts on the levels of embodied carbon and pollution. Additionally, many studies in the existing literature have only focused on the transportation of raw materials (such as equipment, aggregates, cement, structural metals, and ceramics) to the construction site, without taking into account the volume of traffic within the site during the building process, which may lead to an underestimate of emissions. In this research, the influences of sustainable materials on the carbon footprint of reinforced concrete buildings by taking transportation into account are assessed. For this purpose, two 4-stories reinforced concrete buildings are designed using common materials and sustainable materials. Finally, using SimaPro software, version 7.2, the carbon footprint and pollution of each building are evaluated, and then the results are compared. It should be noted that SimaPro is software for conducting LCA studies, used to assess the environmental impact of products and activities throughout their life cycle.

2. Methodology

2.1. LCA Method

LCA is a methodology used to assess the environmental impact of a product, service, or activity over its entire life cycle, from raw material extraction to disposal [23]. The goal of LCA is to identify and quantify the potential environmental impacts associated with a product, process, or service and to provide a basis for decision-making and continuous improvement toward sustainability.

The LCA process typically involves four steps [10]:

- Goal and scope definition: The first step is to clearly define the goals and scope of the LCA study. This includes identifying the product or service to be evaluated, the environmental impacts to be considered, and the boundaries of the study.
- Inventory analysis: The second step is to gather data on the inputs (e.g., materials, energy, water) and outputs (e.g., emissions, waste) of the product or service throughout its lifecycle. This information is used to create a detailed inventory of the environmental impacts of the product or service.
- Impact assessment: The third step is to evaluate the environmental impacts of the product or service by comparing the inventory data to impact categories (e.g., global warming, acidification, eutrophication) and calculating the overall impact of the product or service.
- Interpretation and reporting: The final step is to interpret the results of the LCA and communicate the findings to stakeholders. The results can be used to make informed decisions about the environmental impact of construction activities and to identify opportunities for improvement.

LCA is widely used in various industries, such as manufacturing, construction, agriculture, and consumer goods, to support sustainable product development and decision-making. There are several types of LCA, including:

(a) Cradle-to-grave LCA: This is the traditional type of LCA and considers all stages of a product's life cycle, from the extraction of raw materials to the disposal of the final product.
(b) Cradle-to-gate LCA: This type of LCA focuses on the environmental impact of a product from the extraction of raw materials to the end of the manufacturing process, but not including the use or disposal phase.
(c) Gateway-to-grave LCA: This is the reverse of the cradle-to-gate LCA, and it considers the environmental impact of a product from the point of distribution to its end-of-life disposal.

2.2. Carbon Footprint Analysis (CFA)

The carbon footprint is typically expressed in units of carbon dioxide equivalents (CO_2eq), which takes into account the different warming potentials of different GHGs. CFA is used for a variety of purposes, such as measuring and tracking emissions from a specific activity, evaluating the impact of emissions reduction efforts, supporting decision-making by providing data on the GHG emissions associated with different options and alternatives and improving sustainability by raising awareness about the environmental impact of human activities and encouraging actions to reduce emissions [24,25].

The steps involved in conducting a CFA can be summarized as follows [26]:

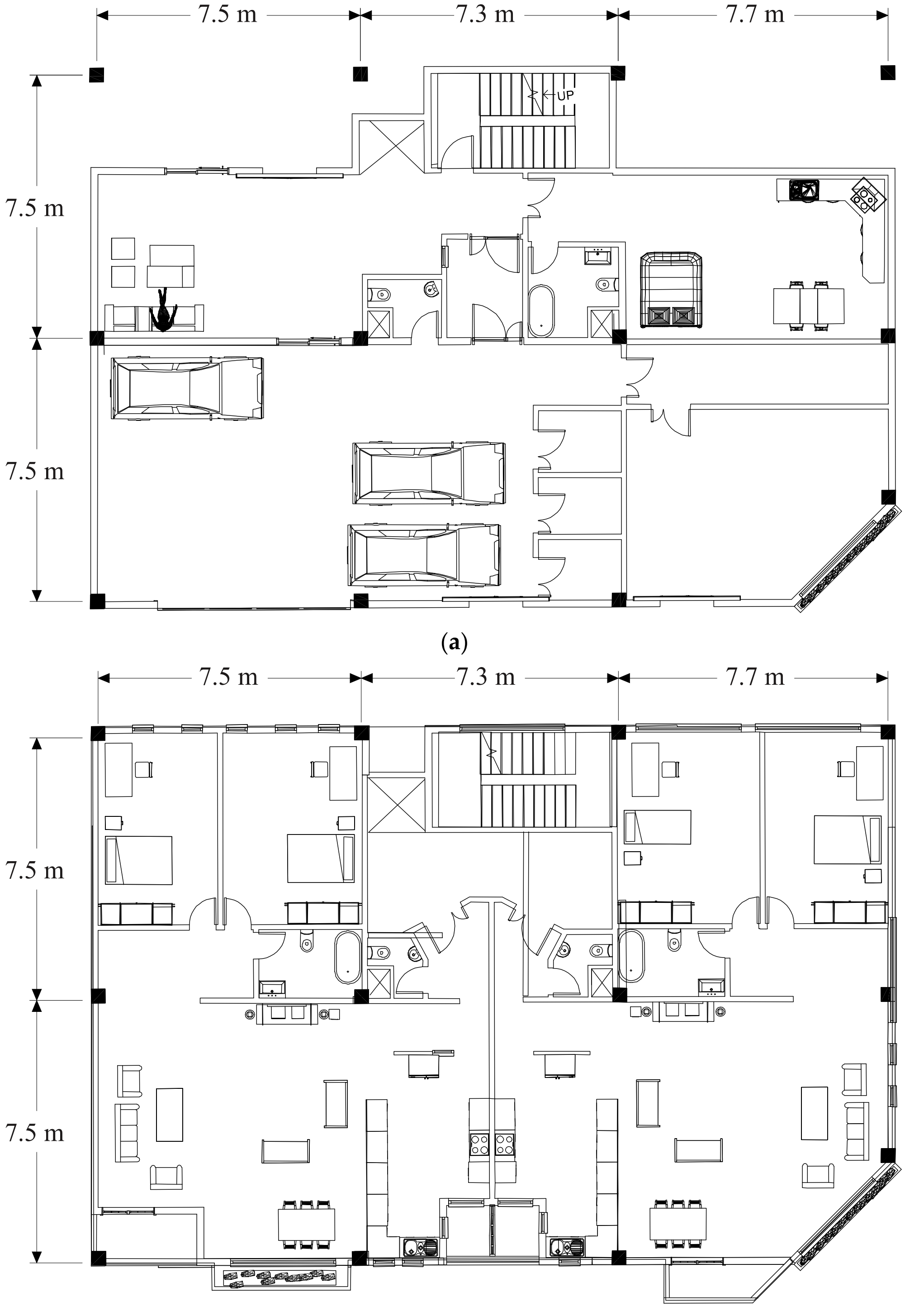
- Define the scope of the analysis: Decide what activities and processes will be included in the analysis. This could be an entire organization, a specific product, a single event, or any other defined boundary.
- Collect data: Gather information on the emissions generated by the activities and processes within the defined scope. These data may include information on energy use, transportation, waste generation, and other relevant factors.
- Identify the sources of emissions: Determine which activities and processes are responsible for the majority of emissions and prioritize them for further analysis.
- Calculate emissions: Use the data collected to calculate the total emissions generated by the defined scope, taking into account the type and quantity of each emission source.
- Evaluate the results: Analyze the results of the carbon footprint calculation and interpret the findings. This could involve comparing the results to industry benchmarks, identifying areas for improvement, or setting emissions reduction targets.
- Communicate the results: Share the results of the analysis with relevant stakeholders, such as employees, customers, investors, and regulators.
- Take action: Based on the results of the analysis, implement changes and initiatives aimed at reducing emissions and improving sustainability. This could include energy efficiency measures, switching to renewable energy sources, or changing business processes and practices.
- Monitor and review: Regularly monitor and review the carbon footprint to track progress and ensure that emissions reduction targets are being met.

It is important to note that the specific methods and tools used to conduct a CFA may vary, depending on the scope, complexity, and specific requirements of the analysis. It should be noted that the results obtained for the LCA using SimaPro Software were utilized for identifying the key source of GHG emissions.

3. Models Description

There are many materials commonly used in manufacturing and construction, including concrete, steel, wood, aluminum, etc. While these materials have many benefits, they also have a significant environmental impact due to the large amounts of energy and resources required to extract, process, and transport them. This can lead to high carbon footprint emissions and other negative environmental impacts. Using sustainable materials can help reduce this impact. Sustainable materials are those that are produced using renewable resources or recycled materials and that have a minimal negative environmental impact throughout their lifecycle. They can also be designed to be easily reused or recycled, reducing waste and conserving resources. By using sustainable materials, engineers can reduce the carbon footprint and other negative impacts of manufacturing and construction, helping to create a more environmentally friendly and sustainable world. In the following, the influences of the selected materials on the carbon footprint of two distinct reinforced concrete buildings are evaluated.

The main contributor to greenhouse gas emissions during material transportation is the burning of fuel by vehicles, specifically diesel trucks used to transport materials from manufacturers to the construction site [18]. It is important to consider the weight of materials and the distances they travel in order to accurately calculate the amount of fuel consumed during transportation. To study the impact of sustainable materials on the carbon footprint of reinforced concrete buildings, two 4-story reinforced concrete buildings are designed. The floor height is 3.2 m, and the lateral force resistance system is an ordinary moment frame. The considered plans of the buildings are shown in Figure 2.



(**b**)

Figure 2. The plan of the building, (**a**) The first floor, (**b**) Other floors.

The differences between the common and sustainable material buildings are evident in their flooring, facade, internal and external walls, doors, and window frames [27–30]. The behavior of block and EPS flooring systems in fire conditions is a critical consideration for their structural safety. Generally, EPS, being a combustible material, can undergo thermal decomposition when exposed to fire, potentially compromising its structural integrity. The fire resistance of these systems is often enhanced through the incorporation of fireretardant additives and appropriate construction practices to mitigate the impact of high temperatures and ensure the safety of the overall structure.

It is worth mentioning that the buildings are optimally designed using ETABS [31]. The grade of concrete and the strength of longitudinal rebar defined for the buildings are C25 and 400 MPa, respectively. A building with common materials requires 32.05 tons of rebar and 734.4 tons of concrete for columns and beams, while a sustainable material building requires 31.10 tons of rebar and 731.0 tons of concrete.

3.1. The Building with Common Materials

The flooring system of the building constructed with common materials is typically a concrete block joisted system. However, the materials used are selected without considering their embodied carbon impact. Cross-section details of the floor and external and internal walls for the building with common materials are presented in Figure 3.

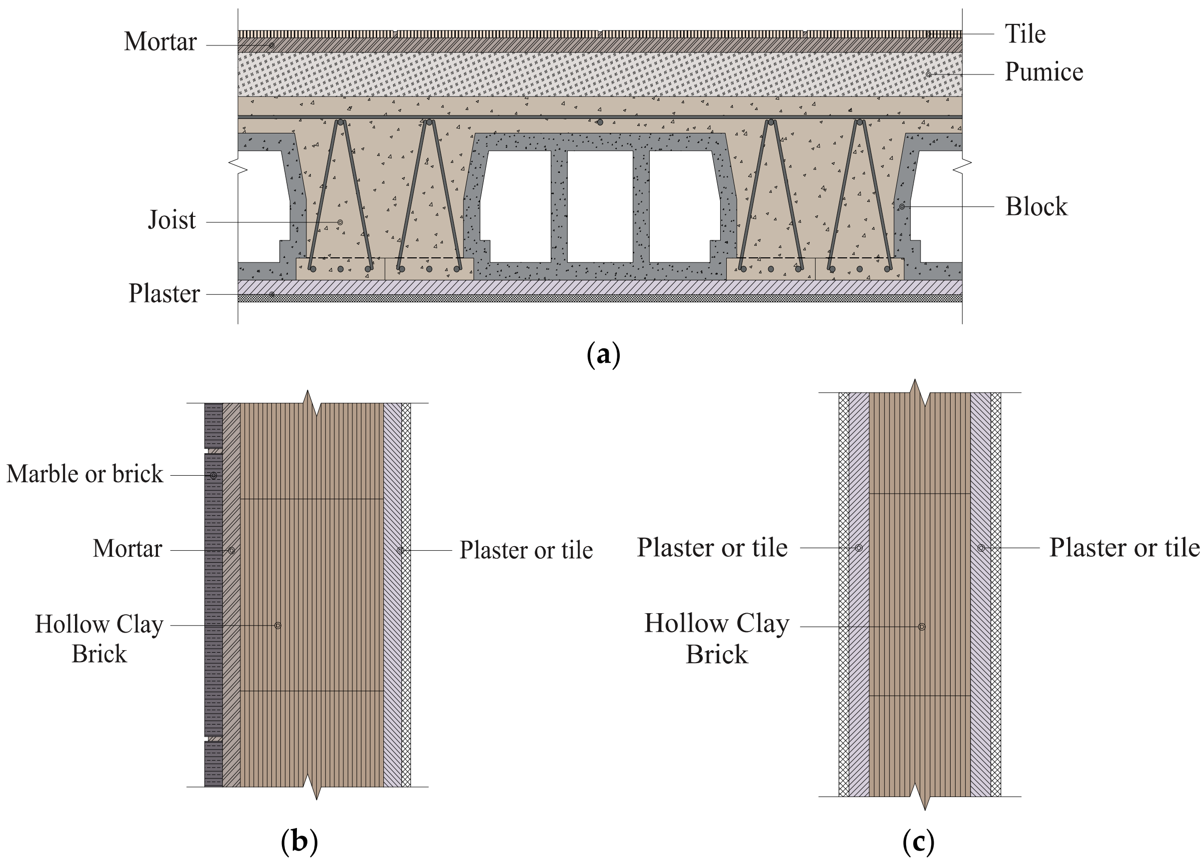


Figure 3. Cross-section details of the structural elements; (**a**) floor system by using concrete block, (**b**) external and (**c**) internal walls for the building with common materials.

3.2. The Building with Sustainable Materials

Sustainable materials aim to reduce the environmental impact of construction while promoting social responsibility [32–34]. For the flooring system, the EPS (Expanded Polystyrene) flooring system, known for its lightweight nature and excellent thermal insulation properties is utilized [35]. This system incorporates EPS, a thermally efficient material commonly used in construction for its insulation benefits. In our study, plywood, an engineered wood composed of thin layers or plies of wood veneers, with each layer's grain running perpendicular to the adjacent layers, for the doors is implemented [36,37]. Wooden window and door frames are also utilized, emphasizing the use of sustainably sourced wood in the building [38,39]. Regarding the structural elements, the use of geopolymer concrete, an innovative alternative to traditional Portland cement binder was explored [40,41].

The durability of ordinary concrete and geopolymer concrete presents distinct characteristics influenced by their respective material compositions. Ordinary concrete, primarily composed of Portland cement, can be susceptible to carbonation and chloride ion penetration over time, potentially leading to corrosion of reinforcing steel and a decrease in structural integrity. On the other hand, Polymer and geopolymer concrete, which utilize alternative binders such as polymer resins, fly ash or slag, has demonstrated enhanced resistance to certain deleterious processes [42,43]. Polymer and geopolymer structures have shown lower permeability, reduced susceptibility to chloride ingress, and an increased resistance to chemical attacks compared to ordinary concrete [43–45]. These properties contribute to a potentially extended service life and a reduced environmental impact, aligning with the broader goal of sustainable construction practices. However, it is crucial to note that the performance of geopolymer concrete may vary depending on the specific mix design, curing conditions, and environmental exposures. Further research and long-term monitoring are essential to comprehensively evaluate and compare the durability of these two concrete types under diverse conditions.

Cork, a natural and sustainable material, which has gained popularity due to its versatility and eco-friendliness is incorporated [46,47]. Figure 4 illustrates the cross-section details of the floor for the building with sustainable materials.

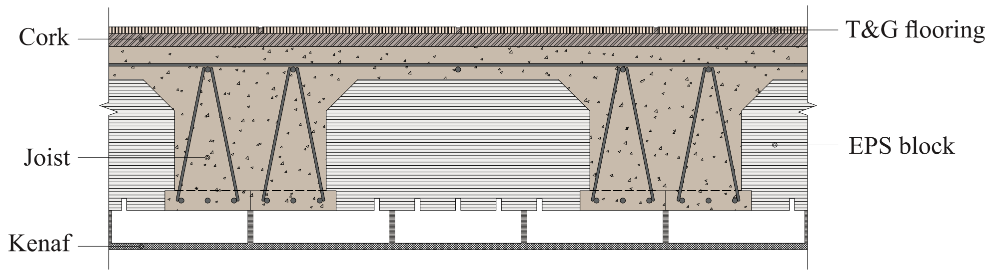


Figure 4. Cross-section details of the floor for the building with sustainable materials.

In addition, recycled glass tiles as an eco-friendly and sustainable option are considered for flooring and wall applications. For the building's facade, a combination of sandwich panels and wood is used [48]. Eco sandwich panels not only provide a modern and streamlined aesthetic but also offer energy efficiency benefits [49–51]. Furthermore, wood was chosen as a renewable resource, aligning with our commitment to environmentally friendly material choices [52].

By selecting these sustainable materials, this research aims to contribute to the advancement of environmentally conscious construction practices, showcasing the viability and benefits of these materials in creating sustainable buildings.

4. Results and Discussion

4.1. The Building with Common Materials

In order to accurately evaluate the carbon footprint of the building, various details must be taken into account, including the weight of the materials used, their transportation to the construction site, and the operation involved in their construction. Researchers in the fields of LCA and CFA face significant challenges in creating a comprehensive database with low uncertainty. The main materials and operations for the construction of buildings are concrete, steel, wood, brick, glass, electromechanical and thermal equipment, etc. Table 1 displays the amount of common materials and transportation involved in construction activity.

Table 1. The materials and construction operations used for the building are constructed with common materials.

Material	Unit	Production	Distance (km) to Site
Concrete	kg	734,400	50
Steel and Rebar	kg	32,050	420
Hollow clay brick	kg	177,560	40
Light concrete	kg	80,420	45
Block concrete	kg	64,440	30
Facing brick	kg	34,900	72
Marble	kg	24,640	415
Whiting	kg	129,690	32
Block	kg	64,430	36
Mortar	kg	120,620	40
Tile	kg	30,320	621
Mosaic	kg	9420	140
Door frame (Steel)	kg	1830	70
Windows (Aluminium)	kg	2040	65
Glass	kg	5790	150
Wood	kg	2760	50
Metal structures and Equipment	kWh	12,480	-
Others (food, . . .)	kg	4080	10

The analysis indicates that the embodied carbon footprint for the entire construction phase of the building with common materials is 448.3 tons. In simpler terms, the use of common building materials results in the emission of 434.8 kg CO_2eq per square meter of construction. To gain a better understanding of how different construction materials and operations affect the carbon footprint, Figure 5 displays the carbon footprint resulting from the construction of the building with common materials.

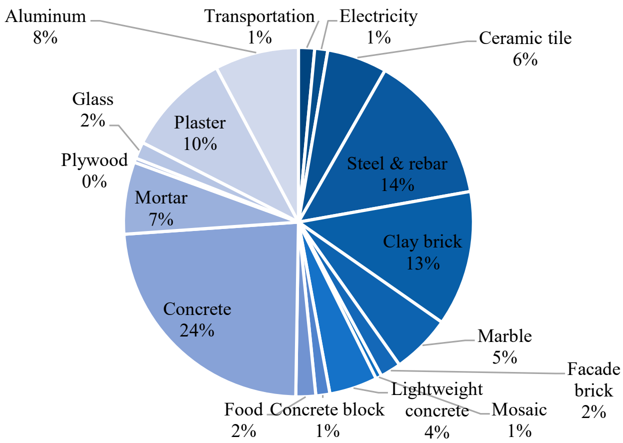


Figure 5. Contribution of construction material and operations of the building with common materials in carbon footprint.

The carbon footprint analysis conducted for the building with common materials provides important insights into the contributions of various materials and activities to the overall carbon emissions of the building. The results show that materials such as concrete, steel and rebar, clay brick and plaster have significant carbon footprints, with contributions of 23.7%, 13.9%, and 9.7%, respectively. These materials are commonly used in building construction, and their high carbon footprint highlights the need for alternative materials and more sustainable building practices. Additionally, the analysis indicates that transportation and electricity usage also have notable carbon footprints, with contributions of 1.5% and 1.8%, respectively.

4.2. The Building with Sustainable Materials

The inventory of the material and construction operation used for the building with sustainable materials is presented in Table 2.

Table 2. The materials and construction operations used for the building constructed with sustainable materials.

Materials	Unit	Production	Distance (km) to Site
Concrete	kg	731,000	50
Steel and Rebar	kg	31,100	420
Recycled glass tile	kg	18,090	140
Mortar	kg	6590	40
Plywood	kg	26,600	621
Eco-Sandwich wall panel	kg	3000	72
Cork	kg	32,800	40
Kenaf	kg	1550	32
EPS block	kg	1050	50
Door and Windows (wood)	kg	3110	65
Glass	kg	5790	150
Metal structures and Equipment	kWh	6240	-
Others (food, . . .)	kg	4090	10

The construction of environmentally friendly buildings results in a total of 264.4 tons of carbon footprint. In other words, the construction of every square meter of building with common materials emits 256.5 kg of CO_2eq. The carbon footprint contribution of construction materials and operations of the building with sustainable materials is illustrated in Figure 6.

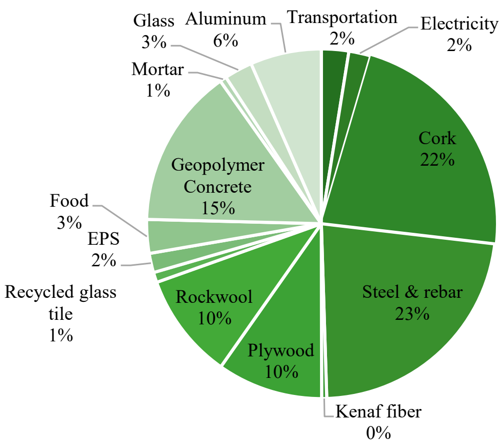


Figure 6. Contribution of construction material and operations of the building with sustainable materials in carbon footprint.

The use of sustainable materials such as cork, kenaf, steel rebar, rockwool, and recycled glass tile significantly reduces the carbon footprint of the building. The contribution of cork is particularly significant, with a 22.28% contribution to the carbon footprint reduction. Kenaf and recycled glass tile also make a notable contribution, with 0.46% and 0.94%, respectively. However, it is important to note that the carbon footprint is not only impacted by the materials used but also by transportation and electricity consumption. The transportation of the materials and the electricity used in the building contribute 2.03% and 2.03%, respectively, to the carbon footprint. The analysis also showed that the use of food in the building had a relatively low carbon footprint contribution of 3.12%. Overall, using sustainable materials can significantly reduce the carbon footprint of a building.

For example, cork, which is used instead of lightweight concrete and clay brick in this particular building, has been found to emit 22.59% less carbon dioxide than traditional building materials. For another example, the use of recycled glass tile instead of mosaic and ceramic tile used in kitchens, bathrooms, and WCs can decrease carbon footprint emissions by a staggering 74.09%.

When comparing a building constructed with conventional materials to one built with sustainable materials, the use of sustainable materials can result in a reduction of hidden carbon emissions by 41.0%.

4.3. Comparison between the Pollution of Both Buildings

Table 3 presents the LCA results for the buildings, utilizing the CML 2 baseline 2000 method. The results reveal significant differences in the environmental performance of the two building types. Notably, the building with sustainable materials demonstrated lower impact across various categories. The abiotic depletion, acidification, and eutrophication impacts were notably reduced, showcasing the positive environmental effects of employing sustainable materials. Moreover, in critical categories such as ozone layer depletion, human toxicity, and aquatic and terrestrial ecotoxicity, buildings with sustainable materials exhibited substantial reductions compared to their counterparts with common materials. This comprehensive LCA analysis provides valuable insights into the environmental benefits associated with choosing sustainable materials in construction, contributing to informed decision-making for environmentally conscious building practices. Additionally, Figure 7 illustrates the proportions of the various components in buildings, according to the same methodology.

Table 3. Total environmental impacts for buildings according to the CML 2 baseline 2000.

Impact Category	Unit	Building with Common Materials	Building with Sustainable Materials
Abiotic depletion	kg Sb eq	2204.177382	1632.37247
Acidification	kg SO_2 eq	1693.811477	1421.462042
Eutrophication	kg PO_4--- eq	466.473465	370.1418538
Ozone layer depletion (ODP)	kg CFC-11 eq	0.021513317	0.012156802
Human toxicity	kg 1,4-DB eq	273,269.7749	206,862.4723
Fresh water aquatic ecotox.	kg 1,4-DB eq	104,210.7088	83,439.50386
Marine aquatic ecotoxicity	kg 1,4-DB eq	172,281,668.6	132,712,548.3
Terrestrial ecotoxicity	kg 1,4-DB eq	1684.194935	1449.112661
Photochemical oxidation	kg C_2H_4 eq	90.63623204	103.9561486

The findings of the study highlight the substantial environmental benefits associated with incorporating sustainable materials in building construction. The utilization of these materials leads to a noteworthy reduction in environmental effects, ranging from 14% to 45%. Notably, the environmental impact of both buildings is influenced significantly by the use of metals, such as steel and aluminum. These materials contribute to various environmental indicators and should be carefully considered in sustainable building practices. Moreover, in the building designed with a focus on sustainable materials, the extensive consumption of cork emerges as a significant factor contributing to its environmental effects. Cork, renowned for its eco-friendliness and versatility, is utilized in various applications within the building. However, its high consumption rate results in notable implications for environmental indicators. It is crucial to acknowledge and address the environmental implications associated with the widespread use of cork, ensuring a holistic approach to sustainable material selection and consumption [47].

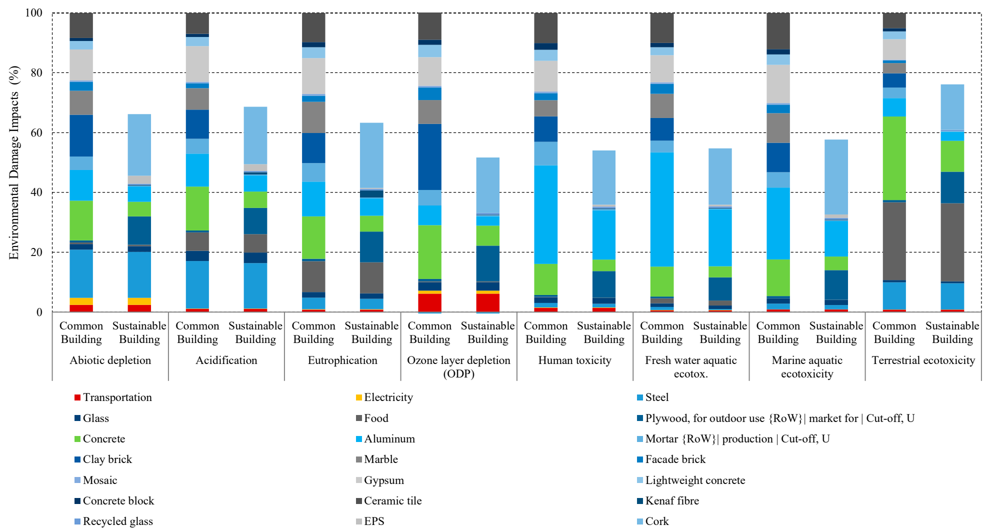


Figure 7. Contribution of building parameters in environmental impacts according to the CML 2 baseline 2000.

Moreover, the ReCiPe 2016 endpoint approach was used to determine the contribution of pollution to three categories—resource consumption, ecosystem pollution, and endangerment to human health—for two buildings. Figure 8 provides an accurate representation of this impact, with pollution levels normalized and weighted according to importance factors using the ReCiPe 2016 method, with values expressed in MPt, standing for millipoints. Given that the objective of this approach is to compare products or components, the significance lies more in the comparative analysis of values rather than the absolute value itself. The graph reveals that pollution created for human health has a much higher score compared to pollution created for the ecosystem and resources, highlighting its importance. Additionally, the results demonstrate that the use of sustainable materials in construction can reduce pollution levels by 31.45%, 23.70%, and 33.34% across the three categories of endangerment to human health, ecosystem pollution, and resource consumption.

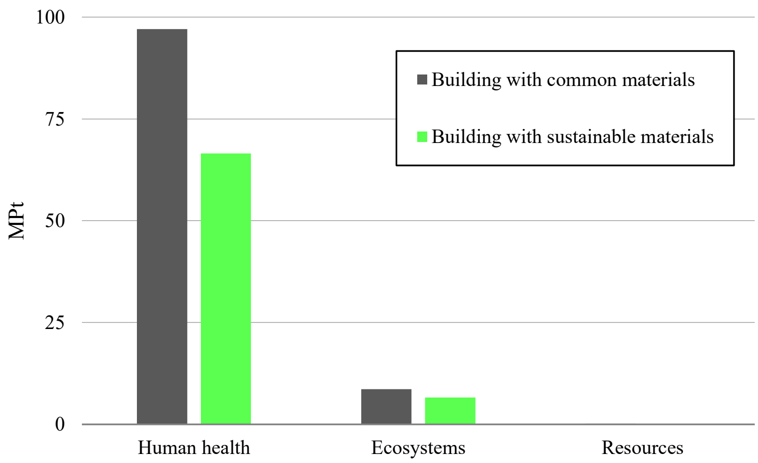


Figure 8. Comparison between environmental impacts of both buildings on ReCiPe endpoint indicators.

In light of the significant findings from this study, several avenues for future research can be explored to further advance sustainable construction practices and environmental impact reduction. Firstly, an in-depth investigation into the life cycle impacts of alternative materials, particularly emerging innovations in construction materials, would contribute to expanding the knowledge base on sustainable options. Exploring the dynamic interplay between design parameters, construction methodologies, and material choices could provide nuanced insights into optimizing environmental performance. Additionally, considering regional variations and assessing the impact of local sourcing on carbon footprints could enhance the applicability of findings in diverse geographic contexts. Future research endeavors could delve into the development and implementation of innovative construction techniques that integrate sustainable materials seamlessly while ensuring structural integrity. Moreover, investigating the long-term performance and durability of buildings constructed with sustainable materials would contribute valuable data for assessing the holistic sustainability of such structures over their lifecycle. Lastly, collaborative research initiatives involving interdisciplinary teams could facilitate a more comprehensive understanding of the socio-economic aspects influencing the adoption of sustainable construction practices, thus fostering a holistic approach towards sustainable urban development.

5. Conclusions

The construction industry is a significant contributor to global GHG emissions. To address this issue, two 4-stories reinforced concrete buildings are designed using common and environmentally friendly materials. This study examines the impact of material selection on the carbon footprint of reinforced concrete buildings. The first building uses materials that are commonly found in construction, such as ceramics, clay bricks, stone, and plaster, whereas the second building incorporates sustainable materials like cork, plywood, and rockwool. According to the analysis, using conventional building materials results in emissions of 434.8 kg CO_2eq per square meter of construction. In contrast, for the building constructed with sustainable materials, this value is 256.5 kg CO_2eq per square meter, respectively. This shows that the use of sustainable materials in construction can lead to a significant reduction in hidden carbon emissions, as evidenced by a 41.0% decrease in carbon dioxide emissions when comparing a building made with sustainable materials to one built with conventional materials.

The most impactful materials on the carbon footprint of the common building are concrete, steel, rebar and clay brick, which together accounted for almost 50.13% of the building's carbon emissions. The most impactful materials used in the building with sustainable materials are steel and rebar (22.66%), cork (22.28%) and geopolymer concrete (14.79%) of the building's carbon emissions. The utilization of these materials leads to a remarkable reduction in environmental effects, with the potential to decrease impacts by 14% to 45%. Moreover, the study used the ReCiPe 2016 endpoint approach to evaluate the contribution of pollution to three categories for two buildings. Results indicate that pollution affecting human health is more significant than pollution created for the ecosystem and resource consumption for both buildings. The study also shows that the adoption of sustainable materials in construction can reduce pollution levels by 31.45%, 23.70%, and 33.34% in the three areas of harm to human health, ecosystem pollution, and resource consumption, respectively.

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