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Reducing embodied carbon emissions of buildings – a key consideration to meet the net zero target

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ABSTRACT

The prevalence of modern techniques and industrialized materials has resulted in environmental contamination. Therefore, prioritizing the use of sustainable materials with minimal CO_2 emissions should be the fundamental principle guiding future developments in construction projects. Rammed earth construction, a traditional method in Latin America, is valued for its sustainable, environmentally friendly properties. The research examines integrating Building Information Modeling (BIM) and Life Cycle Assessment (LCA) in Colombia, a region with limited exploration of BIM-LCA interoperability on earth-based materials. This study applies LCA (Cradle-to-Gate) to assess material use, and transportation, aiming to reduce construction carbon emissions. This study compares the traditional and Sustainable building environmental impacts through the BIM (using Autodesk Revit) and carbon footpring. Findings show that BIM-based models with traditional materials have significantly higher carbon footprints (171.93 kg CO_2 eq per square meter) than sustainable models (62.25 kg CO_2 eq per square meter). This research highlights the importance of low carbon materials for the carbon reduction to meet net zero target in construction industry.

1. Introduction

The built environment is responsible for more than 37 % of CO_2 emissions related to global energy. In the year 2021, the buildings sector exhibited a 5 % increase in operational CO_2 emissions compared to 2020, surpassing the previous peak in 2019 by 2 % [1]. On a global scale, construction, renovation, and demolition activities contribute to approximately 100 billion tonnes of waste, with around 35 % of this waste being disposed of in landfills. Furthermore, the utilization of construction materials, which already accounts for 9 % of total energy-related CO_2 emissions, is projected to double by the year 2060. This escalation in emissions is primarily fuelled by the rapid process of urbanization, which results in the addition of approximately five billion square meters of new floor area on an annual basis [1].

The operation of buildings as well as the materials and processes used in their construction contribute to emissions [2]. Transforming this sector, along with other sectors, by implementing decarbonization measures, stands as a principal objective for a sustainable future [3,4]. The process of transitioning necessitates the development of materials that offer multiple benefits, a holistic approach to the entire lifespan of buildings, and an inclusive methodology that considers the interconnectedness of systems. Stakeholders have a crucial role to play, as they are accountable for their choices in material selection at every stage of the building's life cycle [5].

The Life Cycle Assessment (LCA) emerges as a valuable instrument for quantifying, enhancing, and evaluating the ecological consequences of buildings throughout their entire lifespan. This approach encompasses various stages, including the extraction of materials, manufacturing of building components, and their utilization and eventual disposal [6]. In the realm of sustainability within the architecture, engineering, and construction (AEC) sector, there arises a compelling need to furnish designers with dependable instruments that amalgamate BIM with LCA. This integration would enable the latter to keep pace with the advancements being propelled by BIM [7].

In the context of BIM environments, the integration of LCA necessitates proficiency in programming, thereby transforming it into a

Abbreviations: BIM, building information modeling; LCA, life cycle assessment; CO_2, carbon dioxide; MTO, material take-off; CH_4, methane; NO_2, nitrous oxide; O3, ozone; CFCs, chlorofluorocarbons; H2o, water; 2D, two-dimensional; 3D, three-dimensional; 6D, sixth dimension; LCI, life cycle inventory; Ed, eco-design; CSEB, compressed stabilised earth block; GHG, greenhouse gas; KG, kilogram; Lt, litre; CO_2 kg eq, carbon emission per kilogram equivalent; KM, kilometre.

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multifaceted concern that demands the participation of diverse professionals such as environmentalists, architects, engineers, and programmers. This collaborative involvement is indispensable to crafting effective and functional tools tailored to the specific requirements of LCA within BIM frameworks [8]. The significance of fostering a constructive discourse between LCA and BIM in the realm of sustainable construction is widely acknowledged. However, a prominent challenge that emerges pertains to the intricate nature of BIM models, which complicates the integration process [6,9–14].

Despite the abundance of research addressing the performance of green buildings, a notable gap exists in terms of incorporating a diverse array of eco-resilient materials during the design and construction phases. This deficit necessitates further exploration and implementation through rigorous investigation. While BIM and LCA methodologies have been subject to study for numerous years, there remains a pressing need for continued advancement in green BIM development to enhance the optimization of models and applications during the construction stage [15–19].

Additional research on eco-resilient building materials, specifically those constructed with earth-based materials, holds great promise.

Table 1
Latest literature review on Eco resilient practices.

Title	Author	Methodology/ Tools	LCA stage	Main materials	Type of project/ Case study
Shear behavior of adobe and rammed earth walls of heritage structures.	[23]	Cyclic test on solid walls	Cradle-to-gate	Adobe/Rammed earth masonry	Residential
Seismic experimental assessment of steel and synthetic meshes for retrofitting heritage earthen structures.	[24]	Cyclic loading test	Cradle-to-gate	Adobe/Rammed earth masonry	Residential
Flexural behavior of rammed earth components reinforced with steel plates.	[25]	Element replications, analytical creations, and experimental proof	Cradle-to-gate	Rammed-earth wall; wooden beams	Residential
A holistic vision to achieve sustainability standards using building information modeling technology.	[26]	Research	Cradle-to-grave	__	Institutional
BIM and LCA integration methodologies: A critical analysis and proposed guidelines	[27]	Cases studies analysis	Cradle-to-grave	__	__
Evaluation and Analysis of Unit Prices of a Rammed Earth Construction System	[28]	Application of surveys	Cradle-to-gate	Raw earth, water, and wood	Residential
Proposal of Environmental Impact Assessment Method for Concrete in South Korea: An Application in LCA	[29]	LCA Method	Cradle-to-gate	Concrete	Industrial
Embodied energy and carbon emissions of building materials in China	[30]	Energy and carbon embodied formulae	Cradle-to-site	Steel, Cement, Brick	Mixed-use
Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings	[31]	LCA Method embodied energy	Cradle-to-grave	Steel, Timber, Plasterboard	Residential
Mechanical Properties of an Earth Block Compressed with Cementitious Material	[32]	Experimental and quantitative research	Cradle-to-gate	Compressed Earth Blocks (CEB)	Residential
Effects of sugarcane bagasse fibers on the properties of compressed and stabilized earth blocks	[33]	Statistical tests	Cradle-to-gate	Earth blocks and agricultural fibers	__
Experimental and numerical investigation of mechanical strength characteristics of natural fiber retrofitted rammed earth walls	[34]	Numerical analysis of prototype	Cradle-to-gate	Natural fibers, Earth	Residential
Building a Sustainable Future from Theory to Practice…	[35]	Research review	Cradle-to-gate	Compressed stabilized earth blocks (CSEBs)	__
Sustainability-Based Lifecycle Management for Bridge Infrastructure Using 6D BIM	[36]	BIM software	Cradle-to-gate	Concrete C30, Concrete C55	Heavy Civil
Environmental benchmarking of building typologies through BIM-based combinatorial case studies	[7]	Integration of methods with BIM - LCA	Cradle-to-completion	Steel, concrete, gypsum	Residential
A Conceptual Framework for Estimating Building Embodied Carbon Based on Digital Twin Technology and Life Cycle Assessment	[37]	Radio-frequency identification (RFID) – BIM - LCA	Cradle-to-cradle	__	Residential
Estimation of Carbon Footprint of Residential Building in Warm Humid Climate of India through BIM	[38]	GaBi, Ecoinvent, One Click LCA, ICE database.	Cradle-to-grave	Reinforced Cement Concrete (RCC)	Residential
Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development	[39]	Methodological research	Cradle-to-grave	__	Mixed-use
An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development	[40]	BIM-Autodesk Revit, FirstRate5, LCA-Tally, @Risk Palisade	Cradle-to-gate	Concrete, Clay, Ceramic	Residential
BIM-based approach for the integrated assessment of life cycle carbon emission intensity and life cycle costs	[41]	Life cycle carbon emissions (LCCE), Life cycle costs (LCC), Life cycle carbon emission intensity (CEI)	Cradle-to-grave	Concrete	Commercial
Life Cycle Carbon Footprint Assessments, Case Study of Malaysian Housing Sector	[42]	LCA, BIM	Cradle-to-grave	Concrete, bricks, steel	Residential
The application of life cycle assessment in buildings: challenges, and directions for future research	[43]	Literature review of LCA in buildings.	Cradle-to-grave	Concrete, steel	Mixed-use
Environmental impacts of Design for Reuse practices in the building sector	[44]	Experimental protocol, Ecoinvent, OpenLCA	Cradle-to-grave	Concrete	Commercial use
BIM-Based Multi-Objective Optimization of Low-Carbon and Energy-Saving Buildings	[19]	Dynamo, Autodesk Revit, Green Building Studio, Optimo, Cloud Dalighting	Cradle-to-gate	Glass, Concrete, Structural Insulated Panels (SIP)	Institutional
Minimizing the Carbon Footprint by Using Rammed Earth Technique	[45]	Compression tests	Cradle-to-use	Rammed earth	__
Carbon Footprint Analysis of Bamboo Scrimber Flooring—Implications for Carbon Sequestration of Bamboo Forests and Its Products	[46]	Business-to-Business (B2B)	Cradle-to-use	Bamboo	Industrial
Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks	[47]	SimaPro v8.4 software	Cradle-to-gate	Rammed earth and compressed earth blocks	Mixed-use

Houses made from earth present numerous advantages, demonstrating long-term sustainability by minimizing resource consumption and reducing greenhouse gas emissions [20]. These structures also exhibit commendable thermal and acoustic insulation properties [21] and foster community-building through collaborative construction approaches [22].

Despite these benefits, existing studies often overlook advanced methodologies such as Building Information Modeling and Life Cycle Assessment (BIM-LCA), especially concerning earthen architecture and compressed earth blocks. The utilization of these earthen materials could significantly mitigate the high CO_2 emissions associated with the construction industry. Recognizing this gap, this research aims to leverage BIM-LCA to provide empirical evidence supporting the low carbon emissions of buildings constructed with earthen materials. By doing so, this research seeks to contribute valuable insights to empower the construction industry in achieving global sustainability objectives and preserving the environment.

2. Literature review

This chapter considers research on BIM, LCA, carbon emissions, earth architecture, and sustainable building techniques to enhance eco-resilient materials used during the designing, construction phases, and end-of-life of green buildings (cradle-to-grave). The systematic literature review is presented in the two tables below (*Table 1*) and (Table 2).

Most studies included in *Table 1* reveal that analyses using LCA methodology have been predominantly focused on residential buildings [7,23,25,28,31,32,34,37,38,40,42,48,49]. The reason for this is that the LCA process is a thorough and demanding one that requires a significant investment of time, knowledge, and financial resources.

Several software tools have been employed in these case studies to apply LCA, including GaBi, Ecoinvent, One Click LCA, ICE database, BIM-Autodesk Revit, FirstRate5, LCA-Tally, @Risk Palisade, Ecoinvent, OpenLCA, Dynamo, Autodesk Revit, Green Building Studio, Optimo, Cloud Dalighting, and SimaPro v8.4. These tools are crucial for incorporating the sustainability dimension into projects. However, a challenge identified in this research is that these tools are not freely accessible; companies must possess sufficient financial capability to promote low-carbon emission projects.

Over the last decade, a series of investigations have been conducted to enhance the interoperability between BIM and LCA technologies. However, upon examining the results presented in Table 2, the lack of progress in this area within the Latin American region becomes evident. Most of the referenced studies have been carried out in Asia [19,26,29, 34,36,38,41,42,45,46,50,51].

In contrast, within Latin America, research efforts have primarily focused on evaluating the structural capacity of Rammed Earth Architecture, as indicated by [23–25,28,32]. While this line of investigation is vital, a limitation in exploring the application of LCA in BIM models incorporating earth-based materials has been observed.

The significant findings derived from this analysis underscore the urgent need to explore deeper into the convergence between modern technologies and low-carbon materials such as Adobe and rammed earth. Through increased research at this intersection, substantial progress could be made towards the true role of rammed architecture in promoting a circular built environment [47]. In this regard, Latin America needs to expand its research and adopt a more comprehensive approach that fully harnesses the potential of these BIM-LCA technologies and Earthen buildings in support of sustainable development.

Despite the multiple studies [28,32–34,45,47] about the benefits of rammed earth material for the future of sustainable construction, it has not been standardized by national regulations. This standardization is essential to provide professionals and stakeholders with adequate knowledge and a guiding framework for undertaking projects using earth-based materials. According to the research by [47] 1 m^2 wall made of Rammed Earth and Compressed Earth Blocks (CEB) exhibits approximately half the carbon emissions and embodied energy compared to ceramic brick or concrete.

Prior research has yet to elucidate the connection between the environmental impact of earthen materials and the utilization of BIM-LCA. To illustrate, the environmental footprint of rammed earth architecture has only been validated through controlled laboratory experiments and lacks comprehensive assessment through emissions factors, as evidenced by [45]. As a result, this approach does not provide a complete and accurate depiction of the CO_2 emissions affecting the environment.

3. Research methodology

The proposed methodology for this research is shown in Fig. 1. Involves three key steps: 1) Aim and scope description; 2) Life Cycle Inventory; 3) Impact assessment. This framework will be developed to achieve the target as explained below.

3.1. Aim and scope description

The life cycle analysis method was used to assess the sustainable efficiency of the case studies by considering the embodied carbon from the beginning to the construction of the building's lifecycle (Cradle-to-gate). The scope considered for CO_2 emission from materials production in research includes the direct impacts from 1) raw materials; 2) transportation of materials, and the actual based on the cradle-to-gate stage of LCA.

Through computer simulations, digital models, and carbon footprint applications, this research aims to assess and evaluate the environmental impact and sustainability performance of the two building models. This analysis will provide valuable insights into the benefits and advantages of using sustainable materials in terms of carbon emissions reduction, energy efficiency, and overall environmental sustainability.

The simulations also enabled a comparative analysis between the two models, highlighting the potential of sustainable materials to contribute to eco-resilient and green building practices. This study focuses on the cradle-to-gate stage of LCA, specifically on raw materials production and transportation. The components considered within the scope of the case study incorporate the structure, substructure, walls, windows, and accesses. Electricity and water systems have been excluded from consideration, as the objective is centered exclusively on external materials.

A detailed 3D model of a single-family house of 162.25 m^2 has been created, including the use of traditional construction materials such as masonry traditional bricks, reinforced concrete for the structural elements, ordinary Portland cement (OPC), aluminium for certain components, glass for windows, and other elements as shown in Fig. 2(a). This comprehensive 3D representation allows for visualization and analysis of the house's design, considering the specific characteristics and properties of each material. By accurately incorporating these materials into the 3D model, the construction process, and potential implications, such as structural integrity, thermal performance, and esthetic appeal, can be better understood and assessed. Moreover, Fig. 2 (b) indicates a 3D model of a single-family house with an area of 162.25 m^2 has been designed, with the utilization of sustainable materials that prioritize environmental consciousness. The construction of this model embodies sustainable principles, incorporating environmentally friendly choices such as Rammed earth, compressed and stabilized earth block (CSEB) for the walls, employing rammed earth architecture techniques for structural elements, and integrating bamboo, and wood for external reinforcement. Engineered bamboo is structurally safe for this model since is part of primary structural projects [52]. This 3D representation allows for a comprehensive examination of the house's sustainable design, enabling a detailed analysis of its ecological footprint, energy efficiency, and overall environmental impact. By incorporating these environmentally friendly materials into the 3D model, the house's

Table 2
Potential developments and achievements related to Sustainable Construction Management.

Author	Significant outcomes	Keywords (Max 3)	Future directions	Region
[23]	The breakdowns observed in earthen walls are primarily influenced by the occurrence of diagonal breaks.	Earthen buildings; Adobe walls; Rammed earth walls	Determine the shear capacity of earthen walls while studying their axial load and aspect ratio.	Latin America -Colombia
[24]	Meshes can boost the strength of earthen walls.	Steel and synthetic meshes; Adobe walls	Guidance on enhancing corner links using steel angles and plates.	Latin America -Colombia
[25]	The beam consists of three layers: rammed earth, air, and steel plates.	Interlayer slip; Earthen buildings; Earth walls	__	Latin America -Colombia
[26]	Using BIM applications can make sustainable design operations easier to manage, especially when dealing with complex tasks.	BIM; Sustainability; Green architecture	Make sure BIM technology is used in all projects by creating clear procedures.	Asia - Saudi Arabia
[27]	Organizations using BIM-LCA methods should consider four essential areas: tools, processes, people, and policies.	LCA; BIM; Guideline	BIM-LCA consistency	__
[28]	A significant proportion (92 %) of the respondents possess knowledge about the earth walls technique, whereas a minority segment (8 %) lacks acquaintance with said technique.	Unit prices; Rammed earth construction; budget	To ensure quality construction, it is important to hire qualified labor.	Latin America - Ecuador
[29]	Ordinary Portland cement (OPC) was discovered to have the greatest impact on global warming potential (GWP)	Concrete; life cycle assessment; environmental impact	It is recommended to conduct additional assessments on the potential effects of concrete at various levels of strength.	Asia - South Korea
[30]	Over 70 % of the total embodied energy and carbon of all building materials is attributed to cement, steel, and brick	Embodied energy; embodied carbon; carbon reduction	There is a necessity for a unified approach to precisely and uniformly measure embodied energy	Asia - China
[31]	The total life cycle energy consumption in residential buildings is comprised of embodied energy, which can range from 30 to 100 %. By adopting the principles of embodied energy modeling, it becomes possible to make substantial reductions in the total amount of greenhouse gas emissions produced on the planet.	Embodied energy; greenhouse gasses; Residential	It is important to incorporate the concept of embodied energy in the design of all residential projects	Oceania - Australia
[32]	The mechanical characteristics of Compressed Earth Blocks (CEB) make them appropriate for non-structural masonry applications.	Self-Construction; Compressed Earth Blocks; Soil	__	Latin America - Colombia
[33]	Earthen materials can benefit from the incorporation of these fibers, as they have been shown to enhance their mechanical and durability properties.	Earthen construction; sugarcane bagasse, CEB	__	North America - USA
[34]	The use of treated natural fiber has resulted in a notable increase in the mechanical strength of earth walls.	Rammed earth; ANOVA; Natural fibers	A thorough examination of the practical implementation of sustainable encasement-based retrofitting methods in the future.	Asia - India
[35]	It is possible for waste materials to partially substitute soil if they meet the minimum allowable standards.	CEB; fiber; sustainability	To ensure the quality and safety of (CSEBs) used in construction, it is recommended to implement standardized manufacturing norms	Asia
[36]	Utilizing BIM technology alongside LCA has the potential to deliver a positive outcome that satisfies all parties involved.	Carbon emission; BIM; 6D	6D modeling demands more exploration	Asia - China
[7]	Getting environmental standards through the integration of BIM and LCA	Prediction model; LCA; BIM	Provide consultants with sustainability guidelines for upcoming construction projects	Europe - Spain
[37]	The advancement of low-carbon design in the AEC industry is constrained by the absence of a reliable approach for quantifying embodied carbon.	Embodied carbon; Building design; BIM	Develop new IFC elements to calculate the building's overall embodied impact.	Asia - China
[38]	Using a manual LCA theory and a BIM-LCA approach, the life cycle assessment method can be used to calculate carbon emissions.	Database; carbon footprint; LCA	Improved outcomes execution from BIM-based LCA is necessary to reduce carbon emissions and prepare for the future.	Asia - India
[39]	The most promising option is to use a dynamic approach with graphical programming throughout the design phase.	Integration; BIM; LCA	Including the social factor in BIM-LCA studies will help the building sector become more uniformly standardised.	__
[40]	Buildings that are environmentally friendly, energy-efficient, and star-rated can be evaluated financially and economically using the BIM platform.	Energy consumption; Sensitivity analysis; BIM-LCA	Future research for the thermal efficiency energy estimation model.	Oceania - Australia
[41]	Carbon footprints and costs can be reduced by replacing high carbon emitting materials like concrete, steel, and cement, both during the manufacturing during operation.	Life Cycle Carbon emissions; BIM	Additional study is needed to create techniques for analysing cost inventories and emissions of carbon inventory in a single interaction.	Asia - China
[42]	The physical design elements have a significant role in the variety of environmental consequences.	Operational carbon; Embodied Carbon; BIM-LCA	__	Asia - Malaysia
[43]	The dynamic character of constructions, as well as changing functional and ecological situations, must be considered for LCA adoption to be effective.	Dynamic Data; Semantic models, BIM-LCA	The requirement to create decision-support systems that use dynamic data, machine learning, and optimization techniques for instantaneous design evaluation	__
[44]	Reusing building materials and structural parts has been highlighted as an intriguing factor in the reduction of the release of greenhouse gasses.	Reuse; Circular economy; LCA	Recommendations should be given to ensure that future reuse practises deliver the anticipated advantages.	Europe - France
[19]	Geographical, climatic, material, and economic considerations must be taken into full account when designing low-carbon buildings; this is a very challenging, multidisciplinary research challenge.	Low carbon; BIM; Optimization	The use of cutting-edge modeling and simulation technology, including BIM, parametric design, cloud computing, and evolutionary algorithms, is essential.	Asia - China

(*continued on next page*)

Table 2 (*continued*)

Author	Significant outcomes	Keywords (Max 3)	Future directions	Region
[45]	Using rammed earth throughout the building-construction process can help reduce the amount of carbon dioxide emitted.	Rammed Earth; Embodied energy; Carbon footprint	Research looking at adding recyclables to the rammed earth mixture to improve sustainability and cut down on carbon emissions	Asia - Turkey
[46]	Flooring made from bamboo has zero carbon emissions.	Climate change; Bamboo floor, Green-level	More detailed understanding of the carbon cycle and carbon longevity in the bamboo forest ecosystem	Asia - China
[47]	The benefits of utilizing earthy materials are also explored for the various building life-cycle stages, with a focus on the potential for closed-loop recovery of these elements.	Vernacular architecture; Environmental impacts; LCA	To better understand the true role of rammed architecture in promoting a circular built environment, more research is required.	Europe - Portugal

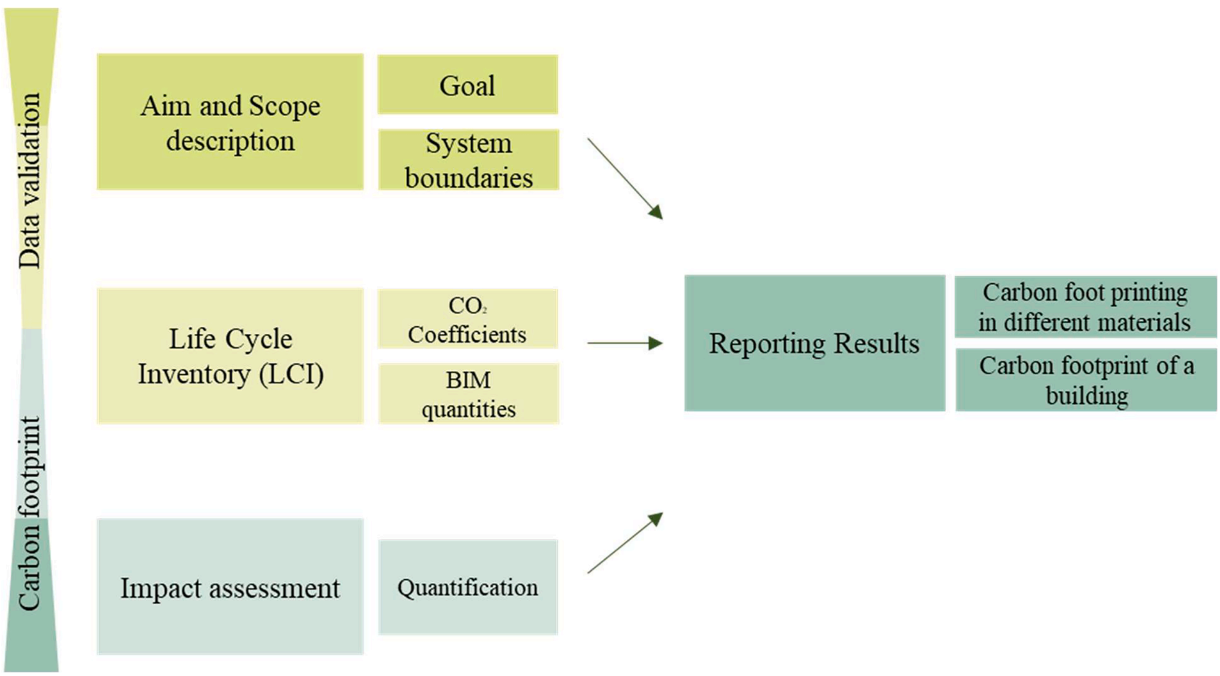


Fig. 1. Methodology for this study.

sustainable features and their integration within the design can be effectively visualized and evaluated. This detailed approach in the 3D model aids in promoting sustainable practices, fostering ecological awareness, and encouraging the adoption of environmentally responsible construction methods.

3.2. Life cycle inventory

Guaranteeing the precision and totality of the data, the quantities were extracted from the 3D models, through the material take-off application in Revit. The data was analysed verifying that the list of quantities shown by the BIM software, includes all and each of the materials in parallel with the tables and the models.

The utilization of a material take-off application in Revit can significantly enhance the process of estimating quantities. This application organizes the detailed information stored in the Revit model to generate accurate and comprehensive lists of materials required for LCI. Manually calculating material quantities can be time-consuming, especially in complex projects. With the use of a material take-off application, the process is automated. Depending on the specific needs of the project, the material take-off application provides flexibility to customize the types of materials, units of measurement, and presentation formats. In this study, the inclusion criteria for the Revit materials application were Material Family, Material name, Count of elements, and Volume in m^3.

3.2.1. CO_2 coefficients

The main equation to establish the carbon footprint in this study includes material production (Ep) and the transportation of materials (Et) as shown in Eq. (1).

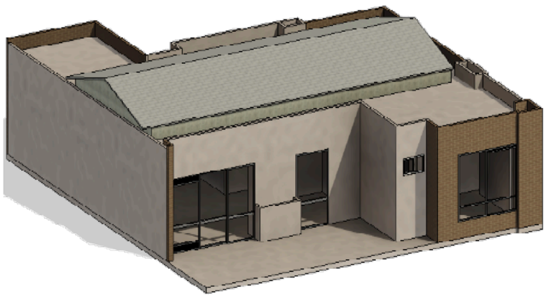
$$E = Ep + Et \tag{1}$$

The emission factor of materials production depends on the production skills, techniques, and processes. In this study, the embodied emission factors for materials and transportation that were used are the ones established by [36,46,47,53–56]. The carbon footprint of raw materials is projected using a standard international Eq. (2) proposed by the Department for Business Energy & Industrial Strategy (BEIS, 2022):

$$\text{GHGemissions} = \text{activitydata x emissionconversionfactor} \tag{2}$$

The greenhouse gas emissions at this stage include the trucks used to deliver materials before construction. All the necessary locations, the factory, construction site, concrete plant, and disposal site - are situated within the capital city and the center of the town. The distances are expressed in km, the fuel consumption in liters multiply by fuel conversion factor kilometers. The carbon footprint of transportation is projected using a standard international Eq. (3) proposed by the Department for Business Energy & Industrial Strategy [[53], 2022]:

$$CO_2 \text{ emission (kg)} = \text{fuelconsumption (km)}^{*} \text{ fuelconversionfactor (kg / km)} \tag{3}$$



(a) 3D Model Traditional materials

(b) 3D Model Sustainable materials

Fig. 2. Developed BIM Model in Revit, a) 3D model with traditional materials and b) 3D model with sustainable materials.

3.2.2. *BIM quantities*

The Autodesk Revit software was utilized as the primary BIM tool to extract initial data for this case study. The process involved in this was known as "Material take-off" (MTO), which quantifies the amounts of construction materials required.

MTO requires extracting quantities and measurements of materials directly from digital models, including concrete, steel, wood, glass, and earthen materials. The software generates reports that list the quantities and dimensions of the materials used in this research, which is valuable for carbon footprint procedures.

3.2.2.1. Materials transportation distance (km). The greenhouse gas emissions at this stage include the trucks used to deliver materials before construction. All the necessary locations, the factory, construction site, concrete plant, and disposal site - are situated within the capital city and the center of the town.

3.2.2.2. Traditional model. The distance materials need to travel can significantly influence their transportation-related carbon emissions due to factors like fuel consumption and transportation mode efficiency (Fig. 3). These distances are important to consider when evaluating the environmental impact of construction materials. as shorter distances can generally lead to lower transportation-related emissions.

3.2.2.3. Sustainable model. The distances for obtaining rammed earth. compressed earth blocks (CEB). wood. and bamboo is shorter compared to the other materials because they are locally sourced and easily available (Fig. 4). This sustainable approach not only minimizes emissions but also promotes the local economy. reduces the overall ecological footprint. and supports local communities. The overall distance of all materials is shown in Fig. 5.

3.3. *Impact assessment*

In the final phase, conclusions take shape as a synthesis of the LCI results, BIM quantities, and emissions factors pertinent to the study's objectives. The quantification process requires the application of manual equations, achieved by multiplying the volume of each constituent element within both models by their respective emission factors. This calculation shows the building's carbon footprint, providing a clear understanding of its environmental impact. Following this analysis, it serves as the foundation for creating an extensive guide that advocates the adoption of earth-based production methods, aimed at mitigating carbon emissions within the construction industry and reducing its ecological footprint.

3.4. *Case study*

3.4.1. *Background*

In Colombia and other Latin American countries, mainly constructions in colonial dates were constructed with adobe and rammed earth material [23]. Earth construction plays a crucial role in the country's architectural heritage. This case study was conducted in the town of Barichara, Santander. The department in the north of Colombia is shown in Fig. 6. This place was chosen because it is a prominent area in the country where the architectural manifestations arising from the use of the rammed earth architecture achieve an evident presence. Around 90 % of the homes are built using rammed earth, adobe, wood, and cane. Regulations require that new architecture maintains a contextual relationship with what already exists.

The 3D model of a single-family house was designed and created based on inspiration from the project shown in Fig. 7: The architectural

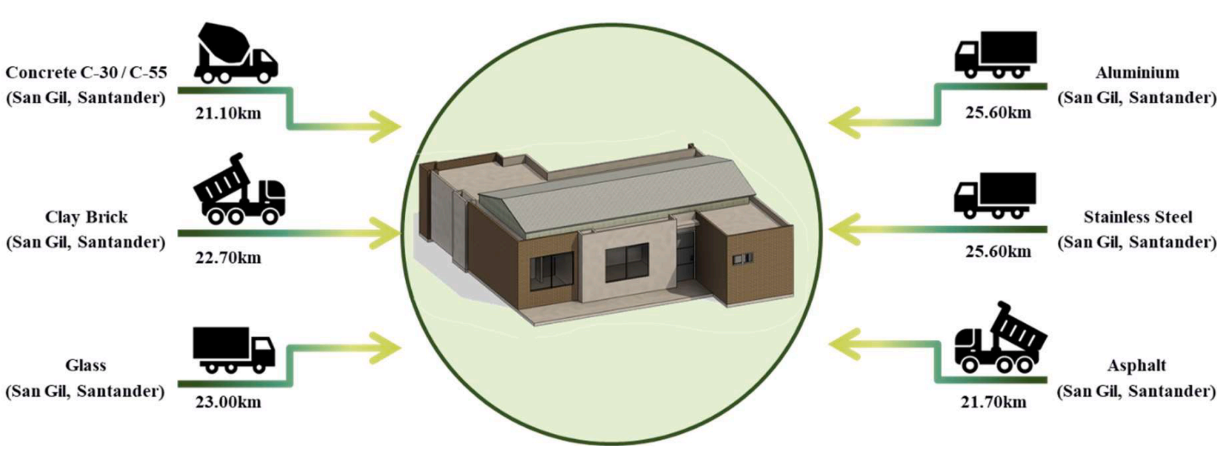


Fig. 3. Traditional model Transport distance (km).

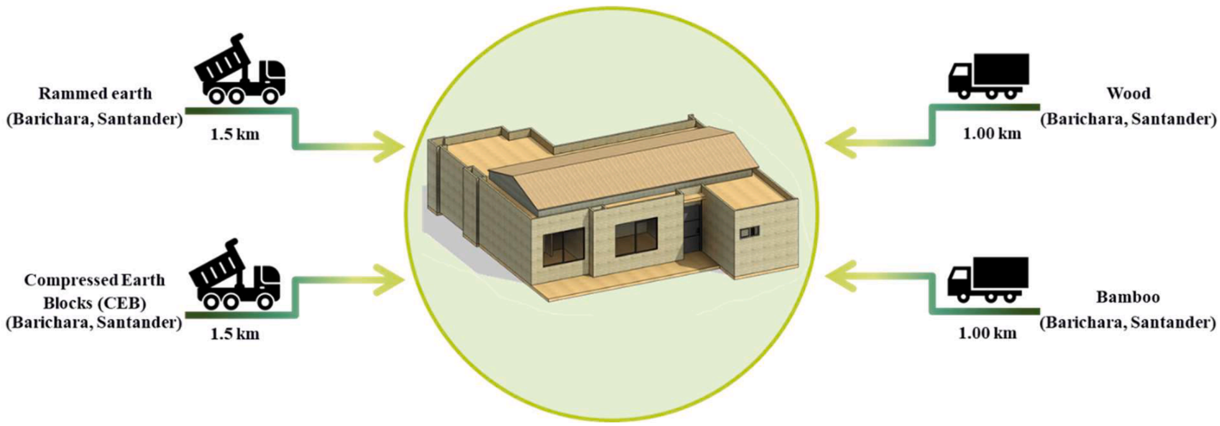


Fig. 4. Sustainable model Transport distance (km).

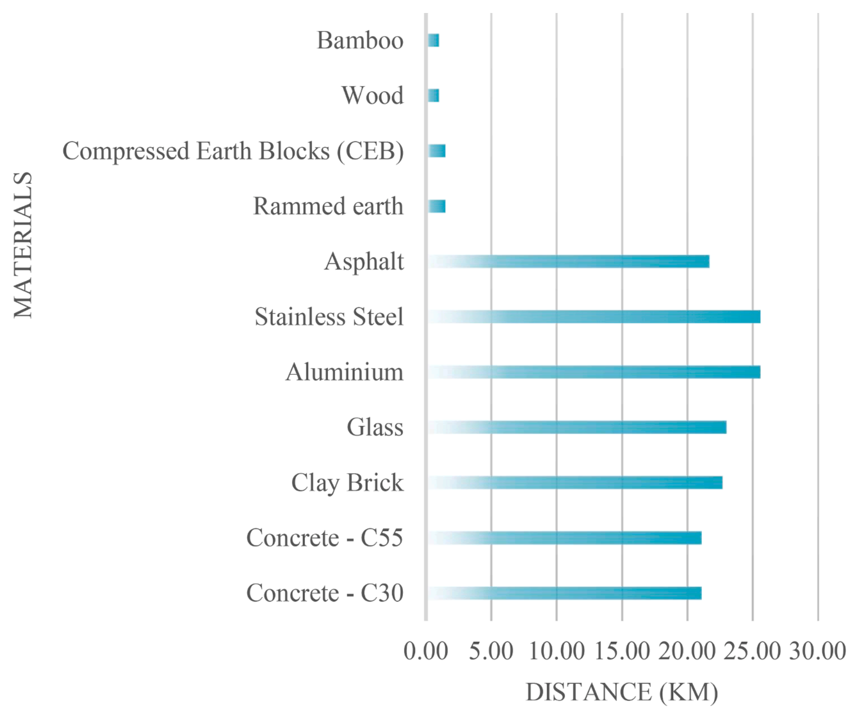


Fig. 5. An overall distance transportation of all materials (km).

style in this home is diverse. It mixes traditional components with more modern ones, such as braided cane roofing. This method results in architecture that satisfies the demands of the residents today while also honoring their history and the area in which it is located: the ancient city of Barichara. Rammed mud, adobe, stone, wood and cane were utilized, along with other regionally typical building materials [57].

4. Impact assessment and results analysis

4.1. Materials production carbon footprint (Model 1 traditional materials)

Within the extraction of data and quantities from the Revit model with traditional materials. The CO_2 emission factor is included for each material as shown in Table 3. Then, the Eq. (2) was applied using the quantification data (m^3) and the emission factors (Kg CO_2 eq./m^3). The results are expressed in embodied carbon emission (kg).

Emissions factors for various construction materials were sourced from different references. For concrete with two different strength grades, C30 and C55, the emissions factors were obtained from [36]. In the case of clay brick, glass, aluminium, stainless steel, and asphalt, emissions factors were derived from a more recent source [53].

The results from Table 3 of the carbon footprint for the traditional materials case study indicate the following: the third column refers to the overall volume of the elements included in the model. The fourth column includes the emissions factors. Finally, in the last column, the total carbon emissions from raw materials production are 27,774.84 Kg CO_2 eq.

The total carbon emissions results for each of the materials are summarized in Fig. 8.

4.2. Material production (Model 2 – sustainable materials)

Within the extraction of data and quantities from the Revit model with Sustainable materials. The CO_2 emission factor* is included for each material as shown in Table 4. Then, the Eq. (2) was applied using the quantification data (m^3) and the emission factors (Kg CO_2 eq./m^3). The results are expressed in embodied carbon emission (kg). Emissions

Fig. 6. Location of the site on the World Map.

Fig. 7. Traditional residential project in Barichara, Colombia (source: [57]).

Table 3
Single-family house traditional materials Carbon Footprint.

Material: name	Volume (m^3)	Embodied CO_2 coefficient (kg/m^3)	Embodied carbon emission (kg)
Concrete - C30	26	317	8275
Concrete - C55	35	362	12,804
Clay Brick	7	685	4888
Glass	0,14	3972	556
Aluminium	0,01	25,832	258
Stainless Steel	0,08	8778	702
Asphalt	3	111	292
Total			27,775

factors have been sourced from diverse reference and adjusted specific to the selected case study in this research. Rammed earth emissions factors were obtained from [55], while emissions data for bamboo were derived from [46]. For Compressed Earth Blocks (CEB), [47] provided the emissions factors. In the case of glass and wood, as well as concrete with a strength grade of C30, the emissions factors were extracted from [53], and [36], respectively.

The results from Table 4 of the carbon footprint for the sustainable materials case study indicate the following: the third column refers to the overall volume of the elements included in the model. The fourth column includes the emissions factors. Finally, in the last column, the total carbon emissions from raw materials production are 10,067 36 Kg CO_2 eq.

The total carbon emissions results for each of the materials are summarized in Fig. 9.

The percentage of carbon emissions based on the total raw materials production of the model with traditional materials is shown in Fig. 10

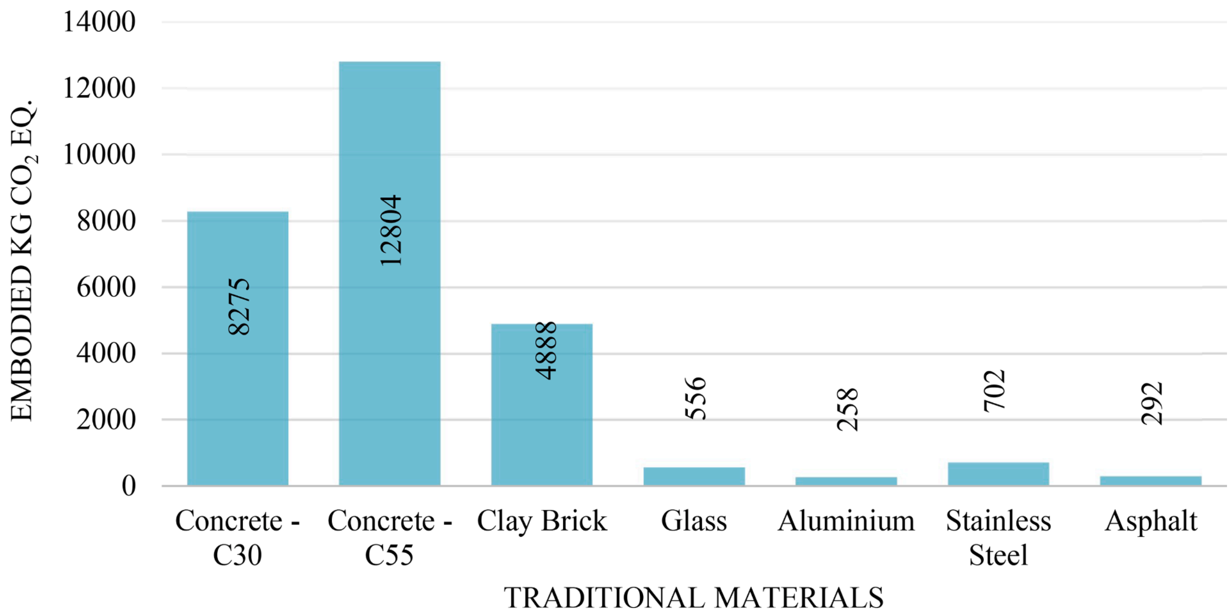


Fig. 8. Total of Kg CO_2 eq. for each traditional material.

Table 4
Single-family house Sustainable materials Carbon Footprint.

Material: name	Volume (m^3)	Embodied CO_2 coefficient (kg/m^3)	Embodied carbon emission (kg)
Rammed earth	19,65	34	668
Compressed Earth Blocks (CEB)	11,04	48	530
Wood	2,72	885,21	2408
Bamboo	35,18	143,37	5044
Glass	0,14	3972,2	556
Concrete - C30	2,72	316,8	862
Total			10,067

(a). Concrete - C30: 29.79 %. This type of concrete emits a significant amount of CO_2. due to the production process involving cement. Cement production is a known contributor to greenhouse gas emissions. Concrete - C55: 46.10 %. Concrete with higher strength (C55) tends to have a higher cement content, which leads to greater CO_2 emissions. While strong concrete is often necessary for specific structural requirements. this data emphasizes the environmental impact associated with its production. Clay Brick: 17.60 %. Clay brick production releases a considerable amount of CO_2, potentially due to energy-intensive processes like firing.

The percentage of carbon emissions based on the total raw materials production of the model with sustainable materials is shown in Fig. 10 (b). Rammed Earth: 6.64 %. Rammed earth construction has a relatively low CO_2 emissions value indicating its eco-friendliness. This is because it primarily uses earth sourced from the construction site itself, requiring minimal processing. Compressed Earth Blocks (CEB): 5.26 %. Like rammed earth. CEB also uses the earth as the primary material, leading to low CO_2 emissions. The compressed nature of the blocks can contribute to their energy efficiency in production. Bamboo: 50.10 %. Bamboo has a high CO_2 emissions value in this model, primarily due to the extensive volume of flooring and roofing included. Despite this, bamboo is generally regarded as environmentally friendly due to its rapid growth and renewability.

4.3. Transportation carbon footprint

The methodology employed for data acquisition and result analysis involves a series of fundamental stages: Firstly, in the "Initial Data Acquisition" phase, essential information regarding the distances covered by vehicles in the two scenarios is collected.

Subsequently, the "Identification of Fuel Emission Factors" stage involves the compilation and presentation of fuel emission factors, expressed in liters. In the "Total Consumption Calculation" phase, the distance covered in kilometers is multiplied by the number of trips, calculated by dividing the total cubic meter capacity of each transport by the total cubic meters of materials needed for construction. Following Eq. (3), this product is then multiplied by the fuel consumption in kilometers and the embodied CO_2 coefficient from Table 5. Ultimately, the "Completion of Final Carbon Emissions" stage yields the final transportation-related carbon emissions, as delineated in Table 5. These outcomes are expressed as kg CO_2 eq., providing a comprehensive understanding of the environmental impact of material transportation.

The percentage of carbon emissions based on the total transportation of the model with traditional materials is shown in Fig. 11(a). These percentages represent the carbon emissions associated with the transportation of these materials. The percentages provide an insight into the relative environmental impact of each material's transportation. Concrete particularly the C55 type, which has the highest contribution to CO_2 emissions among the listed materials. followed by clay brick and asphalt.

The percentage of carbon emissions based on the total raw materials production of the model with sustainable materials is shown in Fig. 11 (b). These percentages indicate the relative environmental impact of each material's transportation with respect to CO_2 emissions. It's evident that bamboo has the highest percentage contribution to transportation-related CO_2 emissions among the listed materials, followed by rammed earth, compressed earth blocks (CEB) and wood. The higher transportation-related CO_2 emissions for bamboo are attributed to the larger volume of bamboo needed and the number of travels required to transport it to the construction site. Transportation emissions are influenced by factors such as material volume, weight, distance, and frequency of transport.

4.4. An overall carbon footprint results

The embodied carbon (Kg CO_2 eq.) from the raw materials and transportation was calculated based on the CO_2 emissions factors. The carbon footprint outcomes acquired from the quantities of the 3D

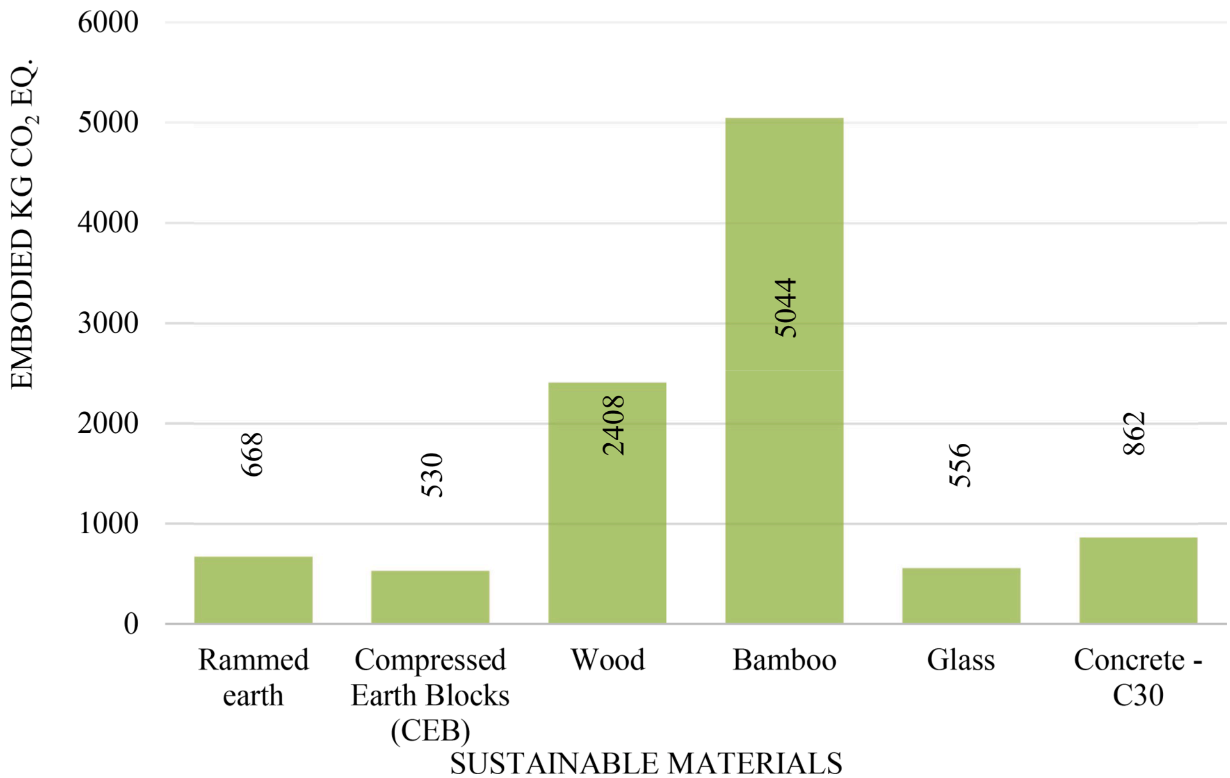


Fig. 9. Total of Kg CO_2 eq. for each sustainable material.

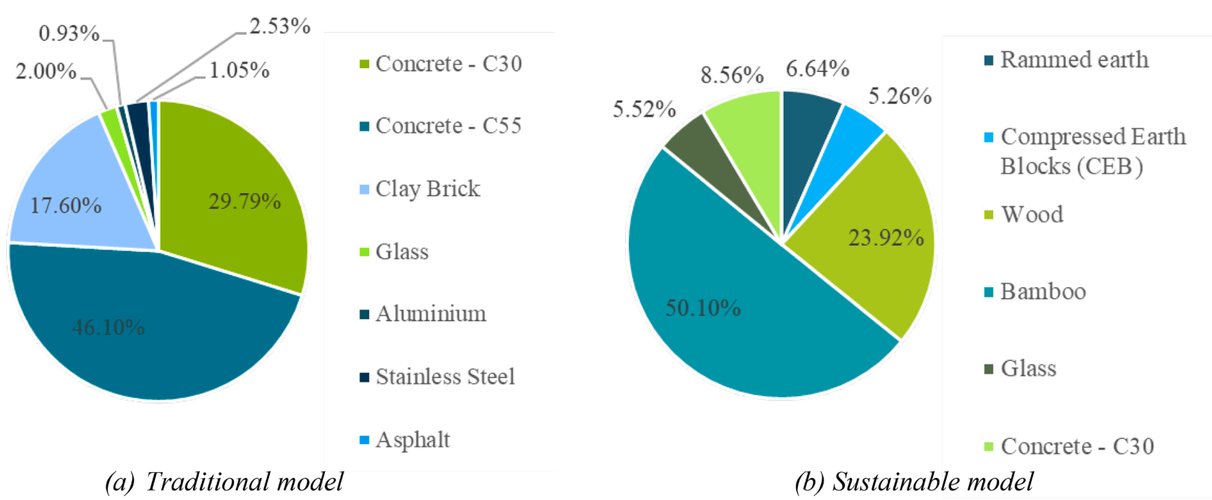


Fig. 10. Contribution % of kg CO_2 eq. per material.

models applying LCI and LCA were: 27,774.87 Kg CO_2 eq. from raw materials traditional model (Table 3); 10,067.36 Kg CO_2 eq. from raw materials sustainable model (Table 4); 122.13 Kg CO_2 eq. from materials transportation traditional model (Table 5); 32.85 Kg CO_2 eq. from materials transportation sustainable model (Table 5). Eq. (1) is applied to obtain the total CO_2 carbon footprint of each model.

According to the comparative analysis above. a pronounced contrast in carbon emissions between the two distinct models considered in this research becomes evident (Fig. 12, Fig. 13). Specifically, concrete, clay brick, aluminium, glass, and steel display significant levels of carbon footprint. Similarly, in places like Barichara, Colombia. and most Latin American cities, the transportation of industrialized materials, primarily centralized in capital cities, involves considerable distances, leading to substantial carbon emissions. Findings show that BIM-based models with traditional materials have significantly higher carbon footprints (171.93 kg CO_2 eq per square meter) than sustainable models (62.25 kg CO_2 eq per square meter). On the other hand, the implementation of LCA as an innovative approach to Earth materials allows us to demonstrate that the utilization of these resources will contribute positively to the reduction of the carbon footprint in Latin American cities. These materials are not only economically accessible to communities but also readily available and boast esthetic qualities and eco-resilience in the construction sector.

5. Research limitations and recommendations

Based on the conducted research, the choice was made to embrace international guidelines and standards. This decision is influenced by

Table 5
Transportation carbon footprint.

Case study	Material	(Km*Travels*Fuel consumption)	Embodied CO_2 coefficient (kgCO_2e/litres)	CO_2 emissions (kg)
Model Traditional materials	Concrete - C30	16.53	2.70	44.62
	Concrete - C55	22.36	2.70	60.35
	Clay Brick	4.86	2.56	12.43
	Glass	0.09	3.18	0.29
	aluminium	0.01	3.18	0.02
	Stainless Steel	0.01	3.18	0.02
	Asphalt	1.71	2.56	4.37
Subtotal				**122.13**
Model Sustainable materials	Rammed earth	3.83	2.56	9.81
	Compressed Earth Blocks (CEB)	2.15	2.56	5.51
	Wood	0.40	3.18	1.26
	Bamboo	5.12	3.18	16.27
Subtotal				**32.85**

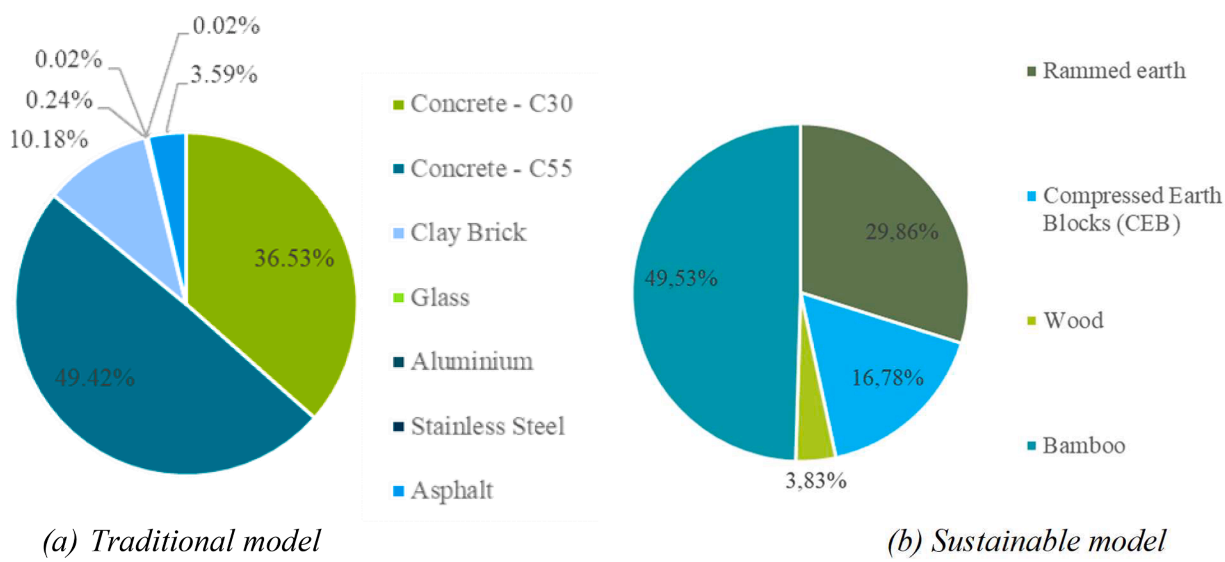


Fig. 11. Contribution % of kg CO_2 eq. for transportation.

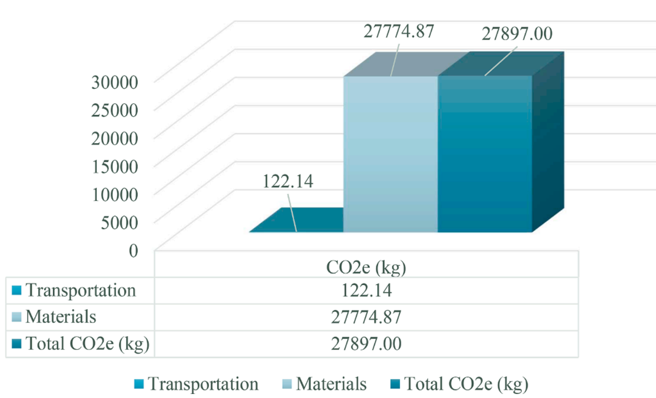


Fig. 12. Total kg CO_2 eq. Traditional model.

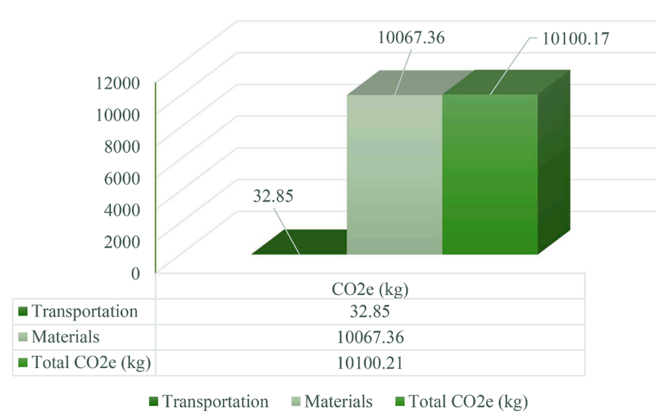


Fig. 13. Total kg CO_2 eq. Sustainable model.

the fact that in Colombia, carbon emission factors are currently not incorporated into the construction regulations. This factor can create challenges when attempting to apply LCA and carbon footprint analysis. The suggested method A BIM-based LCA system can offer a quick and automated way to assess various design solutions to help with the construction of low-carbon buildings [37]. The implementation of technologies such as BIM and LCA can accelerate design and construction processes favorably.

The revival of traditional techniques and the use of natural materials like adobe and rammed earth can reduce the CO_2 emissions that are of significant concern to the construction sector. This study uses the interoperability of current technology practices and sustainable materials through two digital models enabling the verification of carbon emission reduction using earth-based materials. Significant findings and future directions are explained below.

5.1. Lack of available data on eco-resilient materials for life cycle inventory (LCI)

The absence of LCI data for eco-resilient materials is a substantial challenge in the construction industry. It obstructs informed decision-making, particularly for emerging materials lacking established databases. Gathering comprehensive LCI data is complicated, and variations in material performance due to sourcing and production methods must be considered. This data gap hinders the prediction of complex material interactions, potentially leads to greenwashing, and limits transparency and reporting. Addressing this issue is crucial for advancing sustainability in construction through collaboration, research, transparency, and regulatory support.

5.2. Limited access to life cycle assessment (LCA) software

The lack of LCA software access in the construction industry poses various challenges. It hinders the timely adoption of sustainable practices, affects educational efforts, potentially leads to inaccurate assessments, complicates standardization, limits collaboration and data sharing, and impedes progress toward sustainable goals. Solutions may involve increasing access through education, subsidies, open-source tools, or collaborative initiatives aimed at developing more accessible LCA resources. Addressing this issue is essential for fostering sustainability practices and informed decision-making.

5.3. Earthen materials in building information modeling (BIM)

Integrating earthen materials into BIM is a significant step in advancing sustainable construction practices. These materials, such as rammed earth and adobe, are inherently sustainable, aligning with the development of eco-resilient building methods. BIM allows for precise performance assessments, aiding architects, and engineers in optimizing designs for energy efficiency. While promising, challenges exist in accurately representing these materials in BIM, requiring a qualified construction team.

5.4. Investment of time and financial resources in BIM-LCA projects

Investing in BIM-LCA projects involves the integration of BIM technology with life cycle assessment to enhance sustainability analysis in construction management. This process includes data integration, accurate BIM model development, selection of LCA methodologies and indicators, the use of specialized software tools, and, essentially, training to ensure the effective use of integrated tools and methodologies. These investments enable informed decisions to minimize the environmental impact of construction projects.

5.5. The significance of embodied carbon in the decision-making process

The significance of embodied carbon in decision-making lies in recognizing and assessing the carbon emissions across a product or structure's entire lifecycle, encompassing extraction, manufacturing, transportation, and assembly. It's crucial for sustainable design and planning to minimize a project's carbon footprint. Consideration of embodied carbon offers environmental awareness, a holistic perspective on emissions, informed material choices, regulatory compliance, and economic benefits, and aligns with societal expectations.

5.6. Constraints of LCA plugins within BIM software

The Carbon Life Calculator, an Autodesk Revit plug-in for calculating building carbon emissions, was integrated into this study to enhance LCA efficiency. However, it provided generalized results, prompting a detailed investigation of carbon emissions for specific building elements and materials. While such tools simplify sustainable decision-making, they may not offer comprehensive analyses, imposing manual calculations. These tools play a vital role in enabling professionals to quantify and analyse carbon emissions and environmental footprints.

5.7. Cradle-to-Gate focus rather than the whole of life (Cradle-to-Cradle)

This study provides valuable insights into low-carbon building design through a focus on cradle-to-gate life cycle assessment. However, it is crucial to acknowledge the study's limited scope compared to a comprehensive Cradle to Cradle analysis. Findings predominantly address the environmental impact from material production initiation to gate exit. Readers are cautioned to interpret conclusions within the context of Cradle to Gate assessments, representing only a fraction of the entire life cycle embodied carbon. Further studies to examine the models considering the entire life cycle (Cradle-to-Cradle) and to provide a comprehensive environmental impact assessment of the two models may be considered in the future.

6. Conclusions

This study proposed the adoption of sustainable materials like rammed earth, adobe, and compressed earth blocks. These materials often originate from local sources, minimizing transport costs and supporting local economies. The clean production process requires minimal energy consumption, further enhancing its sustainability profile. Additionally, these materials often exhibit superior thermal insulation characteristics compared to conventional construction materials, contributing to energy-efficient designs.

Emission factors for specific construction methods, such as rammed earth architecture, pose challenges due to variations based on factors like location, materials, and practices. Mitigating these challenges involves extensive research and employing various sources and strategies to gather relevant information. Despite these limitations, the integration of sustainable practices into construction processes offers substantial benefits. Utilizing BIM software like Revit streamlines the quantification of material quantities. This speeds up the application of LCA to calculate CO_2 emissions facilitating sustainability analyses. Of these two case studies, the BIM-based model with traditional materials was identified as the primary contributor to Greenhouse gas emissions (GHG) with an evident higher carbon footprint for material manufacturing of 171.93 kg CO_2 eq. per m^2 than the sustainable model 62.09 kg CO_2 eq. per m^2.

Stabilized compressed earth blocks offer uniformity in building component sizes, local material usage, and reduced transportation needs. These attributes simplify construction processes, minimize waste in material manufacturing, and enhance overall efficiency. The use of natural, locally available materials not only ensures affordable housing for more individuals but also stimulates local economies and reduces the environmental impact associated with material transportation. Ultimately, these benefits underscore the positive environmental and social impact of incorporating sustainable practices in construction.

The extraction, production, and transportation of industrialized materials for construction constitute the primary source of CO_2 pollution due to the substantial amount of energy and carbon they generate. By employing the rammed earth construction technique, a significant decrease in CO_2 emissions is observed. as the consumption of petroleum-derived and similar resources is minimal. As the key factor in reduction, the use of fuels for material and machinery transportation is minimized, since the material utilized in this construction method is the local soil from the site where the architectural project is planned to be executed.

The implementation of sustainable construction practices presents several challenges that need to be addressed. One of the notable limitations is the absence of a comprehensive range of sustainable materials and options within widely used software like Revit. This inadequacy can impede architects and engineers from readily incorporating environmentally friendly choices into their designs. Furthermore, the practical implementation of sustainable construction in real-world projects is a rigorous and complex process. This complexity often requires dedicated budget allocation and specialized departments to oversee the sustainable aspects of the project. The lack of a streamlined approach can impede the integration of sustainability from the outset.

Existing software solutions that claim to expedite sustainable design processes are often inaccessible or come with a learning curve. Even tools like the Carbon Life Calculator, which are intended to facilitate sustainability assessments, can require significant time investment and may lack essential information for accurate carbon footprint evaluation. The absence of Embodied CO_2 coefficients in databases focused on sustainable materials such as rammed earth, adobe, and compressed earth blocks contrasts with prevailing international standards that predominantly prioritize industrialized materials. Consequently, the measurement of embodied energy and carbon in these materials becomes challenging.

One of the principal limitations in quantifying the carbon footprint in this study lies in its limited consideration of the carbon footprint associated with materials and transportation (Cradle-to-Gate). Future research should prioritize a Cradle-to-Cradle assessment to comprehensively assess the entire life cycle of the building and compare recyclability and post-demolition waste of the materials.

CRediT authorship contribution statement

Nathalia Fonseca Arenas: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Muhammad Shafique:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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