Understanding the Sustainability of Materials through a Case Study of Rebuilding a Traditional Village House Using the Carbon Footprint Approach

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Abstract

Houses in villages that are traditionally built with locally available materials like wood, mud, and stones are nowadays being demolished and reconstructed. The current trend has been to adopt framed construction with reinforced cement concrete and red bricks as the main materials. This is going to have a significant environmental impact and needs to be addressed with critical observations. This study is conducted for a local village in Tripura state, India, where a new house for the economically weaker section was constructed using stabilized mud blocks and bamboo as a model house. The main objective is to investigate the environmental impact of the transformation of a traditional house constructed out of locally available materials versus masonry and concrete houses. The impact has been represented as the difference in the Carbon footprint of the two houses based on the LCA approach. It was found that the total carbon footprint of the house built with locally available bamboo and stabilized mud bricks is 9.599 tons, 11.736 tons, and 11.401 tons lower in landfilling, waste treatment, and circular economy, respectively, as compared to concrete and masonry houses, and it has the potential to reduce the impact of the production stage to be negative.

Keywords: Carbon footprint, Life cycle assessment, Village house, Local materials, Bamboo, Concrete.

1. Introduction

The global average carbon footprint per person lies around 4 tons (https://www.nature.org/en-us, accessed on 02/05/2021) [1]. According to the emission gap report of the US EPA in 2018 [2], there has been an alarming call from the scientific community indicating an average 1.5-2℃ rise in global temperatures. This will definitely have an adverse impact on the ecosystem of Earth and will raise socio-economic as well as acute health problems for living beings. To have the best chance of avoiding this, the average global carbon footprint per year needs to drop under 2 tons by 2050 (https://www.nature.org/en-us, accessed on 02/05/2021) [1]. Countries like the United States have targeted a total reduction of 88.34 Gt CO2eq (80%) during 2022–2100 from building stocks (Hu, M, 2022) [3]. Buildings are major receptors for the consumption of material resources (GIZ, 2013) [4]. Buildings contribute to 33% of greenhouse gas (GHG) emissions and 30-40% of global energy consumption, which stem from the usage of equipment, the manufacturing of building materials, and transportation (Sakhlecha et al. 2021, Vorsatz et al., 2012) [5] [6]. Different housing projects under various schemes, like the Prime Minister's Scheme for Housing for All, etc., have been launched in which millions of houses are required to be constructed. In this regard, any kind of transformation in this sector can invariably affect global impacts. However, the common approach to construction is still to demolish and replace old mud houses with new masonry concrete houses. These materials certainly have several environmental impacts due to the consumption of considerable raw materials, energy, and fuel during their production process, long-distance transportation, and, of course, the final disposal, which is an inevitable part.

Blanchard and Peppe (1998) [7] analyzed a 2450 ft2 residential home in Michigan. The total life cycle energy was 15,455 GJ, and the life cycle global warming potential (GWP) was 1013 metric tons of CO2 equivalents. Saif et al. (2015) [8] conducted an estimation of the carbon footprint of the paint industry considering three different emission scenarios. Kulkarni and Rao (2016) [9] evaluated the greenhouse gas emissions associated with the manufacturing of fired clay bricks. Hasanbegi et al. (2016) [10] performed a comparative study of the carbon footprint of steel production in three different countries: China, Germany, and Mexico. Venkataraman Reddy (2009) [11], in his review paper pertaining to energy, carbon emissions, and sustainability of building construction with particular reference to the Indian construction industry, emphasized the use of sustainable natural materials. Jim Boyer (2015) [12] demonstrated the methods of assessing carbon liberation, carbon equivalency, fossil, CO2 sequestration, and implications of potential carbon regulation for materials selection and building design. Sathyababu et al. (2016) [13], in their study, carried out investigations on locally available materials such as soil, coir, straw, etc., with cement as stabilizers for improving the strength of locally available mud blocks and thus providing affordable housing. Abanda et al. (2014) [14], in their research, conducted a detailed process analysis approach supported by two popular housing types in Cameroon (mud-brick and cement-block houses) to assess the embodied energy and CO2 impacts from building materials. Their study revealed that the cement-block house expends nearly about 1.5 times more embodied energy and emits at around 1.7 times more embodied CO2 than the mud-brick house. Rajagopalan (2010) [15] conducted a comparative life cycle assessment modeling of an exterior wall section using insulating concrete forms (ICF) and a traditional wooden frame for a double-storey 2,450 square foot residential home in Pittsburgh. Souza et al. (2014) [16] compared the life cycle effects of roof coverings using ceramic and concrete roof tiles. As per the IPCC Fourth Assessment Report [17], emissions of CO_2 from fossil fuel combustion, with contributions from cement manufacture, are responsible for more than 75% of the increase in atmospheric CO_2 concentration since pre-industrial times. Stephen et al. (2018) [18] performed an assessment of the carbon footprint of a high-rise apartment in Hong Kong. Normalized embodied carbon emissions of residential buildings varied between 179.3 kg CO_2eq/m^2 and 1050 kg CO_2eq/m^2, with emissions related to the operational phase ranging from 156 kg CO_2eq/m^2 to 4049.9 kg CO_2e/m^2 (Chastas et al., 2018) [19]. The life cycle GHG emissions for a residential building were 2.95 tons/m^2 for a residential building in India (Sakhlecha et al. 2021) [5]. Ankur and Singh [20] conducted a review on the LCA phases of cement and concrete manufacturing. Martínez-Rocamora et al. [21] reviewed LCA databases focused on construction materials and provided a comprehensive overview of available databases. Hammond and Jones [22] conducted a study on embodied energy and carbon in construction materials. Their research contributed valuable insights into the energy and carbon footprint of various materials.

The literature reveals a lot about the impact of building materials as well as the impact of different life cycle stages in buildings. Another important thing is that the impacts vary from region to region. By 2050, it is projected that India will see an unprecedented escalation of floor area, around 400%, that will further add about 35 billion m^2 (321.36 billion sqft) of new building floor area (Vorsatz et al., 2012) [6]. In this study, the main focus is on evaluating the overall impact of the housing sector of rural housing based on the changing trend of demolishing the old mud houses to masonry and concrete houses in the Indian context. The soul of India lives in its villages. According to the 2011 census of India, 68.84% of Indians live in 640,867 different villages (https://villageinfo.in, accessed on 29/03/2021) [23]. The majority of the houses are constructed using locally available materials, which are (Clay) Mud and Wood and stones. The traditional houses were quite simple and environment-friendly since mud, a natural material, beautifully controls the temperature and keeps a healthy living environment. However, in the current trends of housing, it has been observed that people are converting their traditionally built mud houses to masonry and concrete houses. This study is conducted to investigate the comparative assessment of the environmental impact of rebuilding a traditional mud house in a remote village of Tripura state with sustainable materials. Two cases have been considered. Case 1 refers to building the house adopting framed construction using cement concrete, steel, and masonry, which has become a general trend, and case 2 refers to actual construction undertaken by using stabilized mud blocks and locally available bamboo. The impact has been represented as the carbon footprint of two houses based on the LCA approach considering three end-of-life scenarios: landfilling, waste treatment, and circular economy.

2. Materials and Methodology

2.1 Carbon Footprint

According to the EPA (2010), a carbon footprint is the total amount of greenhouse gases that are emitted into the atmosphere each year by a person, family, building, organization, or company [24]. Overall, carbon emissions can be measured in three ways: (1) considering carbon dioxide alone; (2) including the six gases identified by the Kyoto Protocol, i.e., CO2, CH4, N2O, HFCs, PFCs, and SF6; or (3) including numerous GHG emissions specified by the Intergovernmental Panel on Climate Change (IPCC) framework [25]. It is an important environmental indicator to assess the extent of any product's contribution to global warming and can be used to evaluate an object's (including a region, an organization, or a product) impact on the environment. The ISO 14000 environmental management standard series was implemented in the 1990s, with the 14040-series concentrating on LCA methodologies [26]. The Life-Cycle Assessment (LCA) of buildings has become an essential tool for minimizing the environmental impacts of construction and enabling the construction sector to move towards sustainability. The LCCO2A, also referred to as the "carbon footprint analysis," is a subset of the complete LCA which focuses only on the CO2 emissions of a product, activity, or process [6]. Carbon emissions are categorized into three levels: Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from the generation of purchased energy), and Scope 3 (all indirect emissions not included in scope 2 that occur in the value chain of the reporting company, including both upstream and downstream emissions) (World Resources Institute 2013, 2015; WRI 2013, 2015 [27]), Greenhouse Gas Protocol (GHG) convened in 1998 by the World Business Council for Sustainable Development (WBCSD) [28], Hua et al. 2023 [29].

In terms of the fundamental concept of quantifying the carbon footprint of any product, it can be calculated as the total amount of greenhouse gases generated by various stages of its life cycle. For each life cycle stage, the amounts of materials and energy used, and the emissions associated with the processes, are identified, analyzed, and calculated. It includes direct emissions, such as those resulting from fossil-fuel combustion in manufacturing, heating, and transportation, as well as emissions required to produce the electricity associated with goods and services consumed (https://www.lifecycleinitiative.org/starting-life-cycle-thinking, accessed on 24/04/2021) [30], Evandro et al. (2018) [31]. The emissions are multiplied by characterization factors proportional to their power to evaluate their environmental impact. One specific emission is chosen as the reference, and the result is presented in equivalents with regard to the impact of the reference substance. Global warming is a representative indicator based on the carbon footprint, which is evaluated based on CO2 equivalent.

The emissions from the production of all the materials used in the construction are required to be obtained, and the carbon footprint is fundamentally obtained by converting the impact from contributing gases like CO2, CH4, and N2O using their impact factors, considering CO2 as the reference indicator. There are many tools and software available on open-source platforms as well as in academic and professional versions to conduct a life cycle carbon footprint analysis. SAP Product Carbon Footprint Analytics, CO2 AI, and Carbon Trust can measure the carbon footprint of enterprises or firms as a whole, while Sphera/GaBi Software, Sima Pro, Open LCA, IDEMAT Lite, etc., are more focused on product-specific LCA (https://research.aimultiple.com/carbon-footprint-software) [32]. In our case study, the carbon footprint was obtained directly using the Idemat tool. Idemat is a sustainability-inspired materials selection tool that allows for the comparison of materials and derived processes based on the carbon footprint and Ecocost. The IDEMAT dataset is a set of Life Cycle Inventories (LCI) of more than 1000 materials, services, production processes, and end-of-life scenarios - based on data from the Swiss ecoinvent database and CES EduPack, which has carbon footprint data for materials. The single indicator output of the carbon footprint in terms of CO2 equivalent is obtained from the IDEMAT Tool [33]. The impact values of materials, stabilized mud block, and GI sheet, were not available in the database, so they were taken from a relevant report and research paper [34] [35], and the carbon footprint was calculated separately and added to the result of the software.

2.2 Major Life Cycle Stages of Building

The various stages of the life cycle of a product are shown in Figure 1. The three main stages of a product's life cycle are Production, which includes raw material extraction and manufacturing, Use or Operation, and Disposal. These are discussed for a building as a product.

2.2.1 Production Stage of Building - It is the stage in which the building is constructed on-site. However, it includes environmental impacts due to the manufacturing, transportation, and installation of building materials or products used in the construction until buildings are completed (Gong et al., 2012) [36]. The primary source of the environmental impact is the manufacturing of construction materials. Most of these materials are manufactured in industries, including the process of extracting raw materials, transportation, and production. Raw materials are normally found in nature in impure forms, e.g., in ores. The extraction or purification of materials from their natural ores and the processing of prepared raw materials into the final product form is an involved activity that not only consumes energy but also results in GHG emissions and waste generation.

2.2.2 Operation Stage - The operation stage is the phase where the occupants of the building meet their needs for living. The operational activities for living include cooling, heating, ventilation, as well as lighting and water supply. Energy is required for the functioning of lighting, fans, air conditioners, water heating, television, refrigeration, kitchen appliances, computers, etc. The operation phase accounts for 75-90% of the total life cycle energy (Sakhlecha et al., 2021; Citherlet, 2007; Ramesh et al., 2010) ([5], [37], [38]).

2.2.3 End of Life Stage - It is the stage when buildings no longer remain in a habitable condition. Components of building demolition waste typically include concrete, steel, wood, metals, gypsum wallboard, roofing, paper, plastic, bricks, and glass, etc. The recent assessment of the end-of-life scenario considers three different aspects that can exist at the end-of-life stage of any product. They are landfilling, waste treatment, and the circular economy, as shown in Figure 2.

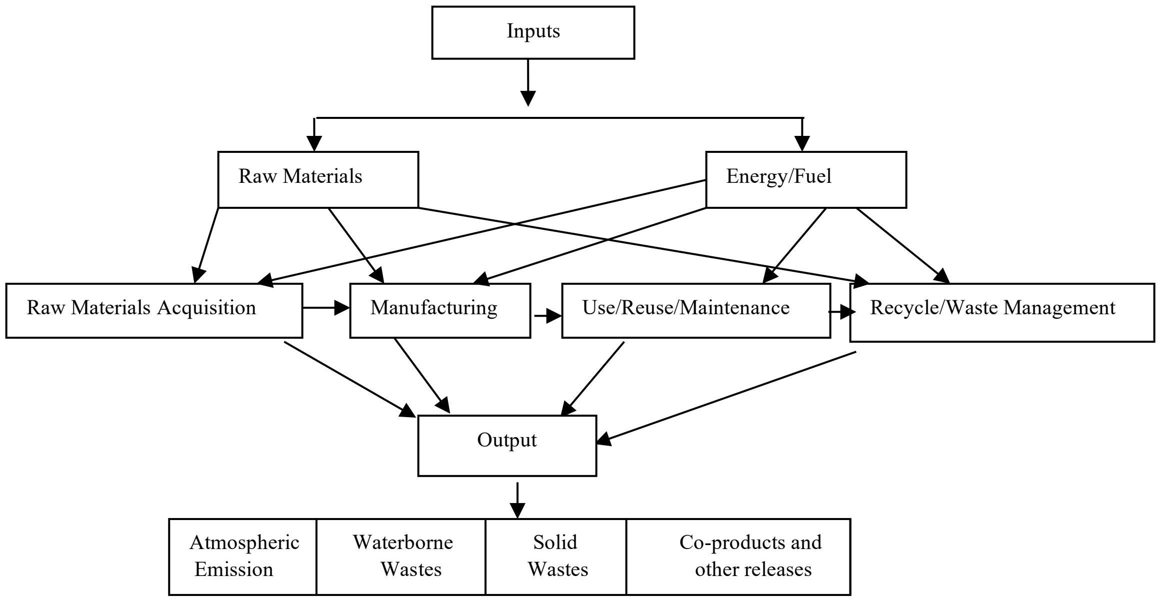


Figure 1. Life cycle stages of a product

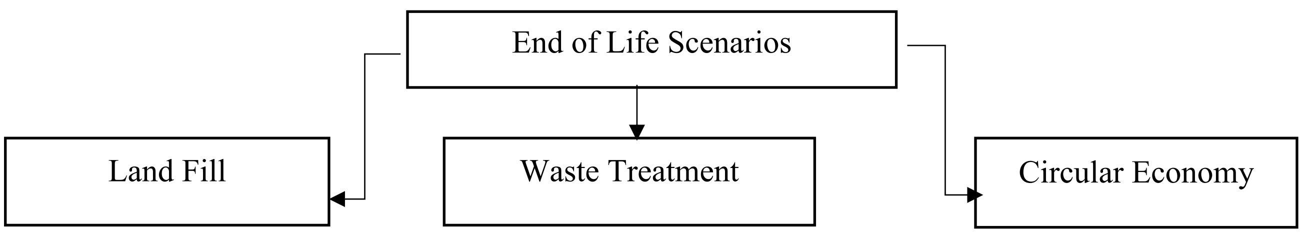


Figure 2. Different end of life scenarios of a product

Landfilling implies the direct dumping of the final disposed form of the product into the soil. Waste treatment implies that the product will be diverted for a different treatment process for final disposal, and circular economy is "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes (Kirchherret al. (2017), Benachioetal.(2020), MacArthur (2015)) [39], [32], [40].

2.3 Case Study

The area where we have visited for our study is 55 kilometers (approx.) from Agartala. The name of the place is Nalchar RD block, Sepahijala district. The plan, elevation, and truss frame of the case study house are shown in figures 3a, 3b, and 3c. It was situated 500 m from Nalchar RD block. The length, width, and height of the house were 6.85 m, 3.65 m, and 2.70 m. A separate front veranda of 1.80 m was provided, and the total built-up area was 25 sqm. The materials used in two different scenarios of the house are discussed below.

Case 1 - The house is modeled with concrete and masonry using a frame structure. The main materials were cement, steel, red bricks, sand, and aggregates. The house is designed using a frame structure of RCC columns (6 Nos - 230mm x 300mm), beams (230mm x 300mm), and a slab (125 mm thick) using the conventional method. The walls were plastered with 12mm thick 1:6 cement mortar, and the flooring was 2.5 cm thick PCC 1:2:4.

Case 2 - The main materials were stabilized mud blocks, treated bamboo, GI sheet, cement, sand, and stone aggregates. The wall of the house is made of stabilized mud block in an open foundation. The treated bamboos are used in the column of the veranda and roof trusses. The veranda is supported by bamboo columns with a diameter of 0.10 m and a height of 2m, which is supported and fastened on a concrete block with the help of steel angles using 2 numbers of bolts in each support. The plan, front elevation, and roof truss made of bamboo sections are shown in figures 3a, 3b, and 3c, respectively. The walls were lime-finished, and flooring was done with a 2.5 cm thick PCC 1:2:4. The roof was made of GI sheet 8 feet long. The same house was modeled and designed for a masonry and concrete house.

Table 1. Materials used in both categories of houses

Case-1		
Cement		OPC grade 43
Steel		Fe-415
Bricks		Red Bricks (215mm* 102mm*65mm
Aggregates		20 mm crushed stone aggregates
Sand		Fine sand following zone-IV
Case-2		
Cement		OPC grade 43
Steel		Fe-415
Aggregates		20 mm crushed stone aggregates
Sand		Fine sand following zone-IV
Stabilised mud blocks		290mm ×140mm×90mm
Corrugated Galvanized Iron (GCI) Sheet		
Bamboo Member		**Diameter in cm**
Column post		10
Truss	Rafter	8
	Tie member	7
	Inclined member	13

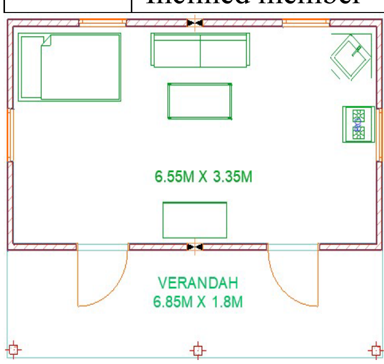


Figure 3(a). Plan of the house

Figure 3(b). Front view of the house

Figure 3(c). Roof truss

2.4 Impact Assessment - The Impact of Production Stage, Transportation, and Operation Stage

2.4.1 Impact of Production Stage

The quantity of materials was estimated based on drawings, specifications of materials, and principles of estimating. Table 1 gives the details of materials used in both cases, and Table 2 gives the quantities used in construction. The inputs of material quantity $Q_i$as per Table 2 were given separately for both cases in the software, and the carbon emission factor C_i for the corresponding material was selected from the default database of the software. The product of Q_i and C_i for each material and the summation of all such values, as represented in Equation 1, provided the results as the carbon footprint in CO_2eq for production (CFp) for three different end-of-life scenarios.

$$(\text{CFp}). = (\sum_{i=1}^{n}(\boldsymbol{Qi} * \boldsymbol{Ci})\text{--------}\textbf{Eq 1}$$

Table 2. Quantity of materials for two houses in case study

S. No.	Materials	Quantity(Kg)	
		Case1	Case2
1	Cement	4800	1200
2	Sand	12600	3000
3	Aggregate	11900	4400
4	Steel	610	55
5	Red Brick	31925	4000
6	Stabilised mud block	0.00	27625
7	Wood	301	301
8	Bamboo	0.00	2696
9	GI sheet	0.00	550
10	Lime	0.00	12

2.4.2 Impact of Transportation

The impact of transportation is based on the quantity of material (Q_i), the distance of their transportation from source to site (D), and the carbon emission factor of fuel (**C_{ef}-**). The distance of materials was determined based on the location of suppliers. Materials like cement, steel, lime, aggregates, and GI sheets are mainly sourced from Guwahati in neighboring states like Assam since the state of Tripura has no cement and steel plants, as well as quarries for aggregates. On the other hand, materials like red clay bricks, bamboo, sand, and wood are locally available in the Tripura region, which has a large production of red clay bricks, wood, and bamboo. The materials were assumed to be transported by trucks with capacities of 28 and 24 tons, and the carbon emission factor of 0.089 kg per ton-km was chosen from the software for calculating the impact. The total carbon footprint of material transport for both cases (Case 1 and Case 2) as obtained using Equation 2 is shown in Table 3 and Table 4, respectively.

$$CFt = (\sum_{i=1}^{8}(Qi)p * D * C_{ef}\text{-})\text{--------Eq 2}$$

Table 3. Material-wise transport impact for Case 1

Material	Quantity in Tonne (Q_i)	Distance in km (D)	Unit impact in Kg co_2 / ton.km	Impact in kg co_2
Cement	4.8	540	0.089	230.69
Sand	12.6	50	0.089	52.07
Aggregate	11.9	540	0.089	571.91
Steel	.610	540	0.089	29.32
Brick	31.925	50	0.089	142.07
Wood	.301	50	0.089	1.34
Total impact				**1031.40**

Table 4. Material-wise transport impact for Case 2

Material	Quantity in tonne	Distance in km	Unit impact in kg co_2/ton.km	Impact in kg co_2 equivalent
Cement	1.2	540	0.089	57.67
Sand	3	50	0.089	13.35
Aggregate	4.4	50	0.089	19.58
Steel	0.055	540	0.089	2.64
Red clay brick	4	50	0.089	17.8
SMB	27.625	20	0.089	4.92
Bamboo	0.3	50	0.089	11.99
Wood	0.550	50	0.089	1.34
GCI	0.0103	540	0.089	26.43
Lime	2.696	540	0.089	0.49
Total impact				**156.24**

2.4.3 Impact of Operation Stage

The operational stage electricity is calculated considering the average monthly power consumption. To obtain an average value, the annual electricity consumption of six different houses in the same locality was collected. The monthly electricity consumption of the existing case study house was 26 units. To account for the rising power demand and consumption over the entire 50-year lifespan, the average of the highest and lowest values was taken (Table-5). The total electricity consumption (TEC) was calculated using equation 3 by multiplying the average monthly unit by 12 and further multiplying it by 50, which is considered the service life of the building.

The maintenance and repair of the building have not been considered in the impact analysis.

$$TEC = \left\{\frac{HC+LC}{2}\right\} * M * S\text{------------}3$$

Where:
HC is Highest Average Monthly Power Consumption = 77.25 Units
LC is Lowest Average Monthly Power Consumption = 24.33 Units
M = Number of months in a year = 12
S = Service life of the house in years = 50

$$TEC = \left\{\frac{77.25 + 24.33}{2}\right\} * 12 * 50$$

= 30,474 kWh
= 109,706.4 MJ
= 109.7064 GJ

Now, the carbon footprint of the operation stage CFo is obtained using equation 4 by multiplying TEC and the carbon emission factor of electricity production (CFe):

CFo $= \{TEC\} * CFe$------------------4

where CFe is the carbon footprint equivalent of electricity production. Its value, as per the data available in the software with reference to the India Ministry of Power in Tripura, is 148.01 kg CO_2 equivalent per Giga Joule.

CFo = (109.7064 * 148.01) = 16,237.85 kg CO_2 equivalent.

Table 5. Operation stage power consumption data for 6 sample houses in the region

Sl. No.	Area of house sqm	Averagemonthly electricity Consumption Units(KWh)
1	34	29.75
2	48	24.33
3	45	30.11
4	38	77.25
5	52	30.58
6	52	25.80

3. Results and Discussion

The total carbon footprint in CO_2eq is obtained by using equation 5, and the values are presented in Table 6.

$TCF = CFp + CFt + CFo$------------5

Table 6. Total carbon footprint of both houses for all the EOL

Impact Stage	EOL (Landfilling) kg CO_2eq		EOL (Waste treatment) kg CO_2eq		EOL (Circular economy) kg CO_2eq	
	Case1	Case2	Case1	Case2	Case1	Case2
Production &Disposal	11706.8 (40.4%)	2982.19 (15.39%)	11468.2 (39.90%)	606.37 (3.56%)	10390.2 (37.56%)	-136.38 (-0.83%)
Transportation	1031.4 (3.55%)	156.24 (0.80%)	1031.49 (3.58%)	156.24 (0.91%)	1031.4 (3.72%)	156.24 (0.96%)
Operation	16237.9 (56.0389%)	16237.9 (83.80%)	16237.9 (56.50%)	16237.9 (95.51%)	16237.9 (58.7%)	16237.9 (99.8%)
Total	28976.1 (1159.04 kg/m^2)	19376.33 (775.053 kg/m^2)	28737.5 (1149.5 kg/m^2)	17000.51 (680.02 kg/m^2)	27659.5 (1106.38 kg/m^2)	16257.76 (650.31 kg/m^2)

3.1.1 Carbon Footprint of Case 1 House

The total life cycle carbon footprint impact of a house built with concrete and masonry is 28.976 tons (1.159 tons/sqm) CO2 equivalent for the landfill case, in which the production stage accounts for 11.706 tons and the operation stage has 16.27 tons, with a distribution of 40.4% and 56.38%, respectively. The transportation stage accounts for 1.031 tons, with a share of 3.55%. The total impact for the waste treatment case is 28.736 tons, with production and EOL contributing 11.468 tons and the operation stage contributing 16.287 tons, sharing 39.9% and 58.65%, respectively. In the case of a circular economy, the total impact is 26.628 tons (1.22 tons/sqm), with the production stage contributing 10.39 tons and the operation stage having 16.287 tons, sharing 39% and 61%, respectively. The values are presented in Table 6, Figure 4, and Figure 5. The per sqm values were obtained by dividing the total impact values for each case by the built-up area of the building (25m^2)

3.1.2 Carbon Footprint of Case 2 House

The total life cycle impact of a house built with bamboo and SMB is 19.37 tons (0.775 tons/sqm) CO_2 equivalent for the landfill case, in which the production stage accounts for 2.98 tons, and the operation stage has 16.237 tons, with a distribution of 15.39% and 83.80%, respectively. The transportation stage accounts for 0.156 tons, with a share of 0.8%. The total impact for the waste treatment case is 17 tons (0.68 tons/sqm) CO_2 equivalent, in which production and EOL contribute 0.606 tons, and the operation stage contributes 16.237 tons, sharing 3.56% and 95.51%, respectively. In the case of a circular economy, the total impact is 16.257 tons (0.65 tons/sqm), with the production stage contributing -0.136 tons, and the operation stage has 16.237 tons, sharing

-0.83% and 99.8%, respectively. The important outcome is that the impact of the production stage becomes a carbon-neutral stage, and only the operation stage contributes to the overall impact. The values are presented in Table 6, Figure 4, and Figure 5.

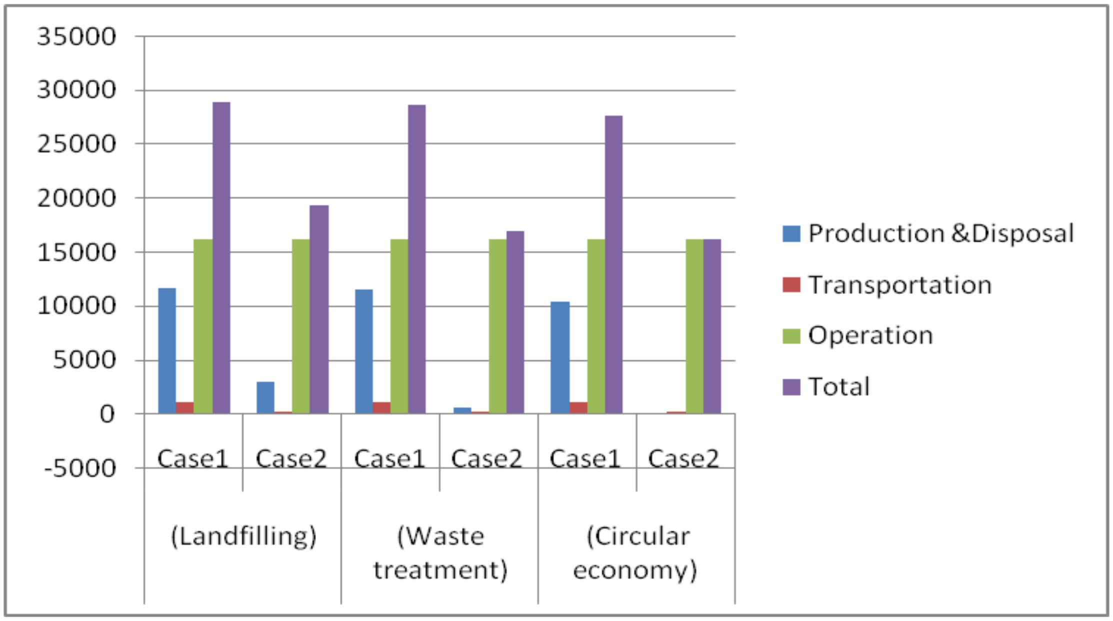


Figure 4. Total carbon footprint for both houses

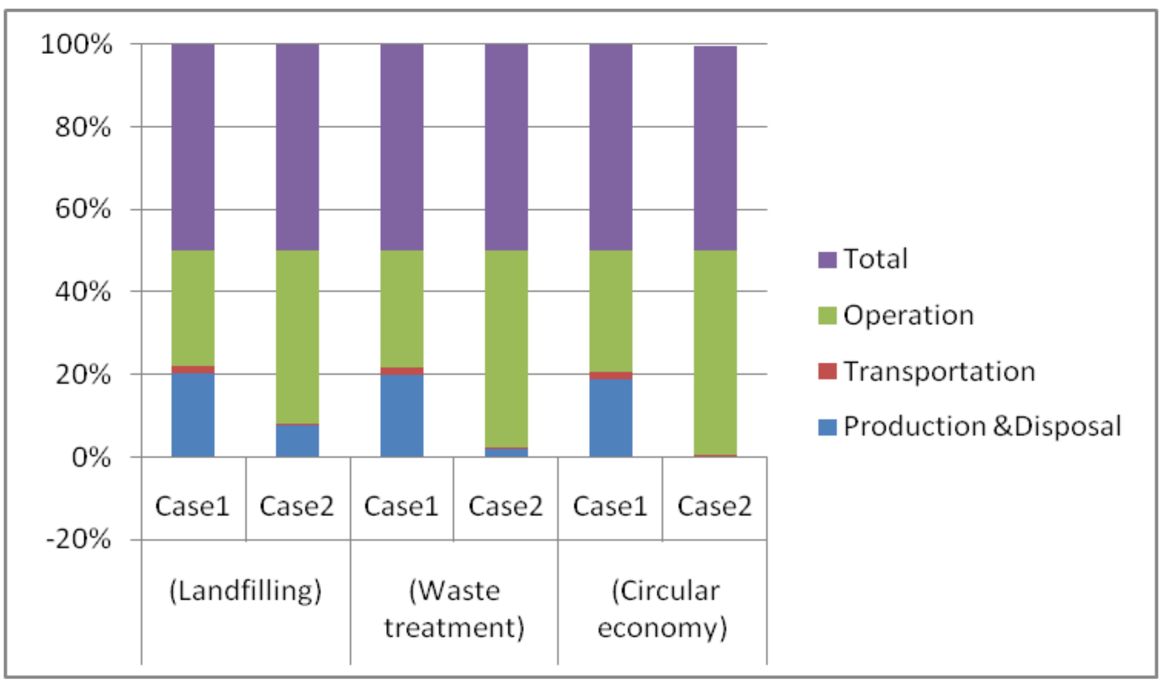


Figure 5. Percentage contribution of total carbon footprint for both houses

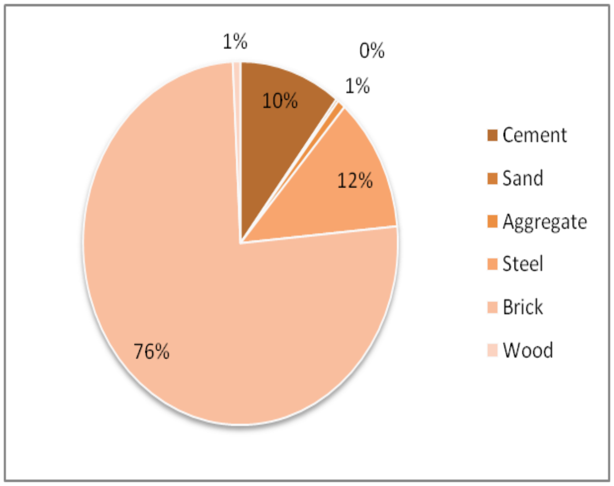
The overall carbon footprint in the bamboo SMB house of Case 2 has a reduced impact of 31% in landfilling, which increases to nearly a 40% reduction in the case of waste treatment and a circular economy compared to the concrete masonry house.

3.2 Carbon Footprint for Different Materials Used in Both Houses in Conventional Landfilling

The impacts of different materials under landfill disposal for both cases are as shown below in Table 7 and Figure 6a and 6b. In Case 1, it shows that red bricks have the maximum impact value of 8862.38 kg with a share of 76%, followed by steel 1406 kg (12%), cement 1221.57 kg (10%), whereas the impact of aggregates, sand, and wood is less than 1%. In Case 2, again, the maximum impact of 1110 kg CO_2 (37.2%) is contributed by red bricks, although it has been used only in the foundation, followed by SMB bricks 767.69 kg (25.4%), Bamboo 379 kg CO_2 (12.7%), cement 305.39 kg CO_2 (10.2%), Galvanized iron 165 kg CO_2 (5.5%), steel 126.8 kg CO_2 (4.3%), wood 91.53 kg CO_2 (3.1%), and others less than 2%.

Table 7. Carbon footprint for different materials used in both houses

Material	Case1			Case2		
	Quantity	Carbon footprint	% Share	Quantity	Carbon footprint	% Share
Cement	4800	1221.57	10.435	1200	305.39	10.2
Sand	12600	29.39	0.251	3000	6.97	0.2
Aggregate	11900	95.77	0.818	4400	35.41	1.2
Steel	610	1406.28	12.013	55	126.8	4.3
Red Brick	31925	8862.38	75.706	4000	1110.4	37.2
Wood	301	91.53	0.782	301	91.53	3.1
SMB	-	-	-	27625	757.69	25.4
GCI	-	-	-	550	165	5.5
lime	--	-	-	10.3	3.1	0.1
bamboo	-	-	-	**2696**	379	12.7



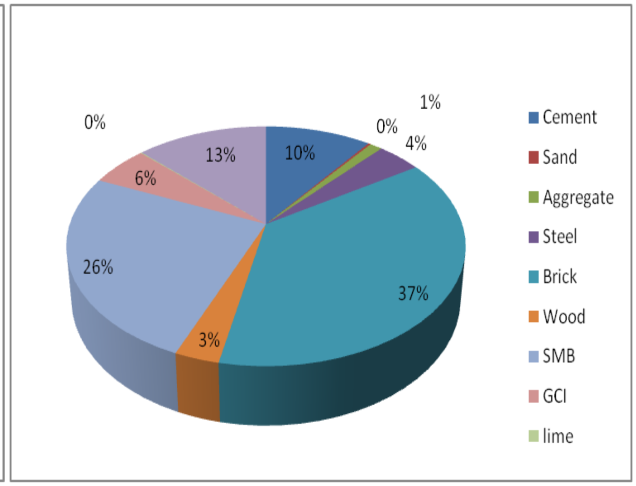


Figure 6a. % Share of impact of materials in Case 1

Figure 6b. % Share of impact of materials in Case 2

3.3 Carbon Footprint from Other EOL Perspectives

As we have kept the impact of the operation stage constant, the major difference in the impact is reflected in the production stage and disposal (end of life scenario).

Table 8. Material-wise impact in different EOL scenarios for Case 2

Sl.No.	Material	Impact in different EOL scenarios in kg $co_{2\ eq}$		
		Land fill	Waste Treatment	Circular Economy
1	Cement	305.39	305.39	305.39
2	Sand	6.97	6.97	6.97
3	Aggregate	35.41	35.41	35.41
4	Steel	126.8	126.8	35.50
5	Red clay brick	1110.40	1110.40	1110.40
6	SMB	757.69	757.69	757.69
7	Bamboo	379.9	-1757.31	-2342.78
8	Wood	91.53	-147.08	-212.56
9	GCI	165	165	165
10	Lime	3.1	3.1	3.1
Total impact		2982.19	606.37	-136.88

Table 9. Material-wise impact in different EOL scenarios for case 1

Sl.No.	Material	Impact in different EoL scenarios in kg $co_{2\ equivalent}$		
		Landfill	Waste treatment	Circular economy
1	Cement	1221.57	1221.57	1221.57
2	Sand	29.39	29.39	29.39
3	Aggregate	95.77	95.77	95.77
4	Steel	1406.28	1406.28	393.75
5	Red clay brick	8862.38	8862.38	8862.38
6	Wood	91.53	-147.08	-212.56
Total impact		11706.92]	11468.31	10390.30

Interestingly, the results of the production and disposal stage signify a 26.39%, 37.75%, and 40% reduction from Case 1 to Case 2. Individually, the reduction of about 3% can be seen in Case 1 house from landfilling to circular economy, whereas the impact contribution of 15% in landfilling reduces to 3.65% and negative, respectively, in waste treatment and circular economy for Case 2. The main reason behind the reduction in the overall impact of the production and disposal stage is the variations in the impact of materials in different scenarios of disposal, as presented in Tables 7, 8, and 9, along with Figures 7 and 8. The impact of cement, sand, aggregates, red clay bricks, and GI sheet remains unchanged in all three EOL scenarios. The impact of steel remains the same in landfilling and waste treatment but reduces from 1406.28 kg to 393.75 kg in Case 1 and from 126.8 kg to 35.5 kg in Case 2, indicating a reduction of 72.2% in impact. Similarly, the carbon footprint impact of bamboo in landfilling is 379.9 kg, which reduces to -1757 kg and -2342.78 kg in circular economy.

These results are obtained based on the per-unit impact of materials in different EOL scenarios as given in the software. Under the normal production process, the impact of blast furnace cement is 0.25 kg CO_2/kg, and its values do not vary in all end-of-life scenarios. The impact of steel in the normal production process is 2.31 kg CO_2/kg, and if this steel is processed through closed-loop recycling, its impact will be -1.66 kg CO_2/kg. The impacts of sand and coarse aggregate in the normal production process are 2.323 x 10^-3 kg CO_2/kg and 0.8 kg CO_2/100 kg, respectively, and their impact in different end-of-life scenarios has no changes. The impact of galvanized corrugated iron sheet (GCI) in normal production condition is 0.3 kg CO_2/kg, and its different end-of-life scenarios also do not impart any changes. In the normal production process condition, the impact of red clay bricks is 0.28 kg CO_2/kg, and its different end-of-life scenarios: landfill, waste treatment, and closed-loop cycling or circular economy have the impact of 0.00 kg CO_2/kg. The impact of stabilized mud blocks (SMB) in the normal production process is 0.0274 kg CO_2/kg, and its different end-of-life scenarios: landfill, waste treatment, and circular economy or closed-loop cycling have the equal impact of 0.00 kg CO_2/kg. The impact of wood in the normal production process is 0.3 kg CO_2 equivalent per kg of wood. When these woods are dumped in a landfill, it will be 0.00 kg CO_2 equivalent/kg; when it is processed through waste treatment and closed-loop cycling, its impacts are -0.79 CO_2 equivalent/kg and -1.01 kg CO_2 equivalent/kg, respectively. The impact of bamboo in the normal production process is 0.14 kg CO_2 equivalent/kg; when its end-of-life is considered as landfill, it is 0.00 kg/kg; when it goes through waste treatment, it gives -0.652 kg CO_2/kg, and if it is closed-loop cycled, then its impact will be -0.87 kg CO_2/kg.

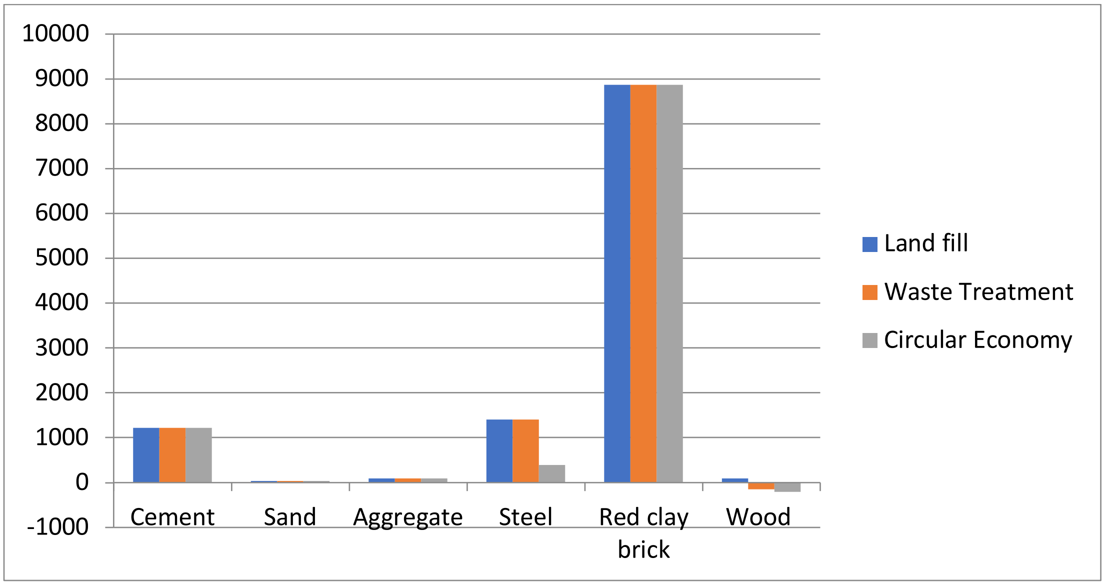


Figure 7. Impact of materials in all the EOL scenarios for Case 1

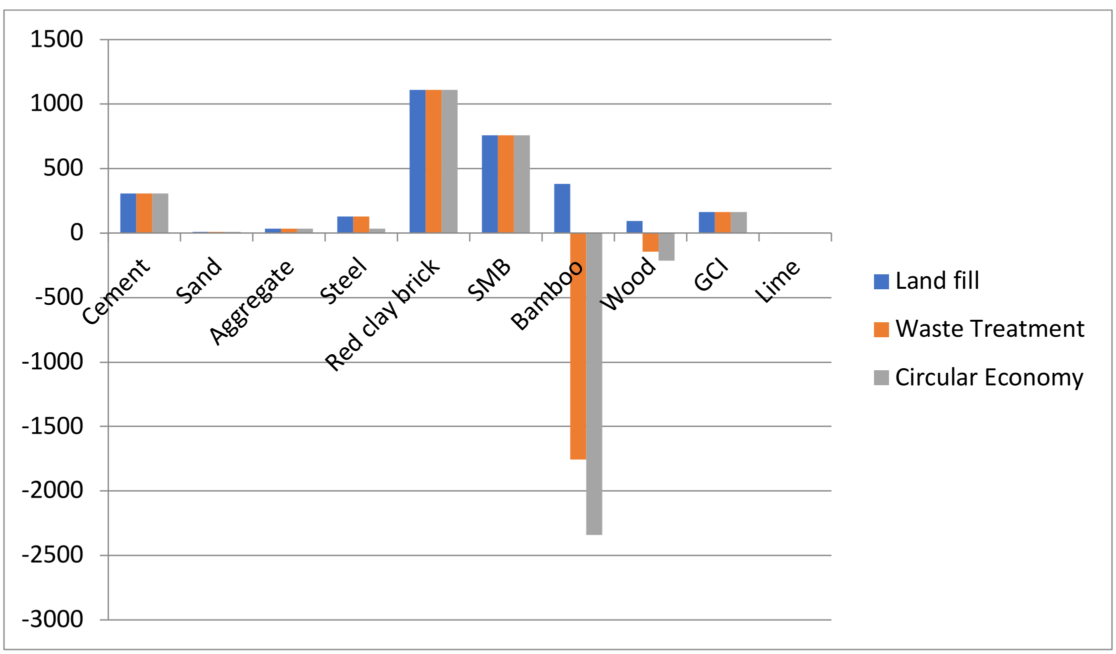


Figure 8. Impact of materials in all the EOL scenarios for Case 2

Conclusion

The study clearly reveals that the construction of purely a concrete and masonry house by demolishing the mud houses in villages is not an environmentally friendly choice. The worst scenario is the landfilling of the concrete masonry house (Case 1) with an impact of 27.9 tons, in which the production stage has 11.7 tons, and the best scenario is the circular economy of the bamboo SMB house (Case 2) in which the total impact is 16.1 tons, in which the production stage has -0.13 tons, thus bringing down the carbon footprint of the production stage to a negative value. The results clearly show that landfilling gives the highest contribution, and circular economy gives the lowest impact. The impact of materials may increase, decrease, or remain constant in different EOL scenarios. Hence, it is important to select the construction materials considering their impact in production as well as the EOL stage. The building sector has an urgent call to apply the concept of reuse and recycle through the planning and design stage and selection of sustainable materials. The house built with materials like SMB and Bamboo is no doubt eco-friendly as compared to the concrete and masonry house. It also has the potential to neutralize the carbon footprint of the production stage, which is an urgent need. The purpose of the study is to stimulate concerns on construction considering the local climatology and geology using locally available resources for environmental protection, particularly for the village and tribal housing sector of the North East region of India. Its primary focus is to sustain the traditional housing to encourage lower carbon footprints while improving life quality and heritage, as well as to mitigate future problems of high energy demand and insufficient environmental protection. It also calls for the local government's attention to implement stringent regulations to adopt earthquake-resistant and low-cost locally available bamboo to deal with higher energy demand and pollution problems in the residential sector and realize sustainable low-carbon development. Moreover, the region of Tripura is one of the largest producers of bamboo in the country, and people use it for art and craft as their source of livelihood. Here, it is important to carry out state-of-the-art studies and promote and develop technology and design models of houses, keeping bamboo as the preferred building material to be effectively used in the housing sector, and the same can be replicated for other parts of the country. In other words, we can say that if we maintain the practice of using environmentally friendly materials in construction, we can achieve the target of reducing global greenhouse gas emissions.

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