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A study of vernacular building materials in Bangladesh based on embodied energy and environmental performance

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Abstract. Concerns over climate change have driven the need for decarbonization of the building sector all over the world. It is proven that manufacturing building materials consumes a substantial amount of non-renewable energy and releases carbon emissions. For this reason, it has become an essential need for finding clean and energy-efficient alternative building materials. In Bangladesh, vernacular houses in rural areas are made of locally found materials like mud, bamboo, thatch, wood, and others and are always used in the construction of houses without any industrial processing, these dwellings are composed of materials with very little or no embodied energy (E.E). However, there has been a significant change in the construction of houses and the use of materials in rural Bangladesh in the last two decades. Concrete, brick, metal sheets, and many other industrial materials have taken possession of indigenous technology and bio-based materials. As a result, environmentally sustainable traditional houses have been transformed into energy-intensive houses. This research aims to study vernacular building materials in Bangladesh to identify their embodied energy, climatic performance, thermal conductivity, and durability for constructing low-carbon and less energy-consumed buildings. Based on several case studies, field surveys, and literature reviews the assessment has been conducted, showing that these materials are highly efficient in terms of embodied energy and can also ensure great thermal comfort. This study also evaluates the durability of these materials and depicts that by enhancing their durability, these materials can act as the best-performing building materials in all aspects.

1. Introduction

Concerns about climate change require global decarbonization of the construction industry. It is consensus that the production of building materials uses a significant amount of non-renewable energy and generates carbon emissions, making it one of the key energy-driven components in the life cycle of a structure. Some studies claim that the building sector has a significant environmental effect since it accounts for 40% of the world's energy consumption and 30% of greenhouse gas emissions (Mostafavi et al., 2021). When some other study depicts that the building and construction sector is responsible for more than 33.3% of energy use and 40% of carbon emissions (Marzouk & Elshaboury, 2022a). Followed by the transportation industry, the construction sector is the second-largest producer of GHGs, and hence the primary contributor to global warming (Rabbat et al., 2022). For instance, the residential and tertiary sectors combined release more than 123 million tons of carbon dioxide (tCO_2) annually, making up over 28% of France's total national CO_2 emissions (Rabbat et al., 2022).

The total life cycle of building energy use may be broken down into two main categories: embodied energy and operational energy. The total amount of energy used to develop, maintain, and demolish a structure, including both direct and indirect energy, is known as embodied energy (Li et al., 2020). Manufacturing, moving, constructing, and assembling building components all require direct energy (Marzouk & Elshaboury, 2022b). Demolition energy, recurrent embodied energy, and initial embodied energy are the three categories under which indirect energy is broken down (Zeng & Chini, 2017). Operational energy includes the energy used for lighting, various building equipment, space conditioning and ventilation, heating, and cooling while a building is being used (Dixit, 2017). Over 32% of the CO_2 released during a building's operating phase is produced during the phases of manufacture, transportation, and construction (Marzouk & Elshaboury, 2022a). Because building materials' embodied energy significantly impacts CO_2 emissions, building materials are an important issue in the practice of sustainable design and construction.

In the context of Bangladesh, traditional houses in rural areas were usually made of locally available materials due to their low cost, familiarity, and acceptance. However, traditional architecture in Bangladesh has recently been turned into manufactured materials because of their availability, and durability (Islam et al., 2022). Therefore, it can be assumed that nowadays vernacular houses are becoming more energy-consuming and cannot keep up with the growing demands or useability. Several studies show that embodied carbon of the materials of a building has a great impact on its overall life cycle of carbon emission. Some studies reported that embodied energy is 30–35% of 100-year life-cycle energy demand based on different building options (Rahman, n.d.). So, it is necessary to consider building materials as an important factor to lower the total carbon emission of a building. Although manufactured materials are more durable and widely available since they are often processed industrially, their embodied energy is inherently higher than traditional Bangladeshi materials, which do not typically undergo machine-based processing. For example, the kilns used to manufacture brick in South Asian countries such as Bangladesh are exceedingly unrefined, resulting in wasteful energy usage and pollution (Rahman, n.d.).

Vernacular architecture on the other hand is formed by indigenous knowledge and experiences over many generations and requires very little specialized work and no involvement from professionals (Saha et al., 2021). These biobased building materials are always utilized in the construction of buildings without any industrial processing and have been recognized as materials with low embodied energy. So, the nature of vernacular architecture is to support the declaration of the future, not to look back but to the answer of sustainable building (Old Town, n.d.). Since Bangladesh is a delta, its soil provides an endless supply of raw materials for mud and clay-based materials. Vernacular houses in rural areas in Bangladesh are made of locally found materials like mud, bamboo, thatch, and wood. According to a World Bank survey from 1998, thatch, leaf, and other natural materials make up roughly 52% of the roofs of rural homes (Khan & Kabir, n.d.). Many traditional settlements in Bangladesh exhibit vernacular architecture as a direct manifestation of a community's lifestyle and culture as well. This country's rural inhabitants have long practiced eco-friendly construction and have acquired this ability via environment and experience (Ahmed & Ahmed, 2015). Therefore, this study has focused on the assessment of the environmental performance of vernacular materials in Bangladesh in terms of embodied carbon, thermal comfort, and durability.

So, this research aims to evaluate the efficiency of vernacular construction materials in Bangladesh to identify potential building materials to cope with the popular manufactured materials. It reviews the climatic performance of Bangladeshi vernacular materials in terms of embodied energy, durability, availability, and thermal comfort. The objectives of the study focus on understanding the case study and its construction method. Identifying the commonly used materials and the construction process of those materials, from the collection, and processing to construction to identify their Embodied Energy (E.E). Then evaluate the durability and thermal comfort of the materials to understand their opportunity and scope for further utilization.

2. Literature review

Every region's traditional vernacular architecture is influenced by factors including its culture, society, religion, environment, and symbolism (Sobhan et al., n.d.). It is characterized by consistent efforts to improve through numerous generations, making the best use of the limited resources at hand. The approaches used in vernacular architecture to mitigate the effects of climate change are typically low-tech, don't rely excessively on non-renewable energy, and don't require specific technological equipment, making them suitable for modern architecture (Fernandes et al., 2015).

Several studies show that traditional houses in Bangladesh are more efficient in terms of thermal comfort than houses with contemporary designs. In one study authors evaluated the indoor thermal comfort between a traditional Bangladeshi house and a contemporary design house in their research to determine the longer duration of thermal comfort hours within a crowded surrounding environment in Dhaka city Bangladesh. The result shows that Bangladesh's traditional houses have the ability to provide better thermal comfort than contemporary design houses (Rumana & bin Ahmed, 2013). Datta et al (2016) employed Ecotect simulations for the brick wall and mud wall modules separately and also carried out fieldwork using data loggers, to determine the real temperature difference in mud and brick-walled houses. According to the study, when compared to a brick wall, mud as a building envelope keeps the indoors of the hut cooler than the outside in the summer and warmer than the outside in the winter (Datta A & Mustafa B, 2016). Mehjabeen Ratree S et al. (2020) also agree with Datta et al. (2016) by asserting that Mud as a building envelope keeps the Indoor environment of the hut cooler in summer (Mehjabeen Ratree et al., 2020). Islam R et al (2021) also reported that Mud and timber homes emit less CO_2 than brick residences, and the embodied carbon of a brick dwelling's basic material is substantially greater than the embodied carbon of wood and mud dwellings. Although N. Monzur (2018) signifies in her research that earth as a building construction material has some disadvantages like reduced durability and compressive strength which affect the applicability of this material. But in spite of the drawbacks, the author suggested some rammed earth and bamboo structure solutions that can validate the concept and virtue of mud houses (Monzur, 2018). According to Tariqul Islam K et al, building a brick house is typically based on status, which is the key driver of the shift to manufactured products, and even though most owners of brick and CI sheet buildings are dissatisfied with the thermal comfort, they opted to build brick homes as a demonstration of their better financial standing (Tariqul Islam & Afroz, 2015). Authors also confirmed in their research that the mud home has higher thermal performance in all-weather than a brick or CI Sheet house because the inside air temperature is less impacted by the outside temperature. So, it is supported by different studies that, vernacular materials offer lower embodied energy than those currently used in the building industry since they are locally accessible, need extremely low-intensive energy manufacturing processes, and do not need to be transported over larger distances (Khan & Kabir, n.d.)(Mateus et al., 2020). And the present study found consistent results with the previous studies.

Natural material is also good for the health and optimization of the environmental design of buildings (Rumana & bin Ahmed, 2013). Bangladesh's traditional homes are recognized as great examples of warm, humid, tropical dwellings that can adjust to the local climate and are perfectly blended with local customs and materials. The embodied energy of rammed earth and mud brick, if produced locally, is estimated to be roughly 0.7 MJ/kg, less than 30% of burned clay bricks' (2.5 MJ/kg) and less than 20% of lightweight aerated concrete blocks' (3.6 MJ/kg) embodied energies (Datta A & Mustafa B, 2016). Carbon emissions from brick homes during construction were approximately 3.86 times greater than those from timber houses, 6.75 times higher than those from mud households, and also higher during the operational stage due to residents' lifestyles and activities (Islam et al., 2022). On the other hand, Bangladesh's brick industries are major energy consumers, using up 25.6% of the country's total natural resources (Khan & Kabir, n.d.).

This is why these biobased materials in Bangladesh must be thoroughly explored and analysed to improve their durability and availability for wider applications. Therefore, this research aims to assess vernacular building materials in Bangladesh to identify their embodied energy, climatic performance, and durability for constructing low-carbon and less energy-consuming buildings. This paper also tends to present detailed findings of several vernacular building materials which would assist in further study and promote sustainable building materials.

3. Methodology

An observational study and field survey was conducted to gain a deeper understanding of Bangladesh's traditional materials to understand the reasons for the transition toward manufactured items.

As different regions of Bangladesh have their own unique type of building construction techniques and materials. Therefore, surveys were conducted in four distinct regions to comprehend the general situation of Bangladesh's traditional materials. Rajshahi, Khulna, Mymensingh, and Sylhet districts were chosen as survey locations. Four distinct types of traditional houses were visually assessed and photographed. Each individual house was then observed and hand sketched the plan, elevation, and section to identify the materials used.

In November 2022, a semi-structured survey was conducted, interviewing approximately 4 inhabitants from each household, encompassing various age groups. In total, around 16 individuals participated in the survey. The focus of the survey was on the house, its maintenance, and thermal comfort. Additionally, a questionnaire survey was carried out for each house’s construction material used, aiming to evaluate aspects such as durability, procurement method, and maintenance process, while also gaining insights into users' perceptions.

In the final step, based on the data acquired through observation and field surveys, the durability and embodied energy of the material are analysed by examining the transportation mode, distance, processing technique, and construction phase of the materials. Thermal conductivity is also evaluated using literature research to better understand the thermal comfort of the materials. Analysis and synthesis of the data were done to determine the strengths and weaknesses of the various types of local construction materials used in Bangladesh.

3.1 Survey Area

Bangladesh is located in the tropical monsoon zone, and its climate can be distinguished by high temperatures, heavy rainfall, typically excessive humidity, and significant seasonal changes. Figure 1 shows the climatic condition of Bangladesh including monthly average temperature.

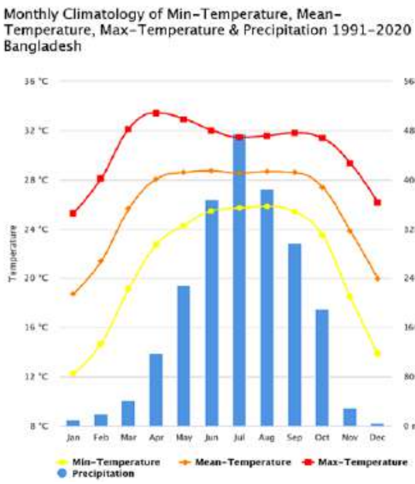

Figure 1. Climatology of Bangladesh (*Bangladesh - Climatology | Climate Change Knowledge Portal*, n.d.).

From a climatic perspective, Bangladesh has three different seasons: the cold dry season (November through February), the hot pre-monsoon season (March through May), and the rainy monsoon season (June through October) (Datta A & Mustafa B, 2016). Because of the seasonal variation and geographical location, different kinds of materials and construction techniques are available in different regions of Bangladesh.

That is why four different locations were selected for the survey. Rajshahi, Mymensingh, Sylhet, and Khulna are four old inhabited areas in Bangladesh. Also enriched with their own history, culture, and indigenous way of life. Figure 2 shows precipitation from 1991-2020 and the location of four survey regions.

Figure 2. Survey regions in Bangladesh to the right.

4. Result and analysis

A set of data were collected throughout the survey about the above-mentioned locations and the materials used to build the houses. Tables 1 and 2 show the plan, section, elevation, materials utilized, and thermal comfort for the four dwellings evaluated.

Case study 01 is located in Alponagram, Rajshahi. This house is 20 years old. The main materials used to construct the house are mud, bamboo, and tin. Walls and plinths are made of mud, bamboo is used as construction material, and corrugated tin is used as a roofing material. Because this house was built only 20 years ago, it only needed minor repairs two or three times.

Case study 02 is located in Bhaluka village in Mymensingh and is about 65 years old. Mud for constructing plinths and walls, brick in partial sections of wall construction, tin as a roofing material, and wood as a structural element used to make the house. This house has been under a couple of modifications and alterations because of its age. Precast pillar replacement along with roof tin replacement needed to maintain the house.

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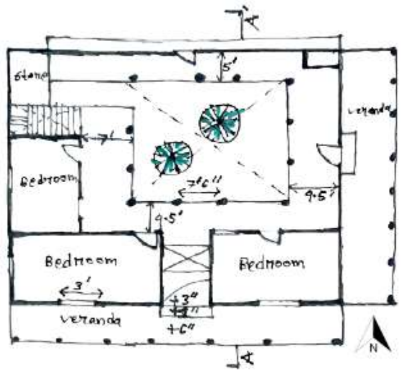
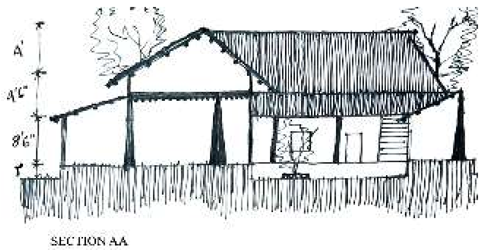
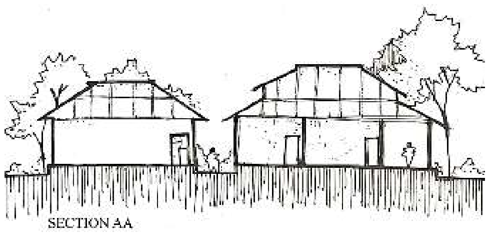
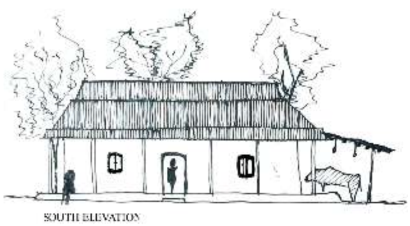
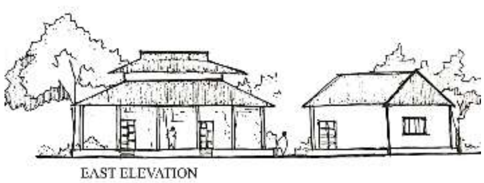
Table 1. Summary of the information of case studies 01 and 02.

	Case study 01	**Case study 02**
Location	Alponagram, Rajshahi	Meduary, Bhaluka village in Mymensingh
Age	20 years	65 years
General description	The homestead is one story containing three bedrooms, one store room, and an earthen staircase for access to the storage space and is raised over a 12-inch-high plinth. An outer veranda is surrounded by two sides of the house which is often used as a cowshed.	The main dwelling is L shaped one-storied house with three bedrooms and one store room in it. A pigeon room and a kitchen are situated at the opposite corner of the rectangular courtyard. The hut is raised over a 12-inch-high plinth made of earth.
List of materials	Mud, Bamboo, Tin	Mud, Brick, Tin, wood
Times of repair	2 or 3 times, basic plinth repair and roof tin modification	More than 6 times with precast pillar and roof tin replacement
Maintenance	The mud wall needs yearly maintenance, and the tin roof needs repair.	The mud wall needs yearly maintenance and the tin roof needs partial replacement every 7 to 8 years.
Plan		
Section		
Elevation		

	Case study 01	Case study 02
Perspective		

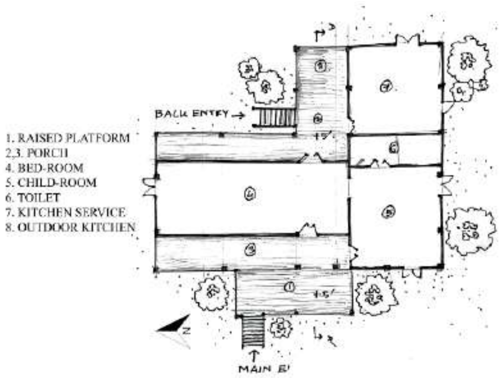
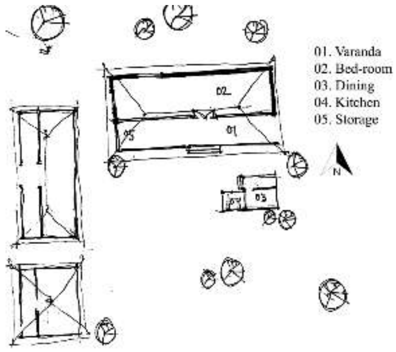
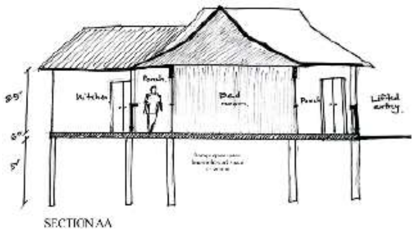
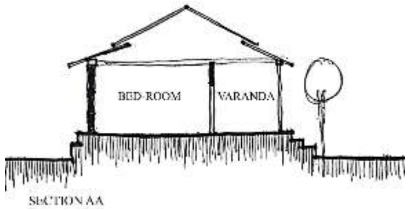
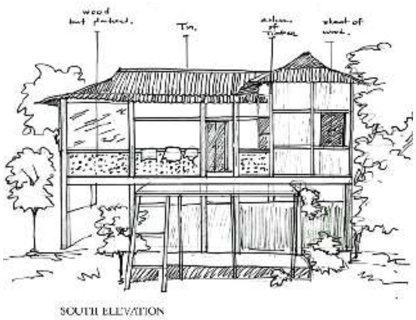
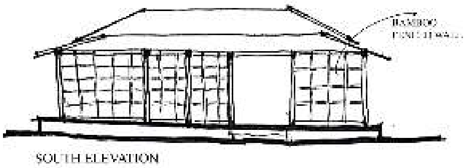
Case study 03 is located at Khasia Palli, Jaflong, Sylhet, one of the major tribal groups in the country. They have been using their own construction method and regional vernacular materials with their ancestral knowledge for generations. This house is approximately 100 years old and over three generations of the family has lived here. Initially, the house was made of wood, timber, and bamboo. Over time the roof was replaced with tin, and the precast column has been added in partial section to gain more structural rigidity.

Case study 04 is located in Botiaghata, Khulna. This house is 30 years old. Mud, Bamboo fence, Wood, Unburnt brick, Nipa palm, and Tin have been used to build the house. Plinth is made of mud while unburnt brick is used to make the walls, and nipa palm is used as roofing materials for kitchen and storage shade.

A questionnaire survey was further assessed for these materials to understand the durability, maintenance, procurement method, and embodied energy of the materials.

Table 2. Summary of the information of case studies 03 and 04.

	Case study 03	Case study 04
Location	Khasia Palli, Nakshiorpuryi, Jaflong, Sylhet	Botiaghata, Khulna
Age	Approximately 100 years	30 years
General description	The house is raised over 5 feet on wooden stilts from the surface. Wooden stilts were replaced by concrete posts during renovation. The dwelling consists of two bedrooms, one toilet, one indoor kitchen service, and one outdoor kitchen located on the raised platform. Two wooden staircases are used for access to the house.	The dwelling consists of three different house forms in an L-shaped manner forming a rectangular courtyard. The house has two bedrooms, one elongated veranda, one kitchen, and a store room. The house is raised over a 16-inch plinth made of earth and the thick wall is also composed of mud or earth.
List of materials	Wood, Timber sheet, Bamboo, Precast reinforced concrete column, Tin	Mud, Bamboo fence, Wood, Unburnt brick, Nipa palm, Tin
Times of repair	Multiple times, with precast pillar and roof tin replacement and wall modifications.	2 or 3 times, basic plinth repair and roof tin modification.
Maintenance	The tin walls need tin roof needs to repair and partial replacement every 4 to 5 years.	The mud wall needs yearly maintenance and the tin roof needs partial replacement every 7 to 8 years.

	Case study 03	**Case study 04**
Plan		
Section		
Elevation		
Perspective		

So, from table 1 and 2, the most commonly used vernacular materials that can be found in the traditional houses in Bangladesh are:

Table 3. Commonly used vernacular materials in Bangladesh.

No.	Material	Image	Using area
01	Mud		1. Wall 2. Fenestration 3. plinth
02	Bamboo (fence, chatai)		1. Construction Frame 2. Piller 3. Door and window frame 4. Wall 5. Boundary wall 6. Fencing
03	Unburnt brick		1. Wall 2. Fenestration
04	Nipa palm		1. Roof 2. Temporary shade
05	Tin (CI sheet)		1. Roof 2. Wall
06	Wood		1. Construction Frame 2. Piller 3. Door and window frame 4. wall
07	Straw /thatch		1. Roof 2. Temporary shade

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Table 4. Summary of the information on vernacular materials.

Material name		Mud/ Earth	Bamboo	Unburnt brick
Raw material supply		From nearby land	Nearby market place	From the land beside the house
Raw material transportation	Transportation mode	Nil	Rickshaw/ van (non-motorized vehicle)	Nil
	Distance from the source (km)	Nil	Around 4 km	Nil
Processing of the material	Place of processing	On the building site	In the community space or courtyard space	In the courtyard of the house
	Processing methods	Water and rice husk are mixed with the mud to strengthen it. Make the wall one and a half feet, dry it then repeat the process.	Refine the bamboo using sharp tools then dry it properly in the sun before construction	Bricks are formed by putting clay into moulds, which are then sun-dried.
	Who processed the material?	The owner himself	Owner himself	Owner with one or two labor
Construction phase	Who builds the house?	Owner with one or two laborers.	Owner with one or two labor	Owner with one or two labor
	Construction period	6-7 months	Around 5 days	Around 6/7 days
Maintenance phase	What kind of maintenance is needed for the material?	Overlapping with mud coat on the walls once every year.	Needs to be replaced if gets damaged or infected.	Overlapping with mud on the walls once every year
Durability		20-30 years	15- 20 years	30 – 40 years
Embodied energy		No embodied processing & transportation energy	No embodied processing & transportation energy	No embodied processing & transportation energy
Disadvantages/ Limitations		• Needs to be coated with mud once every year. • Heavy rain may cause damage.	• Require preservation • If not treated well it gets attacked by fungi.	• Needs to be coated with mud once every year.

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Table 5. Summary of the information on vernacular materials.

Material name		Nipa palm	Tin (CI sheet)	Wood	Straw/ thatch
Raw material supply		Nearby market place	Local Bazar	From self-property	From self-property
Raw material transportation	**Transportation mode**	Rickshaw/ van (non-motorized vehicle)	Van (non-motorized vehicle)	Boat, van (non-motorized vehicle)	No transportation needed
	Distance from the source (km)	Around 4 km	Around 5-6 km	Around 3 km	Around 100 m
Processing of the material	**Place of processing**	In the courtyard of the house	Pre-manufactured	In the community space	At home or in the courtyard
	Processing methods	Can be used right after collecting the leaves. No further processing is needed.	Pre-manufactured	Hand-crafted and minimal processing by submerging in water and drying it properly. Then cut it according to the use (thin sheet or post).	Straw is sorted and then dried in the sun. After that is assembled on the bamboo frame during construction.
	Who processed the material?	Four or five labors	Pre-manufactured	Community people	The owner himself with the help of community people.
Construction phase	**Who builds the house?**	Four or five labors	Owner with one or two labor	Craftsman of the community	The owner himself with the help of community people.
	Construction period	Around 2 days	Around 10-12 days	Around 10-15days	Around 1 – 2 days
Maintenance phase	**What kind of maintenance is needed for the material?**	Repair or replace them after around 4-5 years	Repair or replace them after a specific period	Repair or reframe them after a specific period	Repair or replace them after around 1 - 2 years
Durability		4-5 years	40- 50 years	25 –35 years	1-2 years
Embodied energy		No embodied processing & transportation energy	Pre-manufactured product	No embodied processing & transportation energy	No embodied processing & transportation energy
Disadvantages/ Limitations		• Need skilled labors	• corrosion occurs easily	• Wood can easily rot and be impacted by woodworm.	• Need skilled labors • Needs to maintain properly

In Tables 4 and 5 life cycle (from raw materials supply to the construction phase and maintenance phase) of the above-mentioned materials is analysed and studied based on the case study houses and survey data.

Mud or earth is founded as a very commonly used material in every region of Bangladesh. Being a delta soil is abundantly available in this country which made this material popular. Also, this mud is usually collected from nearby land without any kind of transportation needed. Processing of this material normally took place on the building site or the courtyard space of the house. All the house members participate in the processing of the material and a coat of liquid mud layers needs to be done on the mud wall and floor once every year.

Unburnt brick is also a mud-based material but is more durable because of the processing method. Unburnt brick is created by placing clay into moulds and then sun drying the brick. The brick is then used for the construction of the house and liquid earth coating is used as plaster for finishing.

Wood and bamboo are other available materials for construction. These materials are mostly collected from own properties or nearby market place which are commonly situated 4 to 5 km from the neighbourhood and carried by a non-motorized vehicle to the building site. The maintenance of these two materials is comparatively easier than the others. These materials are needed to be replaced or reframed if infected or rotted after a certain amount of time.

Corrugated tin is a very popular roof material for most houses due to its low maintenance and long durability. This material is collected mostly from the nearby marketplace and transported by nonmotorized vehicles to the building site. One or two laborers are needed to complete the house. Although this material is accessible in local markets, it is a manufactured product that has been subjected to industrial processing. So, the embodied energy of this material is comparatively higher than the other materials. Galvanized steel sheet or corrugated tin's embodied energy value can be varied from 6818 MJ/t to 15090 MJ/t which is much higher than the other materials (Asif et al., 2017; Elsayed et al., 2021).

The other materials are Nipa palm (locally called 'golpata') and straw/thatch which is used as a roofing material. Nipa palm can be found in the northern part of the country. It is one kind of mangrove palm, and the roof is constructed from its leaves. This material can also be collected from nearby marketplaces and is transported usually by any nonmotorized vehicle. It is also a very low-maintenance material and needs to be replaced after every 4 to 5 years.

Straw/thatch can be collected from one's own or nearby land, so no transportation is needed and it is also a very low-maintenance material which is needed to be replaced once every 1 to 2 years.

5. Findings

From the analysis in section 4, it can be understood that most of the materials used to build traditional houses in Bangladesh are locally available, low maintenance, and efficient to use.

In order to further understand the thermal performance of the materials, the thermal conductivity of the materials is assessed based on the literature study. Thermal conductivity is defined as the rate of heat transfer through the unit thickness of a material per unit area per unit temperature difference (Latif et al., 2011). The lower the thermal conductivity, the greater the thermal resistance, which means materials with lower thermal conductivity will have better building performance. In Table 6 thermal conductivity of the selected materials is described based on the literature study.

Table 6. Thermal conductivity of the materials.

No.	Material	Thermal conductivity (W/m K)
1	Mud	0.837 (Baggs & Mortensen, 2006)
2	Bamboo	Longitudinal direction (along the culm length): 0.55–0.59 Transverse/radial direction: 0.39–0.43 (Shah et al., 2019)
3	Unburnt brick	0.837 (Baggs & Mortensen, 2006)

No.	Material	Thermal conductivity (W/m K)
4	Nipa palm	.066
5	Tin (CI sheet)	204 (Koumbem et al., 2021)
6	Wood	0.14 - 0.19 (Dr Don Mclean, 2011)
7	Straw/ thatch	0.066 (Simpson & Nevell, 2022)

Table 6 shows that the majority of the materials used to construct traditional Bangladeshi houses have extremely low thermal conductivity. Mud, bamboo, unburnt brick, wood, and straw/thatch have thermal conductivity values of less than 1 W/m K. This suggests that houses constructed with these materials have strong thermal resistance, which can ensure better thermal comfort. The thermal conductivity value of the nipa palm has not been found and is considered a research gap. However, nipa palm and straw/thatch are more comparable and share similar volume, water, and air content characteristics, making it likely that they will also have comparable thermal properties. Tin (CI sheet) on the other hand is not an indigenous roofing material but is commonly used because of its availability and durability. Since tin is made of metal sheets, it has a particularly high thermal conductivity value of 204 W/m K. So, tin, as a roofing material, cannot provide enough thermal comfort.

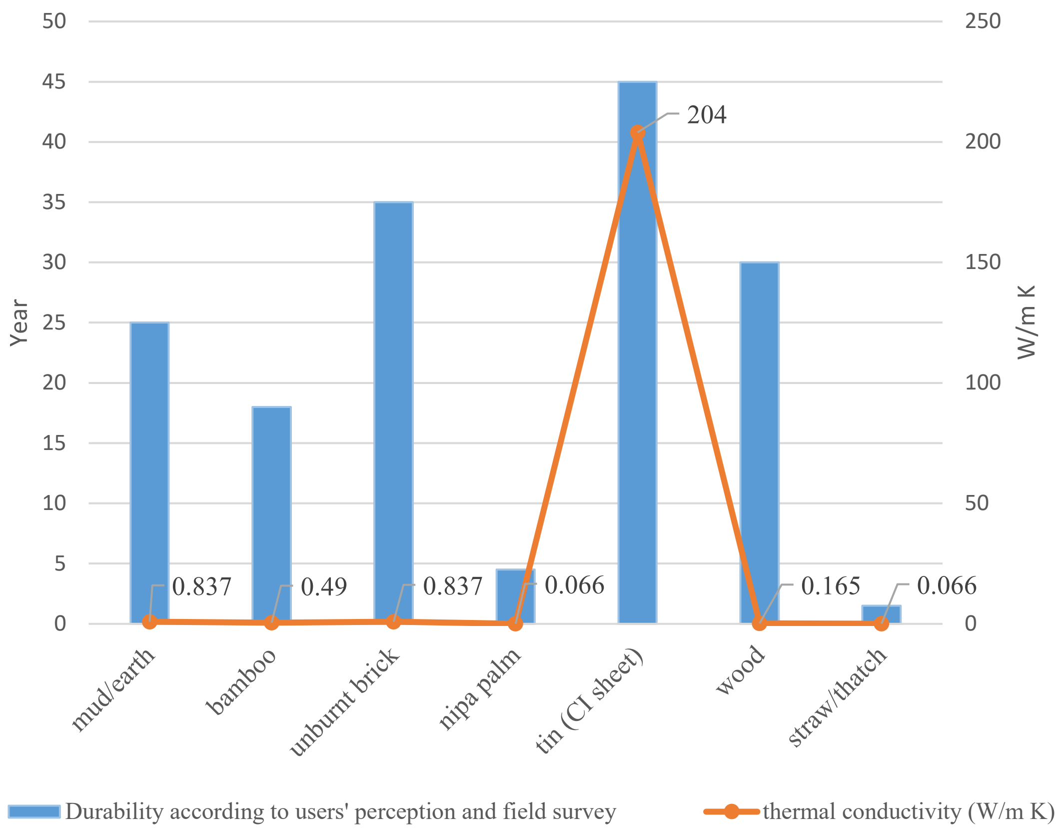

Figure 3. Thermal performance and durability comparison among materials.

Figure 3 depicts a comparison of materials in terms of durability based on user perceptions and a field survey, as well as thermal conductivity based on literature reviews. According to Figure 3, mud, unburnt brick, and wood have relatively average durability of 25 to 35 years. Bamboo has an average durability of 18 years, whereas nipa palm and straw/thatch have 4.5 and 1.5 years, respectively. Tin (CI sheet) has a relatively high durability of 45 years which is one of the primary reasons for using this material.

Evaluations of the findings can be made from the comparison of the materials given below.

Table 7. Findings from the analysis of the materials.

Materials name	Findings
Mud/ Earth	Mud or earth as a building material is readily available in almost every region in Bangladesh and has zero embodied energy and average durability with high thermal comfort. Although this material needs more maintenance than other materials.
Unburnt brick	It is more convenient and durable than mud because of its procurement method. It is also a highly thermal comfortable material with zero embodied energy.
Bamboo	It is also an available material in Bangladesh. Although this material needs to be processed by local experts, it has good durability, high thermal comfort, and no embodied energy.
Wood	Wood is used in many different forms, such as timber sheets or construction posts. It is an available material without any embodied energy and has high durability and thermal comfort.
Tin	Tin is a pre-manufactured product. So, it has high embodied energy and also low thermal comfort. This material is widely used because of its high durability.
Nipa palm	This material is also a roofing element with zero embodied energy and high thermal comfort. But it has less durability compared to other materials as it needs to be replaced within 4 to 5 years.
Straw/thatch	It is mainly used as a roofing material. It is a very available material in rural areas as it can be collected from nearby cultivated land. Therefore, it has zero embodied energy but high thermal comfort. But straw/thatch has less durability and needs to be replaced once every 1-2 years.

6. Conclusion

From the analysis, it can be summarized that vernacular materials like mud, unburned brick, wood, bamboo, nipa palm, and straw/thatch have very low thermal conductivity values, meaning these materials can provide great thermal comfort and have minimal or no embodied energy. So, these materials have high potential as environmentally sustainable building materials.

Durability and maintenance of these materials seem to be the main drawbacks that lead the users towards the manufactured products recently. Therefore, more investigation and studies are required to identify ways to reinforce the materials and increase their durability for greater use. In the present study, the Life Cycle Carbon emission of the selected materials has not been examined. Since most of these vernacular materials are biobased, examining their embodied carbon and end-of-life emissions is necessary to determine their overall life cycle carbon emission.

Assessment of the selected vernacular materials in Bangladesh is represented as a range of databases for embodied energy, durability, and thermal comfort factors. Thus, the current study offers the most important environmental indicators of widely used vernacular materials, serving as a resource for future studies, reporting on EE for building materials, and assisting the relevant professionals in evaluating these materials for sustainable practice.

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