Renewable Building Materials in Vietnam

A study on sustainable construction material potential for the Vietnamese building sector

Legal information

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Contents

1 Executive Summary

This study aims to identify bio-based and renewable construction materials able to replace their conventional counterparts under consideration of geographic and socio-economic conditions in Vietnam. This holistic assessment aims to provide an understanding of the local context and respective market opportunities, thus allowing for relevant recommendations. Ultimately, the findings of this study should help inform relevant stakeholders about existing and potential alternative nationally-sourced material options and thereby assist in building self-reliance and resilience in the Vietnamese building sector within a holistically sustainable framework.

The first part of the study provides a summary overview of traditional to contemporary Vietnamese architecture and construction practices with close consideration of geographic influencers. A look into climate-adapted vernacular and modern architecture practices, trends and barriers in construction and the market perception of building with renewable construction materials help establish the framework to consolidate the best approach toward sourcing and implementing renewable construction material practices in Vietnam.

Vietnam's subtropical climate presents its construction sector with a humid and biologically-dense environment. This geographic typology also translates to an accelerated influence of weathering on buildings and means that Vietnam's building sector can benefit from highly resilient materials, hybrid material compositions, modular construction methods and country-appropriate design solutions. Not surprisingly, all of which were once widely considered in Vietnam's vernacular bio-climatic architecture practices. However, the advancement of competitive industrial processes and the increasing speed of globalisation have progressively stifled these practices.

Current building and construction trends in Vietnam show an increase in high-rise buildings following relatively unsuitable western design models and the predominant use of composite energy-intensive materials such as reinforced concrete, glass and steel. These materials arrive through high-emission production methods and lead to increased landfilling of construction waste for the country. The high-rise building trend is unlikely to change; however, Vietnam has a largely untapped potential for integrating sustainable materials into its modern architecture practices.

Using this framework, the second part of the study analyses the existing renewable raw material production, extraction, by-product generation and disposal in various Vietnamese industry sectors. Considerations include regional availability, seasonal production cycles, landscape/ecological contexts and the sensitivity of impacted ecosystems to stress over time. A matrix of load-bearing and non-load-bearing structural elements is established, and nine bio-based material applications and 3 conventional reference materials have been chosen from a wider range of materials. The result is a preliminary range of potential bio-based renewable materials readily available throughout Vietnam today to replace conventional materials.

However, to be considered sustainable building materials, engineering properties suitable for construction and sustainability need to be met first. Because of the varied local level of development of these materials as building products, comparable and internationally certified twins were selected as a reference, assessed against the respective technical properties and benchmarked against their conventional counterparts. This resulted in nine comprehensive fact sheets of suitable renewable material options with all physical, thermal, chemical, mechanical, functional, environmental and renewable properties for the building sector in

Vietnam. The study concludes with suggestions for implementing these materials using new and conventional hybrid compositions directed primarily at non-load-bearing, lightweight and solid construction and their estimated energetic performance.

The study has shown that Vietnam has a high potential for improving its building performance through sustainable building practices. To achieve this, existing country and bio-climatic design solutions need to be revisited and re-integrated, and the revealed potential of localised renewable material use addressed in practice.

In the next step, the results of this study should be evaluated and tried out in pilot projects in HCMC in cooperation with local developers. These pilot projects will be accompanied and evaluated by the German Energy Agency (dena) and local universities to integrate the know-how into study programmes. This small step will make it possible to implement a life cycle approach in architecture design and construction to increase the sustainability of Vietnam's building sector.

2 Building Sector Overview

This chapter provides an overview of the construction sector in Vietnam. It deals with climatic boundary conditions and climate-adapted building design. In addition, relevant stakeholders and trends, as well as barriers, are discussed with a special focus on renewable building materials.

2.1 Climate-suitable design

The climate in Vietnam is tropical in the south (e.g. Ho Chi Minh City (HCMC)) and subtropical in the northern part of the country (e.g. Hanoi). In Hanoi, a cooler and a warmer season can be observed with average monthly temperatures below 20 °C in December and January and above 30 °C in June and July (see Figure 1). The average monthly relative humidity is 80% in Hanoi all year round. As shown in Figure 2, HCMC has a monthly average temperature between 25 and 30 °C with a lower relative humidity from March to May and higher humidity from June to December. In the mountainous areas in the northwest (Son La), temperatures are similar to those in Hanoi, but the relative air humidity is lower (see Figure 3). In the Central Highlands (Da Lat), temperatures are low (around 20 °C all year round) with a high average monthly relative humidity of 80 to 90% (Figure 4). Under such conditions, the natural drying of material moisture is very limited.

Figure 1: Temperature and relative humidity in Hanoi, Vietnam (own representation)

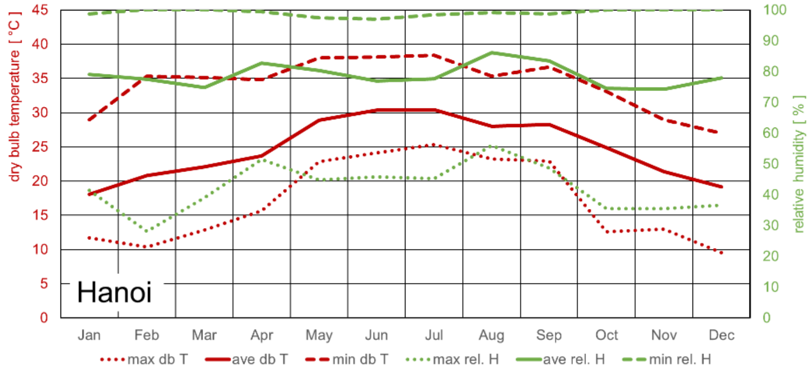


Figure 2: Temperature and relative humidity in Ho Chi Minh City (HCMC), Vietnam (own representation)

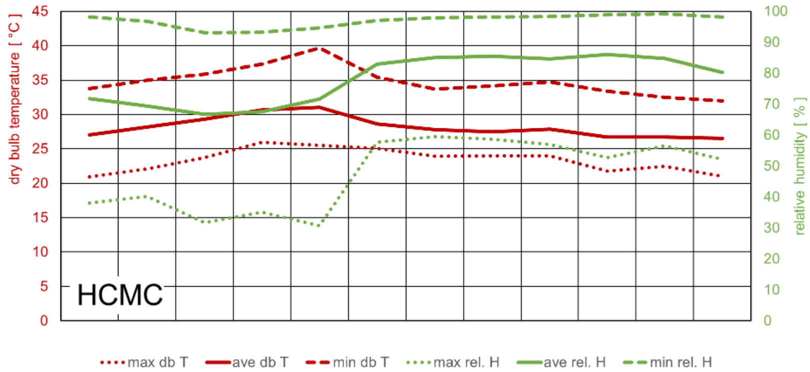


Figure 3: Temperature and relative humidity in Son La, Vietnam (own representation)

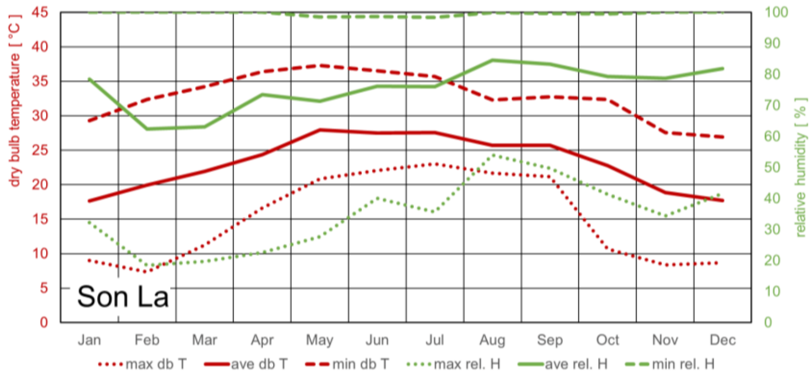
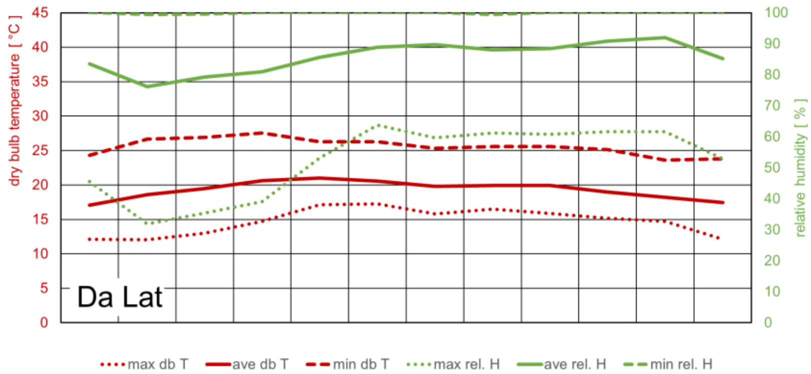


Figure 4: Temperature and relative humidity in Da Lat, Vietnam (own representation)



All locations do experience regular heavy rainfall and strong diffuse solar insolation. The high humidity and the heavy driving rain create demanding hygro-thermal conditions for the structures and materials. Wetting, mould growth and surface algae on surfaces are observed under these conditions and compromise the aesthetics and durability of the buildings. Material selection has been adapted over time to these conditions. Table 1 provides an overview of the various traditional building materials used in the construction of traditional architectural styles.

Table 1: Overview of different building materials related to components in different house styles [1]

Architectural style and year of construction	Foundation	Wall	Structure	Roof	Floor	Openings
Vernacular style, no data available	No foundation	Bamboo lattice or wooden panel	Bamboo and wooden frame	Thatch (rice straw, thatch, reeds, palm leaves)	Broken Neohouzeaua (a kind of very small bamboo)	Bamboo lattice
Traditional Japanese influence, 1860	Stone or burned clay brick	Fired clay bricks with plaster on both sides	Hard timber	Fired clay tile on timber frame	Fired clay brick on wooden floor	Wooden panel
Vernacular style, 1890	Laterite stone (a special	A mixture of clay and straw	Hard timber	Two layers: thatch roof	Rammed earth	Wooden panel

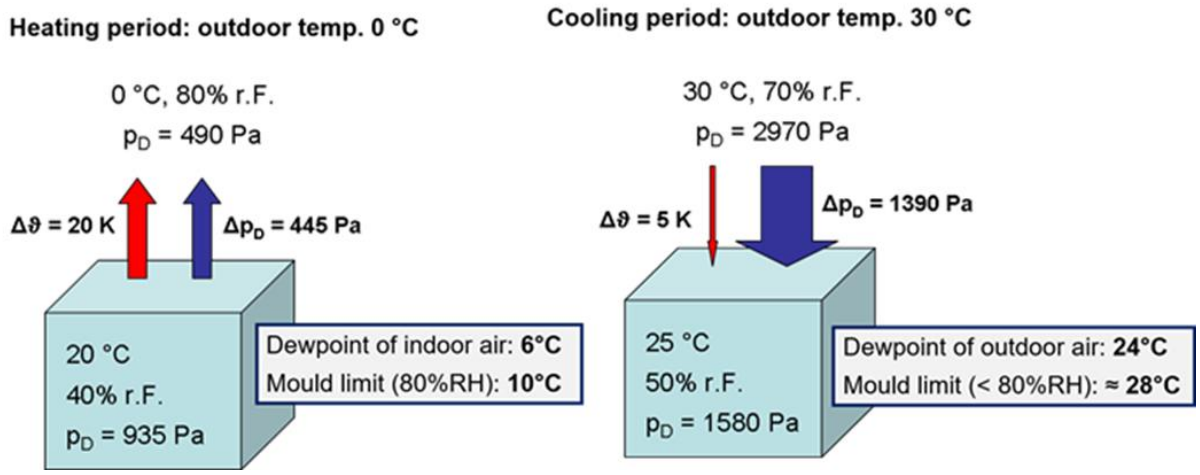
	porous stone naturally formed from laterite soil)	on bamboo lattice		(upper) and rammed earth (lower)		
Traditional style, circa 1903	No foundation	Wooden panel – vertical bars	Hard timber	Fired clay tile on timber frame	Fired clay brick	Wooden panel
Traditional urban style, 1920	Normal solid fired clay brick	Solid brick wall with plaster on both sides	Load-bearing wall and timber	Fired clay tile on timber frame	Cement tiled floor	Timber and glass
Colonial style, 1920	Stone	Fired clay brick with plaster on both sides	Load-bearing wall	Fired clay tile on timber frame	Reinforced concrete + cement tiles	Wooden panel

Traditionally, buildings constructed before air conditioning was available (e.g. colonial buildings) were built with screens, overhangs, wing walls and smaller shaded windows to protect the interior and the solid structures from the sun. In such cases, prevention from overheating is preferred over excessive access to daylight and view. However, in good traditional designs, a comfortable amount of indirect daylight is pleasant while the openings in the building envelope are shaded from direct sunlight, e.g. by wooden louvres. Another strategy was a well-insulated roof comprising large ventilated attics, thick thatch roofs, or thick porous roofing material that absorbs moisture at night and releases it during the daytime, cooling the roof. Also, the white or light colours of the façade or shade from trees helped regulate the high solar radiation. In badly designed buildings, the solar insolation contributes significantly to the cooling load. In some cases, especially in larger non-residential buildings, the opaque wall areas are also shaded by screens (e.g. ventilated permeable brick walls or concrete lattice structures). For the same effect, roof slabs containing ventilated air layers are often built as concrete tiles on piles of brick as spacers. These air layers in the wall and the roof are instrumental in decoupling the outside surface (which is exposed to the sun) from the interior structural wall, preventing the heat from being conducted to the inside. Today, similar effects can be achieved with low-conducting wall materials in solid walls or with insulation layers of moderate thickness on structural walls. However, the fitting of insulation layers is not common practice today.

As in Germany, insulation in Vietnam can be installed on the inside or outside of a building or as core insulation. For the cool mountain regions with a vapour diffusion flow direction from the inside to the outside, similar rules apply as in Germany; thermal insulation on the outside has a lower risk of condensation. However, the insulation must be protected against rain. For interior insulation in these regions, the interior surface should be designed to be as diffusion-tight as possible. In warm and humid regions, the diffusion flow direction is usually from the outside to the inside. This means that the insulation should be installed on the inside. However, it is more likely to be placed on the outside here, which means that the plaster should protect the insulation layer against rain and should also be made relatively vapour-tight to prevent moisture from entering the interior.

The driving force for the water vapour diffusion flows is the water vapour partial pressure difference. If one compares the water vapour partial pressure difference in winter in Germany or Vietnam's mountain regions (Figure 5 on the left) with the water vapour partial pressure difference in a tropical region in Vietnam (Figure 5 on the right), it is apparent that the pressure difference between outside and inside in the tropical region is approximately 3 times higher than in the cold mountain region in Vietnam or Germany in the winter, despite small temperature differences. This means that special emphasis must be placed on proper construction, especially for air-conditioned buildings.

Figure 5: Water vapour partial pressure difference in winter in Germany or Vietnam's mountainous regions (left image) and a tropical region in Vietnam (right image) (Fraunhofer Insititut für Bauphysik n.d.)



2.2 Vernacular and modern construction techniques/examples

The typical construction technique of traditional buildings is as follows:

- The frame structure is built of wood
- The walls are made of wood, an earth-based material or other local materials
- The roof is made of thatch leaves (cottage)

Figure 6 shows an example of a traditional vernacular house with wood frame structure filled with , clay straw mixture and roof structure of bamboo / wood with partly clay-straw plus cladding of reed / banana or palm leaves .

Figure 6: Examples of vernacular houses (©dena / Stefan Schirmer)

Figure 7 shows an example of a traditional house where the structures and walls are made of wood, and the roof is covered with tiles. These types of houses were often inhabited by people with higher income. This type of traditional construction is still common in rural areas today.

Figure 7: Traditional house made of wood structure (©dena / Moritz Limbacher)

The life span of wooden buildings in Vietnam is about 100–150 years, depending on the types of wood, maintenance, climatic conditions, etc. Other traditional construction methods include bamboo, stone, and earth structures. However, these types of construction were less popular than the wooden structures and filled walls.

Since French colonisation (1858–1954) and the American presence in southern Vietnam (1954–1975), there have been many changes in Vietnamese architecture. The large buildings were built following European architecture (Figure 8). Fired clay bricks were used for many residential buildings, especially in the cities. The vernacular building types mentioned above are now used only in rural and mountainous areas. To this day, fired clay bricks are the most commonly used materials for non-load-bearing walls in Vietnam.

Figure 8: Central Post Office in Ho Chi Minh City erected during the colonial period in the late 1800s (©dena / Stefan Schirmer)

Figure 9: The Hanoi Opera House built by the French colonial administration between 1901 and 1911 (©dena / Stefan Schirmer)

This period saw the construction of reinforced concrete structures, which are still widely used today. In Vietnam, there are numerous quarries with raw materials for cement production, so cement production in Vietnam is well developed. For this reason, the price of cement is acceptable for many constructions. The most common type of buildings constructed in Vietnam today is reinforced concrete frames filled with fired clay bricks and coated with cement plaster (Figure 10).

Figure 10: Modern houses in Binh Duong (left), Hanoi (middle and right) (@dena / Stefan Schirmer & Moritz Limbacher)

During the Vietnam War (1954–1975), the main material used for roofs was sheet metal due to its low cost. After the war, tiles made of fired clay were preferred because of their better properties, such as thermal and sound insulation. However, clay tiles can break due to temperature fluctuations. As a result, their use decreased as flat roofs made of reinforced concrete replaced tiles. The flat roof made of reinforced concrete has several disadvantages, such as water permeability if it is not properly constructed. Therefore, roofs made of reinforced concrete may now also be sloped and covered on the outside with fired clay tiles to maintain the aesthetic aspect.

Due to the high population density, the construction of high-rise residential buildings has developed rapidly in cities over the last twenty years. These high-rise buildings usually have 20–40 floors and are often home to commercial activities (shopping centres, supermarkets, banks, gyms, cinemas, swimming pools, etc.). Each high-rise project resembles a "small town". The main structure of these high-rise buildings is made of reinforced concrete (frame and some shear walls), and the infill is made of bricks. Glass, often arranged in small grids, is used for window areas. The Vietnamese government is open to implementing unfired bricks in its building sector; however, the presently predominant building construction type remains reliant on fired clay bricks as material.

Figure 11: Modern high-rise residential buildings (©Dirk Schwede/ private collection)

An analysis of modern buildings with an average year of construction after the year 2000 shows the current use of building materials in different constructions [2]:

- **Frame:** Two main construction types: reinforced concrete (62%) and load-bearing masonry (21%).
- **Walls:** All the external walls are built using clay bricks, with half of the houses built using one layer (100–150 mm) and the other half using two layers (200–250 mm). 90% of the walls are built without any insulation layer.
- **Roof:** Two main types of roof constructions: reinforced concrete or a frame (steel or wood) with tiling. Concrete is still the most popular material for roofs, accounting for 75% of houses. In terms of insulation, 70% of the roofs are constructed with an insulation layer to prevent direct solar gain from the top. The occupants (or architects) appreciated the benefits of roof insulation.
- **Windows:** 82% of the transparent windows are single glazed, while 18% are double glazed. The most popular window frames are wood and aluminium (88%), which can be explained by their economical price. Almost a quarter of the buildings use wooden shutters to keep out direct sunlight and protect it from overheating.

2.3 Residential building types

Most of the residential building stock in Vietnam in 2019 consisted of single-family detached houses (97.8%). Only 2.2% of dwellings were located in larger apartment buildings, as shown in Table 2. Nearly the entire rural population lived in single-family detached houses (99.7%), while 5.8% of the urban population lived in apartment buildings.

Table 2: Percentage of households per type of dwelling, 2019 [3]

	The proportion by type of house	
	Type of dwelling/flat	
	Apartment building	**Single-family detached house**
Entire country	2.2%	97.8%

	The proportion by type of house	
	Type of dwelling/flat	
	Apartment building	Single-family detached house
Urban	5.8%	94.2%
Rural	0.3%	99.7%

Table 3: Vietnam – Common building types, Ownership [3]

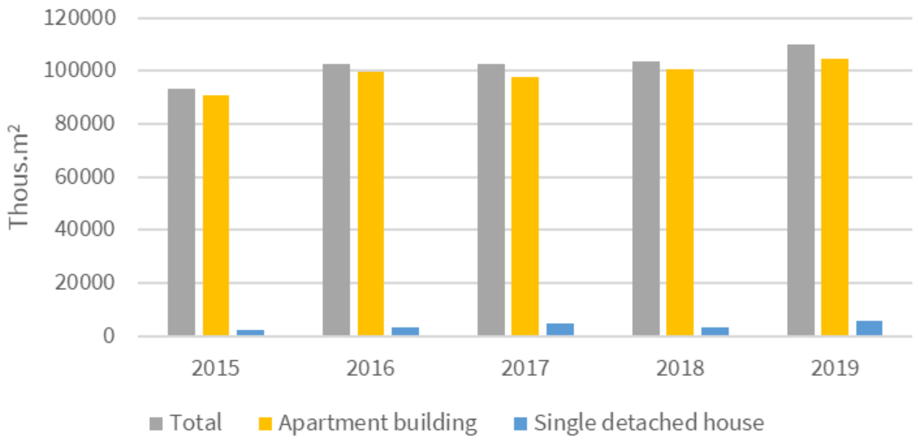
	Private dwelling of household	Rented dwelling	Cooperative building apartment
Entire country	88,1%	11,4%	0,3%
Urban	77,9%	21,1%	0,7%
Rural	93,6%	6,1%	0,2%

However, the construction statistics of newly constructed residential floor area in Vietnam suggest that the trend is moving towards apartment buildings. As the graph in s.

depicts, nearly all newly constructed residential floor area in 2015 to 2019 were located in apartment buildings. However, these numbers could be misleading since small buildings in rural and urban settings might be constructed in less formal projects by small construction teams or self-built, so they may not appear in the statistics.

The differentiation between large apartment buildings, small residential buildings and single-family detached houses is also relevant for using new materials and building products. Since the size of the project affects how decisions on which materials to use are made and to which extent materials are controlled by legislation. For instance, the Vietnamese energy building code only applies to buildings measuring more than 2,500 m^2, while smaller buildings are currently not covered. Further, the economic framework conditions of projects influence the construction techniques and scales of application. Owner-clients might be more open to using unconventional materials and manual craftsmanship. On the other hand, larger commercial developers might require proven materials that professional construction teams can use in large quantities.

Figure 12: Floor area of residential buildings constructed per year by type of dwelling (General Statistics Office 2020)



Traditionally, most households in Vietnam own their dwelling (88.1%), while only 11.4% live in rented dwellings. These numbers are more pronounced in rural settings with 93.6% ownership and less pronounced in urban settings (77.9% ownership), as shown in Table 3.

Many modern dwellings are constructed for sale with different stakeholders in charge of the design, construction and ownership. Therefore, quality and efficiency are not prioritised when decisions on construction techniques and materials are made.

At the same time, the real estate market is characterised by high demand and few offers. In such a context, buyers are in a weak position to demand a high-quality selection of materials when buying an apartment. Therefore, government instruments must support the introduction of resource-efficient materials. Demonstration projects must target decision-makers and the development of standards. Demonstration projects can also be useful for informing people who are building their own small houses.

Table 4: Proportion of households with dwellings by type of ownership, 2019 [3]

	Owned dwelling	Rented dwelling	Housing cooperative	Other
Entire country	88.1%	11.4%	0.3%	0.2%
Urban	77.9%	21.1%	0.7%	0.3%
Rural	93.6%	6.1%	0.2%	0.1%

Table 5 shows that in all areas in Vietnam except the Mekong River Delta in the south, all social housing projects are apartment buildings. In the Mekong River Delta, social housing projects are built as single-family detached houses. The largest number of social housing projects is constructed in the Red River Delta area around Hanoi.

Table 5: Number of houses, total areas of completed social houses in 2019 by types of house and by region [4]

	Number of dwellings (flat/house)			Total dwelling surface area (m²)		
	Total	Apartment building	Single-detached house	Total	Apartment building	Single-detached house
Entire country	14,030	12,621	1,409	701,500	631,050	70,450

	Number of dwellings (flat/house)			Total dwelling surface area (m²)		
	Total	**Apartment building**	**Single-detached house**	**Total**	**Apartment building**	**Single-detached house**
Red River Delta	10,025	10,025		501,250	501,250	
Northwest and Northeast	556	556		27,800	27,800	
North Central and South Central Coast	184	184		9,200	9,200	
Southeast	1,856	1,856		92,800	92,800	
Mekong River Delta	1,409		1,409	70,450		70,450

2.4 Main players and elements of construction practice

Architects and engineers play an important role in the construction of buildings. Their relevance depends on the particular project. The role of engineers is especially important in large projects because more technical problems need to be solved. Smaller construction teams often work based on simple and standard designs with little control in smaller projects, such as detached house constructions.

The Vietnamese government is determined to apply sustainable solutions in construction. Therefore, there are also some differences between buildings in the public and private sectors. For instance, The Vietnamese national standard for energy-efficient buildings has been introduced and updated in recent years. It applies to buildings upwards of 2,500 m^2 as a prescriptive code with several specific requirements for the various building components regarding the building's energy performance. The energy standard requirements target energy efficiency, although technical standards have not yet addressed the embedded energy and resource demand. However, there are programmes and taxes to steer the market toward using alternative wall building materials, such as unfired bricks, to prevent the extraction of clay from agricultural land and pollution from inefficient kilns.

However, when it comes to developing energy-efficient buildings, the private sector is more dynamic because when a project is certified, it's better perceived by the public, as has been shown in a survey by the University of Hamburg in the "Climate Adapted Material Research for the Socio-Economic Context in Vietnam (CAMaRSEC)" project for the example of an "Excellence In Design For Greater Efficiencies (EDGE)" certified building. Apartments in such buildings can be sold at higher prices.

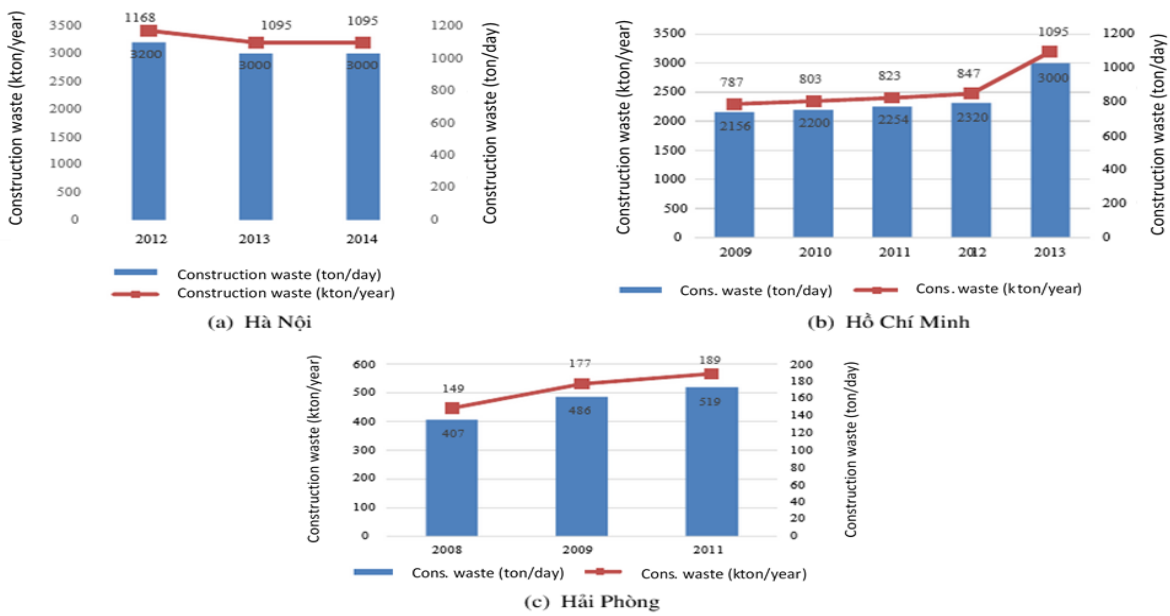
International green building standards also apply in Vietnam. The most common standard for green buildings in Vietnam is the American "Leadership in Energy and Environmental Design (LEED)" certificate.

The Vietnamese LOTUS System from the Vietnam Green Building Council (VGBC) has been in use since 2010 and is well-adapted to local conditions. This system was developed by a non-profit organisation and applied in several projects. Another relevant scheme is the EDGE building assessment scheme which IFC introduced with some supporting projects. Local commercial developers have embraced EDGE because it has an international reputation and its freely accessible web-based assessment forms make it fairly simple to apply.

2.5 Disposal and recycling of construction waste

Figure 14 shows the synthesis of inert construction waste[1] in three major cities in Vietnam: Ha Noi, Ho Chi Minh City, and Hai Phong. The construction waste in Ha Noi and Ho Chi Minh City is more than 3000 t/day, putting pressure on these cities' landfills. Generally, steel is recycled, but other construction waste materials are not recovered. Until now, most construction waste in Vietnam has been landfilled, resulting in several illegal disposals of construction waste. A recent shortage of available land in cities and increased demolition to construct new buildings have brought recycling to the forefront. Various waste management companies have been established lately to meet increasing demand. It is expected that these recycling plants will enable the valorisation of construction waste soon and that the importance of recycling building materials will increase.

Figure 13: Quantity of construction waste in several cities in Vietnam (Own representation with data from [5–7])



[1] Inert waste is waste that is unreactive (biologically and chemically). Once disposed of, it either takes an extremely long time to decompose or it does not decompose at all. Inert construction waste includes concrete, asbestos cement, bricks, glass, demolished walls, road debris, etc.

Figure 14: Construction site in Hue (©dena / Moritz Limbacher)

2.6 Trends and barriers

Due to the energy-intensive and high-emission production of fired bricks, the government has recognised the need to use alternative building materials. Chapter 2.6.1 is dedicated to unfired bricks, which are currently being promoted and have been used increasingly in recent years. The following chapter, Chapter 2.6.2, deals with bio-based materials as a sustainable alternative, which have hardly been used so far but offer great potential.

2.6.1 Current alternatives to fired clay bricks

Under the government's strategy to use environmentally friendly materials in construction, unfired bricks are usually proposed to replace traditional fired clay bricks in the building sector. The production of fired bricks generates significant CO_2 emissions, consumes energy and uses clayey soil, which degrades agricultural soils. Unfired bricks currently available in Vietnam are: Cement pressed blocks and autoclaved aerated concrete (AAC) blocks. There are also prefabricated walls (cement-based or gypsum), but these are less popular.

However, the current unfired bricks in Vietnam have significant disadvantages compared to traditional fired bricks. Firstly, the very low price of fired clay bricks is a challenge. However, the price of unfired bricks has gone down in recent years, making them more competitive. In addition, construction workers have more experience using fired clay bricks, so their use tends to be preferred. Unfired bricks can break more easily than fired clay bricks, which increases the amount of waste and the cost of unfired bricks. Finally, the most important reason is a technical problem: many cracks in walls are caused by unfired bricks, which is the main reason why the use of unfired bricks in construction in Vietnam has slowed over the last years. Several studies have been conducted to find solutions to this technical problem.

Another potential for the building materials industry in Vietnam is the upgrading of fly ash and bottom ash produced by coal-fired power plants. Fly ash and boiler ash are by-products of combustion in coal-fired power plants. If fly ash and bottom ash are properly separated, the fly ash can be used as an additive in the cement industry and concrete production. Unfortunately, the quality of the fly ash produced by several coal-fired power plants in Vietnam is not satisfactory. This fly ash and bottom ash become pure waste and cause serious environmental problems (Figure 17). Therefore, one of the possibilities in the field of building materials is to use fly ash and bottom ash to produce unfired bricks.

While the government promotes unfired materials to prevent the extraction of clay from agricultural land and pollution from inefficient kilns, these materials are commonly cement-based. Such cement-based products have an environmental impact on the production and sourcing of raw materials and also pose recycling problems at the end of their life. They require resources at a level of quality that is not readily available in Vietnam or that need to be sourced with high environmental impacts, such as the extraction of river sand and natural rock crushing. Therefore, research and development of more efficient and environmentally friendly materials are required. The potential of alternative and natural materials is explored in this study.

2.6.2 Renewable construction materials

Although local and renewable materials (clay, wood, stone) were used in the past, in recent decades, their use in construction was frowned upon, as they were attributed especially to the poor population. After the end of the Vietnam War in 1975, houses with roofs made of baked tiles were considered economic progress. During this period, the main building material was fired clay materials (tiles and bricks). Reinforced concrete structures with flat roofs were considered the next stage of development of residential buildings.

In the context of sustainable development, several changes in public opinion have been observed over the last decade. People are more receptive to sustainable and alternative solutions, especially bio-based solutions. More and more projects use bio-based materials such as clay, straw bales, wood and bamboo. However, most of these projects are commercial such as restaurants, cafes, and resorts. Before the Covid-19 pandemic, the tourism sector in Vietnam was growing rapidly, so the development of these "green projects" was also rapid.

Figure 18 – Figure 22 show examples of modern buildings that used clay and various other materials. Rammed earth walls can be built with or without plaster. In the case of plaster, the plaster should be lime or clay based rather than cement based due to vapour permeability.

Figure 15: A modern coffee shop in Hanoi using bamboo (©dena / Stefan Schirmer)

Although the trend to use green materials is gaining traction in Vietnam, their use in housing projects is still limited due to several factors. Firstly, the durability of bio-based materials is limited compared to conventional materials such as concrete, especially in Vietnam's climate, where typhoons and floods occur every year. For plant-based materials (wood, bamboo, straw bales), fire resistance is also a limitation in the public's minds. Moreover, regulations for these non-conventional materials are not well developed, so companies are reluctant to use them.

3 Renewable Building Materials

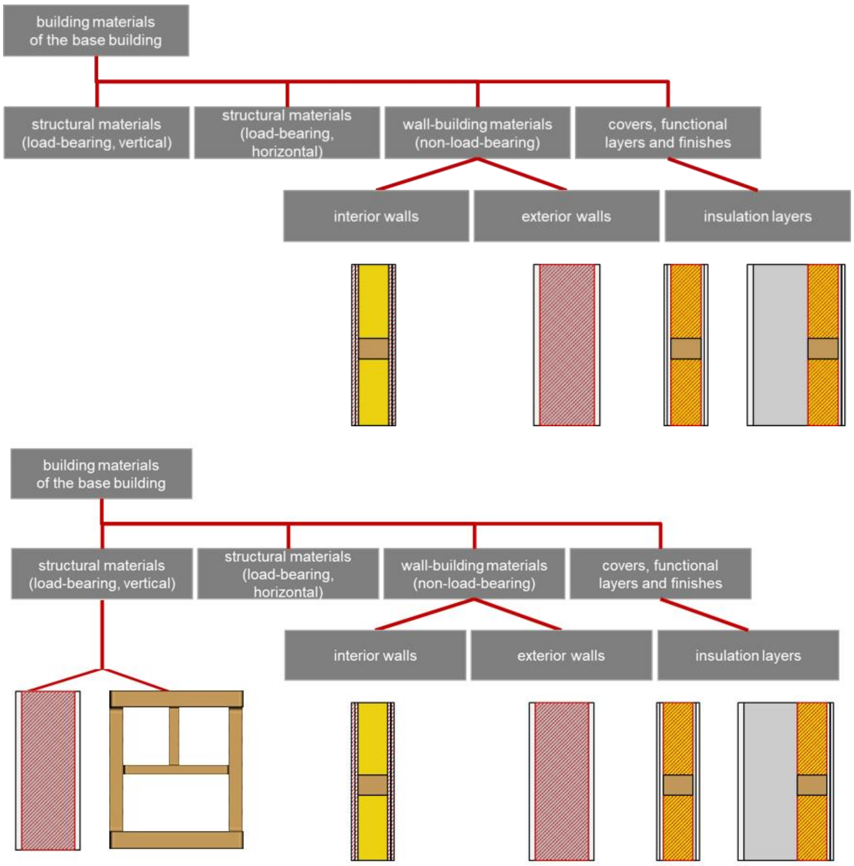
3.1 Structural elements and building materials

For this study, the base building is regarded as a composition of load-bearing and non-load-bearing structural elements with a focus on the latter. Load-bearing elements can be vertical columns or walls and, according to local standards, also unfired clay bricks or rammed earth constructions. Non-load-bearing elements are walls built to separate interior spaces or to separate the inside from the outside, supported by framework structures made of reinforced concrete, steel or, more sustainably, of wood or bamboo plywood. Further functional layers such as insulation layers, plaster, and barriers are classified separately.

In response to the prevailing construction method in Vietnam that uses concrete frame structures, this study will focus on non-load-bearing interior and exterior walls as well as insulation layers as functional layers in internal or external wall structures. The aim of this focus is to avoid high structural performance requirements of renewable materials and to replace large volumes of conventional materials at the same time.

Figure 23 depicts the selection, and the material components addressed are marked red. For all the cases, the structure is analysed with a conventional material as a reference.

Figure 16: Structure of base building elements and use of building materials in the structure, the material applications analysed are marked in red (own representation)



3.2 Material selection

The material selection is made on two levels:

1. **Component application:**

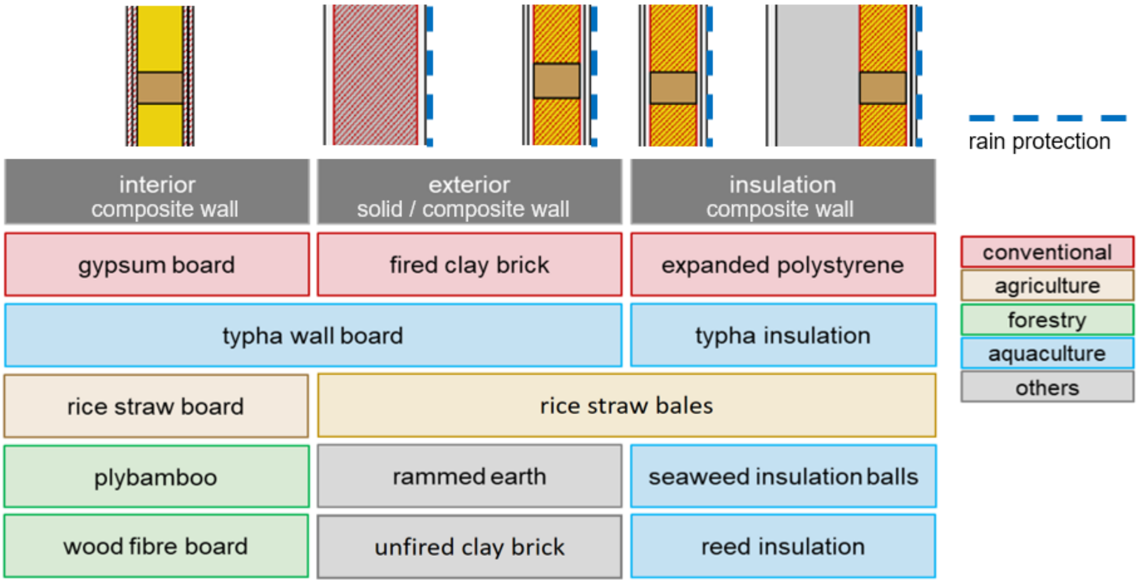
According to the structural elements presented in Chapter 2.1, materials are selected for three different applications. Thus, materials can be compared within a single application, but different applications can also be combined. The consideration of different applications enables mutual complementarity so that exterior and interior walls can be taken into account, for instance. Thus, several potentials can be addressed in the design, and at the same time, different variants can be investigated in a single application.

2. **Material industry:**

The materials investigated are composed of various raw material sources. The aim is to include as many renewable raw material options as possible. Depending on the region, certain industries may be more relevant and are highly dependent on local availability. At least one product from each material industry is included to cover the entire range. Conventional materials are included to compare with the partly new and unknown renewable products.

Material selection is based on the four defined material groups: **agriculture, forestry, aquaculture and other.** Agricultural land, including rice, coconut and sugar cane, accounts for 39.5% of the total area [8]. Rice is the main staple food in Vietnam and is available in both the north and the south of the country. The three harvest cycles spread the harvest over the year. Unused rice straw is an agricultural waste product and is mostly burnt, so its use as a building material is of particular interest. About 46.5% [8] of the country is forested, including wood, bamboo and areca. At around 80% [9], wood accounts for the largest proportion, which means that it can be a considerable resource. Wood products are already in use and have proven their worth as a traditional building material. Bamboo is also used in vernacular buildings and currently accounts for about 10% [9] of the forested area, but it should be further promoted [10]. Due to the country's long coastline and large wetlands, especially in the south, aquaculture materials are also being investigated. Typha leaves have a special fibre-reinforced supporting tissue filled with open-cell spongy tissue. This spongy tissue provides a good insulating effect in building materials, and the supporting tissue provides strength. In contrast, the traditionally used reed does not have a spongy tissue, but it is shaped like a tube and the air enclosed within it creates an insulating effect. Seagrass can also be an appealing raw material for building materials. The Hai Phong Institute of Oceanography has identified 14 different species of seagrass in the coastal areas of Vietnam, which can be divided into 4 plant families and 9 genera [11]. The majority of harvested seagrass is used as feed for livestock and as a fertiliser. The natural salt content means that materials made from seagrass do not require fire protection agents and are more resistant to decay, fungi or pests. Another material that could replace fired clay bricks is unfired products made of clay. In this study, the focus is on rammed earth, which has similar properties to adobe or compressed earth blocks. Figure 24 shows the respective applications and examined materials.

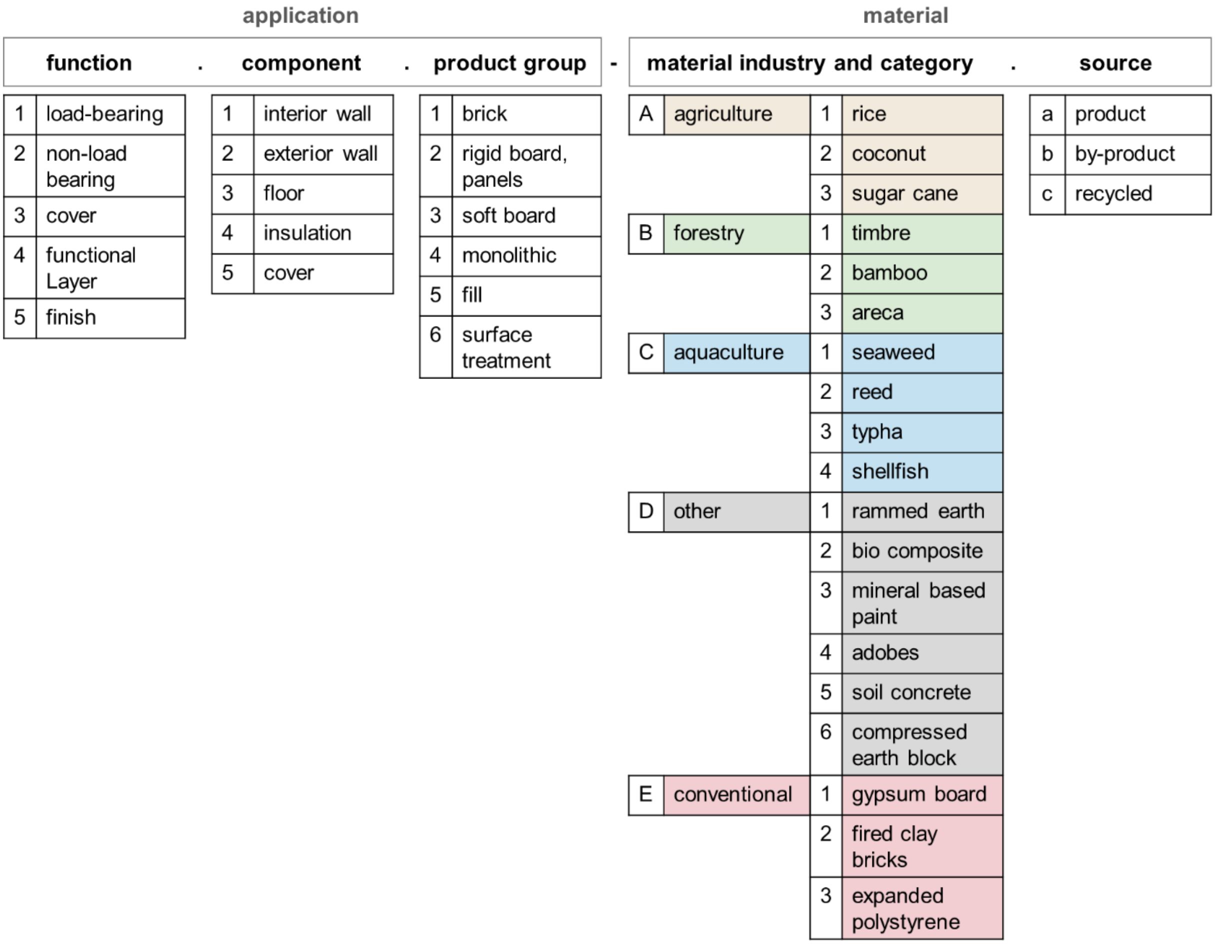
Figure 17: Selection of the studied materials (own representation)



3.3 Material and product codes

The studies on the materials are compiled in a material database. To expand this database variably and filter it according to use, a generally applicable code system has been introduced. An overview is shown in Figure 18. The upper group is sorted according to use and material group, with the use further divided into three subcategories, each of which is assigned a number starting with the function – for example, load-bearing or non-load-bearing. The second subcategory is the construction component. Here, for example, a differentiation is made between the outer and inner walls. The third subcategory is the product group, such as brick or slab. Separated by a hyphen, the material classification follows. First, the material industry and category are assigned. The industry is assigned a letter, while the material category is assigned a number. Finally, the source of the raw material is specified, distinguishing between product, by-product, or recycled.

Figure 18: Material coding system (own representation)



Following are sample codes of the renewable materials studied:

Wood fibreboard	2.1.2 - B1.a
Bamboo plywood	2.1.2 - B2.a
Rice straw particle board	2.1.2 - A1.b
Typha wallboard (interior)	2.1.2 - C3.b
Typha wallboard (exterior)	2.2.2 - C3.b
Rammed earth	2.2.4 - D1.a
Reed insulation	4.4.2 - C2.a
Seaweed insulation	4.4.3 - C1.b
Rice straw bales	2.2.3 - A1.b
Typha insulation board	4.4.2 - C3.b

3.4 Data sheets

The materials are analysed holistically from different angles. The first part of the study is devoted to general data, including the material and product code. More detailed material properties follow in the second part, which is divided into physical, mechanical, chemical, thermal, and renewable properties and comprises qualitative and quantitative values. Qualitative assessments are made in the third section. For each category (functional or ecological), a high/medium/low ranking is assigned and indicated via the corresponding coloured classification, whether it is a positive or negative ranking. The last section is the study of the occurrence and regional distribution of the raw materials. Table 6 shows the described tables filled in for each material/product; see Annexes 1 to 3.

The data sheets are completed based on a comprehensive literature search and own measurements and technical approvals. The literature search prioritises Vietnamese and Asian sources from product manufacturers and scientific publications. Since data on the respective materials are already available, especially in Europe in the form of Environmental Product Declarations (EPD), this relevant source is also used. The data sheets aim to provide an overview of different materials and products. Both product-specific and generic data are used. Deviations in the listed values for other products of the material may result from, for example, varying raw materials, ingredients, compositions or manufacturing processes and cannot be excluded. The data must therefore be understood as orientation values that should be checked for a specific product before use.

Table 6: Analysed material properties

<table>
<tr><th colspan="4">Industry (e.g. agriculture) and raw material group (e.g. rice)</th></tr>
<tr><td>Code</td><td>Material/product name</td><td>Building use category</td><td rowspan="3">Photo of the building material</td></tr>
<tr><td colspan="3">Short description</td></tr>
<tr><td colspan="3">Technical readiness level</td></tr>
</table>

Material/product name – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	
Bulk density [kg/m³]	Quantitative value	
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	
Durability [a]	Assuming that it has been installed in a technically correct manner	
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material.**	
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component.**	
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	
Risk of mould growth	Specify qualitatively in a rough classification	

Moisture sensitivity	Specify qualitatively in a rough classification	
Water absorption [%]	Boundary condition: free saturation	
Water absorption coefficient (w-value) [kg/m²h⁰·⁵]		
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	
Tensile strength [N/mm²]	Quantitative value	
Bending strength [N/mm²]	Quantitative value	
Settlement [%]		
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m² and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	

Renewable properties	Description	Values
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	
Grey/embodied energy	Qualitative description	
Embodied carbon	Qualitative description	

Material/product name – Performance values
Green = positive (compared to conventional material); beneficial effect on resource efficiency

Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	high/medium/low
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	high/medium/low
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	high/medium/low
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	high/medium/low
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	high/medium/low
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	high/medium/low
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	high/medium/low

Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	high/medium/low
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider: Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	high/medium/low
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	high/medium/low

Material/product name – Building material availability							
	Region	**Seasonality**				**Supplies (manufacturers/resellers/ storage)**	**Disposal (recycling/ end of life)**
		1Q	**2Q**	**3Q**	**4Q**		

Northeast						
Northwest						
Red River Delta						
North Central Coast						
South Central Coast						
Central Highlands						
Southeast						
Mekong River Delta						

3.5 Results

In the following, the renewable materials of a category are compared with the respective conventional material. The focus is on the second part of the table. Detailed results with the complete table of a specific material are shown in Annexes 1–3. An overview of the most important properties for the implementation of renewable materials in the construction of walls and roof with the aim of replacing conventional materials is shown in the following table:

Table 7: Comparative properties of materials

	Conventional			**Renewable**								
Material/ product	Gypsum board	Fired clay bricks	Expanded polystyrene (EPS)	Typha wallboard	Typha insulation	Rice straw particle board	Rice straw bales	Reed insulation	Seaweed insulation	Bamboo plywood	Wood fibreboard	Rammed earth
Conductivity Λ [W/Mk]	0.21–0.32	0.075–0.96	**0.031–0.036**	0.06	**0.04**	0.076–0.115	**0.04**	0.06	0.05	0.113–0.134	0.040–0.055	0.6–1.1
Specific thermal capacity Cp [J/Kgk]	**10090**	836	1500	1500	1500	N/A	**2970–3850**	1200	**2000**	**2020**	**1700–2100**	520–1000
Fire resistance/ protection (Class)	A2	A1 / depending on thickness	B1	**B / F60, 60 mm / F120, 120 mm**	B	**B-s1 (high silica content)**	B2	B2	B2	B / C	B2	A / depending on thickness
Risk of mould growth	High	None	None	Low (tannins with high Ph)	Low (tannins with high Ph)	Low / resistant	High	Low (high silica content)	Low (high salt content)	Low (after cooking)	Low	Medium
Diffusion resistance (µ-value)	All vapour open											

3.5.1 Results of materials used to build interior walls

Renewable building materials for interior walls (typha board, rice straw particle board, bamboo plywood, and wood fibreboard) are compared with conventional gypsum board. Table 8 shows an overview of the comparison. All of the materials considered are comparably highly durable, except rice strawboard, as no data is available for this material. Gypsum board is a non-flammable material and thus has a higher fire resistance than the renewable materials, which are flammable materials. In general, the materials should be kept away from water, as there is a certain potential for fungal attack. In the case of typha boards, the natural protection provided by the tannin contained in the substance and its high pH value should be emphasised. Panels made of typha, rice straw and wood fibre also have lower thermal conductivity and thus have a heat-insulating effect, which means that, depending on the respective use, less insulation material may be required, for instance. Gypsum boards can theoretically be recycled or reused. Due to the lack of pure and non-destructive deconstruction, the recycling rate for the boards is only 5% [12]. The renewable variants can be partially composted or otherwise recycled. Around half of the environmental impact of bamboo plywood results from the electricity consumed during manufacturing processes. Depending on the country-specific electricity mix, the share and the impacts caused vary. Gypsum board has the highest share of grey energy. Typha boards, rice straw particle board and wood fibreboard consume the least amount of energy during production. Renewable materials can also have a low grey carbon content due to their carbon sequestration during plant growth. A comparison of the availability of renewable raw materials shows that they are widely distributed across the country. Only typha is found near the coast due to aquaculture. All the plants are available year-round, although preferred harvesting periods must be considered for certain plants, such as dry seasons. The detailed tables for interior walls are listed in Annex 1.

Table 8: Comparison of materials used to build interior walls

Material/product comparison – Performance values					
Material/ product	**Gypsum board**	**Typha wallboard**	**Rice straw particle board**	**Bamboo plywood**	**Wood fibreboard**
Physical properties					
Thickness [mm]	0.125–1.2 [13–15]	20–120	4–20 [16]	Up to 40 mm (5-layer bamboo plywood panel) [17]	0.4–2.5[2] [18] 0.5–1.6[3][19]
Bulk density [kg/m³]	640–1450 [13–15] 900 [20]	285 (DIN EN 1602)	428 (TS EN 323 (1999)) particle board made of rice straw [21] 650 for strawboard made of rice or grain [22]	720–868 [23] 920 [24] 880 [25]	100–400[2] 650–1000[3,4][26]
Porosity n [Vol.-%]	50–60 (after hardening) [27]	75	No data available	No data available	No data available
Durability [a]	≥ 50 [13–15], [28]	>50	No data available	Very durable (CEN/TS 15083-1) [29]	40[5] [28]
Fire protection (class)	A2 Non flammable (DIN 4102-1); A2-s1,d0 (EN 13501-1) [20]	Euroclass B (ISO 5660-1:2015)	Rice straw significantly contributes to the fire resistance of particle boards due to its high silica content [21]	Fire protection class B (EN13501-1) [29]	B2 (DIN 4102-1) D-d0 (DIN 13501-1) [30]
Fire resistance (class)	A2 [13–15]	F60 with 60 mm-Board F120 with 120 mm-Board (DIN 4102-2)	B-s1, d0 (strawboard made of rice or grain) [22]	Fire resistance class C (ASTM E 84) [31]	No data available

[2] Wood fibre insulation board
[3] Medium hardwood fibreboard
[4] Hard fibreboard
[5] Wood fibre insulation board

Weathering resistance	Protection from direct weathering is necessary [32]	Weather protection required (e.g. plaster)	Protection from direct weather protection is necessary [22]	Predominant installation in structures where they are protected from precipitation	Resistant to rotting, vermin, fungal attacks [33]
Risk of mould growth	To prevent mould growth, avoid contact with water [34]	Low, due to the plant's defence substances (tannins) and high pH value	Mould resistant (strawboard made of rice or grain) [22]	Treated before production to become resistant to fungal attack	No data available
Moisture sensitivity	Moisture resistant, but must be protected from permanent moisture [13–15]	Low, but prolonged contact with liquid water must be avoided	Depending on the product, waterproof (strawboard made of rice or grain) [22]	Water-resistant regarding firmness and services. Contact with soil and penetration must be avoided [23]	Without hydrophobisation, not resistant to moisture (in case of prolonged soaking, swelling and risk of rotting) [33]
Water absorption [%]	≤ 5% [35] < 10% [36]	59 (DIN EN 12087)	45–130 (after 24 hours) (binderless rice straw particle board) [37] 90–150 (after 24 hours) [38]	No data available	30% (after 2 hours for wood fibreboard insulation and 24 hours for hard fibreboard) [26]
Water absorption coefficient (w-value) [$kg/m^2h^{0.5}$]	No data available	1.1 (DIN EN ISO 15148)	No data available	38.71 E^{04}kg/(m^2·s$^{0.5}$) (ISO 15148:2002(E)) [39]	No data available
Diffusion resistance (µ-value)	13 [13–15]	Dry Cup: 28 Wet Cup: 20 (DIN EN ISO 12572)	5.2 (strawboard made of rice or grain) [22]	No data available	4–7[6] 30–50[7] 45–100[8] [26]
Sorption isotherm – u_{80} [Vol.-%]	No data available	1.2 (DIN EN ISO 12571)	No data available	No data available	No data available
Mechanical properties					
Compressive strength [N/mm²]	2.4–2.75 [40]	0.5	No data available	20–52 (parallel to fibres) [23]	0.05[2] [26]
Tensile strength [N/mm²]	No data available	No data available	Transverse tensile strength: 0.32 (strawboard made of rice or grain) [22]	26–105 (parallel to fibres) [23]	12[3] 30[4] [26]

[6] Wood fibre insulation board
[7] Medium hardwood fibreboard
[8] Hard fibreboard

Bending strength [N/mm^2]	≥5.8 [13–15]	1.0 (DIN EN 12089)	1.48 [38]	51–94 [23]	0.2[2] 12[B] 35–40[C] [26]
Settlement [%]	No data available	No data available	No data available	No data available	No data available
Chemical properties					
Chemical resistance	No data available	Acid	No data available	No data available	No data available
Corrosion potential/ compatibility	No data available	The magnesite binding agent can corrode metal fastenings at higher levels of humidity	No corrosion behaviour is known, e.g. assembly with steel screws is harmless (strawboard made of rice or grain) [22]	No known risk of corrosion	No data available
Thermal properties					
Specific thermal capacity cp [J/kgK]	1090 [40] 1000 [41]	Approx. 1500	No data available	2020 (ISO 11357-4-2005) [39]	2000–2100[2] [33, 42] 1700[3] [19]
Thermal conductivity λ [W/mK]	0.21–0.32 [13–15] 0.1–0.3 [43]	0.055 (DIN EN 12664)	0.076–0.091 (binderless rice straw particle board) [37] 0.115 (strawboard made of rice or grain) [22]	Orthogonal direction: 0.113–0.134 [44] Parallel: 0.217–0.247 [44]	0.040-0.055[2] [33, 42]
Renewable properties					
Life cycle and recyclability	Gypsum is considered recyclable because its chemical composition does not change. Recycling gypsum board requires shredding, removal of the cardboard layer, and preparation to be used to manufacture new gypsum products. [13–15]	Only consists of leaf mass and mineral binding agent. Easy to dismantle because it is mostly fixed by screws. Boards can be reused or composted.	Depending on disassembly, the boards can be reused. Recycling is possible. Depending on the use of adhesive, the material is compostable. [45]	Recyclability: thermal recycling to produce electricity [17]	Thermal recycling is not a problem. The rind and chips used for production are residual products from sawmills. Thus, their reuse reduces the generation of waste. The raw materials used come predominantly from renewable sources. Waste from the production process is pressed into briquettes, which provide high-quality fuel. [26]

Grey/embodied energy	The largest amount of energy consumption during the whole life cycle comes from the production phase (A1-A3) [13–15]	Low-energy manufacturing, but energy is required for the binding agent magnesite (much lower than cement).	Only a relatively small amount of energy is required for production. [46]	50% of the environmental impact of highly processed bamboo materials occurs due to electricity consumption during processing, so electricity consumption is seen as the main cause. [47]	The production does not include energy-intensive production processes.
Embodied carbon	The largest amount of GWP during the whole life cycle comes from the production phase (A1–A3) [13–15]	About 50 kg/m^3 embodied C (i.e. about 200 kg/m^3 CO_2) in the typha leaf part.	The sequestered carbon outweighs the carbon emissions caused by manufacturing.	Glue-laminated bamboo panels are made of biological materials with a carbon content of about 50%. Lower gross carbon emissions than other materials. [47]	Positive influence, more CO_2 is bound in the tree growth than caused by the production. [19]

3.5.2 Results of materials used to build exterior walls

Materials used to build exterior walls have been considered; an overview is shown in Table 9. Conventional fired clay bricks are compared with panels made of typha, rice straw bales, and rammed earth. All four materials have durability in the same order of magnitude. Typha and straw bales are classified as flammable materials. Fired clay bricks are classified as non-flammable materials and thus have a higher fire rating. Rammed earth is a traditional material used in vernacular architecture and is also considered fire resistant, but more detailed studies are lacking to date. Similar to unfired clay bricks, they can easily be used in smaller buildings in load-bearing elements. All clay materials need outside water protection as clay has a high water absorptive capacity potential without danger of mould growth and vice versa. This makes it particularly useful in climates with high humidity. Typha boards and rice straw bales must be protected from direct weathering, whereas rammed earth and fired bricks do not require protection. However, rammed earth should not be in constant contact with water to avoid possible fungal attacks, for instance. Straw bales also have a certain risk of being attacked by fungi. Typha boards have natural protection against fungi due to the tannin they contain and their high pH value. Regenerative materials can be either recycled into a high-quality recyclate or composted. Bricks are difficult to separate at the end of their life cycle, so they often end up in landfills. They also consume the most energy and emit the most carbon emissions during the manufacturing phase compared to renewable materials. All bio-based materials are widespread and available all year round. It must be taken into account that, due to aquaculture, typha sources are naturally located near the coast. Rice straw is mainly found in the southern Mekong Delta. Rammed earth has high regional availability, but there is especially considerable experience with this building material based on traditional buildings in the north. The detailed tables for exterior walls are listed in Annex 2.

Table 9: Comparison of materials used to build exterior walls

Material/product comparison – Performance values				
Material/ product	**Fired clay bricks**	**Typha wallboard**	**Rice straw bales**	**Rammed earth**
Physical properties				
Thickness [mm]	25–115 [48]	20–120	400–800 [49]	300–500
Bulk density [kg/m³]	550–2000 [50]	285 (DIN EN 1602)	80–150 [49, 51]	1900–2050
Porosity n [Vol.-%]	10–40 [52]	75	No data available	25–30
Durability [a]	≥ 50 [28]	> 50	Longer lasting than previously thought., particularly dependent on penetrated and persistent moisture [53, 54]	At least 50 years, numerous buildings 200–300 years
Fire protection (class)	A1, non-flammable (DIN EN 13501-1) [55]	Euroclass B (ISO 5660-1:2015)	Normal flammability (EN 13501-1:2077+A1:2009 : E) [56]	Well-known high fire resistance, but no quantitative studies to date
Fire resistance (class)	The fire resistance depends on the wall thickness. Spalling can occur in thick, non-load-bearing walls, but it does not spread across the wall thickness. [57]	F60 with 60 mm board F120 with 120 mm board (DIN 4102-2)	The application of plaster or drywall panels to a straw bale wall provides fire resistance at least equivalent to that of many conventional construction methods. [58]	No data available
Weathering resistance	Brick and mortar can be directly weathered. However, damage may occur to both brick and mortar due to frost. [59]	Weather protection required (e.g. plaster)	Rice straw bales must be protected and not directly exposed to weathering conditions. [51]	The walls should be covered by the roof and supported by a foundation (stone or concrete) to avoid constant contact with water.
Risk of mould growth	Due to their moisture-regulating qualities, bricks are less vulnerable to mould. [60]	Low due to the plant's defence substances (tannins) and high pH value	There is a risk of internal condensation, and water infiltration is not prevented. [51]	Low risk of mould and parasitic infestation
Moisture sensitivity	If the masonry remains saturated for a long period, the joints may be destroyed by sulphate attack unless a sulphate-resistant mortar is used. Frost can damage the masonry. [59]	Low, but prolonged contact with liquid water must be avoided	Sensitive to moisture, the materials must be protected. [51]	It is not recommended to use this material in permanent contact with water. The permanent water content of the material should not be more than 6%.
Water absorption [%]	5–10 [61]	59 (DIN EN 12087)	No data available	The saturated state is about 10–12% (in mass). The water absorption test cannot be carried

				out for unstabilised rammed earth.
Water absorption coefficient (w-value) [kg/m²h⁰·⁵]	No data available	1.1 (DIN EN ISO 15148)	Short-term water absorption by partial immersion, Wp [kg/m2] = Wp = 2.7–4.6 kg/m² for 24 h [51]	15–35
Diffusion resistance (µ-value)	5/10 [50]	Dry Cup: 28 Wet Cup: 20 (DIN EN ISO 12572)	3–5 [51]	Wet state: 3–7 Dry state: 7–14
Sorption isotherm – u_{80} [Vol.-%]	No data available	1.2 (DIN EN ISO 12571)	15.73% (of rice straw) [62]	1.5–2% in mass

Mechanical properties				
Compressive strength [N/mm²]	4–28 [50]	0.5	No data available	0.5–3 N/mm2 for unstabilised rammed earth and 2–12 N/mm2 for stabilised rammed earth
Tensile strength [N/mm²]	No data available	No data available	No data available	10–22% of the compressive strength
Bending strength [N/mm²]	No data available	1.0 (DIN EN 12089)	No data available	Similar to tensile strength
Settlement [%]	No data available	No data available	No data available	No data available
Chemical properties				
Chemical resistance	Good chemical resistance [61]	Acid	No data available	Good chemical resistance
Corrosion potential/ compatibility	There is a risk of corrosion in anchorages and fixings with dowels; therefore, requirements apply to the dowel systems, especially with regard to corrosion protection. [63]	The magnesite binding agent can corrode metal fastenings at higher levels of humidity.	No data available	No data available
Thermal properties				

Specific thermal capacity cp [J/kgK]	836 [41] 920 [64]	Approx. 1500	2970–3850 [51]	520–1000
Thermal conductivity λ [W/mK]	0.075–0.96 [50] Directly proportional to the density and, with gross densities of 500 to 1250 kg/m^3, the thermal conductivity is 0.060–1.00 W/m-K. The mortar is also relevant as a composite of individual bricks with mortar. [65]	0.055 (DIN EN 12664)	0.0432 [51]	0.6–1.1 (depending on the density and the moisture content)
Renewable properties				
Life cycle and recyclability	Pure masonry bricks from demolition can be recovered by brick manufacturers and recycled in ground form as a lean agent in production. Demolition waste, however, is rarely sorted and is landfilled. [50]	High because it consists only of leaf mass and mineral binding agent. Easy dismantling because it is mostly fixed by screws. Boards can be reused or composted.	High environmental performance compared to most other traditional materials used in construction. [58] Organic building material that is renewable and compostable.	If the material is unstabilised, it is nearly 100% recyclable.
Grey/embodied energy	The highest energy consumption during its whole life cycle comes from the production phase (A1–A3) [50].	Low-energy manufacturing, but energy is required for the magnesite binding agent (much lower than cement)	Low embodied energy [58]	If the material is unstabilised, the embodied energy is very low. [66] Even for cement stabilised rammed earth, the embodied energy is still lower than that of conventional materials. [67]
Embodied carbon	The highest GWP during its whole life cycle comes from the production phase (A1–A3) [50].	About 50 kg/m^3 embodied C (i.e. about 200 kg/m^3 CO_2) in the typha leaf part	Due to photosynthesis, it is a carbon-negative material. [58]	Very low embodied carbon for unstabilised rammed earth. The embodied carbon of cement stabilised rammed earth is

				expected to be lower than that of conventional materials.

3.5.3 Results of insulation materials

In the following, renewable insulation materials made of reeds, seaweed, and typha are compared to the conventional insulation material expanded polystyrene (EPS). The materials and respective parameters are shown in Table 10. In terms of durability, it can be seen that renewable alternatives can also achieve good lifetimes. EPS, as well as reed, seaweed, and typha, are classified as flammable materials. EPS has better fire protection due to its B1 (flame retardant) classification. All insulation materials cannot be exposed to direct weathering. EPS is especially sensitive to UV radiation. EPS and typha, in particular, are resistant to fungal attacks. Typha has natural protection due to the tannin it contains and its high pH value. Reed also has a natural protection mechanism: its high silicate content decreases its sensitivity to moisture. EPS has the lowest thermal conductivity, followed by seaweed and typha. Reed has by far the highest thermal conductivity. All three renewable insulation materials are compostable and have a higher ecological benefit than EPS. A high-quality recyclate from EPS is currently hardly widespread due to contamination from other substances; therefore, EPS is mainly thermally recycled. Another negative factor is the high amount of energy required to produce EPS, whereas renewable alternatives require little energy. The binding of carbon dioxide (CO_2) during plant growth is an additional positive factor of renewable materials. The bio-based insulation materials under consideration come from aquaculture; it should be noted that they grow particularly in coastal regions year round. The detailed tables for insulation materials are listed in Annex 3.

Table 10: Comparison of insulation materials

Material/product comparison – Performance values				
Material/product	**Expanded polystyrene (EPS) board**	**Reed insulation**	**Seaweed insulation**	**Typha insulation**
Physical properties				
Thickness [mm]	10–300 [68]	40–120	As loose fill, seagrass of any thickness can be installed. Settlement due to its weight must be considered. Mats are currently produced up to 100 mm	20–120
Bulk density [kg/m³]	15–30 [69–73]	130	75	155 (DIN EN 1602)
Porosity n [Vol.-%]	No data available	No data available	No data available	85

Durability [a]	≥ 50 [28]	30–40 as roof covering	> 30 a	> 50
Fire protection (class)	B1 according to DIN 4102 [68]	B2 according to DIN 4102 Class E, EN 13501	B2 according to DIN 4102-1 Class E according to EN 13501-1	Euroclass B (ISO 5660-1:2015)
Fire resistance (class)	Fire classification Euroclass E according to EN 13501-1 [69–73]	No data available	No data available	No data available
Weathering resistance	Poor UV resistance: Direct sunlight causes yellowing and brittleness of the insulation boards. Cracking occurs, which is susceptible to moisture accumulation, creating thermal bridges. [74] EPS is not water-resistant. [68]	The reed insulation boards may only be installed in structures where they are protected from precipitation.	Needs protection	Weather protection required (e.g. plaster)
Risk of mould growth	Resistant to fungal decay [68]	Exterior insulation has to be protected	Rating level 3 according to EN ISO 846 Medium resistant to parasites and mould	Low, due to the plant's defence substances (tannins) and high pH value
Moisture sensitivity	Not sensitive to moisture [75]	Due to its high silicate content, the natural product reed is insensitive to the effects of moisture.	No data available	Low, but prolonged contact with liquid water must be avoided
Water absorption [%]	2–3 (long term water absorption) [68]	No data available	No data available	50 (DIN EN 12087)
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]	No data available	No data available	No data available	1.6 (DIN EN ISO 15148)
Diffusion resistance (µ-value)	20–100 (EN 12086) [70, 71]	No data available	1.5	Dry cup: 18 Wet cup: 16 (DIN EN ISO 12572)
Sorption isotherm – u_{80} [Vol.-%]	No data available	15 [kg/kg] M.-% (DIN EN ISO 1257)	0.33 [kg/kg] M.-%	3.1 (DIN EN ISO 12571)

Mechanical properties				
Compressive strength [N/mm²]	0.06–0.2 [69–73] 0.03–0.5 [68]	No data available	No data available	No data available
Tensile strength [N/mm²]	> 0.1 [69–73]	190 N (metal wire)	No data available	No data available
Bending strength [N/mm²]	0.115–0.25 [69–73]	No data available	No data available	No data available
Settlement [%]	No data available	No data available	5	No data available
Chemical properties				
Chemical resistance	Resistant to alkalis and non-oxidising acids, not resistant to solvents [68]	No data available	The insulation has a salt content that can react.	Acids
Corrosion potential/ compatibility	No data available	No data available	A corrosion test according to Annex E of the CUAP Directive showed that a pH value of 6.9 is achieved in a seagrass-water mixture. Storage of metal foils on moist seagrass did not affect copper foil, while zinc foil showed slight destruction by corrosion.	The magnesite binding agent can corrode metal fastenings at higher humidity levels.
Thermal properties				
Specific thermal capacity cp [J/kgK]	1500 [68]	1200	2000	Approx. 1500
Thermal conductivity λ [W/mK]	0.031–0.036 [69–73]	0.061	0.045	0.043 (DIN EN 12664)
Renewable properties				
Life cycle and recyclability	During dismantling, the bonding causes difficulties and is often difficult to remove again. If it contains the flame	Fully compostable or thermal recycling	Seagrass is a natural product and comes as an insulating material without further additives.	High recyclability because it consists only of leaf mass and mineral binding agent. Easy

	retardant HBCD, which has only been banned since 2016, EPD must be disposed of as hazardous special waste. [74] Due to the poor cleaning performance and economic efficiency of previous processes, no high-quality recyclates can be produced from contaminated EPS waste. Mainly thermal recycling takes place. [76]		Therefore, it can be composted and used as plant fertiliser at the end of its life cycle.	dismantling because it is mostly fixed by screws. Boards can be reused or composted.
Grey/embodied energy	The largest amount comes from the production phase (A1–A3) [69–73]. Generally high energy consumption for the manufacturing processes. [74]	Minimal grey energy for harvesting and production	Compared to other insulation materials, the mining and production of seagrass insulation consume little energy.	Low-energy manufacturing; however, energy is required for the binding agent magnesite (much lower than cement).
Embodied carbon	The largest amount comes from the production phase (A1 – A3) [69–73].	Approx. 30 tons of CO_2 per hectare of cultivated land	No data available	About 30 kg/m^3 embodied C (i.e. about 120 kg/m^3 CO_2) in the typha leaf part

3.6 Implementation examples

Here are some ways renewable construction materials can be used to replace conventional materials. These examples show wall constructions, but roof or ground plate insulation can be designed similarly. What is important is the humidity protection from rainwater, especially for outer walls, wall footings and foundations. Special attention should be paid to the connection details, airtightness layer and thermal bridges.

3.6.1 Lightweight constructions

Lightweight constructions can achieve a higher heat transfer coefficient (U-value) by using more insulation material with a better lambda value in thinner wall/roof constructions. Lightweight constructions can be prefabricated as higher-quality sandwich panels in a factory than on site. This also reduces the construction time.

Example 1: Wood or bamboo plywood framework with seaweed insulation and typha wallboard interior and exterior bracing plating

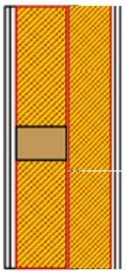
Figure 19: Lightweight-construction wall option 1 (©dena / Stefan Schirmer)

U = 0,28W/m²K d = 250mm

- 30mm typha wall board interior 2.1.2-C3.b
- 160mm wood framework / seaweed insulation 4.4.3-C1.b
- 30mm typha wall board exterior 2.2.2-C3.b
- 30mm plaster (clay + scale + ricestraw)

Example 2: If 100 mm of additional insulation is added to Example 1, the U-value improves to 0.213W/(m²K) / 310 mm wall thickness. With 160 mm seaweed insulation, the U-value increases to 0.190W/(m²K).

Figure 20: Lightweight-construction wall option 2 (©dena / Stefan Schirmer)



U = 0,19W/m²K d = 350mm

- 30mm typha wall board interior 2.1.2-C3.b
- 160mm wood framework / seaweed insulation 4.4.3-C1.b
- 100mm typha insulation board
- 30mm typha wall board exterior 2.2.2-C3.b
- 30mm plaster (clay + scale + ricestraw)

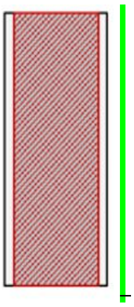
There are many possible wall constructions using the renewable materials investigated in this study.

3.6.2 Solid constructions

Solid constructions have greater resistance to humidity from groundwater and rainwater. They are also more stable and useful for taller buildings, up to high-rises. Fire protection is easier: there must be fire protection from the inside and outside. If we want to use renewable materials with a Class B fire resistance, there must be an additional layer of fire protection panels. Local laws and regulations must be checked.

Example 3: Solid construction with rammed earth used in vernacular architecture in Vietnam. This construction is very impervious to vapour and air humidity, but its U-value is not sufficient. Protection against groundwater is necessary.

Figure 21: Solid construction wall option 1 (©dena / Stefan Schirmer)



U = 1,49W/m²K d = 455mm

- 15-30mm plaster (clay + ricestraw)
- 300-500mm rammed earth 2.2.4-D1.a
- 30mm plaster (clay + scale + ricestraw)

Example 4: If 100 mm of additional insulation is added, the U-value improves to 0.262W/(m²K). This would allow taller traditional buildings to be insulated. Fire protection rules may cause problems if they permit only non-combustible Class A materials. Constructions cased with fire protection boards may be a solution for using renewable materials in high-rise buildings with a reinforced concrete framework.

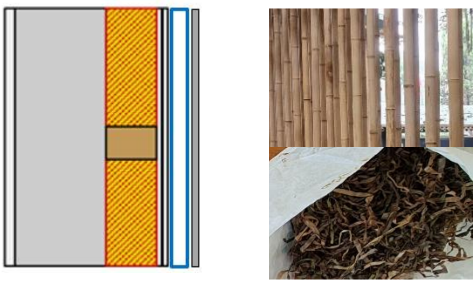
Figure 22: Solid construction wall option 2 (©dena / Stefan Schirmer)

U = 0,37W/m²K d = 510mm

- 30mm plaster (clay + ricestraw)
- 300mm rammed earth 2.2.4-D1.a
- 120mm wood framework / seaweed insulation 4.4.3-C1.b
- 30mm typha wall board (exterior) 2.2.2-C3.b
- 30mm plaster (clay + scale + ricestraw)

Example 5: Conventional construction with concrete walls with additional renewable insulation

Figure 23: Solid construction wall option 3 (©dena / Stefan Schirmer)

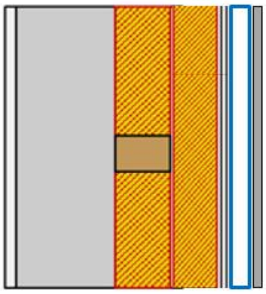


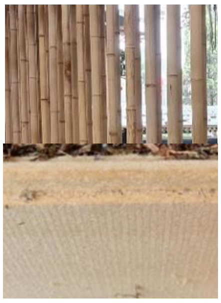
U = 0,34W/m²K d = 500mm

- 15-30mm plaster (clay + ricestraw)
- 200mm ferroconcrete (highrise buildings)
- 160mm plybamboo framework 2.1.2-B2.a / seaweed insulation 4.4.3-C1.b
- 30mm fire protection layer
- 60mm curtain wall + 30mm natural stone

Example 6: Increase in the U-value of Example 5 with an additional insulation layer for a combination of stability, a high percentage of renewable materials and very good heat protection

Figure 24: Solid construction wall option 4 (©dena / Stefan Schirmer)





U = 0,182W/m²K d = 600mm

- 15-30mm plaster (clay + ricestraw)
- 200mm ferroconcrete (highrise buildings)
- 160mm plybamboo framework 2.1.2-B2.a / seaweed insulation 4.4.3-C1.b
- 100mm typha insulation board
- 30mm fire protection layer
- 60mm curtain wall + 30mm natural stone

3.7 Summary

The aim of this study was to identify bio-based materials that can replace conventional materials under the local climatic conditions and in the market context of Vietnam. As bio-based materials, these materials are less resource-demanding and environmentally harmful. Moreover, as locally sourced materials, they support the local economy.

Based on an extensive study of nine bio-based material applications and three conventional reference materials, it has been shown that bio-based materials perform as well as conventional materials in many regards. If used in accordance with their specific properties and performance under local conditions, a high level of function and long durability can be achieved with bio-based materials.

In many cases, it has been found that their performance is better than expected. For instance, the fire protection function of rice straw is high due to its naturally high silicate content. Likewise, the formation of mould fungi is often regarded as critical in the case of renewable materials. Here, for example, typha is naturally protected due to the tannin it contains and its high pH value. Pre-treatments, such as for bamboo, can increase the resistance of an initially vulnerable material.

Furthermore, proper installation has a significant impact on resistance to mould growth. For example, preventing a high moisture load is paramount for long durability and resistance to mould growth in straw bale constructions. In general, however, conventional materials are less vulnerable in this regard. Therefore the materials' sensitivity to moisture must be taken into account when designing for the hot and humid climate in Vietnam.

The thermal conductivity of the natural insulation materials is slightly higher (0.043–0.061 W/mK) than conventional materials (EPS reaches values as low as 0.031–0.036 W/mK). But the development of insulation material is quick, and industrial research and processes are sure to improve the thermal conductivity of renewable insulation. The use of insulation is not yet common in Vietnam, and it is not used in traditional construction methods. The main effect of insulation can be to help prevent the building from heating up. Due to the tropical climate with mild temperatures and high humidity levels, susceptibility to moisture and mould is a more relevant metric.

The fire resistance of renewable materials is a greater challenge – most of them are Class B flammable. Like in western countries, lowering the fire protection requirements to enable the use of more renewable construction materials is currently being discussed. This public debate process should also be initiated in Vietnam to utilise the enormous potential of tropical plants, whose properties are generally very good. But careful design will make it possible to develop possibilities for taller buildings and non-residential buildings (see Examples 5–6 in Chapter 2.7).

Generally speaking, the carbon sequestration of bio-based materials, in particular, has a positive impact on grey carbon. Depending on the material and the manufacturing process, this can offset the CO_2 emissions. In this case, conventional materials are at a disadvantage due to their higher emissions. Since the production of conventional materials is more energy intensive, they also contain more grey energy. In terms of recyclability and life cycle, some bio-based materials can be produced entirely without chemical additives, making them compostable. In particular, panels fastened using screws can be reused in the case of non-destructive deconstruction. Landfilling, which is often the fate of conventional materials, can be eliminated.

The use of bio-based materials must be assessed according to the respective resources and their regional distribution. Rammed earth is traditionally used in northern Vietnam. Since it is available throughout Vietnam, it can also be used in other regions. Unfired bricks can reduce grey emissions when used for non-load-bearing inner and outer walls, as well as a thermal storage material in floors and basements.

Wood and bamboo are also widely available throughout the country, and traditional buildings in various regions have been constructed using these materials. Bamboo, in particular, grows quickly and has great potential for use in buildings as well as in load-bearing elements. The possibility of using bamboo beams in hybrid concrete constructions to provide stability and fire protection should be investigated. On the other hand, Typha, seagrass and reed from aquaculture can be harvested in coastal regions. These resources are available in larger quantities; however, they are as yet unknown as building materials. Rice straw is mainly burnt as a by-product of the agricultural process, so the potential for saving resources is particularly high. Rice straw is also widespread, but it is mainly found in the southern Mekong Delta. Due to its good thermal conductivity as an insulation material, it can be used in the form of straw bales, boards or chopped blow-in insulation.

In conclusion, this study has shown that the use of bio-based materials in construction in Vietnam can contribute significantly to reducing resource demand. While bio-based materials can perform some functions without limitation and even with benefits for health, the environment and the local economy, other functions can be performed better by conventional materials. Therefore, the combination of bio-based and conventional materials in hybrid structures will pave the way to resource-efficient buildings. In this way, industrialised construction techniques and modern building typologies can be supported with bio-based materials.

Figures

Tables

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Abbreviations

µ-value	Diffusion Resistance
a	Year
A1	Non-Flammable
AAC	Autoclaved Aerated Concrete
ASTM E-84	Standard Test Method for Assessing the Surface Burning Characteristics of Building Products
B	Combustible Materials. Little or no Contribution to Fire
B1	Flame Resistant
B2	Normal Flammable
BMB	Bamboo Mat Board
BSB	Bamboo Strip Board
C	Combustible Materials. Limited Contribution to Fire
CAMaRSEC	Climate Adapted Material Research for the Socio-Economic Context in Vietnam
CO_2	Carbon Dioxide
cp	Specific Thermal Capacity
CUAP	Common Understanding of Assessment Procedure
d0	The material does not create flaming particles or droplets when subjected to fire.
dena	German Energy Agency
DGNB	German Sustainable Building Council
DIN	German Institute for Standardization
E	Combustible Materials. Major Contribution to Fire
e.g.	Exempli Gratia, for example
EDGE	Excellence in Design for Greater Efficiencies
EN	European Standard
EPD	Environmental Product Declarations
EPS	Expanded Polystyrene
F120	Highly Fire-Resistant
F60	Highly Fire Retardant
GWP	Global Warming Potential

HCMC	Ho Chi Minh City
IFC	International Finance Corporation
IGTE	Institute for Building Energetics, Thermotechnology and Energy Storage
ISO	International Organization for Standardization
LEED	Leadership in Energy and Environmental Design
LOTUS	Set of voluntary green building rating systems developed by Vietnam Green Building Council (VGBC)
MoST	Ministry of Science and Technology
NFB	Non-Fired Brick
pH-value	Power of Hydrogen. Used to specify the acidity or basicity of an aqueous solution through a scale system.
r.F.	Relative Humidity
s1	The material contributes little or insignificantly to the development of smoke
TS	Technical Standard
UNDP	United Nations Development Programme
UV	Ultraviole.Form of electromagnetic radiation.
VGBC	Vietnam Green Building Council
w-value	Water Absorption Coefficient
Λ	Thermal Conductivity

I. Annex 1 Wall-building materials for interior walls

I.1 Typha wall board

Aquaculture – Typha			
2.1.2-C3.a	Typha wall board	Wall-building material for interior and exterior wall constructions	Figure 25: Typha (©dena / Stefan Schirmer) 
Board made of Typha Angustifolia leaves, bonded with magnesite. No other additives like biocide or fire retardant. Higher density for better load-bearing properties.			
Technical readiness level of 9			

Typha wall board – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	20 – 120
Bulk density [kg/m³]	Quantitative value	285 (DIN EN 1602)
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	75
Durability [a]	Assuming that it has been installed in a technically correct manner	> 50

Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	Euroclass B (ISO 5660-1:2015)
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	F60 with 60mm-Board F120 with 120mm-Board (DIN 4102-2)
Weathering resistance	Specifies whether, for example, a weather protection layer is required, free weathering is possible, etc.	Weather protection required (e.g. plaster)
Risk of mould growth	Specify qualitatively in a rough classification	Low due to the plant's defence substances (tannins) and high pH-value
Moisture sensitivity	Specify qualitatively in a rough classification	Low but prolonged contact with liquid water must be avoided
Water absorption [%]	Boundary condition: free saturation	59 (DIN EN 12087)
Water absorption coefficient (w-value) [$kg/m^2h^{0,5}$]		1,1 (DIN EN ISO 15148)
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	Dry Cup: 28 Wet Cup: 20 (DIN EN ISO 12572)
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	1,2 (DIN EN ISO 12571)
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm^2]	Quantitative value	0,5
Tensile strength [N/mm^2]	Quantitative value	No data available
Bending strength [N/mm^2]	Quantitative value	1,0 (DIN EN 12089)
Settlement [%]		No data available
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	Acid

Corrosion potential/Compatibility	Does steel corrode when used with it? E.g. nails? Qualitative classification	The magnesite binding agent can corrode metal fastenings at higher levels of humidity
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1kg of a substance by 1K.	Ca. 1500
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m^2 and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,055 (DIN EN 12664)
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	High because it consists only of leaf mass and mineral binding agent. Easy dismantling because it is mostly fixed by screws. Boards can be reused or composted.
Grey/embodied energy	Qualitative description	Low energy manufacturing, however, energy is required for the binding agent magnesite (much lower than cement).
Embodied carbon	Qualitative description	About 50 kg/m^3 embodied carbon (about 200 kg/m^3 CO_2) in the Typha leaf part.

Typha wall board – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High Because of the high amount of renewable Typha mass.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium to High, depending on the electric energy source.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low Only cutting off the leaves and pressing the product, no drying necessary.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low A semi-industrial production plant can be built with investment costs for the machinery of less than 500 k€.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the	Low Enables simpler building techniques, since the Typha board unites all qualities relevant for constructions: heat insulation, static stiffening, fire prevention, moisture protection, acoustics, plaster base. Boards can be fixed using glue or screws.

	non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Low Relative insensitive to mould growth or humidity.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low Easy dismantling and reuse, it is mostly fixed using screws.
Demolition - waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low No waste because of its compostability.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider:	High Renewable raw material; produced with low energy amount; easy dismantling; completely compostable; prevention of CO_2-loss by re-wetting of dried fens; bond of CO_2 and other greenhouse gases with its cultivation in fens; cleaning of nutrient polluted surface water.

	Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High Non-toxic; not inflammable; no parasites/insects known; relatively insensitive to moisture.

Typha – Building material availability						
	**Region**	**Seasonality**				**Supplies (manufacturers/resellers/ storage)**	**Disposal (recycling/ end of life)**
		1Q	**2Q**	**3Q**	**4Q**		
	Northeast						
	Northwest						
	Red River Delta						
	North Central Coast	X	X	X	X	Small local manufacturers	No data available
	South Central Coast	X	X	X	X	Small local manufacturers	No data available
	Central Highlands						
	Southeast						
	Mekong River Delta	X	X	X	X	High quantity but not yet popular as a construction material. Can be used for food (young parts) or traditional medicine	No data available

I.2 Rice straw particle board

Agriculture – Rice			
2.1.2-A1.b	Rice straw particle board	Wall-building material for interior wall constructions	Figure 26: rice straw (©dena / Stefan Schirmer) 
Rice plants are renewable lignocellulose resources. They have similar properties to wood due to their fibrous structure and chemical properties. The rice straw is cut into 1 - 3 cm long pieces and further processed in the Wiley mill for use in the outer and middle layers. Straw width depends upon the natural width of the rice straw stem. Rice straws are used after drying to a moisture content of 3 – 4 % before glueing.[21]			
Technical readiness level of 9			

Rice straw particle board – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	4 – 20 [16]
Bulk density [kg/m³]	Quantitative value	428 (TS EN 323 (1999)) particleboard of rice straw [21] 650 for straw board of rice or grain [22]
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	No data available
Durability [a]	Assuming that it has been installed in a technically correct manner	No data available
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	Rice straw significantly contributes to the fire resistance of particle boards because of its high silica content [21]

Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	Class Bd0, according to EN ISO 11925-2:2002 (binderless rice straw particle board) [37] B-s1, d0 (straw board of rice or grain) [22]
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Protection from direct weather protection is necessary. The application is mainly indoors (straw board of rice or grain). [22]
Risk of mould growth	Specify qualitatively in a rough classification:	Mould resistant (straw board of rice or grain) [22]
Moisture sensitivity	Specify qualitatively in a rough classification	Depending on the product, waterproof (straw board of rice or grain) [22]
Water absorption [%]	Boundary condition: free saturation	45 – 130 (after 24 hours) (binderless rice straw particle board) [37] 90 – 150 (after 24 hours) [38]
Water absorption coefficient (w-value) [kg/m²h^{0,5}]		No data available
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	5,2 (straw board of rice or grain) [22]
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	No data available
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	No data available
Tensile strength [N/mm²]	Quantitative value	Transverse tensile strength: 0,32 (straw board of rice or grain) [22]
Bending strength [N/mm²]	Quantitative value	1,48 [38]
Settlement [%]		no data available
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	No data available
Corrosion potential/Compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	No corrosion behaviour is known, e.g. assembly with steel screws is harmless (straw board of rice or grain). [22]

Thermal properties	Description	Values
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1kg of a substance by 1K.	No data available
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m^2 and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,076 – 0,091 (binderless rice straw particle board) [37] 0,115 (straw board of rice or grain) [22]
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	Depending on the assembly and disassembly, the boards can be reused. Recycling is possible. Depending on the use of adhesive, the material is compostable. [45]
Grey/embodied energy	Qualitative description	Only a relatively small amount of energy is required for production. [46]
Embodied carbon	Qualitative description	The sequestered carbon outweighs the carbon emissions caused by manufacturing.

Material/product name – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High The product consists largely of the renewable raw material rice straw, which is a by-product of agriculture.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium to High, depending on the electric energy source
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low By-products are used for production, which usually requires less energy than conventional raw materials. Production needs less process compression or heat.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Medium to low Since rice is a waste product and the technology to produce the material is available, it is assumed that the investment costs will be lower or at least the same.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the	Low The product is easy to assemble in drywall. No special requirements are necessary for transportation. Compared to the assembly of conventional products, it consumes the same or less energy.

	non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Low If installed correctly, no maintenance is required.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Medium The demolition is comparable with conventional products.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low The material can be recycled and therefore does not need to be landfilled.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider:	High Since it is a by-product of agriculture that has so far only been burned, the amount of waste and the use of valuable resources can be saved. It is a natural product that can be recycled or even reused depending on the application, which further saves resources and energy.

	Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High The product does not contain any substances hazardous to humans or the environment. It is resistant to moisture and mould.

Rice straw – Building material availability

Region	**Seasonality**				**Supplies (manufacturers/resellers/ storage)**	**Disposal (recycling/ end of life)**
	1Q	**2Q**	**3Q**	**4Q**		
Northeast	X	X	X	X	Low quantity	Rice straw is usually burned
Northwest	X	X	X	X	Low quantity	Rice straw is usually burned
Red River Delta	X	X	X	X	Small local manufacturers, not yet popular	Rice straw is usually burned
North Central Coast	X	X	X	X	Small local manufacturers, not yet popular	Rice straw is usually burned
South Central Coast	X	X	X	X	Small local manufacturers, not yet popular	Rice straw is usually burned
Central Highlands						
Southeast						
Mekong River Delta	X	X	X	X	The highest quantity in the country. Small local manufacturers	Rice straw is usually burned (in some cases, for fired bricks,…)

I.3 Plybamboo

Forestry – Bamboo			
2.1.2-B2.a	Plybamboo	Wall-building material for interior wall constructions	Figure 27: Bamboo (©dena / Stefan Schirmer) 
Bamboo is the fastest growing plant in the world. Some species can have a growth of more than 90 cm per day, the average for all species is considered a daily growth of 25 cm. Bamboo consists of about 50 M.-% carbon. The (Moso)bamboo is harvested after a standing time of 4 to 5 years and processed while still fresh. At this early stage, bamboo is much easier to work with but is more susceptible to plant and animal attacks. To avoid insecticide infestation, the bamboo is boiled for 6 hours in a mixture of water and borates. [77] Production of Plybamboo (BMB-BSB) [23] Bamboo mat board (BMB) is a bamboo-based material made out of layered bamboo mats that are glued together to form a panel board. Bamboo strip board (BSB) is a bamboo-based material made out of bamboo strips glued together to form a panel board. Plybamboo is the first successfully developed and well-accepted bamboo-based board. [24]			
Technical readiness level of 9			

Plybamboo – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	Up to 40 mm (5-layer Plybamboo panel) [17]
Bulk density [kg/m³]	Quantitative value	720 – 868 [23] 920 [24] 880 [25]

Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	No data available
Durability [a]	Assuming that it has been installed in a technically correct manner	Very durable (CEN/TS 15083-1) [29]
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	Fire protection class B (EN13501-1) [29] Fire resistance classification: Class C, Test surface burning following ASTM E 84 [78]
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	Fire resistance class C (ASTM E 84) [31]
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Plybamboo may be installed only in structures where they are protected from precipitation. Details depend on the respective manufacturer/product.
Risk of mould growth	Specify qualitatively in a rough classification	Bamboo is subject to attack by fungi and insects. Therefore, before production, it is treated to become resistant to fungal attacks. Untreated bamboo structures are viewed as temporary with an expected life of no more than five years .[79]
Moisture sensitivity	Specify qualitatively in a rough classification	Water-resistant regarding firmness and services. Contact with soil and penetration must be avoided. [23]
Water absorption [%]	Boundary condition: free saturation	No data available
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]		38,71 E^{04}kg/(m²s^{0,5}) (according to ISO 15148:2002(E)) [39]
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	No data available
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	No data available

Mechanical properties	Description	Values
Compressive strength [N/mm²]	Quantitative value	20 - 52 (parallel to fibres) [23]
Tensile strength [N/mm²]	Quantitative value	26 - 105 (parallel to fibres) [23]
Bending strength [N/mm²]	Quantitative value	51 – 94 [23]
Settlement [%]		No data available
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	No data available
Corrosion potential/compatibility	Does steel corrode when used in combination? E.g. nail, etc.? qualitative classification	No known risk of corrosion
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1kg of a substance by 1 K.	2020 (ISO 11357-4-2005) [39]
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m² and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of building material.	Orthogonal direction: 0,113 – 0,134 [44] Parallel: 0,217 – 0,247 [44]
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	Recyclability: thermal recycling to produce electricity [17] Adhesives content: 2 % (Adhesives containing formaldehyde are often used and must be regarded as critical in terms of material health) [31]

Grey/embodied energy	Qualitative description	50% of the environmental impact of highly processed bamboo materials occurs as a result of electricity consumption through processing, so electricity consumption is seen as the main cause. The main processing method used in the production of layered bamboo is mechanical processing. Bleached, glue-laminated bamboo panels have the highest potential environmental impact in terms of energy consumption during the three-layer lamination process. [47]
Embodied carbon	Qualitative description	Glue-laminated bamboo panels are made of biological materials with a carbon content of about 50%, and their use is equivalent to carbon storage in organic form. The negative value of carbon emissions shows that the carbon storage function of the bamboo material balances the carbon emissions during the processing stages. Compared to other materials, this represents lower gross carbon emissions. Consequently, the use of glue-laminated bamboo panels results in a positive environmental impact. [47]

Plybamboo – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High The product consists largely of the renewable raw material bamboo, which is a renewable product of forestry.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium The same energy sources are used as for conventional materials.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low The production of Glubam/ laminated bamboo needs less energy.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Median to low No data are available on this. Since the raw material bamboo is used for an existing production technology, no increased investment costs are assumed.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the	Low The product is easy to assemble in drywall. No special requirements are necessary for transportation. Compared to the assembly of conventional products, it consumes the same or less energy.

	non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Low If installed correctly, no maintenance is required.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Medium The demolition is comparable with conventional products.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low The material can be recycled and therefore does not need to be landfilled.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider:	High Glue-laminated bamboo panels result in a positive environmental impact.

	Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High The product does not contain any substances hazardous to humans or the environment.

Bamboo – Building material availability

Region	**Seasonality**				**Supplies (manufacturers/resellers/ storage)**	**Disposal (recycling/ end of life)**
	1Q	**2Q**	**3Q**	**4Q**		
Northeast	X	X	X	X	Many small manufacturers	No data available
Northwest	X	X	X	X	Many small manufacturers. Bamboo from Cao Bang province is well known.	No data available
Red River Delta	X	X	X	X	Many small manufacturers	No data available
North Central Coast	X	X	X	X	Many small manufacturers. Bamboo from Thanh Hoa province is well known.	No data available
South Central Coast	X	X	X	X	Many small manufacturers	No data available
Central Highlands	X	X	X	X	Many small manufacturers	No data available
Southeast	X	X	X	X	Many small manufacturers (E.g.: https://xuongtretruc.com). Bamboo from Tay Ninh province is well known.	No data available
Mekong River Delta	X	X	X	X	Many small manufacturers. Bamboo from An Giang province is well known.	No data available

I.4 Wood fibre board

Forestry – Timber			
2.1.2-B1.a	Wood fibre board	Non-load-bearing wall-building material (interior wall)	Figure 28: wood fibre board (©dena / Stefan Schirmer) 
In the wet process, the wood's binding forces are used by breaking down the wood into fibres by thermomechanical processes and then setting the fibre cake under pressure and heat. Thus, no additional chemical binders are needed. [26]			
Technical readiness level of 9			

Wood fibre board – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	0,4 – 2,5[A] [18] 0,5 – 1,6[B] [19]
Bulk density [kg/m³]	Quantitative value	100 – 400[A] 650 – 1000[3,C] [26]
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	No data available
Durability [a]	Assuming that it has been installed in a technically correct manner	40[D] [28]

[A] wood fiber insulation board
[B] medium hardwood fiberboard
[C] hardfiberboard
[D] wood fiber insulation board

Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	B2 (DIN 4102-1) D-d0 (DIN 13501-1) [30]
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	No data available
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Resistant to rotting, vermin and fungal attack [33]
Risk of mould growth	Specify qualitatively in a rough classification	No data available
Moisture sensitivity	Specify qualitatively in a rough classification	Without hydrophobization not resistant to moisture (in case of prolonged soaking swelling and risk of rotting) [33]
Water absorption [%]	Boundary condition: free saturation	30 % (after two hours for wood fibre board insulation and 24h for hard fibre board) [26]
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]		No data available
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	4 - 7[2] 30 - 50[A] 45 – 100[B] [26]
sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	No data available

[A] medium hardwood fiberboard
[B] hardfiberboard

Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	0,05[2] [26]
Tensile strength [N/mm²]	Quantitative value	12[3] 30[4] [26]
Bending strength [N/mm²]	Quantitative value	0,2[A] 12[B] 35 – 40[C] [26]
Settlement [%]		No data available
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	No data available
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	No data available
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	2000 - 2100[2] [33, 42] 1700[3] [19]
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m² and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,040 - 0,055[2] [33, 42]

[A] Wood fibre insulation board
[B] Medium hardwood fibre board
[C] Hard fibre board

Renewable properties	Description	Values
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	The production takes place without chemical additives, so thermal recycling is not a problem. The rind and chips used for production are residual products from the sawmills. Thus, their reuse reduces the generation of waste. The raw materials used come predominantly from renewable sources. Waste from the production process is pressed into briquettes, which provide high-quality fuel. [26]
Grey/embodied energy	Qualitative description	The production does not include energy-intensive production processes.
Embodied carbon	Qualitative description	Positive influence, more CO_2 is bound in the tree growth than caused by the production. [19]

Wood fibre board – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High The rind and chips used for production are residual products from the sawmills. Thus, their reuse reduces the generation of waste. The raw materials used come predominantly from renewable sources.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Median The same energy sources are used as for conventional materials.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low The production does not include energy-intensive production processes.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Medium to low No data are available on this. Since regionally-sourced raw material wood is used, no increased investment costs are assumed.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it	Low

	require specialised transport solutions? Compared to the non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	The product is easy to assemble in drywall. No special requirements are necessary for transportation. Compared to the assembly of conventional products, it consumes the same or less energy.
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Low If installed correctly, no maintenance is required.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Medium The demolition is comparable with conventional products.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low The material can be recycled and therefore does not need to be landfilled.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life.	High Fibre boards produced by the wet process are characterized by high environmental compatibility in production, use, and disposal.

	Consider: Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High They consist 100% of the main components of the grown wood, no additional chemical binders are needed.

Wood – Building material availability

Region	Seasonality				Supplies (manufacturers/resellers/ storage)	Disposal (recycling/ end of life)
	1Q	2Q	3Q	4Q		
Northeast	X	X	X	X	Large amounts of wood available, but use must be limited due to deforestation.	
Northwest	X	X	X	X	Large amounts of wood available, but use must be limited due to deforestation.	
Red River Delta						
North Central Coast	X	X	X	X	Large amounts of wood available, but use must be limited due to deforestation.	Reused/recycled
South Central Coast	X	X	X	X	Many manufacturers	Reused/recycled
Central Highlands	X	X	X	X	Large amounts of wood available, but use must be limited due to deforestation. The manufacturer Hoang Anh Gia Lai is well known in Vietnam, but mainly for furniture made of wood.	Reused/recycled

	Southeast	X	X	X	X	Large amounts of wood available, but use must be limited due to deforestation.	Reused/recycled
	Mekong River Delta	X	X	X	X	Large amounts of medium quality wood available.	Reused/recycled

II. Annex 2 Wall-building materials for exterior walls

II.1 Typha wallboard

Aquaculture – Typha			
2.2.2-C3.a	Typha wallboard	Wall-building material for interior and exterior wall constructions	Figure 29: Typha (©dena / Stefan Schirmer) 
Board made of Typha Angustifolia leaves, bonded with magnesite. No other additives like biocide or fire retardant. Higher density for better load-bearing properties.			
Technical readiness level of 9			

Typha wallboard – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	20 – 120
Bulk density [kg/m³]	Quantitative value	285 (DIN EN 1602)
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	75
Durability [a]	Assuming that it has been installed in a technically correct manner	>50

Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	Euroclass B (ISO 5660-1:2015)
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	F60 with 60mm-Board F120 with 120mm-Board (DIN 4102-2)
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Weather protection required (e.g. plaster)
Risk of mould growth	Specify qualitatively in a rough classification	Low, due to the plant's defence substances (tannins) and high pH-value
Moisture sensitivity	Specify qualitatively in a rough classification	Low, but prolonged contact with liquid water must be avoided
Water absorption [%]	Boundary condition: free saturation	59 (DIN EN 12087)
Water absorption coefficient (w-value) [kg/m²h⁰·⁵]		1,1 (DIN EN ISO 15148)
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	Dry Cup: 28 Wet Cup: 20 (DIN EN ISO 12572)
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	1,2 (DIN EN ISO 12571)
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	0,5
Tensile strength [N/mm²]	Quantitative value	No data available
Bending strength [N/mm²]	Quantitative value	1,0 (DIN EN 12089)
Settlement [%]		No data available

Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	Acid
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	The magnesite binding agent can corrode metal fastenings at higher levels of humidity
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	Ca. 1500
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m^2 and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,055 (DIN EN 12664)
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	High, because it consists only of leaf mass and mineral binding agent. Easy dismantling, because it is mostly fixed by screws. Boards can be reused or composted.
Grey/embodied energy	Qualitative description	Low energy manufacturing, but energy is required for the binding agent magnesite (much lower than cement).
Embodied carbon	Qualitative description	About 50 kg/m^3 embodied C (about 200 kg/m^3 CO_2) in the Typha leaf part.

Typha wallboard – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High, because of the high amount of renewable Typha mass.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium to High, depending on the electric energy source.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low Only cutting off the leaves and pressing the product, no drying necessary.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low A semi-industrial production plant can be built with investment costs for the machinery of less than 500 k€.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the	Low Enables simpler building techniques, since the Typha board unites all qualities relevant for constructions: heat insulation, static stiffening, fire prevention, moisture protection, acoustics and plaster base. Boards can be fixed using glue or screws.

	non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Low Relatively insensitive to mould growth or humidity.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low Easy dismantling and reuse, mostly fixed using screws.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low No waste because of its compostability.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider:	High Renewable raw material; produced with low energy amount; easy dismantling; completely compostable; prevention of CO_2-loss by re-wetting of dried fens; bond of CO_2 and other greenhouse gases with its cultivation in fens; cleaning of nutrient polluted surface water.

	Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High Non-toxic, not inflammable, no parasites/insects known, relatively insensitive to moisture

Typha – Building material availability

Region	Seasonality				Supplies (manufacturers/resellers/ storage)	Disposal (recycling/ end of life)
	1Q	2Q	3Q	4Q		
Northeast						
Northwest						
Red River Delta						
North Central Coast	X	X	X	X	Small local manufacturers	No data available
South Central Coast	X	X	X	X	Small local manufacturers	No data available
Central Highlands						
Southeast						
Mekong River Delta	X	X	X	X	High quantity but not yet popular as a construction material. Can be used for food (young parts) or traditional medicine	No data available

II.2 Rice straw bales

Agriculture – rice			
2.2.3-A1.b	Rice straw bales	Wall-building material for exterior wall constructions	Figure 30: Straw bale (©dena / Stefan Schirmer) 
Rice straw is a waste product from agriculture that is currently burned. Strawbale constructions are labour-intensive but more cost-effective. A non-load bearing straw bale construction (post and beam method): a frame is first built out of wood, stone, or concrete, and the bales serve as an in-fill.[80]			
Technical readiness level of 9			

Rice straw bales – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	400 - 800 [49]
Bulk density [kg/m³]	Quantitative value	80 – 150 [49, 51]
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	No data available
Durability [a]	Assuming that it has been installed in a technically correct manner	Longer lasting than previously thought. Durability is particularly dependent on penetrated and persistent moisture. [53, 54]
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	Normal flammability (EN 13501-1:2077+A1:2009 : E) [56]

Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	The application of plaster or drywall panels to a straw bale wall provides fire performance at least equivalent to that of many conventional construction methods. Tests have shown that an exposed straw bale wall retains its integrity: Straw exposed to an oven temperature of 1000C for 45 minutes did not burn up and only charred. It is believed that the charring of the outer layer of straw, similar to wood, inhibits further decomposition of the straw as the fire progresses. Flameless combustion is due to the lack of available oxygen, and the rate of the smouldering reaction depends on the rate of oxygen transport through the straw bale. [58]
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	The rice straw bales have to be protected and not exposed to direct weathering conditions. [51]
Risk of mould growth	Specify qualitatively in a rough classification	There is a risk of internal condensation and water infiltration is not prevented. [51] Straw can withstand relatively high levels of transient moisture without serious rot. However, if the conditions for mould growth are met in a new wall of fresh straw, some degree of mould growth may occur in the walls of a building. [54] It is conceivable that similar to wood, the risk of colonization by serious rot fungi exists only if unfavourable conditions are maintained over the long term. [54]
Moisture sensitivity	Specify qualitatively in a rough classification	Sensitive to moisture, the materials must be protected from mould growth or thermal performance. [51] Straw is resilient at low temperatures, but care must be taken during periods when the temperature fluctuates around freezing. In the first year of use, there is a high potential for condensation during drying. [53]

Water absorption [%]	Boundary condition: free saturation	No data available
Water absorption coefficient (w-value) [kg/m²h⁰·⁵]		Short-term water absorption by partial immersion, Wp [kg/m2] = Wp = 2,7 – 4,6 kg/m² for 24 h [51]
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	3 - 5 [51]
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	15,73 % (of rice straw) [62]
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	No data available
Tensile strength [N/mm²]	Quantitative value	No data available
Bending strength [N/mm²]	Quantitative value	No data available
Settlement [%]		No data available
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	No data available
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	No data available
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	2970 – 3850 [51]
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m² and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,0432 [51] For straw bales, the difference for parallel and across the straws should be very small, since the straws are usually not arranged homogeneously. Example values from the attached publication are: parallel 0,0605 W/(mK) and 0,0487 W/(mK) transverse. [81]

Renewable properties	Description	Values
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	Rice straw bale construction offers efficient thermal insulation, low-cost construction, a renewable resource, and high environmental performance compared to much of the other traditional materials used in construction. [58] Organic building material that is renewable and compostable.
Grey/embodied energy	Qualitative description	Low embodied energy. [58]
Embodied carbon	Qualitative description	Due to photosynthesis during growth, the straw absorbs approximately 1,20 – 1,35 kg of carbon dioxide for every kilogram of straw. This allows straw bale construction to be considered carbon-negative as a material and allows the potential to offset the carbon footprint of the building as a whole. [58]

Rice straw bales – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High Based entirely on renewable raw material rice straw.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium The same energy sources are used as for conventional materials.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low Low techniques are used for manufacturing the rice straw bales, so that less energy is necessary.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low A natural product that is technically simple to produce. The waste product is available relatively cheaply.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the	Medium Dry construction requires exact planning and precise construction. Dry storage of the building material must be ensured. Due to this property, the construction process itself is strongly dependent on the weather.

	non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Medium No maintenance is required if installed correctly.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low Easy demolition, no waste is generated for landfill.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low A compostable natural product. It is necessary to ensure that the material is not contaminated by harmful substances.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider:	High Since it is a by-product of agriculture that has so far only been burned, the amount of waste and the use of valuable resources can be saved. It is a natural product that is compostable.

	Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High Healthy indoor climate, no harmful substances, sensitivity to moisture. In general, it provides high comfort level for humans and low negative impact on the environment.

Rice straw – Building material availability

Region	**Seasonality**				**Supplies (manufacturers/resellers/ storage)**	**Disposal (recycling/ end of life)**
	1Q	**2Q**	**3Q**	**4Q**		
Northeast	X	X	X	X	Low quantity	A lot of rice straw is burned
Northwest	X	X	X	X	Low quantity	A lot of rice straw is burned
Red River Delta	X	X	X	X	Small local manufactures, not yet popular	A lot of rice straw is burned
North Central Coast	X	X	X	X	Small local manufactures, not yet popular	A lot of rice straw is burned
South Central Coast	X	X	X	X	Small local manufactures, not yet popular	A lot of rice straw is burned
Central Highlands						
Southeast						
Mekong River Delta	X	X	X	X	The highest quantity in the country. Small local manufactures	A lot of rice straw is burnt (in some cases, for fired bricks)

II.3 Rammed Earth

Other – Rammed Earth			
2.2.4-D1.a	Rammed Earth	Wall-building material for exterior wall constructions	Figure 31: Wall containing rammed earth (©dena / Stefan Schirmer) 
To obtain a monolithic wall, the wall is built by compacting the earth in formwork with a rammer. The thickness of each earth layer is 10-15 cm (after the compaction). To enhance the mechanical strength and durability, hydraulic binders can be added (e.g. cement or lime). In that case, the material is called "stabilised". The material is called "unstabilised" when there is only the earth. Rammed earth walls are usually manufactured on-site, but the walls can also be prefabricated			
Technical readiness level of 9			

Rammed Earth – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	300 - 500
Bulk density [kg/m³]	Quantitative value	1900 - 2050
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	25 - 30
Durability [a]	Assuming that it has been installed in a technically correct manner	A least 50 years; numerous buildings 200-300 years
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	No data available

Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	The walls should be covered by the roof and supported by a foundation (stone or concrete) to avoid constant contact with water. In some cases, plaster can also be used, but this is less popular for recently constructed buildings.
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Low risk of mould and parasitic infestation.
Risk of mould growth	Specify qualitatively in a rough classification	The mechanical strengths of the material decrease when the water content increases, so it is not recommended to use the material in permanent contact with the water. The permanent water content of the material should not be more than 6%.
Moisture sensitivity	Specify qualitatively in a rough classification	The saturated state is at about 10 - 12% (in mass). For unstabilised rammed earth, the water absorption test (water immersion) cannot be carried out due to the sensibility of the material to the water.
Water absorption [%]	Boundary condition: free saturation	15 - 35
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]		Wet state: 3 - 7 Dry state: 7 - 14
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	1,5 – 2 % in mass
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	No data available
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	0,5 - 3 N/mm2 for unstabilised rammed earth and 2 - 12 N/mm2 for stabilised rammed earth.
Tensile strength [N/mm²]	Quantitative value	10 - 22% of the compressive strength
Bending strength [N/mm²]	Quantitative value	No data available
Settlement [%]		No data available

Chemical properties	Description	Values
Chemical resistance	With which chemicals does the material react?	Good chemical resistance
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	No data available
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	520 - 1000
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m² and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,6 – 1,1 (depending on the density and the moisture content)
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	If the material is unstabilised, the recyclability is nearly 100 %. The average life cycle is 50 years, but can be longer in numerous cases.
Grey/embodied energy	Qualitative description	If the material is unstabilised, the embodied energy is very low [66]. Even for cement stabilised rammed earth, the embodied energy is still lower than that of conventional materials [67].
Embodied carbon	Qualitative description	For unstabilised rammed earth, the embodied carbon is very low. For cement stabilised rammed earth, the embodied carbon increases due to the cement's carbon footprint. From the embodied energy, it is expected that the embodied carbon of cement stabilised rammed earth is still lower than that of conventional materials, however, no information on this topic was found.

Rammed Earth – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High If the material is unstabilised earth, it can be made from the in-situ excavated soil. In that case, the recycled material is nearly 100 %. If the material is stabilised rammed earth (e.g. cement is added, about 5 – 10 % by weight), the recycled part from the in-situ excavated soil is still high, around 90 %.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium The same energy sources are used as for conventional materials.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low Unstabilised rammed earth has very low energy consumption when compared to conventional materials. Cement stabilised rammed earth has lower energy consumption than conventional materials.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low The manufacturing is simple when compared to that of conventional materials. The technical requirement is less than that of conventional materials.

Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	Medium The construction of rammed earth walls is not complicated, but it demands manpower because there is less automatisation when compared to conventional materials. Moreover, in this case, if the precast is proposed, the transport is not easy. So, the technique is more suitable for in-situ casting.
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Medium The rammed earth material needs care and maintenance which are comparable to that of conventional materials.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low The demolition of rammed earth constructions is easier than that of conventional materials.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low Due to the high recyclability, the demolition waste of rammed earth construction is lower than that of conventional materials.

Environmental criteria	Description	Rating
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider: Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	High The material has a low environmental impact because: • In the phase of construction the material has a low embodied energy. • In the phase of occupation the material has positive hygro-thermal properties which can regulate the indoor environment (especially the humidity), which has positive effects on energy consumption. • In the demolition phase the material is recyclable.
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High The material is not flammable, can absorb and desorb the humidity depending on the environmental humidity. This capacity can aid to prevent excess moisture, which improves the air quality.

Rammed Earth – Building material availability

Region	**Seasonality**				**Supplies (manufacturers/resellers/ storage)**	**Disposal (recycling/ end of life)**
	1Q	**2Q**	**3Q**	**4Q**		
Northeast	X	X	X	X	Local workers. The material has been traditionally used in Vietnam.	Possible but no specific information found
Northwest	X	X	X	X	Local workers. The material has been traditionally used in Vietnam.	Possible but no specific information found
Red River Delta	X	X	X	X	Local workers. The material has been traditionally used in Vietnam.	Possible but no specific information found
North Central Coast	X	X	X	X	Not yet popular	Not yet popular
South Central Coast	X	X	X	X	Not yet popular	Not yet popular
Central Highlands	X	X	X	X	Not yet popular	Not yet popular
Southeast	X	X	X	X	Not yet popular	Not yet popular
Mekong River Delta	X	X	X	X	Not yet popular	Not yet popular

III. Annex 3 Insulation materials

III.1 Reed insulation board

Aquaculture – Reed			
4.4.2-C2.a	Reed insulation board / e.q. “Hiss Reet Schilfplatten”	Insulation material	Figure 32: Reed (©Fraunhofer IBP / A. Zegowitz) 
Hiss Reed insulation boards consist of bundled and mechanically pressed reed stalks. The reed panels are made of continuous reed stalks with a diameter of about 3mm to a maximum of 15mm. They are tied horizontally along the length (across the direction of the stalk) with 2,2mm thick galvanized wires at a distance of about 100 mm from the edge on both sides. In the thickness direction, the binding is made of 2,2mm thick galvanized hooks (bars) at a distance of 40mm - 60mm and they are connected with the longitudinal binding. The reed panels do not contain any additives added during the production process.			
Technical readiness level of 9			

Reed insulation board – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	40 - 120
Bulk density [kg/m³]	Quantitative value	130
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	No data available
Durability [a]	Assuming that it has been installed in a technically correct manner	30 – 40 as roof covering

Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	B2 according DIN 4102 Class E, EN 13501
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	No data available
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	The reed insulation boards may be installed only in structures where they are protected from precipitation.
Risk of mould growth	Specify qualitatively in a rough classification	Exterior insulation has to be protected
Moisture sensitivity	Specify qualitatively in a rough classification	Due to its high silicate content, the natural product reed is insensitive to the effects of moisture.
Water absorption [%]	Boundary condition: free saturation	No data available
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]		No data available
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	No data available
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	15 [kg/kg] M.-% (DIN EN ISO 1257)
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	No data available
Tensile strength [N/mm²]	Quantitative value	190 N (metal wire)
Bending strength [N/mm²]	Quantitative value	No data available
Settlement [%]		No data available

Chemical properties	Description	Values
Chemical resistance	With which chemicals does the material react?	No data available
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails. Qualitative classification	No data available
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	1200
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m^2 and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,061
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	Fully compostable, can be burned
Grey/embodied energy	Qualitative description	Minimal grey energy for harvesting and production
Embodied carbon	Qualitative description	Approx. 30 tons of CO_2 per hectare of cultivated land

Reed insulation board – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High Thermal insulation from reeds is made manually without chemical additives, only by binding with wire. Reed is a natural and renewable raw material.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	High The harvesting and production of reed insulation can be carried out with mechanical machines and low energy consumption.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low Since reeds are harvested after it dies and is dried out, technical drying is usually not necessary. Therefore, comparatively little energy is required for the production of reed insulation.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low Both harvesting and production are done with mechanical machines that are available on the market and easy to use.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the	Medium Reed insulation is supplied in sheets with a length of 2.0m and a width of 0.8m - 2.0m. A special method of transport is not necessary, but the insulation material must be protected from moisture. The insulation boards can be screwed to the walls both as frame insulation, as well as for interior

	non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	and exterior insulation. The boards can be cut with a saw in the longitudinal direction. In the transverse direction it is necessary to cut open the binding council. The effort is similar to other comparable insulation materials.
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Medium If the material is protected from the weather and a structure is chosen in which the material is protected from moisture, it does not require any further maintenance or renewal.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low Depending on the application, the insulation can be removed by hand. In connection with plaster layers, the bonding wire of the boards can be loosened to separate the materials from each other. The cost of disposal is similar to that of other insulating materials.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low Since the insulation does not contain any additives, the waste materials can be composted. Before composting, it is advisable to burn the material to generate heating energy. Reuse as an insulation material is not recommended due to unknown ageing processes.

Environmental criteria	Description	Rating
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider: Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	High As a renewable resource, the use of reed is an environmentally friendly product and has an excellent carbon footprint due to its CO_2 binding properties. After its usage as insulation, the reed can be composted without hesitation and returned to the biological cycle. The harvesting of reeds can have both positive and negative effects on the environment and must be assessed in advance in the individual areas.
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	Medium Reed has no toxic properties and can be processed and installed in living spaces without hesitation. Declared as B2, it is a normally flammable product that does not produce toxic gases when burned.

Reed – Building material availability

Region	Seasonality				Supplies (manufacturers/resellers/ storage)	Disposal (recycling/ end of life)
	1Q	2Q	3Q	4Q		
Northeast						
Northwest						
Red River Delta	X	X	X	X	Not yet popular as a construction material	No data available
North Central Coast	X	X	X	X	High quantity but not yet popular as a construction material	No data available
South Central Coast						
Central Highlands						
Southeast						
Mekong River Delta	X	X	X	X	High quantity but not yet popular as a construction material	No data available

III.2 Seaweed insulation

Aquaculture – Seaweed			
4.4.3-C1.b	Seagrass (seaweed) / e.g. “Zostera-Dämm”	Insulation Material	Figure 33: Seaweed (©dena / Stefan Schirmer) 
The product Zostera-Dämm is a thermal insulation material made from cleaned and crushed seaweed. The raw material is seaweed washed up on beaches, which is a waste product from beach cleaning. The product does not contain any additives added during the production process. The thermal insulating material is used for the production of non-pressurized insulating layers in the area of wall and ceiling constructions and can be used only in constructions where it is protected from weather conditions and humidity.			
Technical readiness level of 9			

Seaweed insulation – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	As loose-fill, seagrass of any thickness can be installed. The settlement due to its weight must be considered. Mats are currently produced up to 100mm
Bulk density [kg/m³]	Quantitative value	75
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	No data available
Durability [a]	Assuming that it has been installed in a technically correct manner	> 30 a
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	B2 according to DIN 4102-1 Class E according to EN 13501-1

Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	No data available
Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Needs protection
Risk of mould growth	Specify qualitatively in a rough classification	Rating level 3. according to EN ISO 846 Medium resistant to parasites and mould
Moisture sensitivity	Specify qualitatively in a rough classification	No data available
Water absorption [%]	Boundary condition: free saturation	No data available
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]		No data available
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	1,5
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	0,33 [kg/kg] M.-%
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	No data available
Tensile strength [N/mm²]	Quantitative value	No data available
Bending strength [N/mm²]	Quantitative value	No data available
Settlement [%]		5
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	The insulation has a salt content that can react.
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails, etc.? Qualitative classification	A corrosion test according to Annex E of the CUAP Directive showed that a pH value of 6,9 is achieved in a seagrass-water mixture. Storage of metal foils on

		moist seagrass did not affect copper foil, while zinc foil showed slight destruction by corrosion.
Thermal properties	**Description**	**Values**
Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	2000
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m^2 and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,045
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	Seagrass is a natural product and comes as an insulating material without further additives. The existing salt content is responsible for the fact that seagrass insulation does not require any further fire protection agents and is more resistant to rot, fungi and pests. If the seagrass is collected from the beach, it certainly makes sense to clean it by sieving out sand and shell residues. If it is harvested underwater, the cleaning effort would be reduced, but this would certainly harm the ecological aspects. Therefore, it can be composted and used as plant fertilizer at the end of its life phase.
Grey/embodied energy	Qualitative description	Compared to other insulation materials, the mining and production of seagrass insulation consume little energy.
Embodied carbon	Qualitative description	No data available

Seaweed insulation – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	High Seaweed is a 100 % pure building material that, thanks to its high salt content, does not require any further chemical fire protection. The used raw material is washed up by natural circumstances. The product is 100% vegetable waste. [77]
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Medium Seaweed is a renewable raw material that can be collected without great effort on appropriate beaches with light machinery. When the raw material is processed into an insulating material, it passes through various mechanical processing stations where the seaweed is cleaned and dried. The process heat for drying is usually generated by burning petroleum-based fuels. An additional drying step is necessary if the raw material is used to produce board-shaped insulating materials with the help of binding agents.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low The energy consumption during production and the use of renewable energy depends on the production plant. However, it can be expected that a significantly lower amount of energy is required for drying seaweed insulation than for conventional insulation materials.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low Technically simple screening and drying steps are necessary for production. A preparation plant requires comparatively little space.

Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	Low Loose seagrass insulation, like other loose insulations, can be placed by hand or by a blowing machine in a cavity. To obtain a consistent quality and thus a consistent U-value, the appropriate quantity for the cavity must be weighed before installation. Loose material is usually transported in big bags and can therefore be easily moved on construction sites. Also, an application as seaweed mats is possible and can be produced in different shapes and sizes. As with comparable insulating materials, sheets or rolled goods are conceivable. [82]
Cleaning, care, and maintenance	Materials that are long-lasting and need little maintenance are preferred. Is this material comparable to its non-renewable variant? Compared to the non-renewable variant, how much more or less maintenance and care does it require? Please explain your reasoning.	Medium Investigations following the CUAP guideline found that seagrass insulation is suitable as a material in specified building component designs with adjusted vapour and air barrier layers on the inside and outside. Used in a closed construction, it does not require any further maintenance or care and, due to its resistance to mould, it can also be used without problems as an insulating material within exterior walls where moisture can occur due to temperature differences.
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low Since the seaweed has already been thoroughly cleaned during factory processing, its residues can be composted without any problems. The effort required for demolition depends on the type and nature of the site. Used as loose-fill, the material can be vacuumed or removed by hand.[77]
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low Since it is a 100% natural product, it can be introduced into a biological cycle and usefully reused as a plant fertilizer.

Environmental criteria	Description	Rating
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider: Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	Medium Since seagrass is a natural material that can be easily collected and processed with little energy input, it produces a negative carbon dioxide footprint and thus has a great advantage over other building materials. It should be noted that on sandy beaches, washed-up seaweed protects the beach from wind erosion and provides a habitat for many small animal species. The effects of removing alluvial seaweed on the surrounding habitat must be studied separately.
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High Seaweed has resistance to rot and mould due to its internal salinity and is difficult to ignite due to its high silicate content. Since many species of algae are used in food and also for medicinal purposes, it is assumed that as a biological plant seaweed is not toxic and therefore, a safe building material. [83]

Seaweed – Building material availability

Region	Seasonality				Supplies (manufacturers/resellers/ storage)	Disposal (recycling/ end of life)
	1Q	2Q	3Q	4Q		
Northeast	X	X	X	X	Harvest seagrasses (mainly Zostera, Ruppia, and other Hydrophytes) for feed, livestock and fertiliser.	No data available
Northwest						
Red River Delta	X	X	X	X	Harvest seagrasses (mainly Zostera, Ruppia and other Hydrophytes) for feed, livestock and fertiliser.	No data available
North Central Coast	X	X	X	X	Not yet popular as a construction material	No data available
South Central Coast	X	X	X	X	Not yet popular as a construction material	No data available
Central Highlands						
Southeast						
Mekong River Delta	X	X	X	X	Not yet popular as a construction material	No data available

III.3 Typha insulation board

Aquaculture – Typha			
4.4.2-C3.b	Typha insulation board	Insulation material	Figure 34: Typha (©dena / Stefan Schirmer) 
Board made of typha Angustifolia leaves, bonded with magnesite. No other additives like biocide or fire retardant. Low density for lower thermal conductivity.			
Technical readiness level of 9			

Typha insulation board – Performance values		
Physical properties	**Description**	**Values**
Thickness [mm]	Specify the (range of) available thicknesses of the material	20 - 120
Bulk density [kg/m³]	Quantitative value	155 (DIN EN 1602)
Porosity n [Vol.-%]	The ratio of the pore volume to the total volume of the building material element	85
Durability [a]	Assuming that it has been installed in a technically correct manner	> 50
Fire protection (class)	If possible, specify the respective standard (e.g. EN 13501-1, DIN 4102-1) rating for the **material**	Euroclass B (ISO 5660-1:2015)
Fire resistance (class)	If possible, specify the respective standard (e.g. EN 13501-2, DIN 4102-2) rating for the **building component**	No data available

Weathering resistance	Specify whether, for example, a weather protection layer is required, free weathering is possible, etc.	Weather Protection required (e.g. plaster)
Risk of mould growth	Specify qualitatively in a rough classification	Low, due to the plant's defence substances (tannins) and high pH-value
Moisture sensitivity	Specify qualitatively in a rough classification	Low, but prolonged contact with liquid water must be avoided
Water absorption [%]	Boundary condition: free saturation	50 (DIN EN 12087)
Water absorption coefficient (w-value) [kg/m²h$^{0.5}$]		1,6 (DIN EN ISO 15148)
Diffusion resistance (µ-value)	Water vapour diffusion resistance number (µ-value)	Dry Cup: 18 Wet Cup: 16 (DIN EN ISO 12572)
Sorption isotherm – u_{80} [Vol.-%]	Water content at 80% relative humidity	3,1 (DIN EN ISO 12571)
Mechanical properties	**Description**	**Values**
Compressive strength [N/mm²]	Quantitative value	No data available
Tensile strength [N/mm²]	Quantitative value	No data available
Bending strength [N/mm²]	Quantitative value	No data available
Settlement [%]		No data available
Chemical properties	**Description**	**Values**
Chemical resistance	With which chemicals does the material react?	Acids
Corrosion potential/compatibility	Does steel corrode when used with it? E.g. nails, etc.? Qualitative classification	The magnesite binding agent can corrode metal fastenings at higher levels of humidity
Thermal properties	**Description**	**Values**

Specific thermal capacity cp [J/kgK]	The ability of a substance to store thermal energy. The energy required to heat 1 kg of a substance by 1 K.	Ca. 1500
Thermal conductivity λ [W/mK]	Heat flow that passes through a 1 m^2 and 1 m thick layer of a material at a temperature difference of 1 Kelvin (K). The smaller λ is, the better the insulating capacity of the building material.	0,043 (DIN EN 12664)
Renewable properties	**Description**	**Values**
Life cycle and recyclability	Qualitative description, e.g. reuse, compostable	High, because it consists only of leaf mass and a mineral binding agent. Easy dismantling, because it is mostly fixed by screws. Boards can be reused or composted.
Grey/embodied energy	Qualitative description	Low energy manufacturing, but energy is required for the binding agent magnesite (much lower than cement)
Embodied carbon	Qualitative description	About 30 kg/m^3 embodied C (means about 120 kg/$m^3$$CO_2$) in the Typha leaf part.

Typha insulation board – Performance values		
Green = positive (compared to conventional material); beneficial effect on resource efficiency Blue = neutral (compared to conventional material); neutral effect on resource efficiency Red = negative (compared to conventional material); negative effect on resource efficiency		
Functional criteria	**Description**	**Rating**
Functional criteria	Description	High, because of the high amount of renewable Typha mass.
Percentage of recycled, renewable, or by-product material composition	Materials can be manufactured using recycled materials or waste materials at different percentages. Please explain your reasoning.	Medium to Low, depending on the electric energy source.
Manufacturing – energy source	Material manufactured using renewable resources (i.e. renewable energies, such as wind, solar or tidal, as well as renewable materials, such as wood (certain certified species that are rapidly renewable), grass or sand) rather than non-renewable (i.e. fossil fuels) is preferred. Please explain your reasoning.	Low Only cutting off the leaves and pressing the product, no drying necessary.
Manufacturing – energy consumption comparison	Compared to the non-renewable variant, how much more or less energy does it require during manufacturing? Please explain your reasoning.	Low A semi-industrial production plant can be built with investment costs for the machinery of less than 500k€.
Manufacturing – a technical requirement	Compared to the non-renewable variant, how high are the investment costs for manufacturing? Please explain your reasoning.	Low Enables simpler building techniques, since the Typha board unites all qualities relevant for constructions: Heat insulation, static stiffening, fire prevention, moisture protection, acoustics and plaster base. Boards can be fixed using glue or screws.
Construction	Is the material easy to assemble, and does it generate little to no residue during construction (e.g. dry or wet	Low Relatively insensitive to mould growth or humidity.

	construction)? Is the material easy to transport, or does it require specialised transport solutions? Compared to the non-renewable variant, how difficult and how much more or less energy is required during assembly? Please explain your reasoning.	
Demolition – expense/effort	The effort of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how difficult and how much more or less waste does it generate? Please explain your reasoning.	Low Easy dismantling and reuse, it is mostly fixed using screws.
Demolition – waste	Waste of demolition, dismantling, and disposal of other end-of-life scenarios. Compared to the non-renewable variant, how much more or less waste does it generate? How valuable is the waste, e.g. for recycling, compared to the conventional material? Please explain your reasoning.	Low No waste because of its compostability.
Environmental criteria	**Description**	**Rating**
Positive environmental impact	The material used for the construction of buildings must not harm the environment, pollute air or water or cause damage to the earth, its inhabitants and its ecosystems during the manufacturing process as well as during use or disposal after the end of life. Consider: Efficiency in extraction, manufacturing, and construction Waste reduction (avoidance/reduction/reuse, salvage or recycle) Renewable resources Material, product component and assembly	High Renewable raw material; produced with low energy amount; easy dismantling; completely compostable. Prevention of CO_2-loss by re-wetting of dried fens; bond of CO_2 and other greenhouse gases with its cultivation in fens; cleaning of nutrient polluted surface water.

	durability Compared to the non-renewable variant, what is its environmental impact? Please explain your reasoning.	
Positive environmental comfort	The material should be non-toxic and contribute to good indoor air quality. Consider: Material toxicity Flammable materials Parasites/insects Air Moisture Compared to the non-renewable variant, what is its environmental comfort level? Please explain your reasoning.	High Non-toxic, not inflammable, no parasites/insects known, relatively insensitive to moisture.

Typha – Building material availability

Region	Seasonality				Supplies (manufacturers/resellers/ storage)	Disposal (recycling/ end of life)
	1Q	2Q	3Q	4Q		
Northeast						
Northwest						
Red River Delta						
North Central Coast	X	X	X	X	Small local manufacturers	No data available
South Central Coast	X	X	X	X	Small local manufacturers	No data available
Central Highlands						
Southeast						
Mekong River Delta	X	X	X	X	High quantity but not yet popular as a construction material. Can be used for traditional medicine or the young parts for food	No data available

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