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Review

Exploring Low-Carbon Design and Construction Techniques: Lessons from Vernacular Architecture

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Abstract: This paper presents a comprehensive review of low-carbon materials and construction techniques commonly used in vernacular buildings. The study highlights the relevance of vernacular architecture in the context of the shift towards sustainable construction practices. A combination of a climatic zone map, vernacular language type map, and continent map is used to identify the vernacular regions. Eight bio-based low-carbon materials, including wood, adobe, rammed earth, cob, sod, thatch, bamboo, and straw bales, are discussed, along with their characteristics, availability, and environmental impacts. The construction techniques associated with these materials are explained, emphasizing their simplicity, cost-effectiveness, and adaptability. The paper also explores two important design approaches: design for disassembly and design for modularity that were used in vernacular building. The review found the use of low-carbon materials and construction techniques derived from vernacular architecture can contribute to minimizing waste, reducing environmental impacts, and promoting a circular economy in the building industry. This research provides valuable insights for architects, engineers, and policymakers seeking sustainable alternatives in the construction sector.

Keywords: life cycle; low carbon; bio-based material; vernacular; design for disassembly; modularity

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1. Introduction

1.1. Research Motivation

The recent circular economy movement aims to move the industry (including the building industry) from a linear to a circular model, which is characterized by a continuous loop from production to recycling that results in minimal waste and environmental impact [1,2]. In the past, researchers suggested that the building and construction industry adopt a preindustrial model in which bio-based materials are used and the material cycle is closed with minimal waste [2]. In today's world, this model can be described as a low-carbon approach, which uses natural (bio-based) resources and minimizes waste [3,4]. However, this model seems unrealistic to many practitioners and policy makers in the building sector, mainly because it relies heavily on high-tech solutions with a high cost. Multiple researchers have suggested a shift to alternative approaches and solutions that are low tech and low cost, such as returning to traditional and vernacular construction technologies that have been used by local communities for centuries [4–7].

A signature characteristic of vernacular buildings is their use of bio-based materials, which refer to products that mainly consist of substances derived from living organisms and either occur naturally or are synthesized [8]. Some common bio-based materials are wood and leather. They may also refer to products made by processes that use biomass [8]; in this sense, soil can be counted as a bio-based material. Bio-based materials convert CO_2 into biomass through photosynthesis during the plant's growth before being processed to make building materials [9]. Soil carbon sequestration is a process in which CO_2 is transferred from the atmosphere and stored in the soil through plants [10].

Among all bio-based materials, wood has received the most attention [9]. In recent years, many scholars and policy makers in developed countries have mainly focused on the promotion of wood buildings, especially mass timber construction, as the key solution to reducing embodied carbon emissions from the building sector [11]. Researchers have even advocated using engineered timber to turn the global building stock into a carbon sink to mitigate the climate crisis [12]. This solution is incomplete and biased due to two factors. The first factor is a global supply and demand mismatch, which has been overlooked. As pointed out by [13], the largest forest areas that allow for the sustainable sourcing of wood building materials exist in the Global North, that is in North America and Europe, despite these developed countries having much lower new construction rates and demand [13]. The global building stock is expected to double in size, and the largest new building stock increase will happen in developing countries in Africa and Asia, accompanied by a population growth [13]. By 2055, Asia's population is expected to peak at 5.4 billion, while by 2100, Africa's population is expected to reach 10.9 billion [11]. In those areas with the highest population growth, the demand for wood as a primary construction material cannot be fulfilled [9]. The second factor is the heavy reliance on high-tech and high-cost solutions; for example, cross-laminated timber demands a large and sophisticated manufacturing process that leads to a high capital cost [14]. These high-tech and high-cost solutions are not accessible to most developing countries, which have the highest demand for new construction. Regardless of the impracticality of mass timber construction in many countries, the research and development of mass timber is still heavily promoted and funded by many funding agencies.

There is a need to rethink the approach of finding one solution and implementing it everywhere. Rather, other low-carbon solutions should be considered that are derived from locally available materials and construction knowledge and that are low cost, practical, flexible, and adaptable. Vernacular architecture naturally becomes the resource for drawing knowledge and inspiration.

1.2. Vernacular Architecture

Vernacular architecture has been widely understood as "the architectural language of the people with its ethnic, regional, and local dialects: the product of non-experts" [15]. Vernacular architecture responds to local climatic, material, and crafts conditions and reflects the culture, customs, and lifestyle of the local community [16]. Many of the design and construction practices in vernacular architecture are the core of sustainable design principles, which are environmentally friendly and less energy intensive than their modern counterparts [17]. The use of locally available materials and construction techniques familiar to local builders is one of the most important characteristics of vernacular architecture and is an identity factor of regional differentiation [18]. Since the Industrial Revolution, the increasing use of heavy processed and standardized building materials (e.g., steel) has led to the homogenization of design and construction techniques and consequently the buildings' appearance, the so-called International Style [19]. The wide adoption of mass-produced building materials, such as concrete and steel, directly contributes to the disappearing use of local and traditional techniques and materials, or vernacular architecture. In modern architecture, many industrially produced materials not only have a higher energy intensity but also produce considerable environmental impacts, while in vernacular building, natural materials have had positive impacts in their overall life cycle through biogenetic benefits [20].

However, previous literature reviews on traditional buildings revealed a large gap in facilitating "traditional knowledge for preservation and adaptation" and potentially for building climate resilience [21]. Even though local knowledge and insights embedded in vernacular building hold invaluable lessons regarding low-cost climate adaptation strategies [22], they are often underestimated in policy and practice as a practical solution, treated as a one-off example of folk tradition without scientific evidence [23]. To this extent, this paper explores the knowledge and use of various bio-based materials in vernacular buildings globally. It is based on previous vernacular building studies in Africa, Asia, Europe, and North America. The review divides the vernacular materials into three categories: primary natural materials, secondary natural materials, and light-processed materials. Light-processed materials can be derived from natural or synthetic sources and undergo various processing techniques such as foaming, aerating, or incorporating additives to reduce density while maintaining structural or other strength. The processing methods may involve altering the chemical composition, physical structure, or surface properties of the materials. Two design and construction techniques commonly used in vernacular architecture—design for disassembly and design for modularity—are explained in terms of their application and benefits.

2. Research Methodology and Materials

To extract information about the materials used in vernacular architecture, we took the first step of categorizing the vernacular architecture regions. Since climatic conditions, cultural heritage, and geographic location shape vernacular architecture, we adopted the method by [24] to categorize the regions based on these three traits. To classify the climatic regions, we used a simplified Köppen climate classification, which divides the world into 11 zones for this study [25]. To map the cultural heritage, this study adopted a method commonly used by anthropologists, that is, tracing language families based on linguistic similarities. In fact, vernacular is a linguistic term [26]. While religion, geographic location, dialect, and ethnicity can change within a group of people, basic language traits—such as syntax, phonetics, and semantics–often remain the same, and are strong indicators of a shared culture heritage [27]. In this study, the language family division developed from the Evolution of Human Languages project [28] was adopted. Geographic boundaries (continent map) is the last characteristic in developing the vernacular region, according to the notion that geography-specific conditions determine the available building materials. In addition, barriers between continents, such as mountains and oceans, create obstacles to migration, and thus the local culture and traditions are confined in the place that is critical for developing vernacular tradition [28,29].

Combining a climatic zone map, language map, and continent map resulted in 114 vernacular regions. After defining those vernacular regions, a literature review on vernacular architecture building materials and construction techniques was conducted. Meanwhile, an extensive online photo search was conducted for vernacular buildings to better understand the wide range of vernacular material distribution. Since this study focuses on low-carbon, sustainable lessons that can be drawn from vernacular buildings, particular attention is given to vernacular architecture practices within climate zones and continents. Three categories and eight types of representative low-carbon materials used in vernacular architecture are identified in Section 3. Moreover, two low-carbon design and construction techniques that are prevalent in many vernacular regions are explained in Section 4. The conclusion and discussion are presented in Section 5. Table 1 lists the key materials and construction techniques as follows: column 1 contains the materials and techniques, column 2 provide references to the literature where they are found, and column 3 specifies their application by region. The listed materials and techniques are explained in details in the following subsections. Detailed explanations of the listed materials and techniques can be found in the subsequent subsections.

Table 1. Literature included in this review.

Material	Reference	Region/Country
Adobe	[30]	China
	[31]	Portugal
	[32]	Middle East
	[33]	Africa
	[34]	Egypt
	[35]	Egypt
	[36]	Egypt

Table 1. *Cont.*

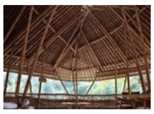
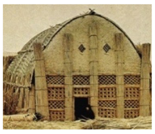
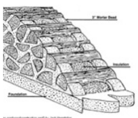
Material	Reference	Region/Country
	[37]	Global
	[38]	France
	[39]	United States
	[40]	Tanzania
Rammed earth	[41]	Fertile Crescent
	[42]	China
	[4]	Portugal
	[1]	Global
	[43]	British Isles
Cob	[44]	France
	[45]	United States
	[46]	Global
	[47]	Europe
	[48]	Central Asia
	[49]	Nigeria
	[50]	Yemen
	[51]	Britain
	[52]	Italy
	[53]	Britain
Sod	[54]	North America
Thatch (reed)	[55]	Middle East
	[56]	Global
	[57]	Japan
	[58]	Indonesia
Bamboo	[59]	South Korea
	[60]	Ghana
	[61]	India
	[62]	Italy
	[63]	India
	[64]	Global
	[65]	Global
	[66]	Global
	[67]	India
Straw bale	[68]	Nigeria
	[69]	Africa
	[70]	Middle East
	[71]	Global
	[72]	Britain
	[73]	Portugal
	[74]	New Zealand
	[75]	Italy
Cordwood	[76]	France
	[77]	Poland, Scandinavia, Central Europe, Eastern Canada, and Northern United States
	[78]	Scandinavia, Canada, Northern United States
	[79]	North America, Europe
	[80]	Canada

3. Use of Bio-Based (Low-Carbon) Materials in Vernacular Architecture

Three bio-based-material categories can be identified in vernacular buildings: primary natural materials, secondary natural materials, and light-processed materials. Primary natural materials refer to the materials found in the natural environment and applied directly to the building construction. Wood, stone, bamboo, mud brick (natural dry), and grass are popular natural raw materials across different climatic regions, and their application extends to the entire world. The second category, secondary natural materials, uses processed natural materials from other industries to make building materials or components; for example, waste wood from logging and agricultural residue (e.g., straw). A large portion of the first and second categories' low-carbon materials sequester CO_2

during their growth as plants and possess a negative carbon footprint. The third category, light-processed natural materials, refers to fired brick, terracotta tiles, burnt wood, and other natural materials that require light processes such as kiln drying. Since there are extensive studies and robust knowledge on light-processed natural materials, and they are still widely used today, this paper will focus only on the first two categories. In the following subsections, the most commonly used vernacular materials in each category are explained. In Table 2, the embodied carbon emission intensity and the mechanical and thermal properties of the materials are listed, and references are provided.

Table 2. Embodied carbon intensity of vernacular materials and references.

Categories	Materials	Sample	Embodied Carbon (kg CO_{2eq}/kg)	Compressive Strength (Mpa)	Tensile Strength (Mpa)	Conductivity (W/mk)	References
Primary natural raw material	Wood		0.5				[81]
	Rammed earth		0.26 (only A1–A3)	1.0–2.5	0.1–0.35	0.833–1.4	[4,82]
	Sod block		NA	NA	NA	NA	[54,83]
	Adobe block		0.0018–0.013	0.66–3.04	0.12–0.4	0.516	[31,84]
	Cob		NA	0.24–0.4	2.5 kN/m^2	NA	[45,46]
	Thatch		0.48	0.67	0.32	0.063	[85,86]
	Bamboo		0.5	4.1–38	7.6–35	0.21–0.34	[66,86,87]
Secondary natural raw material	Straw bale		0.4	NA	0.15–0.35	0.03–0.19	[71,75,88]
	Cordwood masonry		130 MJ/kg	0.43–2.14 0.9–1.8		0.128–0.161	[73,76,89,90]

3.1. Primary Raw Materials

3.1.1. Adobe Block (Mud Brick)

As illustrated in Table 1, adobe is one of the earliest materials humans used to construct buildings worldwide and can be found in China [30], Europe [31], North America [39], the Middle East [32], and Africa [33] (refer to Figure 1). Several historians and archeologists indicate Mesopotamia as the origin of adobe brick use, later spreading to Egypt where mud from the Nile River mixed with straw was used to construct simple houses [35,36]. Some of the earliest adobe buildings recorded can be traced to ancient Egypt. Adobe is masonry block that is made of mixed clay, sand, gravel, and straw. It is sundried and used to build thick masonry walls [37]. Even though the portion of straw is small, but it play important role to bind the adobe blocks together and allowing them to dry evenly to prevent cracking due to uneven shrinkage [38]. Adobe is low cost, locally available, recyclable, and adaptable to a large variety of soil types. In addition, it has good thermal and acoustic properties [32]. Its ease of construction not only makes it accessible to many people but also reduces labor and equipment requirements and consequently the energy and emissions. Adobe also has disadvantages, such as low seismic strength [39]. As illustrated in Figure 1a, most adobe buildings, cob, and rammed earth buildings are similar in appearance [40]; however, it differs from rammed earth as water is added to make the adobe block.

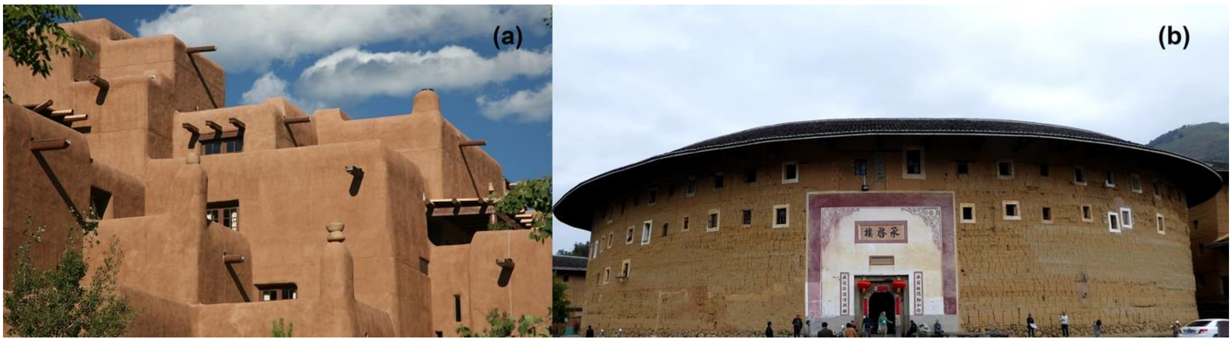


Figure 1. (**a**) Adobe pueblo in New Mexico, US (credit to Wikimedia Commons) and (**b**) Chinese traditional tulou (credit to Wikimedia Commons).

3.1.2. Rammed Earth

Rammed earth construction can be found on all continents except Antarctica, and it is applicable to a wide range of climatic conditions due to its capacity to regulate thermal transfer and humidity [82]. The earliest use of rammed earth as building material can be found in 7th to 9th millennium BC, in Neolithic archaeological sites, such as the Fertile Crescent [41]. It was also found in the Yangshao culture in China, during the 5th millennium BC [42]. Rammed earth wall is made of a mix of sand, clay, silt, and small gravel, similar to the adobe block. Therefore, compressed rammed earth is similar to adobe blocks in appearance, use, and performance (Figure 1b). However, unlike adobe, rammed earth blocks do not require water [40], and hence, the construction techniques are different. Rather than built blocks by blocks (adobe construction), rammed earth walls are built by layers. Each layer is about 15 cm to 15 cm thick soil; it is then placed and tamped into the right location. After the first layer is fully tamed, the second layer can be added and tamped. Because there is no need to wait for the layers to be fully dried, the construction time can be reduced. After the entire wall is built and formwork is removed, the rammed wall is left to dry and cure for several months. At the end, a layer of protective coating is applied when it is necessary. After the rammed earth is completely cured, it behaves similarly to soft sedimentary rock. The rammed earth walls can be thick, up to one meter, and provide excellent thermal mass and structural stability.

There are also disadvantages of rammed earth, such as the requirement for sites to be well drained and maintained and the concern of heavy rainfall. For structural purposes, modern rammed earth buildings require bond or collar beams, as well as reinforced rods. Similar to cob construction, rammed earth construction is labor-intensive due to the compressing and tampering process. However, the use of modern mechanical equipment has made the tamping process easier.

3.1.3. Cob Construction or (Unburnt) Clay Masonry

Cob has a similar material mix as adobe; the main difference between the two is the construction technique. Adobe is first made into rectangular blocks that are sun dried before being used to build, while cob is built while wet [46]. Cob materials and construction can be found in various climate conditions across the globe [47], and thus it is known by many names, such as lump clay, puddled clay, and unbaked clay. Some of the oldest cob houses can be found in Afghanistan [48], Nigeria [49], and Yemen [50]. In Europe, the existing cob-building heritage can be found in Germany, the United Kingdom, and France, and most of those cob buildings date back to the 18th and 19th centuries [47]. Cob walls were often used as load bearing walls for one- to two-story structures [45].

A large variety of fibers were used in vernacular cob construction, based on the availability of materials and local craftsmanship. The most common one was straw, with other materials including barley, bean pods, grass, ferns, and leaves [47]. Fibers were used for assisting handling [51], accelerating the drying process [91], enhancing cohesion and shear resistance of the wall [92], improving weathering resistance, reinforcing the bond between the batches, and distribution of shrinkage throughout the wall [51].

The raw mixture is rolled into bundles (cobs), which some researchers call a lift [48]. The soft bundles are stacked alongside or on top of one another to form layers of up to 45 to 90 cm thick and 10 to 120 cm high, tapering toward the top of the wall [51]. Different from rammed earth construction, additional layer of cob lift is only allowed to be added on the previous one after the previous layer is dried; consequently, cob construction is labor intense and slow [47]. The average drying time of a cob lift ranges from 11 to 21 days, and a whole cob wall can take up to 20 weeks [47].

Despite the labor-intensive nature, cob construction has many advantages. Compared to rammed earth and adobe, cob performs better in terms of shear behavior; it can deform beyond the elastic range with a gradual drop in capacity; therefore, it can be considered as a seismic-resistant material [46]. In addition, research has also shown compacted cob wall with straw reinforcement can resist total failure when subjected to initial flood conditions [53]. As illustrated in Figure 2, adobe, cob, and rammed earth are often grouped together and referred to as earth construction; while sharing similarities, because of the differences of ingrediencies and construction techniques, they have different adoption and implementation around the world. Among the three, rammed earth had the widest adoption, as illustrated in Figure 2c.

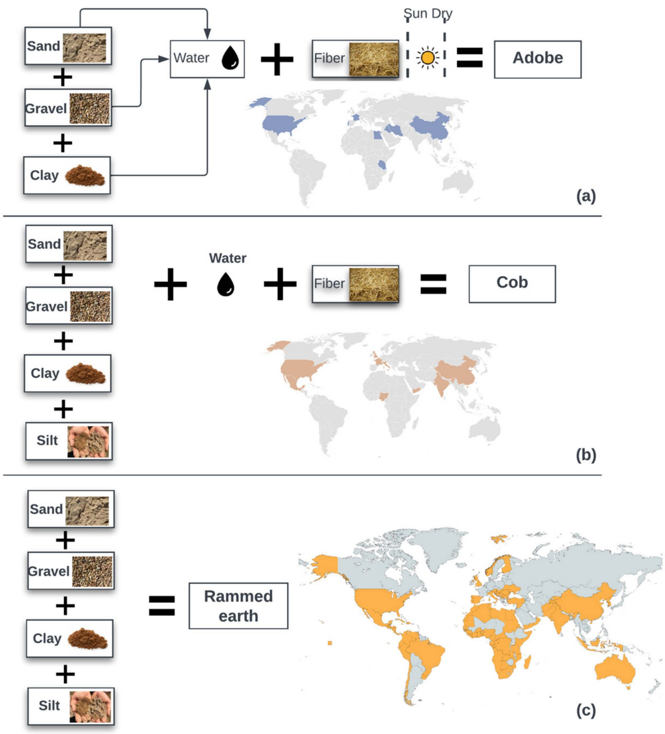


Figure 2. Earth construction comparison. (**a**) Adobe construction. (**b**) Cob construction. (**c**) Rammed earth construction.

3.1.4. Sod Block

Sod refers to the layer including grass and the soil beneath held together by the grassroots [83,93]. Sod is a logical choice, probably the only viable material in the places where trees are limited, such as prairies. First, the sod strips were cut from the ground and divided into blocks, then those blocks were stacked to construct thick walls. Because of the simplicity, sod houses appear in many cultures [54], for example, the turf houses in Nordic countries. Most times, the sod blocks were left unchanged, but in some cases, the sod walls were then plastered with protective layers to increase their durability. In Nordic countries, sod walls were built above and around an excavation or partial dugout to take advantage of earth sheltering, which is an effective passive design strategy to increase the thermal property of a building. Figure 3 illustrates a traditional sod (turf) house built in Iceland. In remote areas, where modern construction materials are not easy to access, this construction can be an alternative option. However, sod construction may not be a viable solution in many locations because of limited supplies and its related environmental impact.

Figure 3. Icelandic turf dugout house (credit to Wikimedia Commons).

3.1.5. Thatch

Thatch construction refers to a building technique that uses dry vegetation available locally. Thatch roofs or walls provide a natural alternative to wood roofing when those materials are not readily available. Among vegetation that can be used for thatch, reed and straw are commonly used materials in many climatic conditions. Other materials have also been used, such as palmetto leaves in tropical climates. Reed grows near wetlands along lakes, swamps, and other water canals, and it also can be found close to agriculture fields and sand dunes [56]. Reed is first found in East Asia [57,58], and then has been cultivated through the Middle East, North Africa, and Southern Europe for thousands of years [55]. Some of the earliest applications of reed as a building material can be found in Egypt thousands of years ago [55], which was the predominant building technique in some regions for housing and communal spaces [56]. Thatch buildings and roofs in general are well ventilated and can be found in temperate, tropical, Mediterranean, and subtropical climatic regions [58]. It has good resistance to seismic forces due to its flexible structure [56]. The primary disadvantage of thatch roofs is their susceptibility to fire, insects, rodents, and rot.

Other materials used for thatch roof include straw and grass. The service life of some thatch huts built with reed is surprisingly long; in Egypt, they can last for 20 years as long as good-quality raw materials are used and regular maintenance is performed [57]. In Japan, some traditional thatch roofs (made with straw thatch and grass thatch) have lasted 40 to 50 years.

3.1.6. Bamboo

Bamboo is a widely used natural material for global building construction. It is a collective name for different species of giant grasses, with up to 90 genera of bamboo in existence, comprising around 1500 species. Bamboo typically grows in subtropical, tropical, and mild temperate climate regions in Africa, Asia, South America, and Oceania [60,61]. Among more than a thousand species of bamboo, only about 20 to 30 species are used in construction, with a few species commonly known and used: Moso bamboo (East Asia), Guadua bamboo (America), Giant bamboo (Southeast Asia), and *Oreobambos* (Africa). In vernacular buildings, bamboo can be used in many forms, such as whole culms, split lengthwise, pressed flat, or woven in mats. The joints are made through tied ropes or by incision of the bamboo [62] (refer to Figure 4). These construction techniques are affordable and simple.

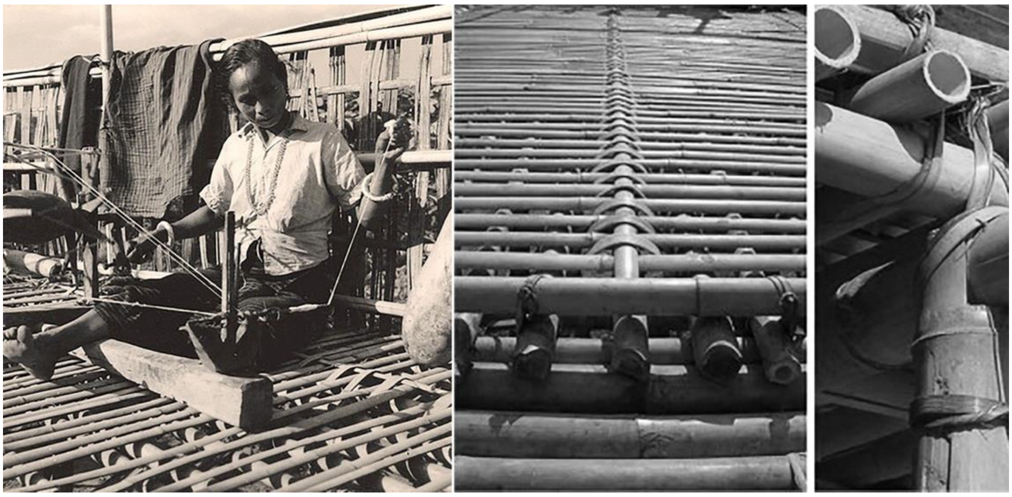


Figure 4. Bamboo construction in Chittagong Hill Tracts, Bangladesh (credit to Wikimedia Commons).

In recent years, the application of bamboo as a cheaper building material substitute for timber has caught practitioners' attention. It has been used to construct affordable housing in developing countries. Bamboo has a high compressive strength that is twice that of concrete, and its tensile strength is similar to that of steel [63]. Bamboo as a primary (e.g., trusses, roof, walls, foundation) and secondary (e.g., flooring) structural material has a relatively high strength and low weight. Bamboo can also be used as a scaffolding material and as a reinforcement within walls [64]. In recent years, multiple studies have found that bamboo can replace steel as a reinforcing material in concrete [94]. This could greatly benefit the low-income housing market, especially in developing countries. Despite the limited actual use of bamboo as a structural material in developed countries, bamboo has been established as a viable structure solution since the 2000s. In 2004, ISO 22157-1 and ISO 22157-2 together officially introduced bamboo's application to structural design worldwide [64]. The first building code for bamboo's application was introduced in India in 1994, "13985: Specification for bamboo mat board for general purposes," followed by the Chinese regulation "GB/T 15780: Testing methods for physical and mechanical properties of bamboo" in 1995 and "GB/T 2690 Bamboo timber" in 2000 [64].

Moreover, bamboo construction can provide an effective structural seismic resisting system. An earthquake's force imposed on a structure depends on its mass and speed of acceleration; with the same acceleration, heavy construction endures a higher earthquake force. Therefore, bamboo is an ideal material as it has a higher density yet is lighter than timber, and thus it will be subjected to a smaller earthquake force due to its small mass [65]. Japan is known for using bamboo as a structural material in vernacular buildings. The 2007 Peru earthquake prompted researchers to examine the earthquake-resistant value of bamboo houses, and in 2012, the country passed bamboo legislation [65]. Furthermore, following the 2016 Ecuador earthquake, Ecuador published a building code for bamboo construction in 2017.

In addition to its structural strength, bamboo is a sustainable material due to its rapid growth rate. It has a shorter maturity cycle of around three to five years, compared to commonly used softwood (e.g., pine) that take 25 to 30 years to mature. Bamboo can produce 12 times more green building materials than wood [63]. Some researchers found a bamboo forest can sequester 17 times as much carbon as that of a typical tree forest [66]. The carbon storage and sequestration rates for bamboo was found to be and 6–13 mg per ha per year [67].

Other more advanced bamboo-based products have been invented and used for commercial buildings in developed countries. For example, laminated bamboo has been tested and used in structural beams [95], columns [96], and shear walls [97]. Their structural strength is competitive with concrete and steel structures, with a much lower associated embodied carbon.

3.2. Secondary Natural Raw Materials

3.2.1. Straw Bale

Straw bale is by-product of grown plants with limited use; it is the dry plant materials or stalks left in the field after the plants have matured and been harvested [68]. The earliest straw constructions appeared in Africa as far back as the Paleolithic Period [68], and the use of straw as a building material in vernacular architecture occurred in the Middle East [98] and China thousands of years ago, by early settlers in areas where trees were limited for wood houses and where sandy soil made sod houses impractical, and thus straw construction became the best, and probably, only solution.

Straw can come from a variety of plants, such as wheat, oats, barley, rye, rice, soybean, corn, and others. It can be exposed or covered by soil or lime stucco. The bale's shape, dimension, and level of compression depended on the baler used, it was found the density of barley straw bales range from 54.6 kg/m^3 to 78.3 kg/m^3, while oat and wheat straw bales range from 81 kg/m^3 to 106.3 kg/m^3 [71]. Research indicated the thermal conductivity of straw bales is lower than that of concrete, brick, and wood. Further, its specific heat capacity ranges between 1075 and 2000 J/(kg·K), which is close to that of conventional materials, which ranges between 1000 and 2500 J/(kg·K) [73]. Multiple studies found straw bale to be a good material for building high-performance exterior walls, with its high thermal property and good hygrothermal performance [73].

In vernacular buildings, straw bale was often used as a load-bearing wall material (refer to Figure 5a). For example, in North America, the "Nebraska style" straw bale wall is a typical load-bearing wall with sufficient structural strength to bear the weight of the roof and comprise the insulation of the wall. On the other hand, the modern-day straw bale construction often uses bales as insulative infill that does not carry structural load. The outer layers around a straw bale core are made of hardwood, plaster, or cement [71].

Figure 5. (**a**) Straw bale load-bearing wall, and (**b**) cordwood wall construction (credit to Wikimedia Commons).

Using straw as an alternative material to wood has several environmental benefits. First, straw is an annual renewable by-product of grain production. Using straw for construction material can avoid the resources and energy required to produce conventional modern building materials, such as insulation. Secondly, as a common practice, straw will be disposed by burning in fields; using straw as construction material can avoid carbon and particulates released from burning. Regarding the straw bale's life cycle assessment, ref. [74] found an annual reduction of 1230 $kgCO_2$ equivalent as compared to a conventional insulated timber house.

3.2.2. Cordwood

Cordwood building is a construction type comprising a collection of building techniques known by various names, such as cordwood, stackwood, and stovewood [78]. In general, it is a masonry construction, in which cut-to-length pieces of raw wood, similar to firewood, are used instead of bricks [80]. The small-dimension logs are placed with the cut ends facing the interior and exterior of the building. Because the logs are set and bound by masonry mortar, small and irregular shaped logs can be utilized, which leads to a highly decorative appearance. Cordwood buildings can be traced back to one thousand years ago in Germany [80], and the building type was also found in Scandinavia, Central Europe, Eastern Canada, and the Northern United States at the end of the 19th century [77,99,100]. According to recorded history since 1850 to present, the use of cordwood construction has appeared in different forms and for various purposes; for example, it was used in barn buildings in Norway and in housing for people and cattle in Sweden and North America [79].

Building a traditional cordwood wall is relatively simple and does not require expensive tools or skilled labor. As illustrated in Figure 5b, the log ends are placed on a bed of wet mortar, which can be done by a pair of hands. Cordwood construction is an exceptionally low-cost building method due to the low-cost material and less-skilled labor requirement. Further, the aesthetics of cordwood building can be appealing. Logs from 38 cm to 60 cm long (long end) can be used to create thick walls, and thus the thickness of cordwood walls varies from 38 cm up to 90 cm [79]. Thicker walls have higher thermal properties and structural stability. Traditional cordwood walls have a greater thermal mass than modern lightweight wood construction (wood stud frames). Therefore, cordwood walls can be found in cold climate regions and seismic areas. In vernacular cordwood construction, clay, cob, sawdust, straw, or other insulative materials were used as mortar. In some cases, even pieces of cloth soaked in mud could be used to hold together the walls [79]. The mortar used in modern cordwood buildings is usually made from a mixture of Portland cement and lime, which has much higher embodied carbon.

4. Low-Carbon Design and Construction Techniques

4.1. Design for Disassembly

According to the United Nations, a circular economy works by extending products' life spans "through improved design and servicing and relocating waste from the end of the supply chain to the beginning" [2]. In the building and construction industry, besides using more durable and recycled materials, an effective way to extend a building product's life span is to reuse building components from old buildings in new buildings. This approach can be achieved through the concept of design for disassembly [101]. In some cases, designing building components to be disassembled and reused in their second life was associated with a decrease of up to 81% in embodied energy and 88% in embodied carbon [101]. However, currently, design for disassembly is not widely practiced in the building industry, mainly due to two issues of reusing building components. First, most modern buildings are designed and constructed for one purpose only, and thus the buildings are not flexible and adaptable. In addition, the buildings were not designed in a way that could be easily dissembled. Second, modern construction techniques and materials make it extremely difficult to disassemble building components. For example, to recycle concrete, it must first be separated from steel, and heavy industrial equipment (with jaws and a large impactor) is required to crush the large pieces of concrete, followed by screening and separation. The whole process makes recycling and reusing concrete difficult and expensive [102]. Therefore, almost all reinforced concrete will be demolished at the end of the life cycle rather than disassembled.

The design process and designers can also play a role in hindering the design for disassembly [103]. In extreme cases, a previous study found that the designer was responsible for almost all the obstacles in the recycling process [104]. To overcome the obstacles, designers need to relearn the skills of design for disassembly. Great examples and lessons can be learned from traditional and vernacular architecture. Design for disassembly has long existed in traditional timber construction worldwide. In Europe, the scarcity of suitable timber in the Middle Ages led to the regular reuse of major structural members from one building to the next [105]. Similar practices can be found in Asian countries. Traditional Chinese and Japanese wood houses were constructed using primary and secondary frames, with the secondary timber members easily disassembled and remodeled with few tools since there were normally no nails or screws used for assembly. In Japanese, the term *kaitai shūri* means "repair by disassembly." This means that traditional wooden buildings are entirely or sometimes partially disassembled and reassembled with new materials, where the primary and secondary structures can be repaired and maintained [106]. This disassembling and reassembling tradition has prevailed through history and has been applied to all building types [106]. As for other natural materials and construction types, such as adobe walls without plaster, it is possible to disassemble adobe blocks for use in other buildings, but to the author's knowledge, no studies or practices on this exist.

4.2. Design for Modularity and Tectonics

Modular building is a construction technique whereby building modules are premade off-site and then shipped to the construction site for installation. Modular design and prefabrication may seem like a modern invention that minimizes construction waste and improve efficiency [107], but it has existed for hundreds of years in traditional and vernacular buildings and is often coupled with design for disassembly.

In the West, the earliest prefabricated timber cottages existed in 1624; they were made in Britain and exported to Australia and other countries [108]. In the East, one of the earliest construction textbooks and manuals on timber structures was published in 1103 BC, during the Song Dynasty, called *Ying Zao Fa Shi*, which means "construction method." The wood module was defined based on its size, then buildings with different functions and hierarchies were built with different modular elements. For example, the first-level wood module has a width of 9 "cun" (~29.97 cm) and a thickness of 6 "cun" (~19.98 cm); thus, this module is suitable for constructing the largest temple with nine to eleven bays. The eighth-level module has a width of 4 "cun" (~13.32 cm) and a thickness of 3 "cun" (~9.99 cm), which can only be used to construct small landscape buildings or utility buildings [109]. The largest module is twice the size of the smallest module, and the other six levels follow gradient series rules that reflect important modular principles. Just like a modern prefabricated modular house, those individual modules of different sizes could be made off-site and transported on-site for installation.

Another example is the bamboo house found in Southeast Asia, where the locally available materials influence the size of the built form. For example, in Chittagong Hill Tracts, Bangladesh, bamboo is used for the floor, columns, and exterior walls (refer to Figure 4), so the housing module is based on the available bamboo material. The lashing method is commonly used for its flexibility, which allows for disassembling the bamboo, adding additional bamboo, and even quickly rebuilding the entire house [110]. Together, the material's structural properties and construction method determine the size of the built form. For a bamboo building, a living space can be around 23 m^2, compared to a wood space that can be up to 60 m^2. Therefore, there is strong modularity and tectonic logic established in vernacular architecture, which differs from the notion that vernacular architecture is organic, random, or even irrational [111].

5. Discussion

In light of the widespread promotion of wood as the ultimate solution for sustainable building, it is crucial to reconsider the approach of adopting a single solution universally. Instead, we should explore alternative low-carbon options that leverage locally available materials and construction knowledge, offering low cost, practicality, flexibility, and adaptability. This review paper provides valuable insights into the contribution of low-carbon materials and construction techniques in vernacular buildings. It encourages a reevaluation of the high-tech approach in the building industry and advocates for the utilization of vernacular knowledge to achieve true sustainability. As listed in Table 2, previous studies have conducted assessments to quantify the embodied carbon (column 4), structural strength (columns 5 and 6), and thermal performance (column 7) of many materials used in vernacular buildings. The included publication covered a wide-range of materials and techniques worldwide, from which we synergized three categorical sustainable areas of knowledge that can be learned from vernacular architecture: (1) sustainability requires contextual factors, (2) design must highlight reuse with low tech, and (3) culturally appropriate solutions should be chosen.

First, **sustainability requires plural but contextual approaches to global challenges**. With 194 countries and the EU joining the Paris Agreement, addressing climate change is a global commitment through political will. In line with this commitment, buildings must be constructed to be carbon neutral by limiting both operational carbon (i.e., emissions because of heating, cooling, lighting, and power) and embodied carbon (i.e., construction-related emissions). The Western solution to this shift toward low-embodied carbon buildings has been mass timber construction, in which the advantages of wood—regarding renewability and atmospheric carbon sequestration—are utilized through products (e.g., cross-laminated or glue-laminated timber) to reduce a building's carbon footprint. While timber buildings are promoted at a global scale, the extent to which the present and future demands of the construction industry can distress the available forests is less clear [112]. In fact, the largest forest areas allowing for the sustainable sourcing of wood building materials exist in developed countries, notably in North America and Europe, while the largest building stock growth happens in developing countries—Asia and Africa—some of which are experiencing significant population growth [11–13]. Accordingly, the application of timber buildings as a one size-fits-all approach to all building types may not be a solution for many developing regions. Research has shown that approaches such as sustainable forest management may not be effective in all countries and can even be associated with higher deforestation in some low-income economies, mainly due to the increased foreign investment and international timber demand. In these cases, locally available low-carbon materials found in vernacular architectural practices can be creatively used in modern construction. Straw bale, for example, is a renewable waste byproduct of grain production of crops [68] and has been traditionally used in vernacular buildings in Africa [68], the Middle East [98], and Asia [98]. Recent scientific research indicates it has superior thermal properties as compared with concrete, brick, and wood [74]. Using natural materials in construction based on their local availability can reduce embodied carbon and emission particulates released from burning [74].

Second, **design for *low tech, low impact versus high tech, high impact***. Nobel laureate ecological economist Herman Daly defined sustainable development as development without growth (i.e., qualitative improvement without a quantitative increase). The development must occur within the biosphere boundaries and be treated with extraordinary caution and by considering its rebound effects, especially in growing economies where the technological advancement has a higher potential to yield an increased resource consumption through growth rates, intensive use, and other factors. In a low-tech and low-process approach to construction, designing for a longer life span, spatial and structural reusability, and adaptiveness to different conditions can enhance the quality of architecture and limit demand for new construction. This approach is the opposite of most modern practices in which buildings are designed and constructed for short life spans, serve specific purposes (e.g., office building), and are fully demolished once their life span is complete. Part of the problem is construction techniques and materials that make it extremely difficult to disassemble building components. Design for reuse, especially for disassembly, has long existed in traditional construction worldwide. In Europe, the scarcity of suitable timber in the Middle Ages led to the regular reuse of major structural members in buildings [105]. Traditional Chinese and Japanese wood houses were constructed using primary and secondary frames, with the secondary timber members conveniently disassembled and remodeled with few tools. In Japanese, the term *kaitai shūri* means "repair by disassembly," meaning that traditional wooden buildings were entirely or sometimes partially disassembled and reassembled with repairs, where the primary and secondary structures could be repaired and maintained to extend the building service life [106].

Third, **design with a cultural foundation**. Cultural relevance has been at the core of architecture for centuries, created through a process of trial and error by civilizations worldwide. Accordingly, vernacular and traditional architecture has continuously evolved to generate features and forms that adapt to the living cultures and collective wisdom of its community. An example is *Yakhchaal*—ancient Persian ice houses—which relied on their dome-shaped forms, underground structure, and the thermal mass provided by thick adobe to provide a local architectural solution to a practical and climatic challenge (i.e., the need to store ice for summertime use in hot and arid conditions). Until the collapse of cultural frontiers in the twentieth century, these distinctive local forms dominated architecture in different societies, and their aesthetics were the co-product of technological availability, environmental responsiveness, practicality, and cultural relevance.

While interest in vernacular forms of knowledge has generated interest for disciplines that include agriculture, health care, and education, in the built environment, it is mostly confined to heritage preservation or nostalgic references to the past. Consequently, the meaningful application of nonmodern forms of knowledge in sustainable building practices is almost nonexistent. What this paper hopes to provide is a systemic review to recognize the complicated, contextual, plural, dynamic nature of sustainable solutions, as opposed to the technology-reliant and optimization-oriented approach highlighted by most existing sustainable design practice and movements.

6. Conclusions

The paper identifies and explains eight bio-based low-carbon materials and two techniques. Compared to conventional modern building materials, vernacular materials and techniques exhibit superiority in several aspects. Firstly, vernacular lessons are derived from the holistic and dynamic relationship between human habitats and the ecosystem, enabling them to adapt to changing environments. Secondly, local climate and natural resources serve as the foundation for vernacular construction techniques, shaping the conception of architectural organisms. Thirdly, low transportation requirements contribute to lower carbon emissions. Additionally, modular design and construction reduce carbon emissions during installation and deconstruction while improving the recyclability of building components. Most vernacular materials are organic, biodegradable, renewable, and have the capacity to store carbon. Lastly, the utilization of local craftsmanship and labor positively impacts the local economy, particularly in low-income communities.

By highlighting the advantages, constraints, and the next steps for integration, the paper offers a comprehensive perspective on the potential of vernacular construction in mitigating environmental impact and fostering resilient communities. However, there is limited quantitative data on sod block, cob, and strawbale compared to other materials. This represents a research gap for future studies. According to available data, compared to wood, other materials all have lower embodied carbon. Some materials, such as rammed earth and adobe wall, have comparable structural strength and thermal performance. Taken together, this suggests that local materials other than wood can be a promising alternative for sustainable buildings.

Moving forward, integrating vernacular building knowledge into climate resilience plans involves two key components. Firstly, there is a need to raise public awareness and understanding of the benefits of vernacular architecture and other materials (rather than wood), leading to the development of new strategies for true sustainable living. The second component entails conducting scientific-based testing and experiments that can bridge the gap between vernacular knowledge and modern practices. This process will ultimately lead to optimized solutions that accommodate the economic development demands of local communities while preserving the local environment. It is essential to acknowledge that wood or mass timber construction alone will not be a singular solution applicable to all countries, regions, and communities.

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