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# Bamboo as a Sustainable Building Material for Innovative, Low-Cost Housing Construction

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**Abstract:** Bamboo is commonly used as a construction material in low-cost housing projects located in tropical and subtropical countries. This practice is especially prevalent in rural areas where bamboo grows naturally and families have experience working with it. Bamboo can be a sustainable building material for homes, even in cases where houses need to be resistant to earthquakes or storms. The traditional bahareque technology was enhanced in Costa Rica and Colombia to make it earthquake resistant. After the year 2000, this technology was transferred to several other countries in Latin America and Asia, gaining recognition as an innovative building technique. Many successful examples of bamboo housing constructions can be found in various countries, where modern architectural solutions are combined with innovative bamboo methods. Local communities can play a crucial role in bamboo processing, allowing residents to actively participate in the construction of their homes under technical supervision. This emphasizes the social sustainability aspect associated with bamboo. Ensuring the durability of bamboo housing constructions is paramount for the longevity of the houses, highlighting the need for technical assistance for self-builders and resident groups. With proper organization, bamboo housing has the potential to become part of the social production of housing.

**Keywords:** bamboo housing construction; low-cost bamboo housing; innovations for bamboo construction; engineered bahareque constructions; composite bamboo shear walls; cement bamboo frame technology



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## 1. Introduction

Bamboo is a fast-growing and versatile plant that possesses beneficial properties for its use in building applications, including a high flexibility, compressive strength, and tensile strength. Certain types of bamboo can serve as replacements for high-carbon-emitting building materials such as steel, bricks, and concrete. Bamboo materials are increasingly being employed in the construction of housing, buildings, installations, and bridges. When harvested and utilized responsibly, bamboo can alleviate the strain on wood resources extracted from forests. In many instances, bamboo is more cost effective compared to other building materials, particularly if it is locally harvested and processed, enabling local communities to actively participate in its utilization. Bamboo belongs to the grass family Gramineae. There are hundreds of bamboo species, 50 of which are suitable for use as structure-building materials. The worldwide occurrence of bamboo or bambuseae, based on Map 2 of Bamboo Phylogeny Group 2005 (Bamboo Biodiversity) of the Iowa State University, is shown in Figure 1.

The traditional use of bamboo in housing is often perceived as "shabby" by residents. However, the use of bamboo offers significant socioeconomic benefits to local communities and can contribute to biodiversity conservation and ecological preservation in these areas. The ecological advantages of bamboo have inspired engineers and architects worldwide to explore innovative applications of bamboo in social housing and other projects. It is expected that the technical and aesthetic qualities of these structures, as well as the perception of bamboo construction, will continue to improve.

**Figure 1.** Distribution of all woody bamboos (Bambuseae). Source: Lynn Clark, Iowa SU.

Bamboo can be found in tropical and subtropical regions across South America, Asia, Africa, Australia, and southern North America. The requirements for housing design vary depending on the climate zone. For instance, Asia has different climate zones ranging from warm–dry areas in Central India to warm–humid regions in southern India and throughout Southeast Asia. Conversely, there are also cool and cold areas in China, Japan, and Korea. Families construct their traditional homes based on the availability of locally grown bamboo species. The suitability of bamboo for housing depends not only on its quality but also on the geological and climatic conditions of the area, as well as the potential threats posed by natural disasters. Bamboo plants have the ability to retain water in semi-arid regions and prevent soil erosion in wet areas.

Housing affordability holds great significance in numerous nations across Latin America, Asia, and Africa. Therefore, it is imperative to consider the low incomes of impoverished families. This means that homes should be designed as basic or starter homes so that they can be expanded over time by the families themselves. This can be effectively achieved with bamboo houses, particularly in areas where bamboo forests and plantations exist.

Cooperation between professional builders and resident groups is often necessary to ensure high-quality bamboo homes, especially in areas prone to natural disasters. The foundation of bamboo houses must always be durable, and the use of bricks, cement, and concrete is essential. Since many homes are constructed in zones susceptible to natural phenomena, specific requirements for building structures and materials should be taken into account. These phenomena primarily include earthquakes, volcanic eruptions, severe storms, heavy rainfall, floods, tsunamis, and landslides. Alongside climate change, these events can pose significant threats to low-cost housing. Professionals believe that bamboo houses can play a crucial role in withstanding these phenomena, provided that the homes are constructed properly. NGOs, government institutions, and entrepreneurs can assist households and building groups in various ways.

In many cases, households themselves, along with the assistance of local communities, construction workers, small businesses, and housing cooperatives, are responsible for building homes. Self-help can reduce construction costs, while technical assistance can improve the quality of the housing. According to UN-Habitat, affordable housing must play a central role in sustainable development. This involves improving existing housing and taking a proactive approach to new housing construction. However, certain prerequisites must be met for housing construction, such as the following: (1) having an urban plan in place, (2) access to land for construction, (3) secure tenure, (4) basic services, (5) resident group participation, (6) adherence to safety standards in construction, (7) use of sustainable building materials, and (8) availability of housing financing. Additionally, it is important to provide technical assistance to self-builders and enforce municipal building regulations. These prerequisites align with contemporary development visions, exemplified by the United Nations' Global Housing Strategy for the year 2025 (GHS 2025) [1]. They also apply to situations in both urban and rural areas, where low-income households are engaged in organized construction projects utilizing bamboo structures and materials. Additionally, UN-Habitat highlighted the importance of green building materials, including the use of bamboo materials for housing [2].

Several international organizations are involved in promoting environmentally friendly and sustainable development through the use of bamboo. One such organization is the International Bamboo and Rattan Organization (INBAR), which represents 47 countries. The INBAR focuses on facilitating the development of strategies that benefit the underprivileged by designing and constructing sustainable bamboo housing. Another organization, the World Bamboo Organization, is a collective of individuals, companies, and institutions, both public and private, who advocate for the use of bamboo to benefit both the environment and the economy. Their motto is "it's time to plant bamboo; not just use it" [3]. Bamboo can also play a crucial role in restoring degraded soils around the world and creating diverse habitats. The Food and Agriculture Organization (FAO) of the United Nations is dedicated to combating global hunger and promoting the sustainable use of biodiversity for agriculture. The FAO and INBAR have formed a partnership to coordinate their efforts in providing affordable housing, addressing climate change, and preserving biodiversity for those living in rural areas. The FAO actively promotes bamboo as a sustainable crop and asserts that bamboo housing can regenerate deforested areas, empowering communities to become self-sufficient in their resource cultivation [4]. The establishment of bamboo plantations is increasing, particularly in China. The EcoPlanet Bamboo Group, which owns and operates bamboo plantations, has branches in Nicaragua, South Africa, Ghana, Rwanda, and the Philippines [5]. According to the FAO, international forces are coming together to "put bamboo on the map". The UN's Global Forest Resources Assessment 2020 (FRA) has reported that bamboo covers approximately 35 million hectares of land in Africa, Asia, and the Americas, especially in regions that are at risk of desertification. The FRA also mentioned a 50 percent increase in bamboo-covered areas between 1990 and 2020, mainly driven by its expansion in China and India.

The above demonstrates that the potential for bamboo to be used sustainably in residential construction is widely acknowledged in terms of its environmentally friendly properties. This has prompted national and international efforts to promote the use of bamboo materials in social housing. However, there are several obstacles hindering the timely achievement of these objectives. One issue is that the durability of bamboo materials can diminish if building structures are not constructed properly. Consequently, bamboo homes may not last as long as desired, resulting in disinvestment. Nevertheless, by employing sound construction practices and properly preserving bamboo materials, these houses can endure for decades. Risks to consider include insect and fungal attacks, as well as rot caused by moisture. To mitigate these risks, it is essential to have technical expertise, have supervision during implementation, and offer technical assistance to professionals working with bamboo. Ensuring the constructive durability is a crucial aspect that receives attention in this article. Additionally, other research avenues are explored, such as investigating whether scaling up these improved bamboo housing solutions is possible and how to integrate them into the social production of housing.

*Reasons for the Research and the Research Method*

The use of bamboo in construction has been a longstanding tradition for centuries. Nowadays, bamboo is increasingly being utilized in high-quality building applications, including schools, villas, hotels, public buildings, pavilions, and restaurants located in parks. It is also used in the construction of spatial structures. Many architecture books and publications demonstrate this trend. The International Bamboo Construction Competition of 2019 showcased the creativity of young architects and engineers who designed captivating bamboo solutions for spatial structures and buildings [6]. So far, the social and self-help segments have received limited attention. This article showcases numerous interesting new developments in bamboo design. The prevalence of bamboo houses in social housing and local communities is not extensive. However, bamboo is frequently cited in publications as an eco-friendly and sustainable material for residential construction, benefiting both people and the planet. As a result, low-cost bamboo housing is being promoted globally,

but is it feasible to expand bamboo housing production to a larger scale? There are several obstacles that need to be addressed.

The materials were collected from several countries where bamboo is prevalent. These countries were chosen based on the following criteria: (1) availability of publications on low-cost housing construction using bamboo, (2) vulnerability to natural disasters such as earthquakes and severe storms, and (3) the presence or potential for housing projects, regardless of their size. This search provided sufficient material to address some of the research questions. Research materials were found in the vast literature on bamboo structures, through a search on the Internet and through consulting some international specialists.

Additionally, apart from the countries discussed in this article, there are other countries where bamboo housing is being utilized, either in an experimental phase or on a larger scale.

## 2. Bamboo Materials in Housing Construction

The popularity of bamboo as a building material is on the rise, particularly among renowned architects. This trend has led to innovative architecture, particularly in the higher-end construction sector, including schools, hotels, restaurants, community houses, and holiday resort buildings. Two noteworthy examples are the Handmade School in Rudrapur, Dinajpur, Bangladesh, designed by Anna Heringer and Eike Roswag, and the Green School in Badung, Bali, Indonesia, designed by Effan Adhiwira [7]. Technical innovations include methods for making the bamboo material more sustainable, applying improved joints and connectors, and processing bamboo into composite panels, glued beams, and planks. The latter development is mainly occurring in China, India, and Japan. This has resulted in high-quality bamboo materials which, unfortunately, are too expensive for use in low-cost housing construction in the rural areas of developing countries.

In areas where bamboo grows naturally, families often have experience in building shelters using bamboo. Small entrepreneurs frequently engage in crafting bamboo furniture and various consumer goods. Bamboo is also utilized in the paper and clothing industries, and as a result, it is harvested for export. The fast growth of bamboo contributes to local economic development. The increased use of bamboo for industrial purposes can lead to higher prices, necessitating the establishment of bamboo plantations. Planting bamboo may also be necessary in order to address environmental issues such as desertification and deforestation. All of these factors require effective spatial planning and management. If bamboo is used in construction as a substitute for wood, it has the potential to reduce logging activities. Using bamboo in housing construction requires professional skills, but experienced carpenters and other construction workers can quickly learn how to build with it. This allows residents to contribute to reducing construction costs. If the local knowledge and skills are not available, it is essential to establish training programs.

Bamboo can be effectively used in housing construction when combined with wood, bricks, compressed earthen blocks (CEBs), and concrete. Due to its excellent properties, bamboo enables the construction of earthquake-resistant and storm-resistant homes. However, using bamboo panels for exterior walls necessitates regular maintenance. By plastering bamboo panels, durable walls with a refined finish can be achieved. Bamboo is predominantly used as a building material in low-rise buildings in the following ways:

- for frames and trusses, all for the basic structure of a home;
- as fill-in material in the frames in the form of plastered braided bamboo panels or laminated sheet material.

In Figure 2, the structure of a bamboo house (a) is shown, besides a cemented wall consisting of infill panels (b). The images are derived from workshops given by Shyam K. Paudel and Maxim Lobovikov of INBAR, in the period 2001–2004, which showcase the early improved bamboo housing experiences. Technical challenges in the application of bamboo include the following: (1) ensuring sustainability that is ecologically sound, (2) ensuring strong anchoring to the foundation, (3) providing reliable corner connections, and (4) complying with regulations for earthquake-resistant or storm-resistant construction.

(**a**) (**b**)

**Figure 2.** (**a**,**b**) Frames for house construction. (**a**) Wall with infill frames. (**b**) Sources: INBAR.

Bamboo is treated with preservatives to prevent termites, beetles, and fungi from affecting it, and needs to be kept dry. If it is not treated properly, its service life is only 5–10 years. Exposing untreated bamboo to rain causes a short lifespan. However, if the material is properly treated and is under the cover of a roof, it can last for at least 50 years and even decades more [8,9]. Sometimes, it is desirable to plaster the outer walls of bamboo houses—on wattle—to provide protection against the influences of the climate and insects. If the exterior walls are completely covered with bamboo wattle work, the houses can look like an "ordinary" house.

In a study on the utilization of bamboo housing in Guayaquil, Ecuador, it was discovered that after the construction of paved roads in a residential area, the bamboo houses, which were previously built by the NGO "Hogar de Cristo", were transformed by the families themselves into houses made of bricks and concrete blocks. This transformation was motivated by the desire for an improved housing quality. In a similar example in Guatemala, the NGO IDESAC worked with families in rural areas to promote the use of bamboo in construction. However, the families viewed bamboo as a "poor man's building material" and were reluctant to incorporate it into their homes. This perception was shared by architect Luis Estrada from IDESAC, who was interviewed by the author in 2016. To change this mindset, it is crucial to construct more sample homes made of bamboo that are both sustainable and visually appealing.

In the Chittagong Hill Tracts in southeastern Bangladesh, traditional houses were constructed on elevated platforms using bamboo and chhan (sungrass). These stilt houses were built to offer protection against wildlife and flooding. Additionally, the space beneath the platform was utilized to accommodate livestock. However, there has been a significant decline in chhan cultivation, resulting in a rise in the cost of the roofing material. Obtaining bamboos and trees from the forests has also become more difficult and expensive. As a result, many residents have gradually replaced their traditional dwellings with modern homes made of bricks, cement, and concrete [10]. This is partly the reason why the Machang houses are falling into disrepair, but another cause is that untreated bamboo only lasts for three to four years. As "modern" building materials became more accessible to local communities, families started preferring materials like stone for construction. As a result, the rich customs and architecture of the Machang houses are at risk of disappearing. To prevent this, we should promote the use of improved bamboo techniques in constructing new model homes. The citation in Box 1 states that the improved bamboo construction technique, also known as "engineered bahareque", is important for environmental sustainability, as well as the durability of the homes.

**Box 1.** Engineered bamboo for housing.

From: Design guide for Engineered Bahareque Housing (Kaminski, Lawrence, Trujillo, 2016 by INBAR) [9].
"Engineered bahareque housing has been shown to be environmentally superior to other forms of housing such as masonry, with as little as half of the embodied carbon and the ability to be built largely using fast-growing sustainable materials such as bamboo. Its sustainability can be maximized by ensuring the bamboo and timber is taken from a local and sustainable source, minimizing the thickness of cement mortar render and maximizing the use of cement replacements such as lime. Non-toxic treatment chemicals should be used whenever possible for the bamboo and timber".

## 3. Research Materials: Bamboo Housing in Three Regions of the World

### *3.1. Bamboo Housing in Latin America*

There are many bamboo species in Latin America; the one predominantly used for construction purposes is guadua angustifolia. In Colombia, the traditional method of building with bamboo is known as "bahareque", while in Peru and Ecuador, it is referred to as "quincha". Similar techniques are also found in other countries such as Brazil and Venezuela. These ancient construction techniques typically involve using uprights of wood or bamboo and horizontal elements made of twigs or reeds. A braid can be single sided or double sided and is plastered with "mud" (loam), clay, gypsum (mixture of lime and water), or a combination of similar raw materials. The finishing of these walls always involves plastering with cement, lime, or earthen materials.

Due to the occurrence of earthquakes in many countries, the bahareque and quincha structures—when they were in poor condition—were often proved unable to withstand severe seismic activity, resulting in the collapse or damage of numerous houses. These techniques were therefore commonly referred to as "non-engineered". Where the structures were in good condition (properly built, preserved, and maintained well), their physical behavior during earthquakes was acceptable. Consequently, a global search began for technically improved bamboo-based building constructions (or engineered bahareque). Today, the improved bahareque technique for walls is widely regarded as earthquake-resistant and aesthetically pleasing. The bahareque walls are normally called "engineered bahareque", or "composite bamboo shear walls" (CBSW). The CBSW system is an effective way of creating low-carbon housing that provides excellent code-compliant strength, ductility, and durability, and has significant potential for affordable housing in highly seismic lower- and middle-income countries, where bamboo grows [11].

In Colombia, the pioneering use of bahareque constructions, plastered with earth, dates back to early times. Since 2002, this guadua-based system has been included in the national building codes for seismic resistance. Following the devastating earthquake of 1999 in Colombia's coffee region, which resulted in 1185 deaths and over 4000 injuries, it became evident that significant damage had occurred to many houses, particularly in the departments of Quindío and Risaralda. However, numerous houses were reconstructed using the improved bahareque technology. Engineer Luis Felipe López played an integral role in this process and later introduced the enhanced technology to the Philippines.

Colombian architect Simón Vélez has gained international recognition for his innovative designs in bamboo construction, making bamboo buildings widely renowned. As a result, Colombia has become a leading country in this field, with many bamboo experts being sent to other countries to share their knowledge and transfer bamboo techniques. In Colombia, there is a wealth of knowledge, and construction workers are extensively trained to work with bamboo. Currently, there are no known social housing plans of any size that incorporate the improved bahareque technique. However, ongoing studies are being conducted in the coffee region to explore the use of this new architecture for the construction of social housing.

In Costa Rica, the National Bamboo Project (NPB; 1986–1995) introduced a strategy to combat deforestation by replacing the use of wood with bamboo as a seismically sound and affordable building material. The project aimed to promote the use of bamboo in a housing

program, the industrialization of bamboo, and the marketing of its by-products. Initially, 700 low-cost homes were constructed, and 200 hectares of bamboo was cultivated by 1989. Unfortunately, the NPB did not receive the intended large-scale follow-up. However, it did contribute to the improvement of construction techniques, such as using stone, bricks, and cement for foundations, bamboo piles for frames, and bamboo panels for plastered walls. The NPB demonstrated that the bamboo houses designed have the potential to be sustainable and seismically resilient alternatives to houses made of more "modern" building materials like stone, concrete, and steel. Consequently, well-designed homes using engineered bamboo have a higher chance of acceptance among local communities. In Costa Rica, bamboo can often be found in the buildings and homes of holiday resorts.

In Ecuador, the NGO Hogar de Cristo (HdC) built approximately 265,000 traditional bamboo houses for and with local communities until 2012. These housing types were designed to be built quickly. One of the prototypes, known as the "MACAHO" model, utilizes timber frames and preserved bamboo for wall panels. This particular model is often designed as an expandable home, which keeps the cost of the basic module relatively low and affordable for a large number of low-income households. According to the HdC brochure from 2020, the purchase price for the "Salomé" housing model is USD 2684 [12]. This is, however, a temporary home with a limited lifespan. The brochure also includes models that can be expanded on the ground floor with walls made of concrete blocks, as well as final housing models with concrete block walls and metal frames. Bamboo is only used for partitions in these instances, while the house frames are constructed from wood. In 2022, the Ecuadorian government initiated a new program focused on bamboo houses, which will be implemented by the Ministry of Urban Development and Public Housing. The first type of bamboo house was constructed in the canton of Omedo, located in the province of Manabí. The local vocational training institution "Escuela Taller Manabí", specializing in bamboo constructions, was involved in the project, with assistance provided by INBAR and the Spanish aid organization AECID. However, the cost of a single home is USD 18,700, which is relatively high for low-income households. Nevertheless, the government has pledged to finance the construction of 220 homes as part of this project.

In Nicaragua, bamboo housing is not yet widespread. However, the National University of Engineers in Managua, UNI, has developed a prototype for use in social housing in the country. This project serves as a research center for safe building in Nicaragua, a volcanic country prone to frequent earthquakes. Moreover, young architects and engineers have designed a hurricane-resistant bamboo house in the city of El Rama, located in Nicaragua's Caribbean region. Architect Jorge Bonilla's start-up, "Bambuksa", assists local communities in constructing bamboo houses. The organization EcoPlanet Bamboo owns and operates three bamboo plantations in the El Rama region, which collectively cover more than 4000 hectares of restored forest landscapes [13].

El Salvador, another volcanic country susceptible to frequent earthquakes, explored the improved bahareque technique in 2002 through a collaborative study involving the NGOs Fundasal, Misereor, and CRATerre-EAG. The study aimed to develop a low-cost, seismic-resistant house for rural areas using bamboo and timber. Around 2015, a consultancy firm called ARUP, the Salvadoran NGO REDES, and the University of Cambridge collaborated to develop an innovative model house using bamboo, timber, and cement mortar. The resulting house was low-cost, seismically resistant, and sustainable. Technical testing was conducted at the University of Cambridge, and the authors concluded that this type of housing could be suitable for highly seismic areas [14]. Fundasal completed an improved bahareque model house for Mrs. Bersaides Ramirez in 2022 [15]. The development of bamboo houses in El Salvador is still at a small-scale level, but there is significant potential for growth.

In Peru, bamboo grows in the northeastern provinces of Cajamarca, Lambayeque, Piura, and Amazonas. Bamboo material is also imported from Ecuador. In the Piura region, bamboo is traditionally used by lower-income families. However, during earthquakes, many building structures using the old quincha wood and bamboo techniques

were destroyed. Currently, there are pilot projects being set up in the country to construct earthquake-resistant bamboo houses. But sometimes, initiators did not prove, using calculations, that houses would become earthquake resistant. The IVUC housing institute of the University of San Martín de Porres in Lima prepared a valuable guidebook for building houses with bamboo in Peru [16]. The architects Yann Barnet and Faouzi Jabrane from IVUC developed a small temporary house made of bamboo for the victims of the 2007 earthquake. A total of 50 growth houses consisting of prefabricated panels were built. The residents themselves assembled the houses under the technical supervision of IVUC [17]. Later, two other housing models were developed (IVUC 2 and 3), both with an additional floor. The IVUC's work is innovative in several ways: the houses are constructed quickly, they can be individually expanded, an extra floor can be added, and the architecture is modern and colorful. Architect Tania Cerrón also has experience in designing structures with bamboo, including rural dwellings [18]. In the region around the city of Piura, which is often affected by floods and tropical storms, the "Mesa Técnica Regional del Bambú" was established by the regional government. Its purpose is to enhance the value of bamboo crops and improve stock management to promote Guayaquil's bamboo production for the construction sector. With the support of the European Union, 400 construction workers will receive training in the construction of climate change-resilient bamboo houses in the Piura region. Additionally, some model homes will be built in low-income communities [19].

In Mexico, attempts have been made in certain states to promote housing construction using bamboo and improved bahareque techniques. North of the city of Puebla, a project was initiated to construct model houses utilizing prefabricated bamboo elements. The "Comunal Taller de Arquitectura" in Mexico City collaborated with local communities to develop housing designs. However, the initial building plan, which included domestic bamboo as well as local wood and stone, was rejected for a first home due to regulatory constraints imposed by CONAVI (2016), the National Housing Commission. As a result, government funding was not yet possible. Undeterred, the construction group proceeded to design a second prototype for social housing in a mountain village, utilizing a prefabricated bamboo frame. To circumvent the use of local bamboo species, bamboo was imported from abroad. Eventually, a model house was successfully constructed through collaboration with local residents, and it was subsequently recognized and awarded by CONAVI. In addition to these government initiatives, there are also private ventures focused on bamboo housing in Mexico. One such example is the ecological bamboo house called "Casa Milpa", which was created by Cooperativa Las Cañadas in Huatusco, Veracruz [20]. Another noteworthy project is the "Crece tu Casa", a bamboo structure designed by architect Lucila Aguilar in Tuzantán. This design received the second prize in the World Design Awards 2021, organized by The Architecture Community. "Crece tu Casa" is an adaptable model house with walls made from various materials [21]. Currently, Mexico is actively working on establishing a new standard (NMX) for the design and construction of bamboo structures. Exemplary bamboo dwellings in some Latin-America countries are shown in Figure 3.

### *3.2. Bamboo Housing in Asia*

In various Asian countries, bamboo is abundantly available for use in various applications. Traditionally, bamboo has been extensively used in agricultural areas and rural villages. It continues to be a cost-effective material for many families who construct their homes, either individually or collectively. Examples of countries known for their bamboo resources include Bangladesh, China, the Philippines, India, Indonesia, Japan, Nepal, and Thailand.

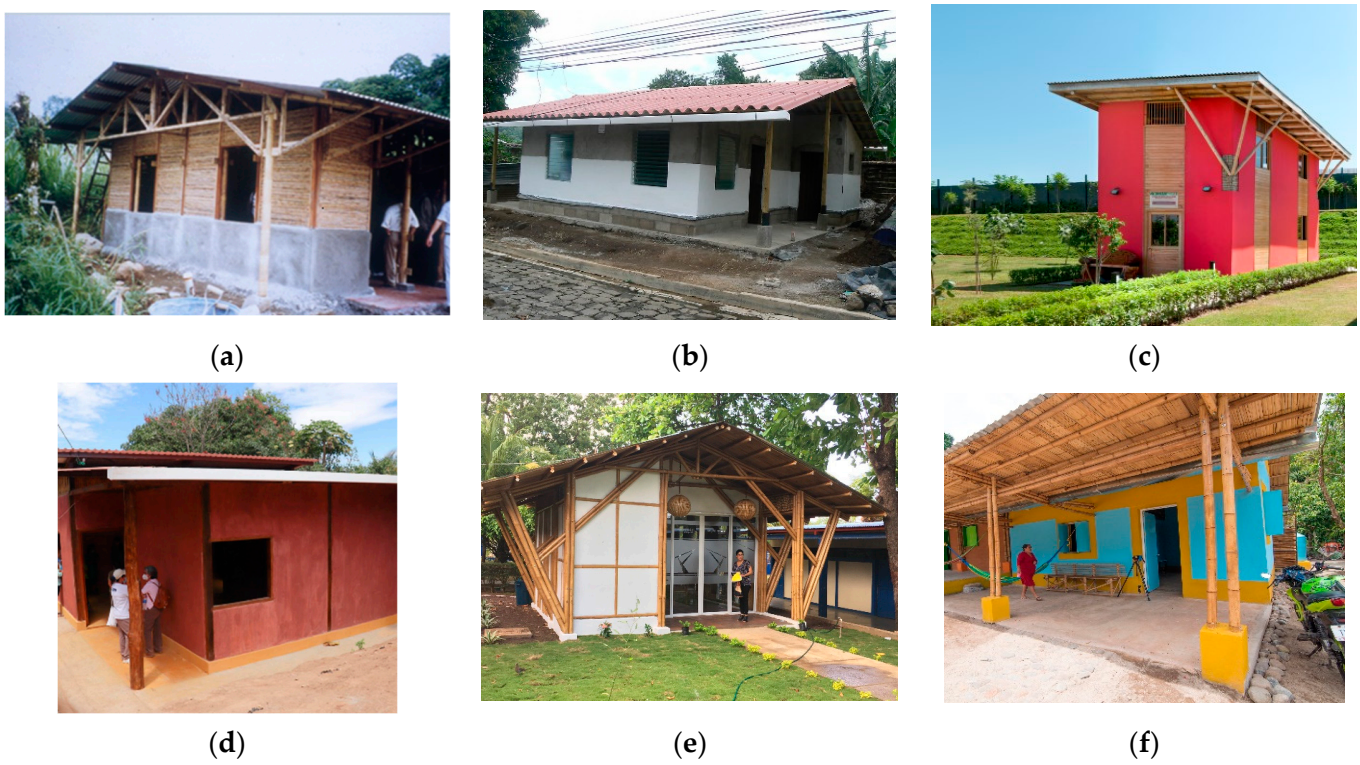

**Figure 3.** (**a**–**f**) Improved bamboo dwellings in Latin America. (**a**) Costa Rica. Example house with cemented exterior walls. Around 1987. Source: Jules Janssen. (**b**) El Salvador. Engineered house (cane and timber), fully plastered. Source: Sebastian Kaminski [9]. (**c**) Peru. IVUC 2 house for various purposes, 2 floors. Source: Yann Barnet [17]. (**d**) El Salvador. Example home. Source: Fundasal [15]. (**e**) Nicaragua. Example house at UNI campus, Managua. Source: author. (**f**) México. Grow House. Source: Lucila Aguilar [21].

Bangladesh has an extensive delta area and is frequently affected by river flooding, as well as rising sea levels. The climate in Bangladesh is greatly influenced by its long, tropical rainy season. There is a high demand for affordable housing, with a large portion of the population relying on traditional building materials like bamboo for their homes. However, there is a shortage in the bamboo supply due to poor management, even though bamboo is still abundant. The most commonly used bamboo species is Melocanna Baccifera (muli). In areas like the Chittahong Hill Tracks, houses are constructed using bamboo, wood, and rammed earth. In flood-prone areas, homes are often raised on stilts, which can be vulnerable. In new constructions, the foundations of the dwellings must be made of concrete or stone, with wooden or bamboo structures built on top. It is preferable for elevated houses to be supported by concrete piles. Homes not only need to withstand rising water levels but also cyclones, placing additional demands on the building structures. Therefore, there is a pressing need for climate-resistant housing to tackle the consequences of climate change.

Nearly 1 million Rohingya refugees from Myanmar have found temporary shelter in Bangladesh, where they are forced to live in camps in very poor circumstances. Many temporary shelters are made of bamboo and are very fragile. Aid organizations are trying to improve the technical conditions of the bamboo houses with measures to counteract the worst problems [22]. Heavy rainfall and severe flooding can damage shelters or completely destroy them. The temporary shelters showed in Figure 4 can be improved but are not durable in a technical sense in the case of flooding and heavy storms.

In the Philippines, bamboo naturally grows in backyards, riverbanks, forest areas, and sometimes on private lands. The archipelago provides an excellent climate for various bamboo species. The bamboo industry in the Philippines is steadily growing and gaining

recognition as a sustainable source of income for farmers. The country's climate, with abundant rainfall and fertile soil, is conducive to bamboo cultivation. Houses located on the coast or riverbanks are constructed on stilts, as the country frequently experiences typhoons, necessitating improved construction techniques. The Cement Bamboo Frame Technology in the Philippines [23], developed by the Base Bahay Foundation (BBF), is an enhancement of the traditional "wattle and daub" technique, known locally as "tabique Pampango". This method involves using vertically placed wooden posts and horizontally woven branches covered in clay or loam. The BBF frame is covered with a mesh to hold cement mortar plaster, resulting in smooth outer walls that maintain an ordinary appearance. The BBF has successfully built over 1000 small homes in 12 municipalities in the Philippines. The BBF states that their "Cement Bamboo Frame Homes" are resistant to typhoons, earthquakes, fires, and termite attacks. Similar homes are also being constructed in Nepal through a partnership with the NGO Habitat for Humanity. Furthermore, the Forest Products Research and Development Institute (FPRDI), an agency under the Ministry of Science and Technology, is working on a low-cost, DIY bamboo shelter for the impoverished. This ready-made house designed by FPRDI can be assembled in just 2 days [24]. Some exemplary dwellings in Bangladesh and the Philippines are shown in Figure 4.

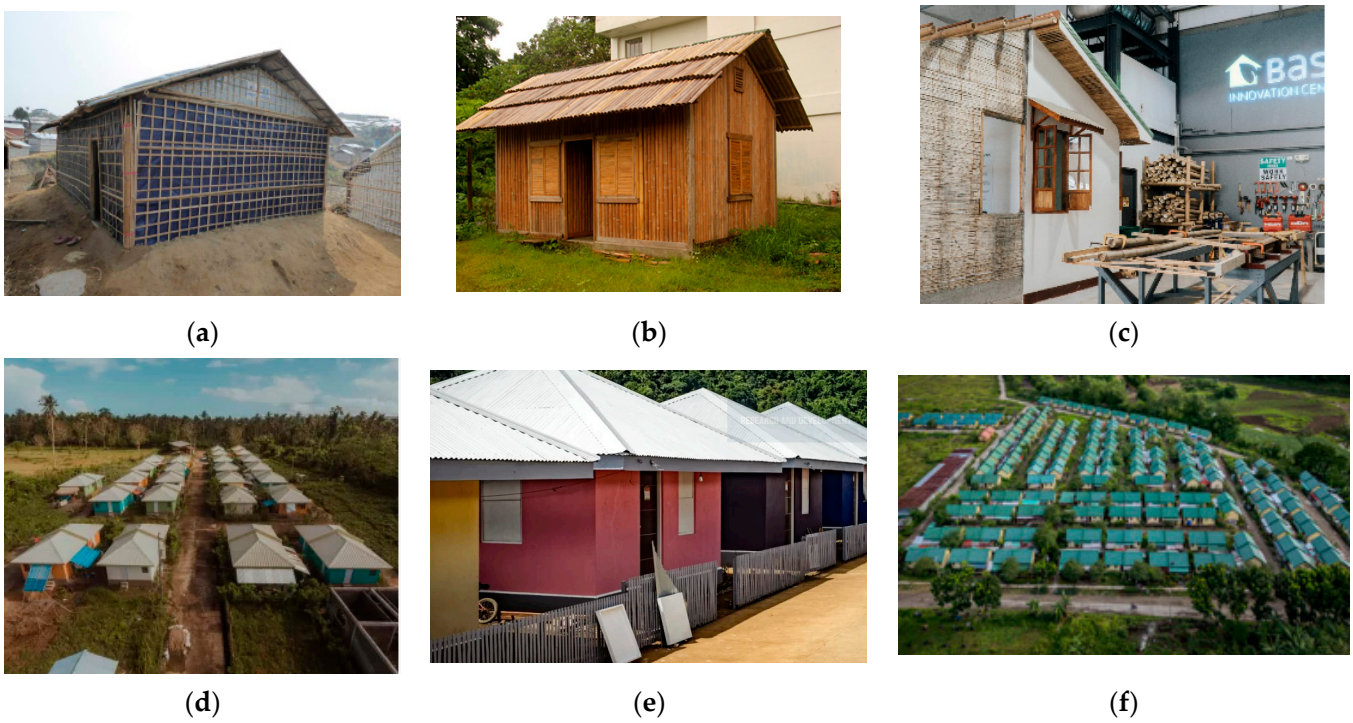

**Figure 4.** (**a**,**b**) Temporary shelters in Bangladesh and the Philippines. (**c**–**f**) Cement bamboo frame homes in the Philippines. (**a**) Bangladesh. Typical NGO-led bamboo shelter in Cox's Bazar. Refugee camp. Source: S. Kaminski [22]. (**b**) The Philippines. Do-it-yourself bamboo shelter for low-income families. Source: FPRDI [24]. (**c**) The Philippines. Base Bahay Innovation Center. Source: Base Bahay Foundation [23]. (**d**) The Philippines. Neighborhood bamboo houses. Source: Base Bahay Foundation [23]. (**e**) The Philippines. Housing project with plastered houses. Source: Base Bahay Foundation [23]. (**f**) the Philippines. Social housing of Base-Bahay and Habitat for Humanity in Negros Occidental. Source: Hilti Foundation [23].

India is a major producer of bamboo and has a rich history of indigenous bamboo construction. India is home to more than 135 different species, 50 percent of which are cultivated in the eastern/northeastern states of India. Bamboo has been historically and economically important in India for cookware, food, and construction purposes. In the colder and cloudier climate of northeast India, the "wattle and daub" construction technique, also

known as "Ikara", is used. This technique involves wooden or bamboo frames with split bamboo fabrics that are covered with "mud" (soil/earth) to form the wall elements. The bamboo or wood frame is smothered with soil mixed with a slurry and allowed to dry. The foundation of the dwelling is elevated and consists of tamped earth, and more recently, cement mortar has also been used.

Today, improved techniques are employed using wooden or bamboo frames filled with split bamboo fabrics as wall panels. These panels can be prefabricated, and the house frames are often made of metal. Social enterprise Bamboo House India offers such homes in the market. Their metal construction frames are relatively lightweight and easy to assemble [25].

In October 2022, the Indian Plywood Industries Research and Training Institute (IPIRTI) in Bangalore merged with the Institute of Wood Science and Technology. They have developed an earthquake-resistant bamboo house that combines traditional methods with modern construction techniques. Their research has demonstrated that bamboo can be utilized to create earthquake-resistant frames and wall panels. This system is suitable for prefabrication or in situ fabrication [26].

According to architect Harikrishnan Sasidharan from NO Architects, the Kerala region in southern India has recently faced heavy rainfall and flooding. The floods in 2018 resulted in significant devastation. In response to these challenges, NO Architects has been researching reusable construction methods, leading to the development of a pilot project. The main structure of this project can serve multiple purposes, such as a residential unit, clinic, aid station, shelter, library, or even toilets. The infill panels can be easily modified depending on the specific use. To avoid the need for concrete foundations, a set of screw piles has been employed as the structural system. The metal construction frame consists of standardized components that can be assembled without the need for skilled labor. An estimated cost for completing a two-bedroom structure, including sanitary facilities, ranges from EUR 5500 to 6600 [27]. Three exemplary bamboo dwellings are shown in Figure 5.

(**a**) (**b**) (**c**)

**Figure 5.** (**a**–**c**) Example homes in India. (**a**) House in Aleru. Source: Bamboo House India [25]; (**b**) Earthquake resistant house with bamboo frames and panels [26], (**c**) Modern bamboo house on stilts, in Kerala. Source: NO Architects [27].

Indonesia is a country that is abundantly rich in various bamboo species, which are used for a wide range of purposes. Advanced bamboo constructions have been utilized in various sectors, including hotels, restaurants, and buildings in the tourism industry. These structures are always designed by architects. Another segment of buildings comprises affordable bamboo houses, constructed by families or local communities. The Indonesian government expects that families and communities take responsibility for building their own homes. Bamboo houses are often elevated and designed to promote proper ventilation. Improved bamboo houses are made using "plastered bamboo", a novel construction technique in Indonesia that resembles the improved bahareque techniques seen in Latin America. Private companies like PT Karisma in Depok, West Java, provide simple homes, either as ready-to-assemble kits or fully constructed. The architects from Institut Teknologi Bandung (ITB) have developed a new concept called "Mabuter", which involves plastered

bamboo houses that are affordable and of a decent quality. According to architect Akhmad Gunawan, this concept is both environmentally friendly and resistant to earthquakes. In 2000, a plaster bamboo house was built in Sukabumi, West Java, for earthquake victims. Remarkably, it remained in good condition until 2023. Recognizing the importance of disaster relief, especially in earthquake-prone areas, ITB and Universitas Mataram established a joint knowledge center in North Lombok in 2018 [28]. The aim is to initiate learning projects focused on bamboo houses for local communities residing in rural areas. Example homes constructed with plastered bamboo in Indonesia are shown in Figure 6.

(**a**) (**b**)

**Figure 6.** Example homes in Indonesia. (**a**) Bamboo house with two floors in Lombok. Source: ITB and UMRAM [28]. (**b**) Bamboo house with gypsum plaster in Cianjur, West-Java. Source: ITB [28].

China is a leader in the production of bamboo products and building materials. It has established industrial processes for manufacturing, assembling, and exporting high-quality bamboo products, including prefabricated elements for model homes. China is renowned as one of the most significant bamboo-producing countries, where various new techniques have been developed and implemented. Traditional Chinese bamboo houses, such as the Galan bamboo house and those belonging to the Dai group in Xishuangbanna, are well known. These bamboo houses are designed with a double-layer structure to prevent moisture, with the Dai people residing upstairs while keeping cattle and poultry below [29]. Dai housing is shown in Figure 7a.

(**a**) (**b**)

**Figure 7.** Bamboo homes in China. (**a**) Dai house. China Daily [29] (**b**) Bamboo house in Nankou, Beijing, China. INBAR [30].

The focus of the industry is on producing prefabricated elements for housing. In Kathmandu, Nepal, and Addis Ababa, Ethiopia, a demonstration house measuring 40 $m^2$ was constructed using Chinese bamboo and structural parts. Such applications have great potential, particularly for temporary housing in the aftermath of natural disasters. The production of laminated bamboo is a key aspect of the bamboo industry, with various shapes

and dimensions being produced for housing and building applications [30]. Industrially constructed demonstration house is shown in Figure 7b.

### *3.3. Bamboo Housing in Africa*

Large-scale logging is taking place in Africa, partly due to the economic value of tropical timber as an export product. Wood is frequently used as a construction material, as well as for firewood and charcoal. Although bamboo grows naturally in 36 out of the 54 African countries, its utilization is not yet widespread. Expanding the cultivation and use of bamboo could help mitigate deforestation. The economic potential of bamboo is substantial, making the establishment of numerous bamboo plantations viable. However, there is still a lack of or limited presence of a bamboo processing industry. From an economic standpoint, there is potential for expanding bamboo cultivation in Africa. Planting bamboo forests in areas at risk of desertification could yield positive and rapid results. Various initiatives focus on commercializing bamboo, primarily for furniture production and other consumer goods, creating an income source for small-scale entrepreneurs. However, large-scale purchases of bamboo raw materials by industrial players could sideline local residents.

Africa possesses vast natural bamboo forests ranging from sea level to mountainous regions. Approximately 4 percent of the continent's forests consist of bamboo. In Kenya, many bamboo species are solid rather than hollow. It has versatile uses in manufacturing consumer items and can be employed in public housing as well. If bamboo is utilized and applied locally, fostering a strong collaboration with local communities, a win–win situation can be achieved for the local economy and the environment (by preventing desertification). Oxytenanthera abyssinica is a native species found in East Africa, thriving at altitudes between 1200 and 1800 m. Through international agreements facilitated by the UN, opportunities exist to enhance farmers' and their organizations' expertise in bamboo cultivation in countries like Ethiopia, Uganda, and Kenya.

In Uganda, the government has initiated the implementation of the National Bamboo Strategy and Action Plan for the period of 2019 to 2029. This strategic plan aims to maximize the utilization of the country's bamboo resources. The implementation of this plan is being facilitated by INBAR, the Ministry of Water and Environment, and the National Forestry Authority (NFA). Currently, there are around 67,000 hectares of bamboo in protected areas. Additionally, there is a plan to expand the bamboo acreage outside of protected areas by an additional 375,000 hectares. The entrepreneur Fred Ijjo from FOB Consult Ltd., a social enterprise that collaborates with local communities for housing projects, has successfully developed model homes using bamboo.

There are many opportunities for utilizing bamboo as a sustainable building material in Ethiopia. The country boasts numerous bamboo forests in certain regions. With an impressive 1 million hectares of native bamboo, Ethiopia is one of the largest bamboo producers in Africa, hosting 67 percent of all African bamboo species. Two main species, yushania alpina and oxytenanthera abyssinica, are commonly found in the country's highlands and lowlands, respectively. Despite the vast natural bamboo resources, Ethiopia has only recently started harnessing its potential. Efforts are currently being made to develop innovative housing designs using bamboo.

In Tanzania, the adoption of bamboo houses is still in its early stages. The National Housing and Building Research Agency is currently investigating the potential use of bamboo for the production of doors, windows, and roofing materials. The primary focus of this research is to identify building materials that can enable families to construct more modern homes at a lower cost. If found feasible, families will be encouraged to invest in bamboo cultivation for the production of these materials. A common construction technique in Tanzania is known as "wattle and daub", which involves using earth (or mud) for walls. However, these structures often need to be restored after the rainy season. Tanzanians are growing more concerned about the health issues associated with houses built using earthen walls, such as insufficient ventilation and the risk of infestation by insects and fungi. In Figure 8, two bamboo houses in Uganda and one in Ethiopia are shown.

(**a**) (**b**) (**c**)

**Figure 8.** (**a**–**c**) Bamboo houses in Uganda and Ethiopia. (**a**) Uganda, model house. Source: Fred Iijo [e4impact.org], (**b**) Uganda, model house. Source: INBAR, (**c**) Ethiopia. Improved Sidama house. Source: Kibwage and Misreave, INBAR.

In other sub-Saharan African countries, despite their warm and humid climate, bamboo is still not widely used as a material for housing. Traditionally, homes were constructed with earthen walls, known as wattle and daub. These houses mostly consist of a single floor, with a tamped earth or cement floor and walls that are plastered with earth. Nowadays, these walls are often replaced with bricks. However, there is tremendous potential for the utilization of bamboo in Africa, especially if governments take measures to encourage the cultivation of bamboo for (public) housing and mitigate the effects of desiccation and desertification.

### *3.4. Discussions on Results of Housing Construction with Bamboo*

Latin America: Improved bahareque techniques for housing can be found in several countries. In 2013, Kaminski provided a general overview [31]. However, some of these developments are still in their early stages and have not yet resulted in large-scale bamboo housing construction. In some cases, government regulations have posed obstacles to the construction of homes with local bamboo, as seen in Mexico. Nevertheless, educational and research institutions are carrying out various pilot projects, with NGOs also actively participating in these efforts. Governments recognize the importance of promoting bamboo cultivation in the context of new climate and environmental policies, as well as for enhancing sustainability in the construction sector. There is a growing recognition that improved bahareque techniques can enable the construction of social and affordable housing that is resistant to earthquakes and storms. Thanks to the longstanding efforts of Hogar de Cristo in Ecuador, many homes have been built using wood and bamboo, particularly those designed for individual growth potential. Numerous families have transitioned from their original homes to ones built with more "modern" materials like bricks and concrete blocks. NGOs have played a crucial role in making bamboo construction accessible to low-income families, such as Habitat for Humanity did in several countries, as well as Progreso in Piura, Peru. To ensure an adequate supply of bamboo in the future, the organization and management of bamboo forests are often incorporated into national policies for forest and agricultural management, as well as nature development.

Asia: In the countries mentioned, bamboo houses are traditionally widespread, particularly in rural areas and small villages. Natural disasters and climate change heavily impact large parts of Bangladesh, India, the Philippines, and Indonesia. Bangladesh is facing severe challenges due to floods and tropical storms. The most significant threats in Indonesia are earthquakes and volcanic eruptions, given its geographic location along the "Ring of Fire". Therefore, attention is focused on constructing earthquake-resistant buildings. In Bangladesh, homes in vulnerable areas are often built on stilts, and foundation piles are preferably made of concrete, despite the higher cost. The Philippines has made progress in adopting the Cement Bamboo Frame Technology, thanks to initiatives by aid organizations, which serve as important exemplary projects. Floods, severe storms, and typhoons pose specific demands on building structures in the Philippines, similar

to Bangladesh. Coastal areas in both countries have numerous stilt houses that require reinforcement. India has four distinct climate regions, each with unique housing construction requirements. Among the challenges faced in India are heavy flooding, necessitating waterproof foundations, as well as the need for earthquake-resistant construction in other regions. China, with its vast industrial potential, is the largest exporter of bamboo and plays a significant role in supplying the construction sector. India and Japan hold the second and third positions, respectively.

Africa: This continent has numerous bamboo reserves in the countries located south of the Sahara. People traditionally used the "mud-wall" (earth) technique to construct their homes. Whenever a village is established, all members of the community, irrespective of age or gender, come together to support each other. By embracing modern technology and increasing awareness about the advantageous properties of bamboo materials and constructions, sustainable development can be initiated. If villagers utilize communal aid, it is hoped that an affordable, low-tech bamboo building technique can be employed. However, it is crucial for the improved bamboo techniques to reach the local communities. Some governments aim to harness the potential of bamboo to benefit local economies and combat land desiccation and degradation.

## 4. Technical Aspects of the Global Innovations

### *4.1. Technical Durability of Bamboo Structures*

Bamboo materials and structures, including wall finishes, require proper preservation and maintenance to ensure a long lifespan. It is important to emphasize the technical durability in housing construction, along with the social and ecological sustainability. Scientific research has demonstrated that traditional bamboo buildings have an excellent seismic performance during earthquakes, mainly due to the following combined properties:

- A good strength-to-weight ratio makes bamboo constructions relatively lightweight and poses fewer risks to the safety of the residents in the event of a collapse. Repairs can be performed more easily and at a lower cost. Both properties are relevant for comparing bamboo constructions to buildings made of masonry and concrete.
- Traditional bamboo jointing systems, such as nails and carpentry joints, are usually able to withstand significant deformations without failing and can provide some level of absorption. Similarly, wall systems like the "wattle and daub" technique, with mud plaster, also possess this capability.
- Traditional bamboo buildings have a certain degree of internal bonding, which helps in distributing forces evenly throughout the structure of the building.

The improved bamboo systems, such as "engineered" bahareque or "composite bamboo shear walls", clearly outperform traditional ones in the mentioned aspects [32]. Attention is always required for the foundation, building structure, frames and panels, connection solutions, and floors, especially if a second or possibly third floor is desired.

Unpreserved bamboo should never be used in construction. Durability is achieved through various methods and techniques, such as immersing the bamboo poles in a mixture of minerals like borax and boric acid for a long period and allowing them to thoroughly dry. In addition, when incorporating bamboo materials in housing design, it is essential to keep them dry and protected from heavy rain, even if they has been treated. Preventing insects and fungi from infesting the bamboo and ensuring that water does not enter the columns is crucial. The phases of impregnating the bamboo poles, and the drying process are shown in Figures 9a and 9b respectively. Local workers and participating households need proper training for processing the bamboo. To achieve the desired architectural appearance of the houses, the wattle and daub walls are usually plastered. This step is necessary due to the prevailing climatic conditions and should also be carried out on the inside. Applying a smooth layer of stucco helps keep insects from nesting in any crevices.

(**a**) (**b**)

**Figure 9.** (**a**,**b**). Impregnation and drying. (**a**) immersion bath for bamboo. Source: INBAR. (**b**) storage of bamboo for the drying process. Source: IVUC-UVMP.

The mechanical properties of bamboo housing can be tested according to the International Bamboo Structural Design Code: ISO 22156 (ISO, 2021) [33]. As a result, improved bamboo structures and buildings have become increasingly common in the construction practice [33]. In most cases, countries have their own technical standards. Colombia and Ecuador were among the first to establish their own standards, which were later adopted by other nations.

Fire safety is also crucial when it comes to bamboo materials and structures. A study conducted by ITB, UI, Indonesia, and Base Build, Philippines, has revealed that applying mortar stucco can enhance the fire insulation capabilities of flattened bamboo wall samples. Conversely, the absence of a mortar layer would greatly reduce the fire-resistant properties of bamboo walls. The most effective application of mortar is on both sides of the sample, with a recommended thickness of 25 mm to 30 mm [34].

### *4.2. Foundations and Building Structures*

The foundations of the houses must always be solid and made with heavy materials such as stones and/or concrete, to which the lighter bamboo structures are anchored. The foundation must be able to withstand groundwater and flooding. The frames should be securely attached to the foundation, ensuring that the anchors and joints do not weaken during an earthquake or heavy storm. To construct earthquake or storm-resistant buildings, bamboo or timber frameworks are typically used and assembled onsite. In the Philippines, the Cement Bamboo Frame Technology involves plastering walls and panels with cement. In Indonesia, improved plastered walls have been developed with the assistance of the ITB. It is essential to calculate the optimal specifications for both the frames and panels based on structural and climatic requirements.

The framework and trusses made of wood and bamboo can be filled with materials like clay plaster and insulating sheet materials such as panels. The panels can be customized to meet the desired dimensions. These solutions are considered “low tech”. Prefabricated bamboo frames enable houses to be rapidly assembled on site. The first image of Figure 10 shows the organizing process of prefabricated panels on the ground. The second image shows (another) house assembled on a building site. Larger composite walls can be manufactured in factories using laminated bamboo materials, which are used to construct entire exterior walls. The latter method is considered “high tech” and may not be affordable for low-income families.

(**a**) (**b**)

**Figure 10.** Prefabricated panels; bamboo house under construction. (**a**) Frame ready for assembly. Source: INBAR; (**b**) Assembly on the site. Source: Bambuksa [bambuksa.org].

### *4.3. Jointing Solutions*

Making corner joints and welding with bamboo was originally completed using rope and bamboo strips. However, nowadays, it is more common to use bolts and other steel connecting methods such as clamps, brackets, and plates. There are various variations of these techniques found across the world, and continuous technical advancements are also being made. Examples of a new connection with bolts, and an improved corner connection, are shown respectively in Figures 11a and 11b. Ensuring the strength of these corner joints is crucial for the safety of homes, especially when they need to be resistant to earthquakes or storms. Therefore, it is essential to have engineers design, calculate, and test these joints.

(**a**) (**b**)

**Figure 11.** (**a**,**b**) Connections with bolts; improved corner connections. Source: author.

### *4.4. Floors*

From a technical standpoint, there is no issue in constructing houses with two levels using bamboo as a supporting structure. However, in areas prone to flooding, it is preferable to build the foundation and first floor using stone materials. The second floor can then be constructed using lighter materials like bamboo and wood. Some test homes have already been successfully built, such as in Lima, Peru. In these structures, wooden beams are used for the first floor instead of bamboo beams, as they are more suitable for providing structural support. Figure 12 shows a family house built in the municipality of San Juan de Lurigrancho, near Lima. The house has two floors and is developed with the help of IVUC-USMP, Lima.


**Figure 12.** Bamboo house in Lima, Peru. Source: Y. Barnet.

## 5. Conclusions

The search for affordable bamboo homes has led to an assessment of sustainable bamboo construction examples in Latin America, Asia, and to some extent, in Africa. These examples provide insights into the adoption of improved bamboo techniques for construction in the selected countries. These examples showcase low-cost homes that can be easily expanded by residents within the context of urban planning. The overview demonstrates that engineered bamboo houses exhibit a higher earthquake resistance compared to non-engineered homes, as well as those constructed with fired bricks, concrete blocks, and cement. This finding has been supported by various studies, including those conducted by Kaminski [35] and Barnett [36]. The technique of engineered bahareque has served as a guideline for housing projects, especially in Latin America and Asia. However, improved bamboo techniques for housing are not yet widely applied, with some countries only in the initial phase. However, in the case of the Philippines, bamboo housing production is very promising through the projects of the Base Bahay foundation. Architects, engineers, and technical universities have made valuable contributions through technological innovations, while also engaging motivated students in tackling technical design challenges. Furthermore, national governments have shown an increasing interest in the utilization of bamboo in housing construction.

A potential future application of bamboo housing on a large scale could lead to an increase in the demand for bamboo, potentially driving up the prices of the material. As the economic exploitation of bamboo resources continues to grow, it may become less accessible to local residents. Governments should be aware of this and implement measures to protect local communities accordingly.

The use of wood in residential construction is quite similar to the use of bamboo, but it is more dimensionally stable for certain applications. However, it is also heavier. Combining a timber frame with braided bamboo panels, whether plastered or not, can be done effectively. It is also possible to combine it with other building materials. It is not recommended to build all-wood or all-bamboo dwellings in densely populated areas due to the risk of fires. The fire safety of bamboo houses requires continuous attention. In areas prone to flooding, homes are constructed on stilts. In such cases, the piles must be made of durable materials like reinforced concrete.

This article demonstrates that there are enough examples of bamboo homes worldwide to support their application on a larger scale for housing low-income families. The production of social housing using bamboo implies that governments will facilitate the use of bamboo as a construction material, making these homes more accessible to families. This can be achieved through various means, such as applying subsidy schemes for social

housing. If families participate in the processing of bamboo materials and the construction of their homes, technical assistance becomes necessary. Training programs may be required, especially for local construction workers who have no previous experience in building with bamboo, particularly in areas prone to natural disasters and climate change. It is desirable to have international exchanges regarding realistic housing typologies and affordable bamboo constructions.

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