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The cover of this publication was created by Magali Studer of UNCTAD.

CONTACTS

For further information about this publication, please contact the Division on International Trade and Commodities, Commodities Branch, UNCTAD, Palais des Nations, CH-1211 Geneva 10, Switzerland, email: commodities@unctad.org, tel. +41 22 917 6286

NOTE

The term “tons” refers to metric tons.

Unless otherwise stated, all prices in this report are in nominal terms.

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CHAPTER I

Introduction

This report discusses the general uses of bamboo and explores its potential as a modern building material. It also highlights the benefits developing countries could derive from developing bamboo sector through its use in downstream industries.

Bamboo is a woody perennial evergreen plant in the grass family (Poaceae). Many of the large species look like trees with culms that can reach up to 30 metres in height and 30 centimetres in diameter.[1] For centuries, in Asia, South America and Africa, bamboo has been an integral part of the lives of inhabitants who live close to bamboo forests for food, cottage industries and construction. The use of bamboo has expanded over the last few decades, with applications in industries such as textiles, paper and modern construction, spurred in part by substitution effects of wood-based materials and efforts to reduce greenhouse gas emissions. This has contributed to increased trade in bamboo-based products and has underscored the economic importance of establishing downstream industries with growth potential, one of which is construction. More information is needed on the properties of bamboo and the innovative products manufactured from culms that provide viable options for substituting traditional building materials in order to drive this growth.

A major component of this report is a comparative analysis of the physical and mechanical properties of bamboo relative to traditional building materials. The construction industry uses man-made building materials such as cement, concrete, steel, bricks and concrete blocks, as well as a wide range of natural building materials such as timber, bamboo and clay. Selecting the material to use for a specific application depends on several factors, including strength (ability to withstand different external loadings), availability, durability, affordability, cost-effectiveness and aesthetics.

Timber, steel and concrete are the conventional building materials used in construction, largely because their mechanical properties are known and their codes of practice for designing and building are available to assist and guide engineers and architects. However, using these materials increasingly presents challenges in terms of sustainability. The manufacture of steel and concrete requires energy-intensive processes in extraction, leading to high greenhouse gas emissions. According to the International Energy Agency (IEA), the iron and steel sector is the largest emitter of carbon dioxide emissions among heavy industries, accounting directly for 2.6 gigatons of carbon dioxide annually (IEA 2020). The cement industry is the third-largest industrial energy consumer and the second-largest industrial emitter of carbon dioxide (CO2) worldwide. It has also been estimated that production of one ton of cement, which is the raw material used in making concrete, results in approximately one ton of CO2 emissions (UNCC 2017), and that the production of one ton of steel releases about 1.85 tons of CO2 into the atmosphere (Hoffman et al. 2020). Hence steel and cement contribute to making the construction industry one of the worst emitters of greenhouse gases. Timber production also raises environmental concerns because the felling of trees diminishes the critical role they play in capturing carbon, which helps to mitigate climate change.

Given the environmental challenges created by timber, steel and concrete, modern construction puts emphasis on using materials that have a low impact on the environment. Bamboo is among a few materials that have potential to replace conventional materials in construction because of its low environmental footprint. It absorbs carbon dioxide and releases over 30 per cent more oxygen into the atmosphere than an equivalent stand of trees.[2] On average, bamboo forests

[1] Bamboo culms are the stems of a bamboo plant characterized by solid joints at intervals called nodes.

[2] See the Bamboo Botanicals website at http://www.bamboobotanicals.ca/html/about-bamboo/bamboo-facts.html (accessed 6 December 2021).

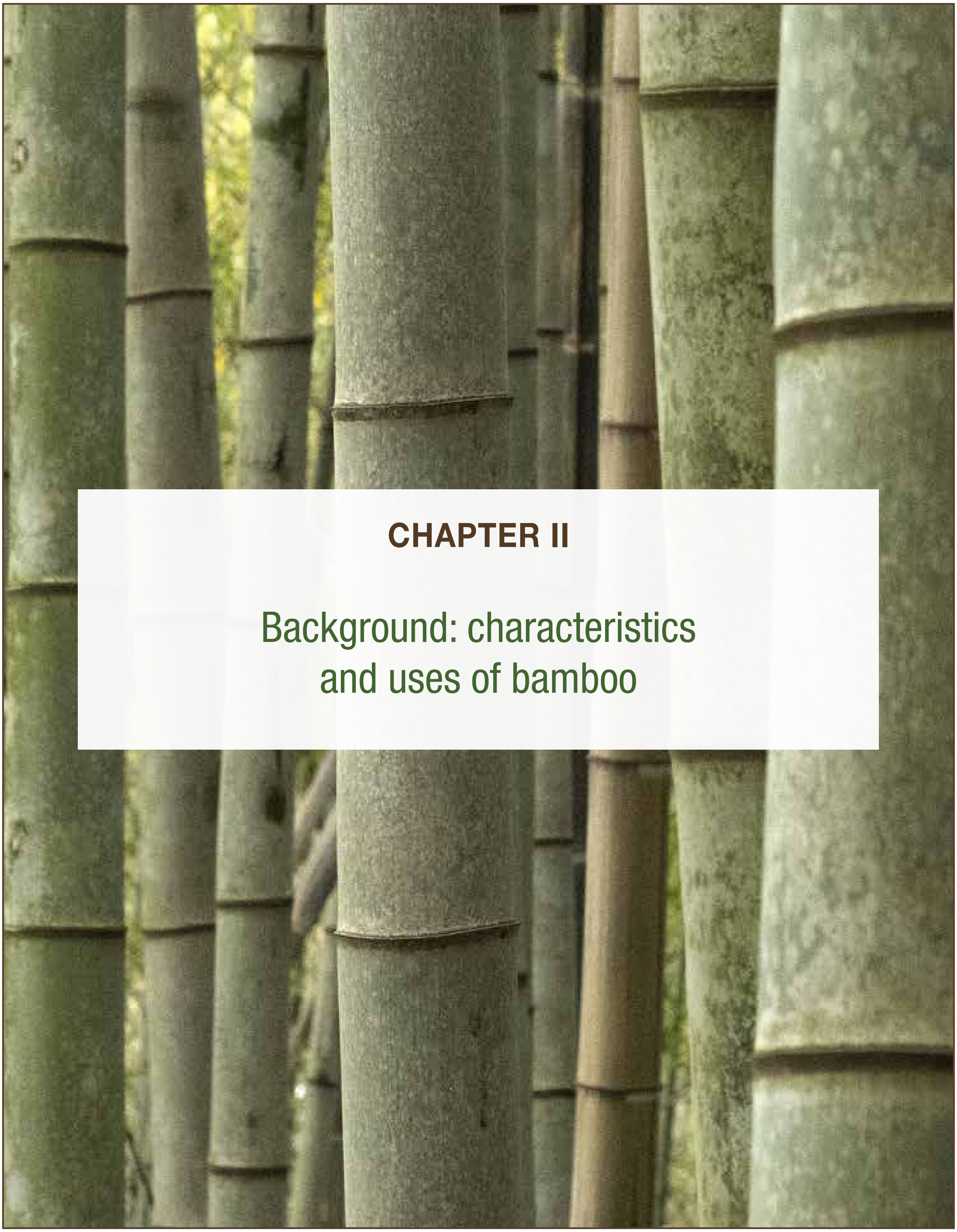
have up to four times the carbon density per hectare of spruce forests over the long term.[3] In addition, the greenhouse gas emissions associated with the production of bamboo culms used in downstream industries are relatively low. Furthermore, bamboo grows very fast and is harvested and replenished without destroying the natural forest that acts as a carbon sink.

The adoption of bamboo in modern construction is growing at a slow pace due to a combination of several factors, including limited knowledge of its mechanical and physical properties; challenges in treating culms against attack from pests; a limited number of architects and engineers trained in designing structures using bamboo; a limited number of carpenters with the skills to build with bamboo; limited knowledge of bamboo's environmental properties and benefits; and a dearth of international codes of practice for design and building. The potential for widespread use of bamboo in modern construction will depend on how these limiting factors are addressed.

The aim of this report is to help fill this information gap by providing information on the properties of bamboo. This could encourage greater use of bamboo as a building material and foster the cultivation and trade of bamboo species that have strong potential in construction. In addition, building with bamboo could facilitate plans by governments to provide affordable housing for millions of people in developing countries because it is cheaper than conventional construction materials and widely available.

This report has six additional chapters following this introductory chapter. Chapter 2 provides background information on bamboo related to growing conditions and the growth cycle, geographical distribution, characteristics and uses. Chapter 3 provides information on the historical uses of bamboo and an analysis of its physical and mechanical properties. It also highlights the opportunities and challenges for using bamboo as a building material. Chapter 4 examines value addition in the manufacturing chain of bamboo products used in the construction industry. Chapter 5 provides information on international trade in bamboo products, including those used in construction. Chapter 6 examines the economic, environmental and social impacts of the bamboo industry. The final chapter highlights policy issues associated with bamboo development and draws lessons from the study in the form of policy recommendations to assist commodity-dependent developing countries in their efforts to achieve inclusive economic growth and sustainable development.

[3] The amount of carbon per unit area for a given ecosystem or vegetation type. High carbon density signifies high carbon storage.



CHAPTER II

Background: characteristics and uses of bamboo

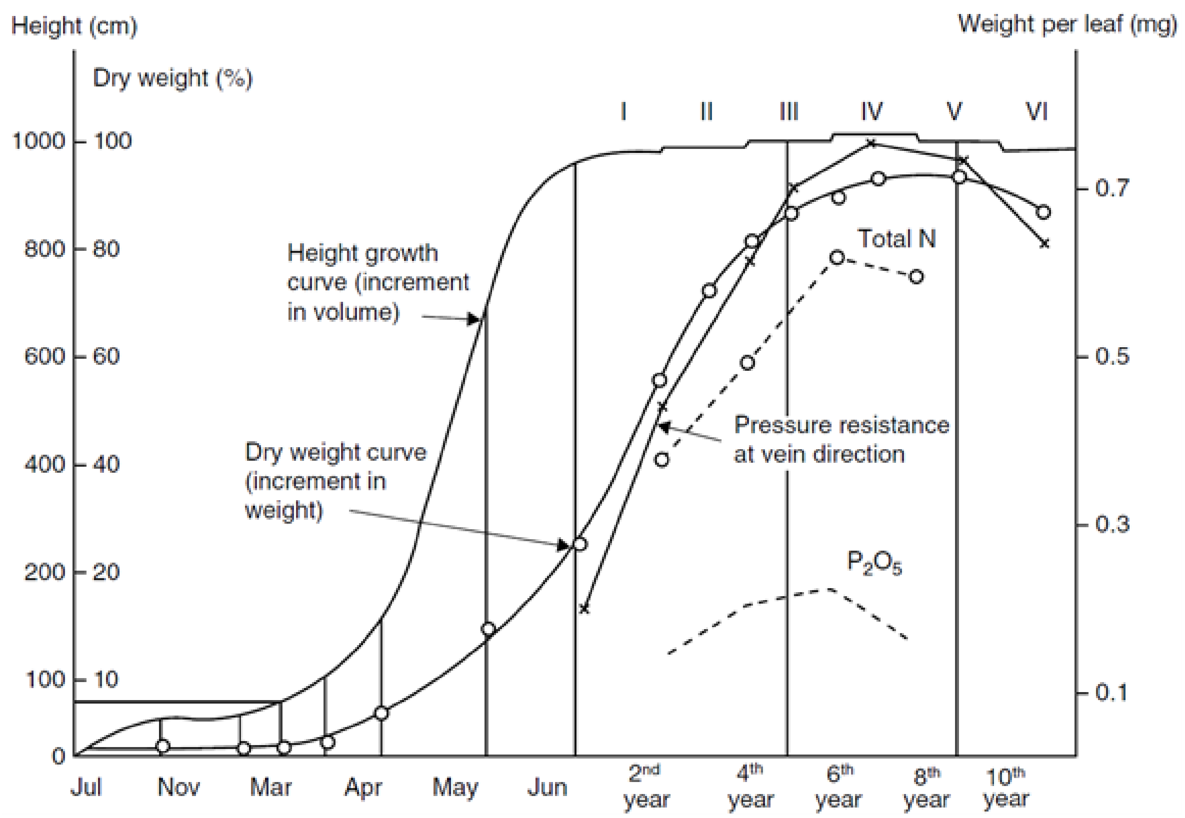
2.1 BAMBOO GROWING CONDITIONS

Bamboo is a natural, multifaceted plant that grows naturally or by cultivation in diverse climatic conditions. Tropical and subtropical climates offer optimum growing conditions for most species. Some bamboo species may also successfully grow in mild temperate zones of Europe and North America (Lobovikov et al. 2007). Almost any soil type will support bamboo growth, but bamboo thrives in moist aerated soils that are light in structure and rich in organic nutrients, thereby encouraging healthier root systems and promoting accelerated growth. Constantly wet, boggy or extremely dry conditions do not support bamboo growth.[4]

2.2 GROWTH CYCLE OF BAMBOO

Bamboo is a fast-growing plant that typically undergoes three stages of growth. First is the underground growth stage that takes place mainly in the rhizome of the plant. Then comes the surface growth stage, during which growth in height is at its fastest. Bamboo reaches almost full height in just about two months during surface growth (see May and June in Figure 1), representing almost 80 per cent of the total increase in height. Thereafter, the height of the plant stabilizes. In the quality increment stage, the bamboo culm rapidly gains weight and pressure resistance, until it starts to weaken around eight years after planting. Figure 1 shows the growth cycle of a common bamboo species, Phyllostachys edulis heterocycle (also known as Moso bamboo).

Figure 1 Growth process of Moso bamboo



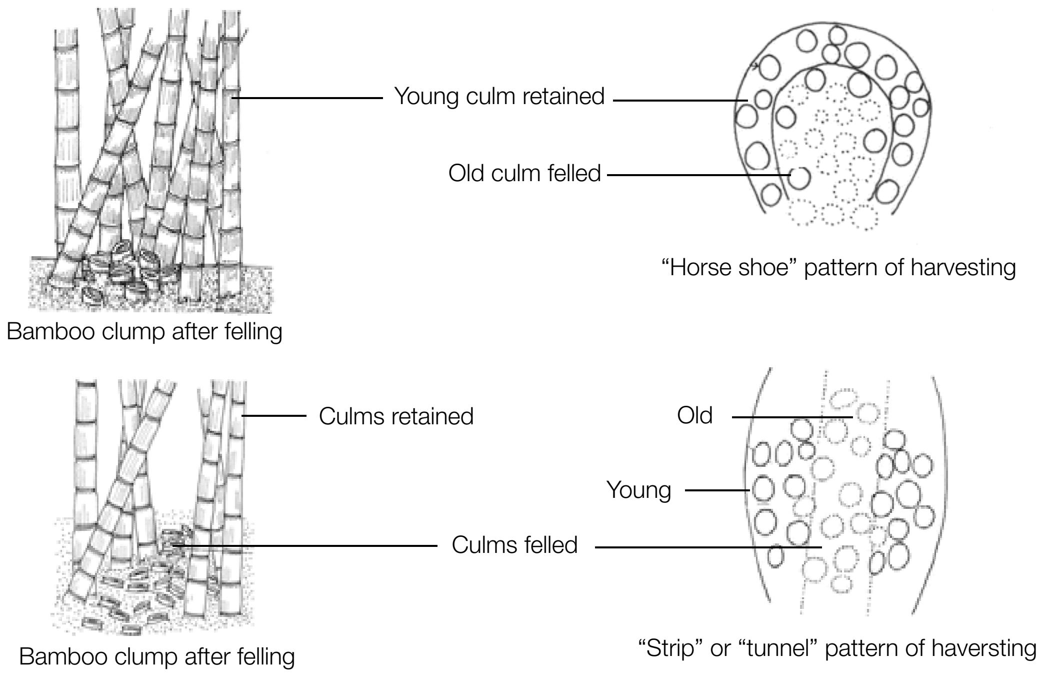
Source: Zhaohua and Wei (2018) as adapted from Danren (1999).
Note: P_2O_5 indicates phosphate content; N indicates nitrogen content.

[4] RHS, "How to grow bamboo," https://www.rhs.org.uk/advice/profile?PID=79 (accessed 6 December 2021).

2.3 HARVESTING BAMBOO

Upon reaching maturity, bamboo plantations can be harvested regularly every one to two years, whereby mature culms representing 20 to 30 per cent of the bamboo clump are cropped through selective felling. Figure 2 provides some examples of such felling techniques that distinguish between young and old culms. The horseshoe technique is based on making an opening in a dense bamboo clump, opposite the densest concentration of bamboo culms. It allows for the extraction of older culms while maintaining young and growing culms. The tunnel technique is based on creating two tunnels through the centre of the bamboo clump, which divides it into four sections and allows for harvesting from the inside out. This technique also enables selective harvesting while maintaining healthy and growing culms (NECTAR 2004). This high frequency of bamboo harvesting is a unique characteristic, enabling annual yields that can reach 10 to 20 tons per hectare. Such yields are higher than those of some tree crops such as cocoa beans in Cameroon and Côte d'Ivoire, according to FAOSTAT.

Figure 2 Selective bamboo felling techniques



Source: Liese and Köhl (2015).

2.4 BAMBOO RESOURCES, SPECIES AND GEOGRAPHICAL DISTRIBUTION

Bamboo is widely distributed in Asia, Latin America and Africa. In 2020, bamboo covered an area of 35 million hectares, representing less than 1 per cent of the global forest area (FAO 2020). Asia had close to 25 million hectares of bamboo in 2020 (more than 70 per cent of global resources), with India, China, Viet Nam, Japan and Cambodia accounting for the largest amounts.[5] South America reported 5.4 million hectares, primarily in Brazil. The most important bamboo resources reported from Africa were in the United Republic of Tanzania, Ethiopia and Senegal, representing a total area of 4.64 million hectares. Total bamboo area increased by more than 70 per cent in the last three decades around the world, with decreases in Africa but with the increase due primarily to the expansion of bamboo in India and China.

[5] India has the largest area of bamboo under cultivation, estimated at 15.69 million hectares (Invest India 2021).

There are about 1,600 species of bamboo in 121 genera found in different regions of the world (Canavan et al. 2017). They are grouped as either an herbaceous or a woody type of plant. The herbaceous bamboo species are not plentiful, tend to be very small in diameter, look a lot like grass, and are generally less economically important than woody bamboos.[6] It is estimated that there are about 110 species of herbaceous bamboo, mainly concentrated in Brazil, Paraguay, Mexico and the West Indies (Yeasmin et al. 2015). In contrast, woody bamboos look like trees, although genetically speaking they are members of the grass family. They are characterized by larger diameters and woody culms and are important in terms of their use as construction materials (Kaminski et al. 2016a), as well as in the production of various commercial products.

About 80 per cent of all bamboo species are found in Asia. Although India reports the largest bamboo resources in overall terms, China accounts for the largest diversity of species, with approximately 500 species belonging to 40 genera, many of which are of the woody type. Woody bamboo is also abundant in America, with 20 genera and 429 species found in many countries including Brazil, Colombia, Venezuela, Ecuador, Costa Rica, Mexico and Peru. Africa has the lowest diversity of woody bamboos, with only five species representing five genera. These species are mostly found in the United Republic of Tanzania, Malawi, Uganda and Zambia (Bystriakova et al. 2004). Generally, the distinction between different types of bamboo species is based on their botanical characteristics, and their identification is a laborious task. Nevertheless, there are some observable characteristics discussed in the next section that help distinguish one species from another, and that can be useful in selecting ideal species for the manufacture of bamboo-based products.

2.5 CHARACTERISTICS AND IDENTIFICATION METHODS

Height, stem diameter, culm wall thickness and colour are some of the characteristics used in identifying the species of bamboo from different genera. This report focuses on five genera that have species commonly used in industries: Guadua, Dendrocalamus, Bambusa, Gigantochloa and Phyllostachys. The species of the Guadua genus are among some of the largest varieties of bamboo.[7] They grow between 20 to 30 metres tall with stem diameters of 22 to 25 centimetres and culm wall thickness of 8 to 30 millimetres.[8] The Dendrocalamus strictus species, which are used frequently in construction, grow between 15 to 19 metres tall with mature stems of 10 to 13 centimetres in diameter,[9] and culm wall thickness of 6 to 20 millimetres (Javadian et al. 2019). Some species in this group have almost solid culms when they grow in dry conditions.[10] The Bambusa genera have the largest and most diverse groups of bamboo.[11] The common species found in this group, Bambusa vulgaris, can grow between 10 to 20 metres tall with a stem diameter between 4 to10 centimetres and culm wall thickness of 7 to15 millimetres.[12] The species

6 Bambu Battu, 2020, "Woody vs herbaceous bamboo: Introducing Olyreae," 16 September, available at https://bambubatu.com/woody-vs-herbaceous-bamboo-olyreae/ (accessed 6 December 2021)

7 Bambu Battu, 2020, Genus Guadua: Giant neotropical bamboo," 20 November, https://bambubatu.com/genus-guadua-giant-neotropical-bamboo/ (accessed 6 December 2021)

8 Bambusa Estudio, "Guadua bamboo," https://bambusa.es/en/characteristics-of-bamboo/guadua-bamboo/ (accessed 6 December 2021).

9 Bambu Battu, 2021, "Genus Dendrocalamus: The biggest bamboos of all," 28 January, https://bambubatu.com/genus-dendrocalamus-the-biggest-bamboos-of-all/ (accessed 6 December 2021).

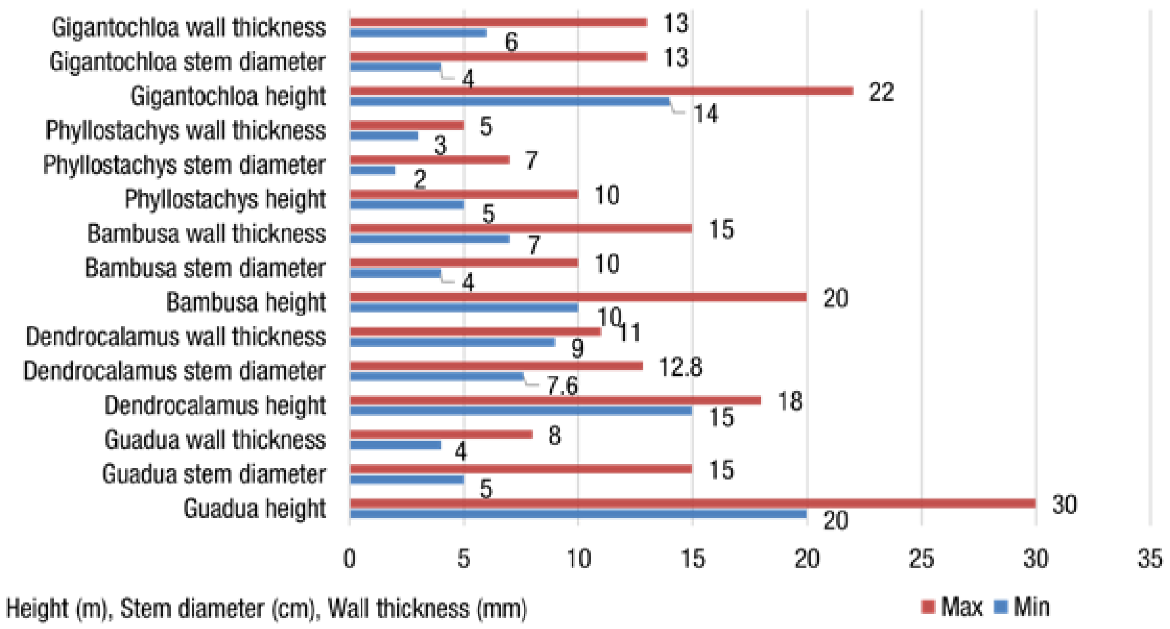
10 Ibid.

11 Bamba Battu, 2020, "Genus Bambusa: Paragon of bamboo," 9 November, https://bambubatu.com/genus-bambusa-paragon-of-bamboo/ (accessed 6 December 2021).

12 Ibid.

found in the Gigantochloa genus grow between 7 to 20 metres tall with an average diameter between 5 to 15 centimetres,[13] and stem wall thickness of 6 to 13 millimetres.[14] The Phyllostachys genus are found in a variety of sizes. They grow to a height of 2.5 to 27 metres with diameters ranging between 1.5 and 18 centimetres,[15] and a wall thickness range of 8 to 15 millimetres.[16] Figure 3 summarizes information on characteristics related to height, culm diameter and wall thickness of selected species/genera commonly used as industrial materials.

Figure 3 Characteristics of selected bamboo genera



Source: UNCTAD secretariat calculations based on data from Guadua Bamboo (https://www.guaduabamboo.com/species/gigantochloa-apus), CAB International (https://www.cabi.org/isc/datasheet/8398), and Bambusa Estudio (https://bambusa.es/)

Different species of bamboo are also identified by a complex classification system that helps in understanding their characteristics and differentiating between species in the vegetative state and distribution. In traditional classification, components of flowers are often used as a crucial part of the plant to categorize a species. Flowering in bamboo is unpredictable and happens occasionally, but when it happens, the flowers can be used to identify different species (UNIDO 2009). For example, many of the big timber bamboos that are preferred in construction exhibit gregarious flowering (Zheng et al. 2020). In this type of flowering pattern, species can flower and die at the same time regardless of where they grow because all plants originating from a source are clones of the mother plant (bamboo is usually multiplied by replanting stem cuttings or clump divisions).[17] Other bamboo varieties exhibit sporadic flowering patterns that are usually not widespread and occur in either singular plants or all plants belonging to the same species

[13] American Bamboo Society, "Gigantochloa," https://absfcc.org/gigantochloa/ (accessed 6 December 2021).

[14] Guadua Bamboo, "Gigantochloa apus," https://www.guaduabamboo.com/species/gigantochloa-apus (accessed 6 December 2021).

[15] Guadua Bamboo, "Phyllostachy," https://www.guaduabamboo.com/blog/phyllostachys-species-list?rq=phyllost (accessed 6 December 2021).

[16] Ibid.

[17] Bamboo Land: Nursery and Parklands, "About bamboo," https://www.bambooland.com.au/useful-info/about-bamboo (accessed 6 December 2021).

within a localized area. The flowering is believed to be triggered by environmental factors (such as drought or cold) rather than genetics.[18] Some species that exhibit sporadic flowering grow into the woody type of bamboo and are suitable for construction. Sporadic flowering rarely results in the production of seeds that germinate into young plants, but on the upside, the plants very rarely die after the event. The third pattern of flowering happens annually in only a few bamboos (usually only some species of the Schizostachyums genera). The plant is not affected by the annual flowering and viable seeds are seldom produced.[19]

In addition to bamboo flowers, many genera can be identified by colour, number of nodes, blades and location. Although similar colour variations can occur in different species, the more distinctive culm colour patterns can sometimes be used for positive identification of distinct species. For example, bamboo can be found in yellow, brown, black, red, and blue. The distinctive yellow colour of bamboo and distinctive groove that runs along its internodes can be used to identify species that belong to the Phyllostachys genus, frequently used in construction and scaffolding. The dominant hue of bamboo is green, but many change their colour as they age to yellowish brown with maturity and on drying. Another way of identifying bamboo is by examining the blades of the bamboo shoots, which tend to have dominant parallel venation. Bamboo species used in construction tend to have cross veins when viewed under a microscope and are very tough (Lewis and Miles 2007). Additional factors used to identify bamboo are the occurrence of joints between hollow sections of the culm (nodes), and the length of internodes and their shape (in longitudinal section) and appearance.

Bamboo species are also classified as running (monopodial) or clumping (sympodial) in line with the pattern of growth. The running type of bamboo, also known as invasive bamboo, produces long horizontal roots called rhizomes that grow away from the main plant and will spread rampantly if not contained. By contrast, clump-forming bamboo grows in tight clumps and is less invasive. Both running and clumping type bamboos are very fast-growing plants. The runners grow by an average of 0.9 to 1.5 metres in a year, while the clumping varieties grow slower, averaging 0.3 to 0.9 metres in height growth per year.[20] This average growth pattern is not maintained at the same rate throughout the life cycle of the plant. Furthermore the established bamboo plants tend to grow faster than newly planted ones.[21] The size and appearance of any bamboo variety may vary significantly depending on climate and conditions. For example, the size of bamboo is greatly affected by various factors, including temperature, water and sun exposure. In the construction industry, the clumping type of bamboo is preferred because this bamboo grows tall and upright and has thick walls. With few exceptions, woody bamboo species found in the tropical regions of the Americas, Africa, Asia and Australia are generally of the clumping type and are not invasive.[22]

The most important data in identifying bamboo are the botanical names of the genera and species and their geographical distribution, along with their references. These data help to provide, inter alia, information on plant descriptions, diagnoses and keys for plant identification, botanical drawings, photographs of the plants, precise plant localities, and vernacular names.[23]

18 Ibid.

19 Ibid.

20 The Happy Bamboo, 2019, "How fast does bamboo grow," blog, May 30, https://thehappybamboo.com/how-fast-bamboo-grow/

21 Ibid.

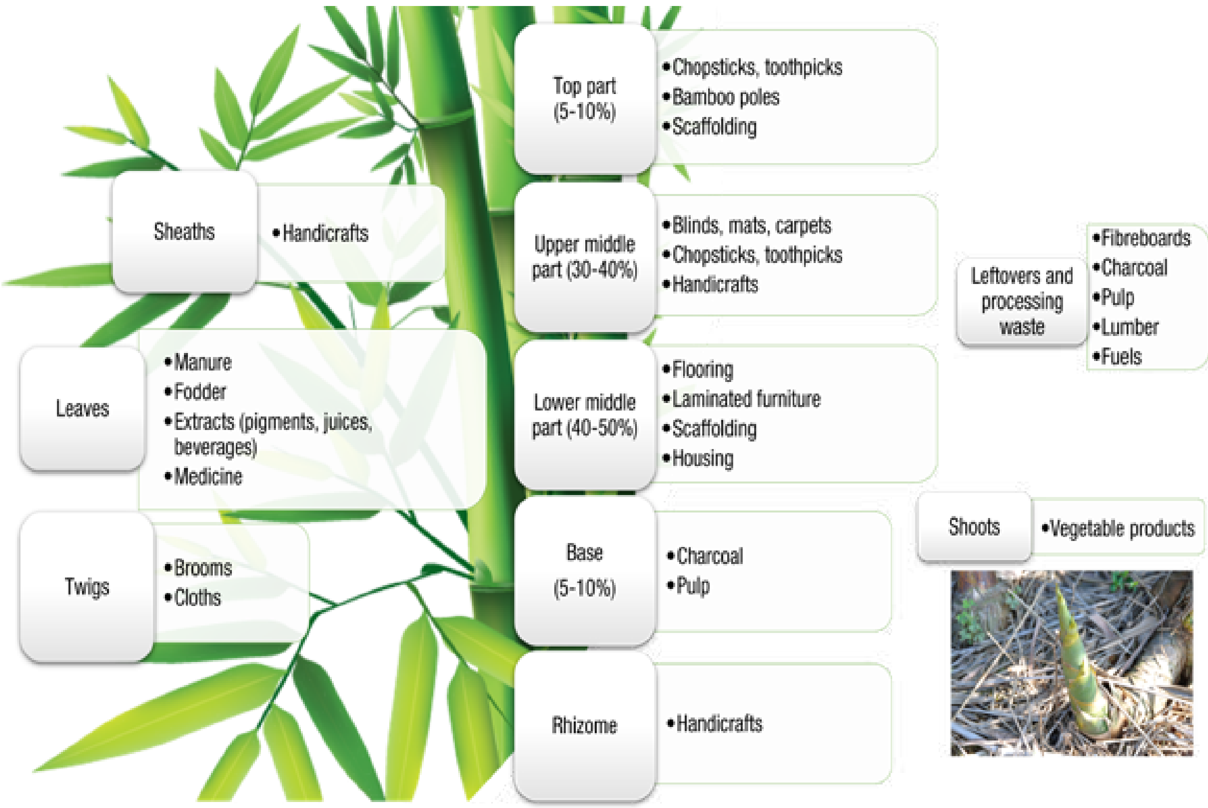
22 International Bamboo and Rattan Organisation, "Bamboos and invasiveness," https://www.inbar.int/bamboos-and-invasiveness/ (accessed 6 December 2021).

23 Several compendiums of bamboo species are available from online resources. See Bamboo Botanicals (http://www.bamboobotanicals.ca/html/bamboo-species/phyllostachys-vivax-aureocaulis.html) and the CABI Invasive Species

2.6 DIFFERENT PARTS OF BAMBOO AND GENERAL USES

The bamboo plant is typically divided into six parts; top, upper middle, lower middle, base, shoots, and leaves. Figure 4 shows some examples to the uses of different parts of a bamboo plant. Each part has uses in industries such as textiles, paper, construction, furniture, food and agriculture.

Figure 4 The bamboo plant: Different parts, different uses



Source: Adapted by the author from Zhaohua and Wei (2018).

2.6.1 Top

The top part of the bamboo plant is used predominantly by the construction industry, for which bamboo fibres have intrinsic value, such as in their use for scaffolding. They are believed to be much stronger and more resilient than wood or other timber species, in addition to being lighter and therefore easier to be carried and transported to the construction site (Ingram et al. 2010).

2.6.2 Upper middle

The upper-middle part of bamboo is used in manufacturing fabrics and is a valid substitute for cotton and other textile fabrics, such as polyester. As early as 1864, a patent was granted to Philipp Lichtenstadt for the invention of a "new and useful process for disintegrating the fibre of the bamboo, so that it may be used in manufacturing cordage, cloth, mats, or pulp for paper" (Waite 2009: 2). The upper-middle part is also suitable for making handicrafts. Basketwork is

Compendium (https://www.cabi.org/isc/datasheet/8398).

among the most valuable uses of bamboo. Bamboo used for plaiting includes kitchen utensils such as fruit baskets, chairs and tables, hats, plaited mats and other woven bamboo products.

2.6.3 Lower middle

The lower-middle part of bamboo plants is predominantly used as an input for the manufacture of wooden products, including household and office furniture such as beds, chairs, cupboards and tables or desks. In addition, bamboo serves to process small wooden speciality items such as cups and sticks. Engineered bamboo products such as bamboo flooring are among the most valuable uses of the plant. They are manufactured by intensive processing of raw culms to form industrial products that have a wide range of applications, including in construction. Box 1 describes the process of transformation of raw culms into engineered bamboo. Bamboo flooring can be classified as a distinct category of industrial bamboo products because of its high importance. Bamboo culms cut from this section of the plant are also used as posts or columns in construction to carry load in lightweight structures.

Box 1. Engineered bamboo

The common engineered bamboo products are laminated bamboo and bamboo scrimber. They are created by processes that glue cut strips from the culm together to form rectangular boards (laminated bamboo) or by crushing fibre bundles (bamboo fibres, fibre bundles, and bamboo strips) saturated in resin and compressing them under high pressure to create a dense material that gives strength, flexibility and stability (bamboo scrimber, also referred to as strand woven bamboo or parallel strand bamboo). The laminated bamboo process utilizes approximately 80 per cent of raw bamboo inputs. Both materials retain the inherent strength of bamboo by maintaining the longitudinal fibre orientation. They have many applications in construction, including for surface applications. Furthermore, the engineered product creates a uniform section for connections and joints in structural applications, which makes it appealing as a structural material such as glue-laminated timber products.

Source: Bamboo Import Europe (2016a).

2.6.4 Base

The base part of the bamboo plant can be used to produce bamboo charcoal (biochar), as well as pulp. The adjacent photograph shows a bamboo charcoal sample. Bamboo charcoal is a fuel that can be used to boil bamboo shoots, thereby removing natural toxins and allowing their consumption as food. Therefore, trade trends of bamboo charcoal follow those of bamboo shoots, with Japan as its largest importer. In addition to its use as fuel, bamboo charcoal presents some additional advantages, including as a potential carbon sink and effective fertilizer (Yiping et al. 2010). That explains why countries such as Saudi Arabia, the United States, the Netherlands and the United Arab Emirates are major importers of bamboo charcoal without being large consumers of bamboo shoots. Bamboo biochar stocks carbon

Bamboo charcoal

Source: International Bamboo and Rattan Organisation.

through a process of pyrolysis (thermal decomposition of materials), whereby it can transfer up to 50 per cent of the carbon from plant tissue when biomass is heated to temperatures between 350°C and 600°C in the absence of oxygen (Yiping et al. 2010).

2.6.5 Shoots

Bamboo shoots are edible vegetables that grow from the rhizome, which are the underground stems of the bamboo tree. Food made of bamboo shoots represents a great source of nutrients for human beings and animals alike. Shoots are among the most valuable parts of bamboo, and their consumption is increasing. They are a well appreciated vegetable delicacy in African and Asian cuisine across the world. Approximately US$260 million worth of bamboo shoots were exported in 2020, predominantly from China to Japan, as well as from China to Viet Nam, the Republic of Korea, the United States, and the European Union.

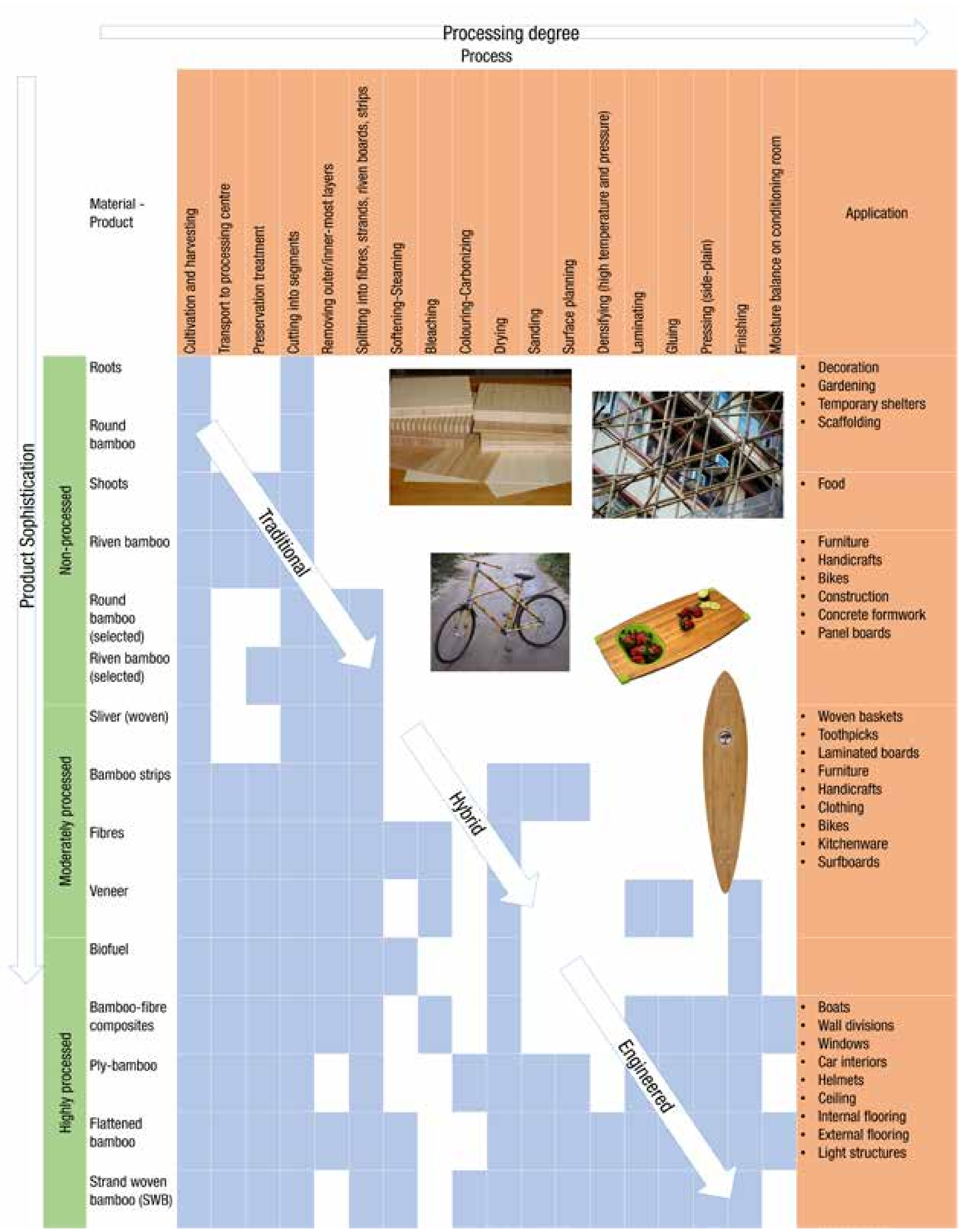
2.6.6 Leaves

Bamboo leaves have been used in Chinese traditional medicine since ancient times. They are listed as a natural plant with food and medical uses by the Chinese Ministry of Health. Medical uses include lowering blood lipids and cholesterol, as well as antioxidants and anti-aging. Extracts from leaves can be used in beverages and juices. Leaves can also be utilized as animal fodder, especially for pandas, contributing to biodiversity (Zhaohua and Wei 2018).

Figure 5 demonstrates the range of applications from low-tech to high-tech, depending on the degree of processing, that results in various levels of sophistication of bamboo products. While in some cases the processed bamboo product itself is an end product (such as shoots for nutrition, biofuels, woven baskets, or furniture), it often has applications as an intermediate product (e.g. when used in boats, cars or buildings). In the figure, rows represent various bamboo products according to their level of sophistication as per how much processing they have undergone. Columns represent specific processing activities. The corresponding cells that match products with a specific processing activity are indicated in light blue.

As bamboo products increase in sophistication from traditional to hybrid and engineered, they require many more processing steps. Applications of specific bamboo products are mentioned in the furthest right column of figure 5. The light blue cells create a triangular form leaning on the bottom left part of the figure, which means that the more sophisticated the bamboo product, the more processing steps it undergoes. For example, bamboo roots only undergo two processing steps (cultivation and harvesting, and cutting into segments), while strand woven bamboo undergoes almost all processing steps mentioned in the figure.

Figure 5 Applications of bamboo products by level of sophistication



Source: Adapted by the author from Zea et al. (2019).

CHAPTER III

Bamboo in modern construction

MOSO Bamboo Products, photo by Isa Steinhauser

3.1 HISTORICAL OVERVIEW

Bamboo has a long history of use as a building material in many parts of the world, particularly Asia, South America and Africa.[24] In China, bamboo has been used to construct bridges dating back to the 10th century.[25] In the Philippines, bamboo has been used for hundreds of years to build inexpensive, hurricane-resistant housing, called "nipa huts."[26] The post-and-lintel system was the main system of construction employed in these types of buildings. Bamboo was often sourced from naturally grown forests in and around villages and used by people who lived nearby. In Central and South America, bamboo is a common part of the local architecture. It was widely used in southern Colombia and northern Ecuador in the construction of houses that stood for 50 to 100 years on unstable sites such as steep slopes, earthquake-prone regions or swampy coastal areas that are frequently inundated (Bystriakova et al. 2004). In El Salvador, indigenous buildings were constructed using timber, bamboo elements, and mud. They are highly flexible and elastic when carefully constructed and well-maintained, and they perform well against dynamic loads such as earthquakes. When they do show high vulnerability during earthquakes, it is largely due to poor workmanship (carelessness and cost-cutting measures during construction), lack of maintenance (resulting in a rapid deterioration of building materials), and heavy roofs made of tiles (Lange et al. 2007). In Africa, traditional houses were built using a combination of building materials including bamboo as far back as the 18th century.

The use of bamboo in construction has continued to grow in the 20th and 21st centuries because it is cheaper relative to other building materials such as timber, steel and concrete. More recently, innovative ways of using bamboo as a building material have led to the development of standardized engineered bamboo-based products that have low variability in their properties as compared to the natural material (Sharma et al. 2015).

Bamboo culms and engineered bamboo products can play a significant role in construction. For example, they can be used as load-carrying members (beams and columns), walls, and in external and internal surface applications. However, they are not extensively used as a building material due in part to the dearth of information on their properties and the lack of building codes for them that would provide tolerance limits and detail designs. Traditional building materials like timber, concrete and steel became popular in construction largely due to a broad understanding of their properties and the advent of codes that supported their broad usage. Codes of practice on designing in steel brought new options in building materials to architects and engineers and spurred its regular use in the framed system of construction in buildings,[27] factories and other load-bearing structures such as bridges. The first codes and regulations for the design of reinforced concrete structures were published in the United Kingdom at the beginning of the 20th century, contributing to widespread use of concrete in building large structures using a frame system of construction. Timber also became a widely used building material as its properties became well understood and several international design codes emerged. This facilitated the design of timber-framed or half-timber-framed structures where the weight of the structure is carried by a skeletal frame as opposed to being supported by walls.

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24 Bamboo is often used in lightweight structures that employ a post-and-lintel system of construction, which essentially consists of two upright members, the posts, holding up a third member, the lintel or beam, laid horizontally across their top surfaces. The posts carry the loads that rest on them from the lintel, and when the structure cannot withstand this load it fails. The post-and-lintel system of construction has dominated the construction industry for centuries and is often employed when the technological skills of users are limited.

25 Build Abroad, "Bamboo construction: Drawing on ancient traditions," https://buildabroad.org/2016/10/18/bamboo-construction/ (accessed on 6 December 2021).

26 Ibid.

27 The framed system of construction uses a combination of beams, columns and slabs to resist the lateral and gravity loads.

The discussion in the next section focuses on the physical and mechanical properties of bamboo and compares them with the aforementioned traditional building materials often used in the construction industry (timber, steel and concrete). The section also highlights the opportunities and challenges in using bamboo as a building material.

3.2 PHYSICAL PROPERTIES

The physical properties of building materials are used to estimate their quality and condition when not subject to any applied load. The main physical properties that are often used in the selection of building materials are density, moisture content and shrinkage, and fire resistance. Density is a measure of how heavy an object is for a given size. It is defined as the mass of material per unit volume and expressed in kilograms per cubic metre (Kg/m3). Density is a useful property because it helps in the selection of materials where weight is of importance in the design of structural components. A building material with high density indicates a high degree of compactness, which influences its behaviour under loading with respect to strength and thermal conductivity. The moisture content of building materials is a measure of the amount of water that they hold and is technically expressed as a percentage of the oven dry weight. The shrinkage in materials is directly related to changes in their moisture content. Fire resistance shows the ability of a building material to withstand a fully developed fire and maintain its structural stability. It is a useful property for selecting materials to design structures that would ensure limited damage when fire breaks out so that structural stability and integrity is maintained.

3.2.1 Density

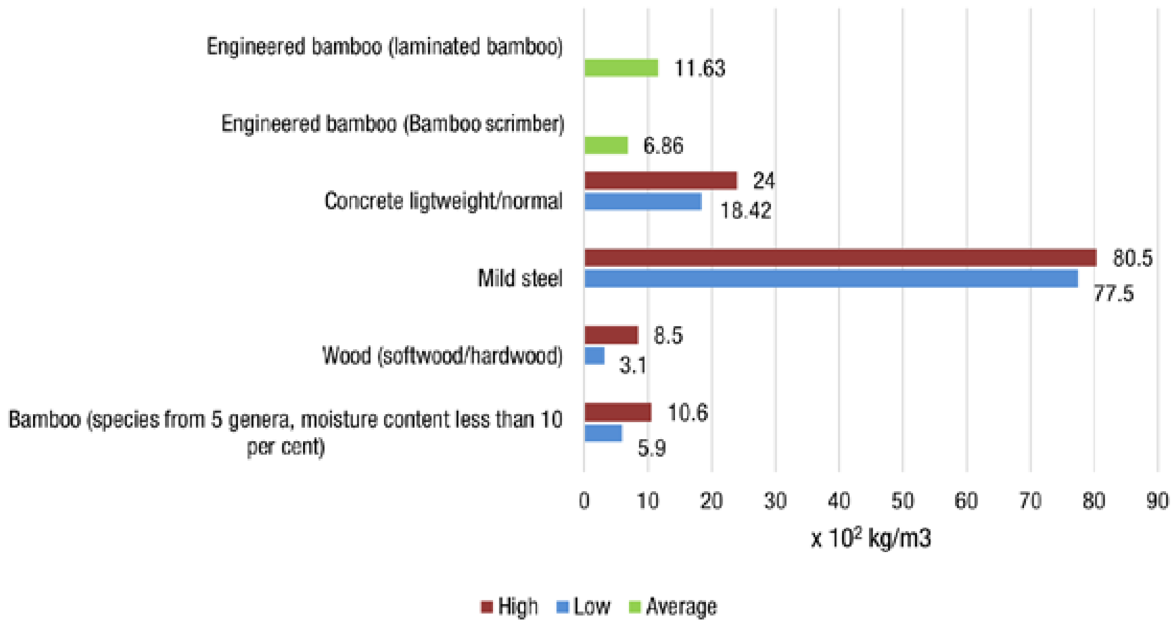
The density of bamboo varies with different species and along the stem due to the variation in volume fraction of vascular bundles in the stem and the solid fraction within the vascular bundles (Dixon and Gibson 2014). Figure 6 presents the results of density tests of selected bamboo species used in construction. The tests show a variation from 590 Kg/m3 to 1,006 Kg/m3 with a moisture content of 8.5 per cent and 7.8 per cent, respectively (Bamboo Import Europe 2016b). In tests performed on engineered bamboo specimens, results show an average density of approximately 686 Kg/m3 for laminated bamboo and 1,163 Kg/m3 for bamboo scrimber (Sharma et al. 2015). By comparison, density tests on selected species of softwood and hardwood timbers used in construction with varying moisture contents show values ranging from 310 Kg/m3 to 850 Kg/m,[28] while steel density ranges between 7,750 Kg/m3 and 8,050 Kg/m3. The high-density alloys produce greater-density steel.[29] Concrete density ranges from 1,842 Kg/m3 in some lightweight concretes to 2,400 Kg/m3 in normal concrete.[30]

[28] The Engineering ToolBox, "Wood, panel and structural timber products - Mechanical properties," https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html (accessed 6 December 2021).

[29] Toppr (learning app), "Density of steel – How to calculate the density of metal?" https://www.toppr.com/guides/physics/fundamentals/density-of-steel-how-to-calculate-the-density-of-metal/ (accessed 6 December 2021).

[30] Density of concrete varies according to the type, amount and density of the aggregate, how much air is entrapped or purposely entrained, the cement concentration, and the maximum size of aggregate used. See https://www.aggregateresearch.com/news/understanding-the-density-of-concrete/ (accessed 6 December 2021).

Figure 6 Density of selected building materials
(Kg/m3)



Source: UNCTAD secretariat calculations based on data from Sharma et al. (2015) and the following websites: https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html, and https://www.toppr.com/guides/physics/fundamentals/density-of-steel-how-to-calculate-the-density-of-metal/ (accessed 6 December 2021).

The low density of bamboo has many benefits in construction that include the ability to build lightweight structures on foundations where the bearing capacity of soils is low, reduce foundation sizes and costs related to construction such as labour, and transport bamboo materials. Furthermore, because bamboo has low density and weight compared to heavier building materials, it is less energy-intensive to transport and therefore has less environmental impact with respect to greenhouse gas emissions. On the other hand, denser materials such as steel can carry more load than similar-sized materials.[31]

3.2.2 Moisture content and shrinkage

Moisture content is an important property in woody materials because when it falls below the fibre saturation point of the material – that is, the amount of water held within the cell walls while the cell cavities are free of water – the physical and mechanical properties of the material are affected (Smith 1986). Above the fibre saturation point, most mechanical properties are constant with changes in moisture content. Bamboo experiences similar changes in moisture content on its properties because it is a hygroscopic material. In general, mechanical properties of woody plants are affected by changes in the moisture content below the fibre saturation point, but are largely unaffected when it rises above (Evans and Youngquist 2004).

Tests performed on selected bamboo species show that at different moisture contents, compressive

[31] Continuing Education Center: Architecture and Construction, 2015, "Achieving higher quality in high-density residential: The strengths of structural steel," https://continuingeducation.bnpmedia.com/courses/american-institute-of-steel-construction/achieving-higher-quality-in-highdensity-residential-the-strengths-of-structural-steel (accessed 6 December 2021).

strength and modulus of elasticity were negatively correlated with the change in moisture content below the fibre saturation point (Wang et al. 2013). For example, tests performed on Phyllostachys edulis bamboo, a common species used in construction, show compressive strength increasing from 67 Newton per square millimetre (N/mm2)[32] at 50 to 99 per cent moisture content to 147 N/mm2 at 0.1 to 0.3 per cent moisture content (Bamboo Import Europe 2016b). The stiffness also declined from 9,400 N/mm2 at less than 5 per cent moisture content to 6,400 N/mm2 when the moisture content increased above 30 per cent, the nominal fibre saturation point (Bamboo Import Europe 2016b). Moisture content tests on timber also show variations in strength properties with changes in moisture content.

The variation of moisture content may lead to changes in the physical state of the building material. When there is too much moisture, the material may undergo swelling, while loss of moisture may result in shrinkage. These changes may contribute to structural problems that often lead to failure. For example, shrinkage or swelling in bamboo reinforcement in concrete may lead to cracks and loss of bond and to loss of its function as reinforcement, which in turn reduce the efficiency of the structural member. Shrinkage may also lead to differential settlement, which could generate internal stresses leading to cracks in finished walls, floor squeaks, and non-serviceability of buildings (Onysko et al. 2008). By contrast, high moisture content in bamboo is likely to facilitate decay, attract insects and reduce structural integrity.

3.2.3 Fire resistance

Bamboo is a poor conductor of heat, and it burns at a slow and predictable rate because its exterior shell is made of a protective layer made from silica, which is about 0.25 millimetres thick, and relatively impermeable. (Kaminski et al. 2016b). Nevertheless, bamboo loses strength rapidly when exposed to prolonged fire.[33] Therefore, by itself it is unable to provide a minimum time of 30 minutes to withstand a developed flame and the transmission of heat that will lead to structural failure (Fire Resistance Rating of 30 minutes) (Kaminski et al. 2016b). Timber is also a poor conductor of heat, and like bamboo burns at a slow and predictable rate. Timber derives its resistance to fire mainly from a char layer that forms on the burning surface that provides insulation to the inner core of the timber, enabling it to resist heat penetration and slowing the overall combustion rate.[34]

Engineered bamboo products such as laminated bamboo and bamboo scrimber char in a similar way to timber and have been shown to match or even outperform some timber products when exposed to fire. By comparison, concrete is a non-combustible material that has low thermal conductivity. This means that it takes a long time for fire to affect its structural, load-bearing ability, and it has protection from the spread of fire. Steel has high thermal conductivity. Therefore, steel surfaces exposed to heat quickly transmit it to other parts of the material, and their load-carrying capacity decreases. However, because structural elements are not usually loaded to their full design strength, even bare steel may have sufficient load-carrying capacity to withstand the effects of fire.[35] In general, structural steel retains 60 per cent of its ambient temperature yield

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[32] The unit of strength measured from the force of one Newton applied per unit area.

[33] The recommended minimum time for occupants of a building to escape a fire is 30 minutes. See Rawlins Paints and Coatings, "30 and 60min fire resistance for wood – is it possible and how to do it," https://www.rawlinspaints.com/blog/30-and-60min-fire-resistance-for-wood/ (accessed 6 December 2021).

[34] American Wood Council, "Codes and standards," https://awc.org/codes-standards/publications/tr10 (accessed 6 December 2021).

[35] American Institute of Steel Construction, "Why steel?" https://www.aisc.org/why-steel/resources/fire-protection/ (accessed 6 December 2021).

strength at 538 degrees Celsius.[36] When steel is properly designed and constructed, steel framing can preserve its structural integrity in the event of a fire and exposure to prolonged elevated temperatures.

The fire resistance of bamboo is low compared to the conventional building materials examined in this report. Therefore, fire safety is an issue that needs to be addressed if bamboo is chosen as the preferred building material in construction. Bamboo should be treated with suitable fire retardants to reduce flammability and guarantee its safe use in construction. In Bahareque type construction,[37] the use of mud to plaster both sides of bamboo woven walls helps to improve fire resistance. However, in modern construction, fire retardant treatment is preferred, although it is expensive and does not guarantee effectiveness (Janssen 2000). Additionally, some fire retardants such as ammonium polyphosphate, diammonium phosphate, and monoammonium phosphate release toxic fumes during burning. Boric acid and borax are less toxic but can be irritating when they meet the skin (Yu et al. 2017).

Timber is also easily combustible and should be treated to improve its fire resistance. Hence concrete and steel offer better fire resistance and are often preferred to bamboo as building materials when considering exposure to fire. Weighing the options available, bamboo is more likely to be used as a building material in situations where there are low fire resistance requirements, such as roofs and possibly the walls of single-story buildings (Kaminski et al. 2016a).

3.3 MECHANICAL PROPERTIES OF BAMBOO AND COMPARISON WITH TIMBER, CONCRETE AND STEEL

Mechanical properties play a crucial role in selecting building materials.[38] They are used to set standards prescribed by codes on maximum allowable working loads, stresses and strains for maximum performance of the building material used. These standards help architects and engineers design safe and efficient structures for a given mode of loading. Therefore, a good knowledge of mechanical properties helps in selecting the best material for a given application when multiple materials satisfy the service conditions. This section reviews the principal mechanical properties related to strength in tension, compression, flexure and shear.

3.3.1 Tensile strength

The tensile strength of a building material measures its capacity to withstand an applied load that causes the material to stretch until it breaks. It is an important property often used as a basis to compare load capacity of materials and to select materials. Tensile strength is rarely used in designing structures with ductile materials because they undergo substantial plastic deformation before failure.

Figure 7 summarizes the test results of tensile strength of selected materials. Tests on bamboo specimens taken from stems of different ages and species from the five genera frequently used in construction showed tensile strength values expressed in Newton per square millimetre (N/mm2) ranging from 120 to 384 N/mm2 (Bamboo Import Europe 2016b). The test results also showed

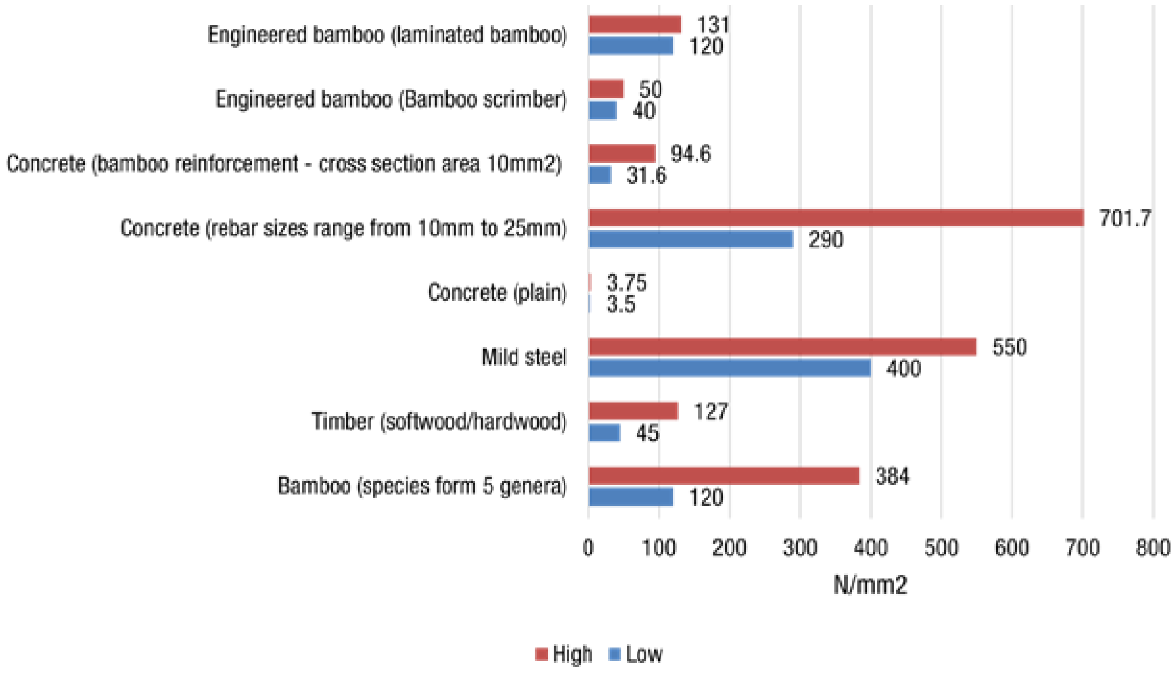
36 Ibid.

37 The Bahareque type of construction refers to a mixed timber, bamboo and mud wall construction technique that was the most frequently used method for simple houses in El Salvador before the 1965 earthquake.

38 Multiple sources of data from experimental studies performed on selected bamboo species are used to discuss the variations in mechanical properties (see Annex).

that tensile strength increased with the age of the specimen. In tests performed on engineered bamboo specimens made from Dendrocalamus strictus,[39] results showed that tensile strength of laminated bamboo varied from an average of 120 N/mm2 to 131 N/mm2, while tensile strength of bamboo scrimber ranged from an average of 40 N/mm2 to 50 N/mm2.

Figure 7 Tensile strength values of selected materials (N/mm2)



Source: UNCTAD secretariat based on data from Ahmed et al. (2016), The Engineering ToolBox (https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html), Bamboo Import Europe (2016b), and USDA (2010).

Note: N/mm2: Newton per square millimetre.

In comparison to test results on timber, steel and concrete, the tensile strength of selected species of softwood and hardwood used in construction ranged from 45 to 112 N/mm2 and from 50 to 121 N/mm2, respectively (USDA 2010).[40] For steel, it ranged from 400 to 550 N/mm2 (the tensile strength of steel varies with temperature, as high-strength steels offer higher performances in tensile strength exceeding 950 N/mm2). For concrete, tensile strength ranged from 3.5 to 3.75 N/mm2 depending on mixture proportions and type, size and volume of coarse aggregate used. The tensile strength of concrete improves considerably when it is reinforced with materials such as bamboo and steel. Tests on concrete beam specimens reinforced with bamboo strips (cross-sectional area of 10 mm2) produced tensile strengths ranging from 31.55 to 94.6 N/mm2 (Ogunbiyi et al. 2015). When bamboo strips were replaced with steel rebars of sizes ranging from 10 mm to 25 mm in diameter, tensile strengths increased to a range from 290.49 to 701.74 N/mm2. (Ogunbiyi et al. 2015).

[39] The specimens of engineered bamboo tested were taken from culms of Dendrocalamus strictus. The results obtained vary according to density, moisture content and thickness of specimens. See Verma et al. (2012).

[40] The timber specimens tested for mechanical properties include pine, spruce and hemlock (softwood); and oak and maple (hardwood)

The tensile strength of bamboo along the culm is its highest mechanical strength property.[41] It allows bamboo to withstand external forces such as wind and gravity acting on it. Steel has the best tensile strength, but it is much more expensive and relatively heavier than other materials analysed in this report. When the unit weight of bamboo is considered, tensile strength is about 3 to 4 times higher than steel (Ogunbiyi et al. 2015). In the context of construction, the high tensile strength and low weight is significant because bamboo can bear its own weight and would be very suitable in applications that require large spaces and fewer supports compared to steel and concrete, where their heavy weight reduces the allowable span of the member when considered for use as a horizontal structural member.

Steel is ductile and allows plastic deformation before it breaks, whereas bamboo undergoes brittle failure when it is in a dried state, i.e. it breaks sharply without plastic deformation (Xu et al. 2014). The lack of plasticity in dried bamboo may result in failure when subject to tensile loading and may not be suitable for structural elements that are expected to experience dynamic forces during their lifetime. Bamboo resists higher tensile loads than most construction-grade timbers,[42] with some species showing tensile strengths almost double that of high timber grades. It also has higher tensile strength than plain concrete. When it is introduced as reinforcement, bamboo may benefit from the durability and versatility of concrete as a building material, making it useful in many structural applications.

3.3.2 Modulus of elasticity

The modulus of elasticity, also known as Young's modulus, is a measure of stiffness in building material. It is determined by the ratio of the stress to which a specimen is subjected to and the strain it experiences during tensile or compressive tests (ratio of load to deformation). It is an important indicator expressed in N/mm2 that is used to evaluate the material's deformation under working loads and is a good indicator of its strength. The higher the modulus of elasticity of the building material, the greater its stiffness. More force must be applied to produce a given deformation on a structure that has high stiffness.

The modulus of elasticity (tensile) determined for different species of bamboo from the five genera typically used in construction have test results that ranged from 8,987 to 27,631 N/mm2. The test results presented in figure 8 also show that elasticity values declined with reduced wall thickness. The elasticity values obtained for tests conducted on engineered bamboo products (laminated and scrimber bamboo) ranged from 1,000 to 10,000 N/mm2 for laminated bamboo and 2,000 to 11,000 N/mm2 for scrimber bamboo. By comparison, elasticity test values for selected hardwood and softwood species used as timber in construction ranged from 5,500 to 15,600 N/mm2, while concrete ranged from 14,000 to 41,000 N/mm2. Depending on the composition of the mix, in composite materials such as steel or bamboo-reinforced concrete beams the modulus of elasticity increased by the value of the added material, in effect increasing its stiffness. The elasticity value for steel is often taken as 200,000 N/mm2, but tests have established that the modulus of elasticity varies with the grade of steel and thickness.

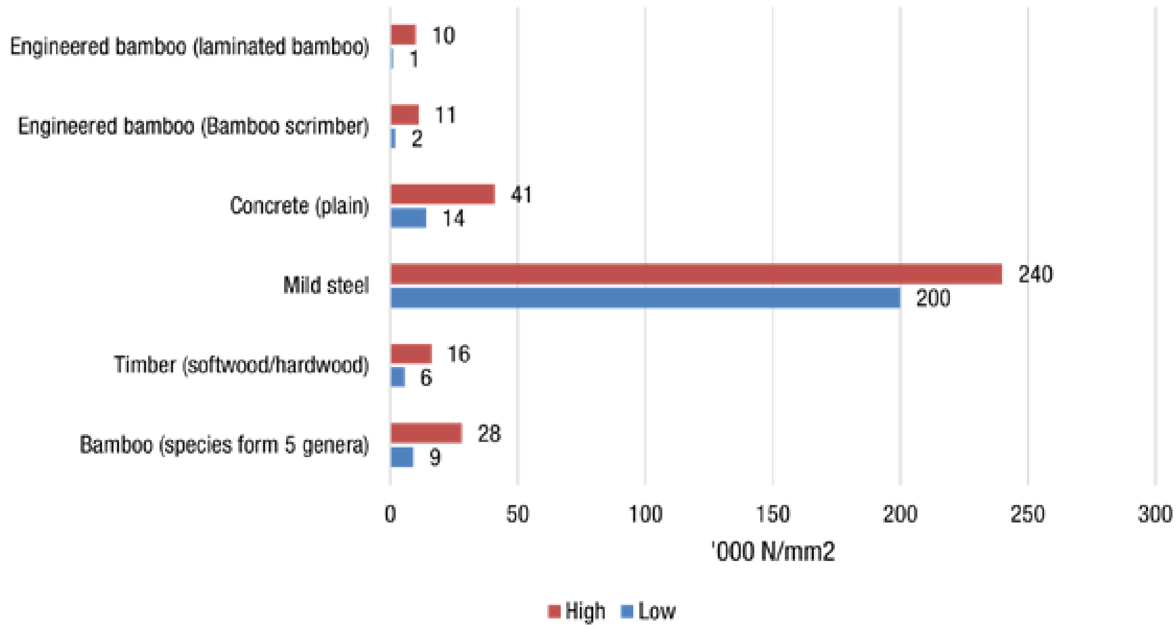
Bamboo has a higher modulus of elasticity than most softwood and hardwood timber, which allows it to stretch and deform less easily before breaking under working loads. However, bamboo in composite structures can be a brittle material and would fracture suddenly when the elastic limit is reached. This property would make bamboo reinforcement in composite unsuitable in heavy

[41] Bamboo properties perpendicular to the fibres tend to be poor.

[42] A variety of softwood and hardwood species are used in construction. Examples of softwood used in construction include pine, cedar, fir, spruce and redwood. Examples of hardwoods used include oak, maple, cherry, mahogany, and walnut.

structural applications that require some ductility, such as those in seismic environments (Archila et al. 2018). By contrast, the higher modulus of elasticity values for concrete and steel allow these materials to change their shape only slightly under elastic loads. As such, they are attractive materials to reduce deflections. On the bright side, the stiffness of engineered bamboo products promotes their use as structural elements because of the ability to create standard sections and connections that are difficult to construct using culms.

Figure 8 Modulus of elasticity of selected materials (N/mm2)



Source: UNCTAD secretariat calculations based on data from The Engineering ToolBox (https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html), Bamboo Import Europe (2016b) and USDA (2010).

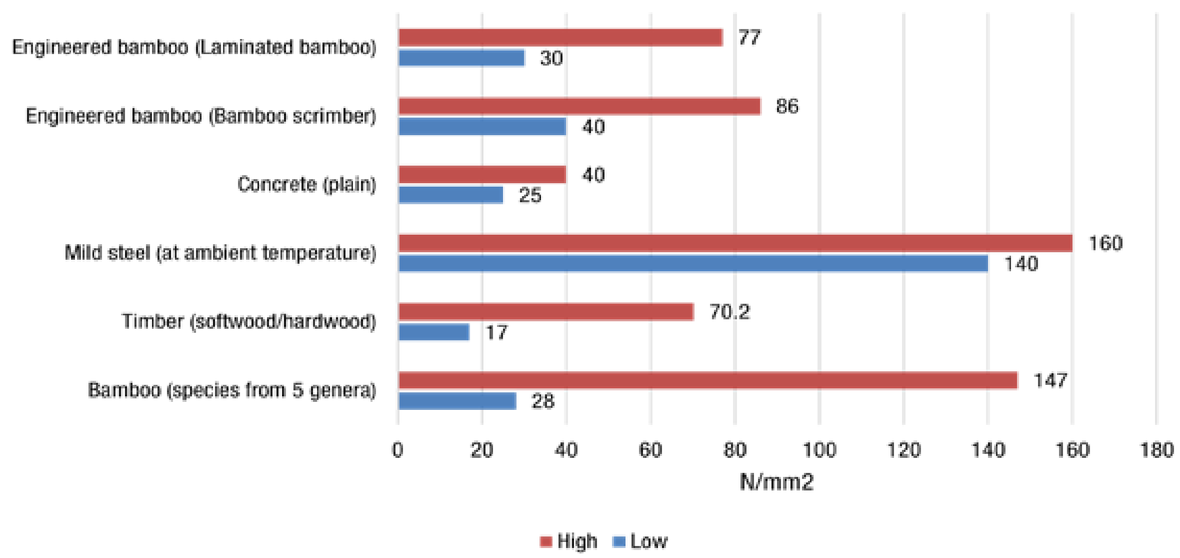
Note: N/mm2: Newton per square millimetre.

3.3.3 Compressive strength

Compressive strength is the capacity of a material to withstand loads without causing it to fracture or deform irreversibly. Although deformations to the material are not often perceivable, they are crucial in determining whether or not the structure will be serviceable. The compressive strength of building materials is the most common property considered for construction and is a measure used by engineers in designing buildings and other structures to determine whether they are structurally acceptable.

The compressive strength of bamboo varies along different sections of the stem because the culm does not have a continuous cross-section. There are differences in structural properties between the lower part, which has a larger diameter, and the upper part, described as the “leader” and “stick,” which has a smaller diameter. The lower part is more suitable for construction purposes because the length of fibres in this section of the culm is longer than those in the upper part, and this influences the strength of fibres in compression (Mahesh and Kavitha 2016). The leader and stick parts of the culm are generally not suitable for construction (Bamboo Import Europe 2016b). Tests on different species of bamboo specimens taken from different sections of the stem at a specified moisture content show average strengths ranging from 28 to 147 N/mm2, as shown in figure 9. Tests on engineered bamboo species show compressive strength values ranging from 40 to 86 N/mm2 for bamboo scrimber and 30 to 77 N/mm2 for laminated bamboo. By contrast, the compressive strength of a variety of softwood and hardwood timber specimens used in construction tested along their longitudinal axis or parallel to the grain, and at moisture contents below their fibre saturation point, range from 17 to 70.2 N/mm2. Steel has the highest compression strength of the materials in comparison with bamboo timber and concrete, at 250 N/mm2, due in part to its homogeneity and its high modulus of elasticity. Concrete compressive strength ranges from 25 and 40 N/mm2.

Figure 9 Compressive strength of selected materials (N/mm2)



Source: UNCTAD secretariat calculations based on data from The Engineering ToolBox (https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html) and Bamboo Import Europe (2016b).

Note: N/mm2: Newton per square millimetre.

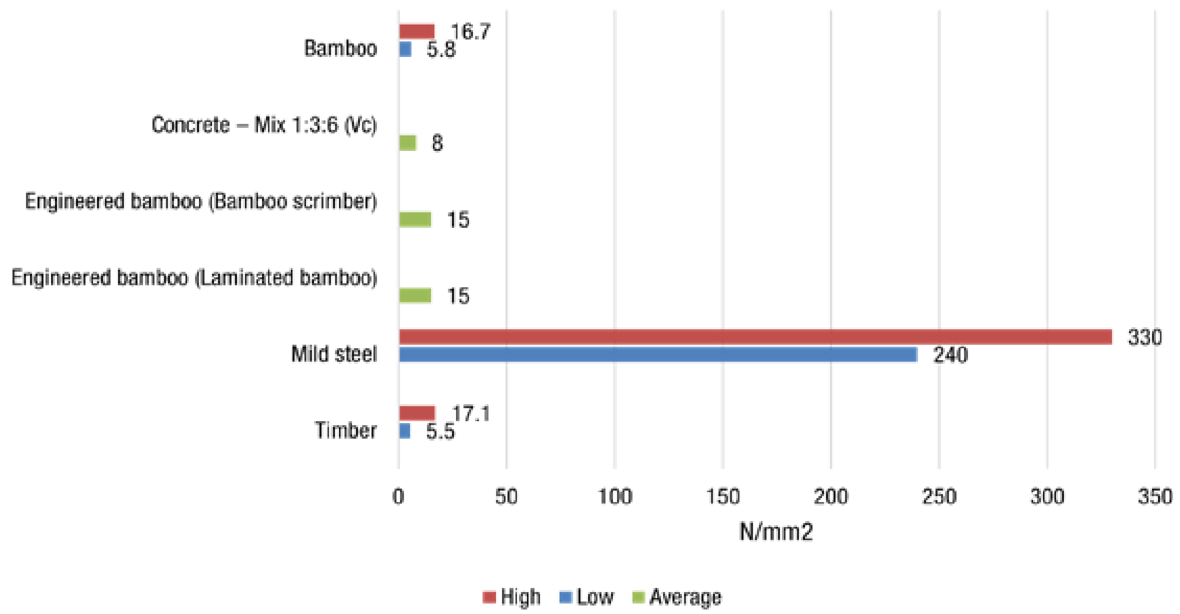
The results of tests on compressive strength show that bamboo has better performance than some species of timber and mixtures of concrete when subject to compressive loading. Its high strength-to-weight ratio allows for substitution of building materials that are heavier without compromising on the strength offered. It also enables designing structural members with smaller dimensions, which would result in lightweight structures (particularly on soils with low bearing strength), lower costs, and ease of construction. Steel has a very high strength-to-weight ratio, but compared to bamboo, its production is generally more expensive and very energy-intensive, and with high associated greenhouse gas emissions. Based on compressive strength comparisons, bamboo would be a suitable material in most structural applications except a few where the material absorbs moisture and causes its compression capacity to degrade significantly (Xu et al. 2014). In general, steel has the highest compressive strength and is suited for most structural purposes.

3.3.4 Shear strength

Shear strength defines the maximum capacity of a material to resist sliding forces acting in opposite directions in the same plane. The shear failure load depends on numerous factors, including the dimensions, cross-sectional area, moisture content, temperature, and stiffness of the material. Shear strength plays an important role in preventing the material from failing and in ensuring the stability of the overall structure.

Test results on selected bamboo species used in construction show shear strength values ranging from 5.8 to 16.7 N/mm2, as shown in figure 10. In tests performed on engineered bamboo products, shear strength averaged 16 N/mm2 for laminated bamboo and 15 N/mm2 for bamboo scrimber. By comparison, test results of selected species of hardwood and softwood timber show shear strength values ranging from 5.5 to 17.1 N/mm2. The shear strength of mild steel is approximately 0.6 times the experimental tensile strength (Seeley and Putnam 1919), which suggests shear strength values ranging from 240 to 330 N/mm2. Higher values can be obtained depending on a variety of factors, including grain size, method of production,[43] temperature, microstructure and impurities or contaminants. The shear strength of concrete depends on the mix of concrete and aggregate size, and increases in proportion to the span-to-depth ratio of the specimen (Vagera et al. 2016). Experimental results of shear strength in concrete made from a mix of 1 portion cement, 3 portions sand and 6 portions stone averaged about 8 N/mm2. When shear reinforcement was introduced to concrete beam specimens, shear capacity increased by 32 per cent to 132 per cent for a range of beams, compared with the control beam without reinforcement (Said and Elrakib 2013).

Figure 10 Shear strength values of selected materials (N/mm2)



Source: UNCTAD secretariat calculations based on data from The Engineering ToolBox (https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html) and Bamboo Import Europe (2016b).

Note: N/mm2: Newton per square millimetre; Vc: shear strength in concrete.

Bamboo culms do not perform well when shear forces are applied. This is due in part to their hollow section, which gives them less area to resist shear forces, thus making them prone to longitudinal

[43] For example, cold working strengthens the metal by physical manipulation below its respective recrystallization temperature.

splitting. By contrast, engineered bamboo products are denser and can resist higher shear forces. They also create a uniform section for connections and joints in structural applications, thus increasing the versatility of bamboo as a building material. The low shear strength of bamboo, timber and plain concrete places these materials at a disadvantage for applications in construction that requires resistance to high shearing loads, such as cantilevered structures and high-strength joints. Although the lack of shear strength is considered a disadvantage for the structural use of bamboo, it is a big advantage for end users making products in which split bamboo is used, such as bamboo boards, mats and walls. By far, steel is the best material for use in applications where shear forces are dominant.

3.3.5 Flexural strength

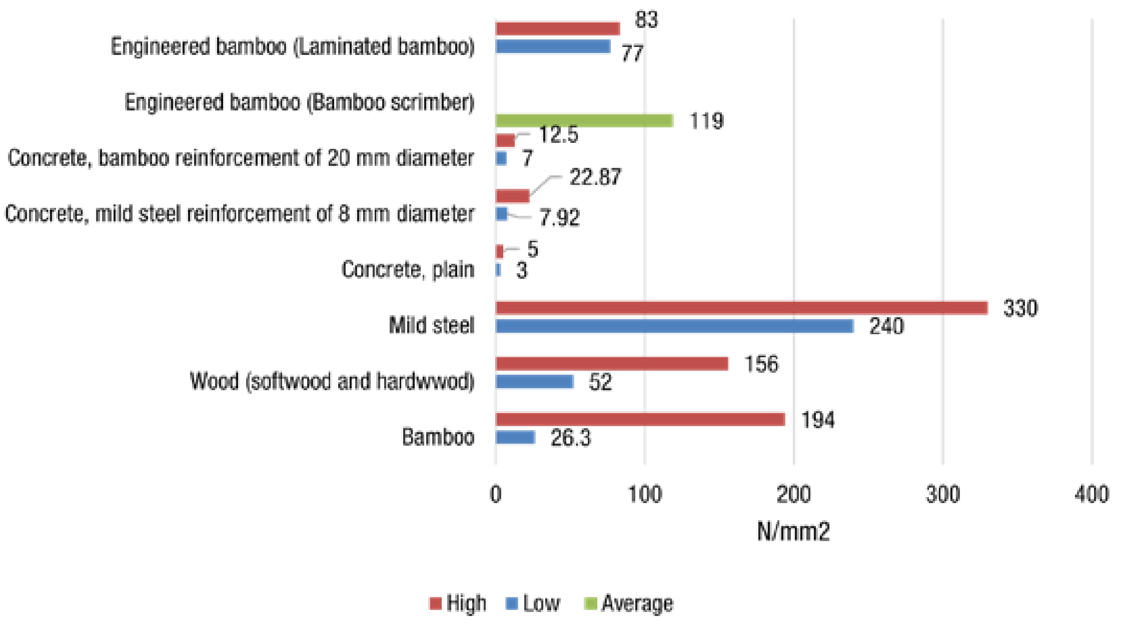
Flexural strength, also known as bending strength, modulus of rupture or transverse rupture strength, is a measure of the maximum load the material can carry when it is subject to bending forces perpendicular to its longitudinal axis. It is an important parameter used in the selection of materials for applications that require minimal deformations during bending. Materials with high flexural strength offer advantages to structural members to withstand high loads, causing them to bend, and allow for smaller sizes of structural members.

Figure 11 summarizes flexural strength test results of selected materials. Specimens taken from bamboo species belonging to the Bambusa, Dendrocalamus, Gigantochla, Guadua and Phyllostachys genera show values ranging from 26.3 to 194 N/mm2 at varying moisture contents. Tests on engineered bamboo specimens show flexural strength ranging from 77 to 83 N/mm2 for laminated bamboo and an average of 119 N/mm2 for bamboo scrimber. By contrast, flexural test results on selected species of North American softwood timbers commonly used for structural purposes show bending strength ranging from 55 to 139 N/mm2, while for hardwood timber species the bending strength ranges from 52 to 156 N/mm2. The flexural strength of steel depends on its chemical composition and varies according to the dimensions of the specimens tested. Often taken as the point of yield is 250 N/mm2, which is considered as the point of failure. The flexural strength of concrete differs by type of mix. For low-strength concrete, flexural strength is estimated at approximately twice its tensile strength, and for high-strength concrete flexural strength is usually found to be at least 30 to 50 per cent higher than direct tensile strength (Wittmann 2005). Experimental testing of concrete specimens found the flexural strength for normal concrete to be in the range of 3.0 to 5.0 N/mm2. However, when concrete is reinforced with rebars or pre-stressed steel in tension, flexural strength increases because ductility is increased. This reduces the deflection and cracking behaviour at service loads that cause the material to bend and subsequently lead to failure. Flexural strength test results on steel-reinforced beams vary with the concrete mix design, size of beam and reinforcement. At 28 days, specimens of sizes of 750 mm length x 150 mm width x 150 mm depth, and with two 8-millimetre reinforcement at the top and bottom, show results varying from 7.92 to 22.87 N/mm2 with different mixes of concrete (Ahmed et al. 2016). Flexural tests on specimens of bamboo-reinforced concrete beams having the same dimensions also indicate an increased load-carrying and bending capacity. For singly and doubly reinforced bamboo specimens of 20 millimetres in diameter, the load-carrying capacity increased by 2 and 2.5 times, respectively, compared to plain concrete (Rahman et al. 2011).

A comparison of flexural strength test results shows that some species of bamboo can carry more bending forces than timber and concrete and, because they are lighter, have potential in many structural applications where clear spans are needed. Furthermore, as plain concrete is weak in flexure, bamboo-reinforced structural members could expand the applications of bamboo in modern construction because of the versatility of concrete in building different structural forms.

Further research is needed to resolve issues relating to bonding between the bamboo reinforcement and the surrounding concrete. This is because bamboo can absorb moisture and swell in moist environments, but will shrink when it dries up, causing a reduction in friction with the surrounding concrete that generates the bond force. Furthermore, the smooth surface of bamboo force does not facilitate the development of mechanical interlocking with surrounding concrete, which is the main method of transferring the bond force (Achila et al. 2018). By contrast, corrugated rebars generate a good bond force with the surrounding concrete, making steel very effective in reinforced concrete structural members. An added advantage of bamboo over conventional materials is its low cost, as discussed earlier.

Figure 11 Flexural strength values of selected materials (N/mm2)



Source: UNCTAD secretariat calculations based on data from The Engineering ToolBox (https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html) and Ahmed et al. (2016).

Note: N/mm2: Newton per square millimetre.

The mechanical and physical properties of the selected bamboo species and engineered bamboo products discussed compared to conventional materials contribute to understanding the strength capacity of bamboo. They also help in establishing minimum standards when developing codes that allow for consistency and guidance to engineers and architects in bamboo design and build. Further testing under combined loading conditions is required to enhance understanding of bamboo and contribute to the development of bamboo codes of practice. Table 1 provides a summary of the discussion on physical and mechanical properties.

Table 1 Summary of mechanical and physical properties of bamboo, timber, steel and concrete

	Tension	Modulus of elasticity	Compression	Shear	Flexure	Fire resistance	Shrinkage
Bamboo	Good	Low	Good	Low	Good	Average	High[1]
Engineered bamboo	Good	Low	Good	Average	Good	Average	Low
Timber	Average	Low	Good	Average	Good	Average	High[2]
Concrete	Weak	High	Good	Weak	Weak	Good	Low
Reinforced concrete	Good	High	Good	Average	Good	Good	Low
Mild steel	Good	High	Good	Good	Good	Good	n.a.

Source: UNCTAD secretariat based on the analysis of physical and mechanical properties.

[1] Some building materials experience volume or size reductions when subject to moisture loss. In bamboo, shrinkage can be between 10 and 16 per cent in the diameter and 15 and17 per cent in the wall thickness. See Burger et al. (2016)

[2] Volumetric shrinkage of wood is within the range of 9 to 15 per cent for most wood species. See The Wood Database, "Dimensional shrinking," available at https://www.wood-database.com/wood-articles/dimensional-shrinkage/ (accessed 6 December 2021).

3.4 OPPORTUNITIES

The good tensile and compressive strengths of bamboo make it suitable for use in many construction applications. For example, bamboo is particularly useful in truss support systems because its good strength properties make it suitable for building a triangulated system of straight interconnected structural elements acting together to resist tensile and compressive forces. The main materials currently used are timber and steel, but they are more expensive than bamboo, and therefore contribute to increasing the overall cost of the structure. Bamboo trusses can be used to create clear spans.[44] They are found in bridges and roofs all over the world. In the Philippines, the local bamboo species (Dendrocalamus asper) was used to build a 23-meter free-span bamboo truss footbridge over the Matina River, which is known for strong flash floods capable of sweeping away piers.[45] When bamboo is used in properly jointed roof trusses, it offers a good substitute for the traditional roof support system that combines rafters and purlins made from timber for supporting roof loads (Xiao et al.2008). Several roof trusses have been built using bamboo to create clear spans, including the Bamboo Sports Hall for the Panyaden International School in Thailand, where bamboo trusses allow the roof to span more than 17 metres without steel reinforcements or connections.[46] The high strength-to-weight ratio enables bamboo to support its self-weight and increases its versatility as a building material over conventional materials.

Bamboo can play an important role in the supply of affordable housing and shelter because it is generally cheaper than conventional building materials, easy and fast to erect, and one of the most environmentally friendly construction materials. There are three main types of housing through which bamboo can contribute to boosting supply: traditional houses that use bamboo culms as

[44] "Clear span" is an architectural term to describe the distance between the two inside surfaces of the span supports. See BuildingsGuide, "What is a clear span building," https://www.buildingsguide.com/faq/what-clear-span-building/ (accessed 6 December 2021).

[45] Fitrianto A, "Community bamboo footbridge," Architecture-in-Development, https://architectureindevelopment.org/project.php?id=298

[46] Designboom, "Chiangmai life architects constructs zero-carbon sports hall in Thailand entirely from bamboo," https://www.designboom.com/architecture/chiangmai-life-architects-bamboo-sports-hall-panyaden-international-school-thailand-08-09-2017/ (accessed 6 December 2021).

a primary building material, often employed in regions where the raw material is readily available; traditional Bahareque bamboo houses that have a bamboo frame plastered with cement or clay; and modern prefabricated houses made of bamboo laminated boards, veneers and panels (Mera and Xu 2014). Traditional bamboo houses can be built at very low cost, but the perception that bamboo is not a mainstream building material often limits this type of construction in urban areas. Modern uses of bamboo tend to be skewed toward large-scale usage of engineered and prefabricated bamboo-based components (Manjunath 2016). These modular structures are easy to construct and cheaper than houses that use conventional raw materials. Including bamboo in national housing policies and regulations could contribute to meeting Target 11.1 of United Nations Sustainable Development Goal 11 (Ensure access for all to adequate, safe, and affordable housing and basic services and upgrade slums by 2030).

Bamboo structures are mostly designed to carry light loads, but the mechanical properties of some bamboo species show their potential to carry heavier loads when they are used as load-carrying members in ordinary structures or as reinforcement in composite structural members. Using bamboo as reinforcement in concrete could expand its applications in construction because of the versatility of concrete in casting different forms and shapes (Trout 2010). The fibres of bamboo can also be used to produce bamboo fibre-reinforced polymer composites, a sustainable alternative to synthetic fibres used as reinforcement for structural-concrete beams (Md Shah et al. 2016).

Bamboo can be used in a wide range of temporary works that require stiffness and compressive strength to support structural loads. Common applications of bamboo in support systems include shoring towers to provide temporary support formwork for concrete cast in situ (Johnston 1996), or as scaffolding to support workers and tools to perform various activities in construction. Timber, steel and aluminum are materials frequently used for these purposes, but the compressive strength and stiffness of some species of woody bamboo make them possible substitutes for conventional materials. In addition, these species of bamboo have an advantage over conventional materials because they are cost-effective, convenient and readily available, particularly in regions where they are cultivated or grow naturally. However, bamboo would require horizontal and diagonal bracing to avoid buckling when used as props exceeding 1.5 metres in height because of its slenderness (ratio of height to width) and its repetitive use as props is generally not recommended.[47] Steel props have the highest bearing capacity and can be used multiple times in high loadings, but they are expensive and may not be affordable for construction purposes in poor regions.

The ductility of green bamboo enables it to be bent and used in structural systems such as arches, where the function is essentially to carry compression stresses. The bamboo arch is cheaper than those made of conventional materials such as timber and steel, which are frequently used in construction. Furthermore, it can serve the traditional uses of arches, which include, inter alia, bridging an opening in a wall, serving as a load-bearing element in large free spaces by supporting roofing elements, or simply being used for decorative purposes or to blend with local architecture (Joffroy 1994). Bamboo arches can be manufactured by splitting bamboo into planks, then tying them into a bundle (Nurdiah 2016), or by other methods such as cold bending or immersing straight bamboo stems in lukewarm water until the fibres become soft enough to be curved using clamps, or by heating bamboo sections to the desired heat (greater than 150 degrees Celsius) that causes bamboo fibres to become soft and easy to bend. Bamboo arches can also be easily constructed because some bamboo species have a natural curvature that facilitates their manufacturing.

[47] https://www.yourarticlelibrary.com/building-engineering/props-used-in-buildings-design-material-and-life/86071 (accessed 6 December 2021).

Rising demand for substitutes for wood presents an opportunity to create downstream industries that manufacture engineered bamboo products for both architectural and structural use. This includes the manufacture of glued laminated bamboo boards to form beams ranging from simple and straight to complex curved members, similar to glued wood beams. Engineered bamboo has good strength properties and its homogeneity and workability make it versatile for use in the construction industry.

The transformation of bamboo from hollow stems into laminated and strand-woven products has many applications in the construction industry. For example, structural elements such as beams and columns can be manufactured from laminated bamboo (Xiao et al. 2014). These engineered products also have hardness and stiffness qualities that make them suitable for hard, resistant and long-lasting flooring, panelling and decking.[48] The manufactured panels can be widely used in modern construction as structural elements, as forms for concrete mouldings or as roofing sheets. They are more stable in moisture and temperature changes when compared to several timber-based products (Sullivan 2016). Because of its hardness, laminated bamboo can be used for external applications such as decking, and is often used internally for flooring, cladding, partitions, doors, and window frames. For example, laminated bamboo has been used in the roofing of the Barajas airport in Madrid, which is the largest industrial bamboo project in the world. Bamboo panels have some advantages over timber boards due to their rigidity and durability (FAO 2007). The use of bamboo in composite panels and boards overcomes differences in quality related to the culms and allows for the production of homogeneous products that are attractive to markets in Europe, Japan and North America (FAO 2007). There is large availability of bamboo species that can be used as raw materials in industries manufacturing these products. Hence, providing incentives to acquire the manufacturing technologies for these bamboo-based products may contribute to growing the bamboo sector and impact livelihoods at different stages of production and manufacturing, increasing the sector's potential economic impact on poor rural communities.

Roofing sheets can be manufactured using bamboo and could replace corrugated sheets made from materials such as zinc, aluminum, plastic or asbestos that have been established as standard roofing materials for decades. For example, the bamboo mat corrugated sheet can be made by impregnating woven bamboo mats with an adhesive resin and pressing them together between two specially designed corrugated pressing plates.[49] The load-bearing capacity of such sheets is comparable to asbestos cement corrugated sheets, and being light in weight, it possesses high resilience. Bamboo mat corrugated sheets are waterproof and resistant to decay, termites and fire (Shyamasundar and Vengala 2006). The thermal conductivity[50] of the sheets (0.1928 kilocalorie per metre per degree Celsius [Kcal/mc]) is lower compared to asbestos (0.3422 Kcals/mc) and provides better thermal comfort compared to houses having asbestos or galvanized iron sheets as roofs (Shyamasundar and Vengala 2006). Furthermore, bamboo mat corrugated roofing sheets are environmentally friendly and a safe alternative to plastic, zinc or corrugated asbestos roofing panels known to have adverse health impacts when disturbed. Finally, bamboo mat corrugated sheet roofs are quieter in the rain and cooler in the sun than conventional metal or plastic sheets.[51]

48 See Evergreen Lifestyle, "Bamboo panels & flooring," https://www.chemaxis.ch/en/index (accessed 6 December 2021).

49 Guadua Bamboo, "Corrugated bamboo roofing sheets,," https://www.guaduabamboo.com/blog/corrugated-bamboo-roofing-sheets (accessed 6 December 2021).

50 Thermal conductivity expressed in kilocalorie per metre per degree Celsius (kcal/mc) is a measure of the capacity of a material to conduct heat through its mass; see https://www.sciencedirect.com/topics/engineering/kilocalorie (accessed 6 December 2021).

51 Guadua Bamboo, "Corrugated bamboo roofing sheets," https://www.guaduabamboo.com/blog/corrugated-bamboo-roofing-sheets (accessed 6 December 2021).

3.5 CHALLENGES

Although bamboo has good mechanical properties compared to timber, steel and concrete, it has some drawbacks as a construction material. For example, untreated bamboo is susceptible to fungal infection and attack by insects (beetles and termites are the most common) because the rich organic nutrient in raw bamboo creates a good environment for breeding. This often leads to infestation and degradation of bamboo.[52] Therefore, it is imperative to chemically treat bamboo before it is used in construction, but most chemical preservatives used to protect bamboo against biological attacks and degradation are toxic. Copper-chrome-arsenic (CCA) preservatives contain harmful carcinogenic elements that can be leached from CCA-treated surfaces into soil and water. In addition, pentachlorophenol (PCP) and its salts contained in preservatives is extremely toxic to humans (Kaur et al. 2016). PCP has been found to cause acute and chronic poisoning through dermal absorption, inhalation and ingestion, mainly to people working in in sawmills or living in log homes treated with PCP-containing timber protecting formulations. As a result, it has been banned in many countries (Jorens and Schepens 1993). By contrast, preservatives such as boric acid, borax and boron are less harmful to the environment, but because they are water-soluble, they can leach out over time if the treated bamboo is exposed to running water, such as rain (Arup 2018). Furthermore, the high amount of nutrients located in the inner circle of the raw bamboo, in comparison with the outer skin and fibre, makes protection and treatment of raw bamboo much more difficult than treatment of timber (Xiao et al. 2019). There are some non-chemical treatments that can be used, such as seasoning and water soaking, but they improve durability only slightly and are not long lasting (Arup 2018). High-temperature steam treatments can also be used, but they have a higher cost, their technology is less accessible to low-income communities, and they also lead to a decrease in bamboo's mechanical properties. In sum, bamboo preservatives should be selected and applied with great care to meet performance and environmental requirements as well as prevent adverse health consequences.[53]

Bamboo absorbs moisture from or expels it to its surroundings until an equilibrium is reached. The sensitivity of bamboo to moisture can cause it to shrink by 10 to 16 per cent in the cross-section, and in the wall thickness by 15 to17 per cent, and may lead to the stems tearing apart at the nodes (Chu 2014). Therefore it is necessary to take essential steps to prevent water loss when using bamboo as a building material to maintain integrity of the structure. Bamboo must undergo treatment to reduce its capacity to absorb moisture and to improve its long-term durability compared to other building materials (Bui et al. 2017).

Experimental results of strength tests on bamboo-reinforced concrete specimens show that bamboo reinforcement in concrete is technically possible (Adewuyi et al. 2005; Adom-Asamoah 2011; Ghavami 2005; Baldaniya 2011). However, many studies have highlighted the challenges of using raw bamboo in reinforced concrete with respect to, inter alia, swelling, shrinking, biological decomposition and thermal expansion (Archila et al. 2018). These changes in the physical characteristics of bamboo reinforcement generate internal tensile stresses, causing the concrete to crack (Alireza 2017). This may lead to reduced bonding between the concrete and natural bamboo, and subsequently result in the loss of load-carrying capacity of the bamboo-reinforced concrete elements, and ultimately result in the structure collapsing (Alireza 2017). Without some type of protection, bamboo will swell before the concrete has developed enough strength to prevent cracking and may lead to structural damage (Nayak et al. 2013). Attempts to reduce bamboo's moisture absorption and improve its durability have yielded mixed results, and it is unclear whether this type of reinforcement can replace steel bars. It may also make the treated bamboo less environmentally friendly and more expensive (Bui et al. 2017).

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[52] Guadua Bamboo, "Bamboo insect infestation," https://www.guaduabamboo.com/blog/bamboo-insect-infestation.

[53] Ibid.

The construction of structurally sound bamboo joints when joining poles presents challenges of structural reliability. In traditional bamboo construction, joining technology often utilizes rope, wire or simply nailing sections together, none of which provide long-term structural integrity. The fibre in bamboo runs along the length of the pole with only the nodes providing lateral strength, making it susceptible to cracking under stress (Vahanvatti 2015). Therefore, using nails and screws increases the chance of cracking, with a risk of joints becoming loose and the structure losing its integrity. Tying sections together also has its challenges because the mechanical characteristic of this jointing method relies completely on the wrapping tightness of the rope, which loses its strength due to the continuous shrinkage-swelling behaviour of bamboo and repeated external loads on the structure. Various techniques have been adopted, such as a sleeve bolt connection where a steel sleeve is embedded into the hollow connecting end of the bamboo and fixed to the bamboo using a bolt, which is put through the predrilled holes in the sleeve and in the bamboo panel. Also commonly used is a plate connection in which the end of bamboo tube is slotted and embedded with a steel plate, connected by bolts. These connections offer better structural reliability compared to tying, nailing and screwing sections together, but the brittleness of bamboo makes the connections prone to shearing-split failure (Fu et al. 2012). In addition, the overall cost of the structure is increased and the attractiveness of the truss as a truly natural element for aesthetic reasons is reduced (Eichenberger et al. 1999).

CHAPTER IV

Value addition

4.1 ENGINEERED BAMBOO MANUFACTURING CHAIN

Engineered bamboo products and culms are the main forms of bamboo-based materials used in the construction industry as structural elements and in architectural finishes.[54] Increasingly, engineers and architects are employing these materials in a variety of applications, as discussed in Chapter 3 of this report. As the market for bamboo-based products expands, there will be implications for developing downstream industries associated with these products in countries where the right species can be found. Such industries can contribute to growing the bamboo sector and impact livelihoods at different stages of production and manufacturing. They can also increase bamboo's potential economic impact on poor rural communities. A simplified chain of activities in this type of downstream industry will be comprised of nurseries providing plants for cultivation, farmers creating plantations, processors, and the manufacturing process.

4.1.1 Nurseries

The manufacture of good-quality engineered products depends on production of healthy bamboo plants. The planting material for bamboo may come in the form of seeds, wildings, air-layering, offsets, cuttings and tissue-cultured plantlets that are raised in a nursery before being transplanted into the main planting area.[55] Alternatively, good-quality bamboo plants can be obtained from naturally grown managed forests and used as inputs in downstream industries. Establishing a local bamboo nursery can be a profitable business. For example, a nursery plant sold at US$0.80 to plantation cultivators in Latin America can generate a gross profit margin for the nursery of 40 to 50 per cent of the sale price depending on the volume of plants produced and sold.[56] In general, at least 0.5 hectares is required for every 10,000 seedlings or young plants that will be raised annually (UNIDO 2009). Therefore a nursery raising seedlings on one hectare of land could generate between US$6,400 and US$8,000 in gross profit annually.

4.1.2 Farmers and plantations

At plantations, bamboo plants are spaced at specified intervals (depending on the species) so that they have good exposure to light, soil moisture and nutrients.[57] The optimum spacing for a medium diameter species such as Guadua angustifolia, which is widely used in construction in South America, is 5 x 5 metres. However, spacing is sometimes reduced to accommodate more plants.[58] A farmer cultivating one hectare of land will be able to use 400 clumps that will provide a harvest of approximately 2,000 poles per year from the fifth year onward. The total cost of developing a bamboo plantation is estimated between US$500 and US$750 per hectare. The variations in cost are largely driven by land preparation and the cost of planting material, which varies between US$300 and US$400, depending on the planting density used. In Latin America, the selling price of poles varies between US$1 and US$10.[59] Therefore, for a hectare of cultivated land, plantations can yield between US$2,000 and US$20,000 per year. Usually the cost of

[54] The common engineered bamboo products on the market include custom-made beams manufactured from glued laminated bamboo boards (similar to glued wood beams) to form simple and straight to complex curved structural members and standard sized wood flooring.

[55] AgriFarming, "Bamboo farming project report, cost and profit details," https://www.agrifarming.in/bamboo-farming-project-report-cost-profit (accessed 6 December 2021).

[56] Bambustic, "Bamboo solutions for the world," https://versteegde.nl/Bambustic/ (accessed 6 December 2021).

[57] Guadua Bamboo, "How to plant bamboo," https://www.guaduabamboo.com/blog/how-to-plant-bamboo (accessed 6 December 2021).

[58] Ibid.

[59] https://versteegde.nl/Bambustic/ (accessed 6 December 2021).

establishing the plantation is recovered after the second harvest period. However, harvesting can be maintained annually with minimal investments for 80 to 120 years.[60] Thus, the plantations can provide stable income streams to farmers over time.

4.1.3 Processors and manufacturers

After harvesting, the bamboo culms are sorted and processed. This involves splicing them into thin strips before peeling away their green outer layer.[61] The processing stage does not require high capital investments but is labour-intensive and contributes significantly to employment (UNIDO 2009). The cost of making finished products from processed culms varies depending on the location and proximity of bamboo forests to enterprises and manufacturing industries. The transformation from culms into engineered products adds costs related to, inter alia, treatment of culms to protect against insect infestation and preservation against rotting, drying by solar kiln or air/sun drying, and machinery and labour to produce a regular supply of products. For example, a manufacturing plant that produces 40,000 square metres of laminated bamboo flooring per year would require a machinery unit costing approximately US$366,000. Each square metre of flooring produced costs approximately US$12.40 to manufacture. Table 2 provides a breakdown of costs involved in producing a square metre of bamboo flooring from an anonymous manufacturer in South China. Investing in the production of engineered bamboo items has the potential to earn investors US$16 to US$38 per square metre in retail markets, depending on the quality (QiSheng and Bin 2021).[62] Currently, most laminated bamboo products are made from the species Phyllostachys edulis heterocycla (also known as Moso) coming from plantations in China. However, the strength properties of other varieties of bamboo such as Guadua have potential to be used in manufacturing high-value-added engineered products that are competitive on global markets.

Table 2 Cost breakdown per square metre of manufactured bamboo flooring at an anonymous plant in South China
(U.S. dollars)

Item	Cost
Bamboo material	6.5
Chemicals	2.5
Water and power	0.7
Wages	1.4
Manufacturing costs	0.8
Other materials	0.5

Source: QiSheng and Bin (2021).

4.2 ENABLING ENVIRONMENT FOR VALUE ADDITION

The production of engineered bamboo is dominated by China, and the manufacturing industries located there are the major global suppliers. This is a result of over 30 years of research and

60 https://bamboologic.eu/investeren (accessed 6 December 2021).

61 Ambient, "How is bamboo flooring made? What is the manufacturing process?" https://www.ambientbp.com/how-bamboo-flooring-is-manufactured.php (accessed 6 December 2021).

62 Costhelper home & garden, "Bamboo flooring cost," https://home.costhelper.com/bamboo-flooring.html (accessed 6 December 2021).

development and innovation in producing bamboo-based products. By contrast, the bamboo industry is in its infant stages in several other countries where resources are plentiful or growing conditions permit cultivation of specific species. Development of the industry has been hindered by such major constraints as limited knowledge of the importance and benefits of bamboo, a lack of technical knowledge of bamboo species, and a lack of nurseries, plantations and management (FAO and INBAR 2018). Additional constraints include the lack of availability of land for bamboo plantations, limited supply of large quantities of good-quality bamboo poles, and the lack of appropriate technologies and machinery for processing. Furthermore, there is a lack of interest in growing bamboo due to the perception that, when established, bamboo takes over arable land and such land cannot be put to any alternative use (FAO and INBAR 2018). Overcoming these constraints could lead to a vibrant bamboo sector, promote the use of bamboo products as building materials in local modern construction, and boost trade due to rising demand for wood-substitute products. In this regard, strong support is needed from governments to provide an enabling environment to strengthen production linkages, and to help private organizations overcome these constraints and leverage the opportunities presented in the production chain. This can contribute to enhancing international trade in bamboo-based building materials, which are gaining ground as substitutes for conventional materials.

CHAPTER V

International trade

5.1 BAMBOO PRODUCTS

Over several centuries, bamboo has served numerous inhabitants of many countries in Asia, South America and Africa, mainly for food, wood and building materials, and in cottage industries. In recent years, a wide range of bamboo-based products made from woody species like Phyllostachys edulis (Moso) and Guadua angustifolia have also emerged in markets around the world. For example, bamboo is used to make pulp and paper, fabric and engineered products that have numerous applications in daily life. Some of these products are widely consumed locally in countries that have downstream industries manufacturing them. In Colombia, Ecuador and Brazil, bamboo is commonly used to make a wide variety of handicrafts and laminated panels that are widely used in the local economy. However, the most commercial use of bamboo comes from China, which reaps most bamboo industry revenue. According to the China bamboo industry association, the total output value of China's bamboo industry in 2019 was US$46 billion, of which US$2.14 billion is estimated to be from international trade (INBAR 2021). The statistics suggest that bamboo-based products manufactured in China are predominantly destined for domestic use. International trade in bamboo products is expected to increase as more consumers switch to sustainable materials. Bamboo trade figures are based on the totals of 18 six-digit codes of the United Nations Harmonized System (2017 edition) that have been identified by the International Bamboo and Rattan Organisation (INBAR) as bamboo products.

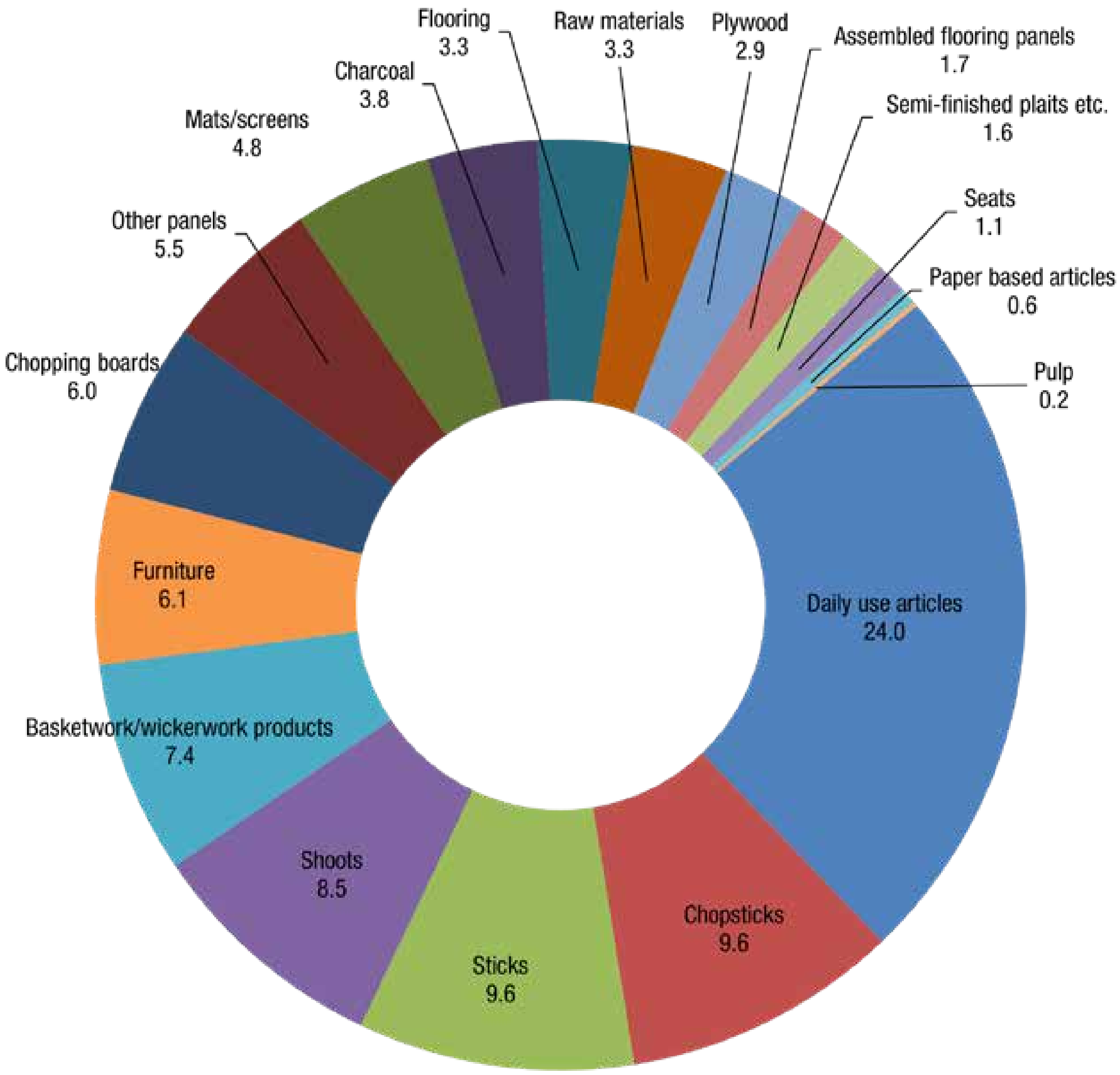
The global construction industry is one of the main beneficiaries of trade in bamboo-based products, and many countries have the potential to participate in this buoyant market because they have large resources of suitable bamboo species that make for good-quality products. However, they lack the technology and expertise to start downstream industries. Consequently, this vast opportunity in international trade is grossly underexploited. The discussion on international trade highlights the major players for bamboo products destined for the construction industry and the markets that present opportunities for suppliers of such products.

5.2 GENERAL OVERVIEW OF TRADE

Bamboo products are traded in different forms, some of which are like timber-based wood products. The Harmonized System (HS) of trade classification provides various categories in which bamboo products are classified. This encompasses engineered bamboo (laminated bamboo, flooring, plywood), raw materials (bamboo for plaiting),[63] semi-finished plaits, bamboo shoots, mats and screens, basketwork, charcoal, chopping boards, chopsticks, sticks, pulp, paper-based articles, and bamboo seats and furniture. The market share of each category of bamboo products in total exports in 2020 is shown in figure 12.

[63] Bamboo poles are classified under bamboo products for plaiting.

Figure 12 Global exports of all bamboo products, 2020
(per cent)

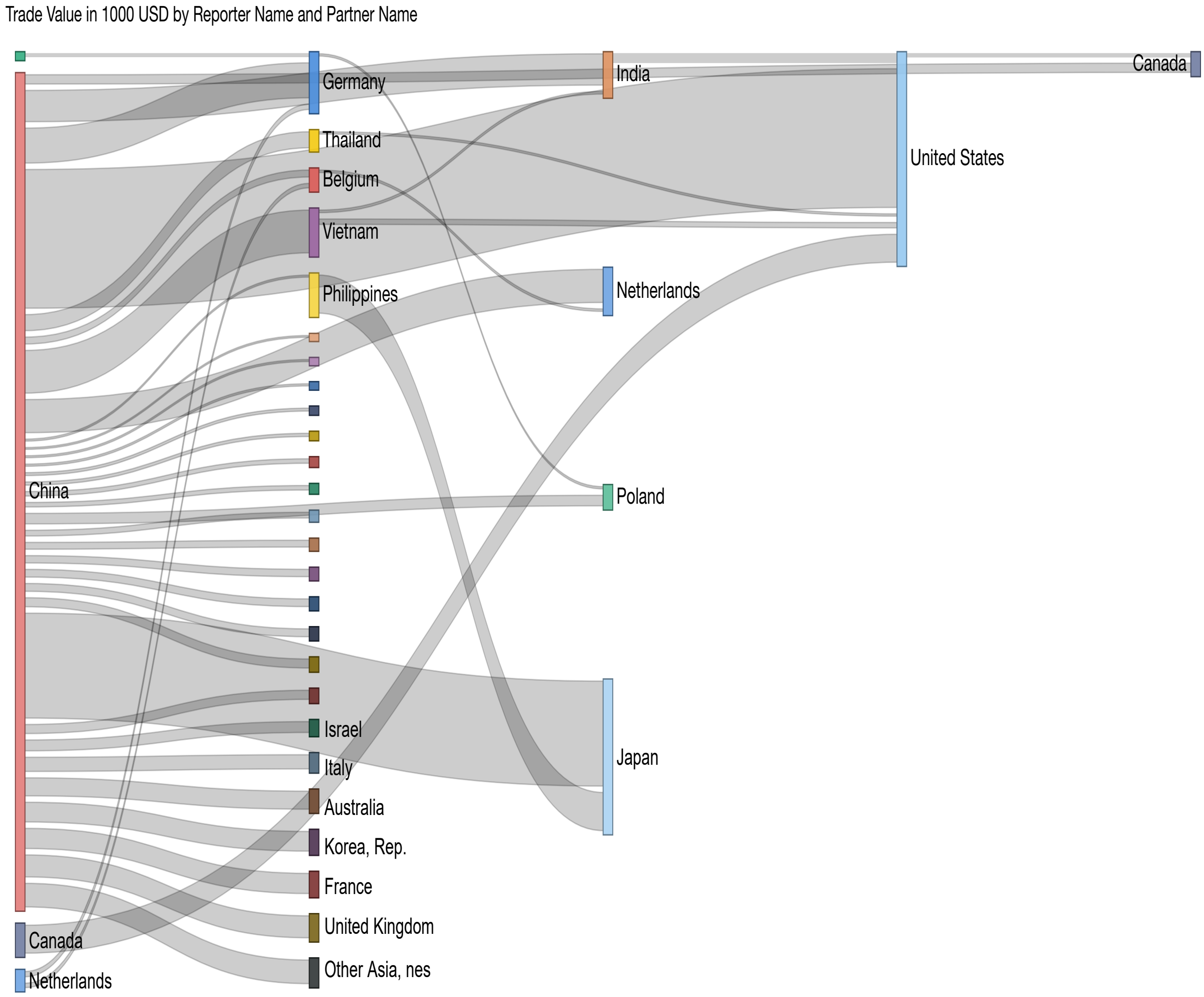


Source: UNCTAD secretariat calculations based on data from United Nations Comtrade database.

According to the United Nations Comtrade database, the total value of bamboo- based product exports in 2020 was an estimated $3.03 billion, of which China contributed approximately 65 per cent.[64] The remaining top exporting countries in 2020 were highly segmented. Apart from China, the top 10 exporters of bamboo in 2020 were the Philippines, Viet Nam, Canada, the Netherlands, Germany, India, the United States, Thailand, and Indonesia. Figure 13 represents an overview of global trade flows of exports in value over US$10 million of bamboo products in 2020.

[64] The similarity of bamboo end products to wood often leads to lower reported values under the various headings of traded products in the Comtrade database. See INBAR, 2020, "International bamboo and rattan trade: Key takeaways," https://www.inbar.int/international-bamboo-and-rattan-trade-key-takeaways/ (accessed 6 December 2021).

Figure 13 Global trade flow of all exports of bamboo products, 2020



Source: UN Comtrade.

Note: nes: not elsewhere specified.

5.3 BAMBOO-BASED CONSTRUCTION PRODUCTS

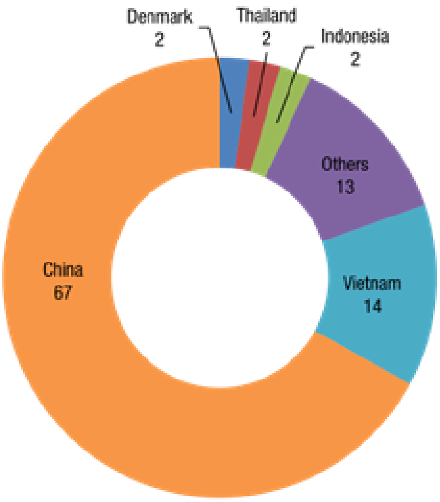
International trade in bamboo products used in construction has flourished in recent years largely due to increasing consumer demand. This is because bamboo products offer consumers a sustainable substitute for timber-based products, which are increasingly coming under stringent government regulations regarding the legal origin of the timber and forest certification requirements to control deforestation. According to the FAO, the world's forests decreased from 32.5 per cent to 30.8 per cent of total land area between 1990 and 2020, which represents 178 million hectares of forest lost (FAO and UNEP 2020). Another reason for the increasing demand for bamboo products is that they are relatively cheaper than timber-based products, durable and easily workable, and contribute to greening the construction industry.

The main bamboo products used in the construction industry that are traded internationally are bamboo poles and engineered bamboo. The value and quantity of trade is reported in the 2017 edition of the United Nations Comtrade database under product codes 140110 (bamboo used primarily for plaiting) for poles,[65] 440921 (wood made of bamboo, including stripes and friezes for parquet flooring), 441873 (assembled bamboo flooring panels), 441891 (other bamboo panels) for engineered bamboo,[66] and 441210 (veneer panels and similar laminated timber, of bamboo),

5.4 BAMBOO USED PRIMARILY FOR PLAITING, HS 140110

China has one of the largest bamboo resources in the world and is also the world's leading producer of bamboo building materials (Yuming and Jiru, undated). In 2020, Chinese exports of bamboo used primarily in plaiting (HS 140110) accounted for 67 per cent of total exports and a trade value of approximately US$66.9 million. Viet Nam was the second largest exporter with an estimated value of US$13.4 million. Smaller quantities were exported from Indonesia (US$2.4 million), Thailand (US$2.3 million) and Denmark (US$2.2 million). The top five exporters accounted for 87 per cent of global exports of bamboo used primarily for plaiting, estimated at US$100 million. Figure 14 summarizes this information.

Figure 14 Top five exporters of bamboo used primarily for plaiting, 2020
(per cent)



Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

The main destinations of Chinese bamboo used primarily for plaiting in 2020 were the United States (US$10.5 million), the Netherlands (US$7.1 million), Poland (US$5.5 million), Hong Kong Province of China (US$4.8 million) and the United Kingdom (US$4.7 million). Table 3 provides a summary of the top five destinations of leading exporters of bamboo for plaiting and total global exports for each exporter.

65 This category of exports includes bamboo split or whole, cut to length round, bleached, rendered non-inflammable, polished or dyed. See http://www.wcoomd.org/-/media/wco/public/global/pdf/topics/nomenclature/instruments-and-tools/hs-nomenclature-older-edition/2002/hs-2002/0214e.pdf?la=en

66 The export/import values of goods reported by the exporter and the importer may be recorded in different categories.

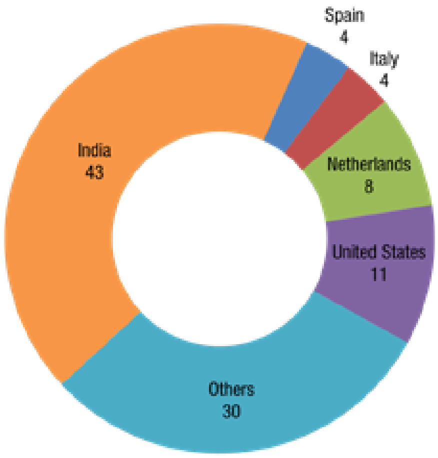
Table 3 Leading exporters of bamboo used primarily for plaiting and destinations, 2020
(U.S. dollars)

Leading exporting countries	Destinations of exports and value					Total exports
China	United States	Netherlands	Poland	Hong Kong, Province of China	United Kingdom	World
	10,502,481	7,133,657	5,452,697	4,803,638	4,684,519	66,905,469
Denmark	Netherlands	France	Portugal	Germany	Belgium	World
	576,019	509,323	363,514	231,413	133,247	2,204,540
Indonesia	Australia	Saudi Arabia	Germany	France	United Arab Emirates	World
	1,866,830	81,845	46,964	45,496	42,608	2,370,382
Thailand	Italy	Spain	Israel	Greece	United Arab Emirates	World
	1,387,234	381,601	236,651	111,430	75,922	2,291,687
Viet Nam	India	China	Sri Lanka	United States	Pakistan	World
	12,147,681	514,974	289,782	102,843	66,223	13,395,309

Source: United Nations Comtrade Database, Harmonized System Code 140110.

Based on available data, the top five importers of bamboo used primarily for plaiting in 2020 were India (US$84 million), the United States (US$20.4 million), the Netherlands (US$16.4 million), Italy (US$7.1 million) and Spain (US$7 million). Together they accounted for almost 70 per cent of total global imports estimated at US$193 million.[67] Figure 15 summarizes this information. The main sources of imports by value of the leading importers were China, Viet Nam, Thailand and Argentina, but several countries contributed to the global supply. The quantities imported varied between countries, but overall China was the dominant supplier.

Figure 15 Top five importers of bamboo used primarily for plaiting, 2020
(per cent)



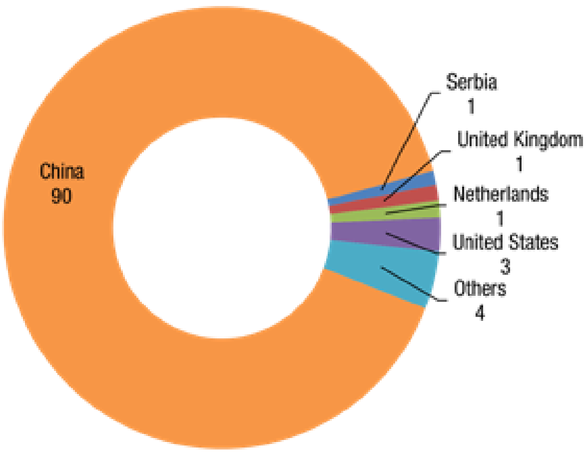
Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

[67] Import and export data reported in UN Comtrade may not be mirrored for two reasons. First, imports are recorded cost insurance and freight (cif) while exports are free on board (fob), which may represent a 10 to 20 per cent difference. Second, data quality may vary among countries despite the efforts of national and international agencies. For a given country, imports are usually recorded with more accuracy than exports because imports generally generate tariff revenues while exports do not. At a detailed level, the same good may be recorded in different categories by the exporter and the importer. See World Bank, World Integrated Trade Solution database, https://wits.worldbank.org/wits/wits/witshelp/content/data_retrieval/T/Intro/B2.Imports_Exports_and_Mirror.htm (accessed 6 December 2021).

5.5 WOOD MADE OF BAMBOO (INCLUDING UNASSEMBLED STRIPS AND FRIEZES FOR PARQUET FLOORING), HS 440921

In 2020, total exports by value of wood made of bamboo were approximately US$98.3 million. The largest exporter was China, accounting for approximately 90 per cent of total wood made of bamboo exports, with a trade value of US$88.4 million. Among the leading exporters, smaller quantities came from the United States (US$2.4 million), the Netherlands (US$1.19 million), the United Kingdom (US$1.16 million) and Serbia (US$1 million). Figure 16 summarizes this information. The manufacturing industry in China has most of the established downstream industries producing and exporting such products (INBAR 2019).

Figure 16 Top five exporters of wood made of bamboo (including unassembled strips and friezes for parquet flooring), 2020
(per cent)



Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

The main destinations of countries exporting wood made of bamboo in 2020 were the United States, countries in the European Union (the Netherlands, Germany, Ireland) Japan and Australia. Table 4 provides a summary of the top five destinations of the leading exporters of bamboo wood and total global exports for each exporter.

Table 4 Leading exporters of wood made of bamboo (including unassembled strips and friezes for parquet flooring) and destinations, 2020
(U.S. dollars)

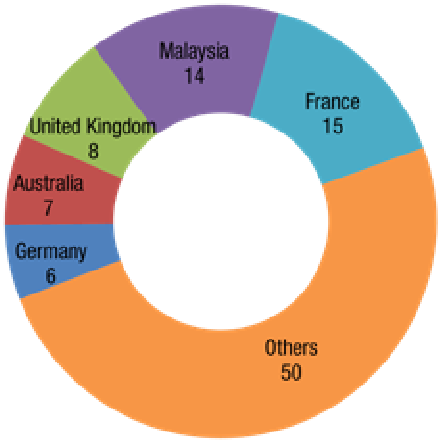
Leading exporting countries	Destination of exports and value					Total exports
China	United States	Netherlands	Japan	Germany	Australia	World
	29,634,018	7,305,583	5,943,185	5,456,585	4,348,233	88,351441
Netherlands	France	Switzerland	Belgium	Germany	Italy	World
	232,696	231,230	128,599	125,158	88,258	1,187,380
Serbia	Greece	Bosnia Herzegovina	Bulgaria	Montenegro	Belarus	World
	212,670	203,203	181,659	95,521	87,38	1,004,870

Leading exporting countries	Destination of exports and value					Total exports
United Kingdom	Ireland	Germany	United States	Netherlands	Norway	World
	1,012,991	65,821	65,391	11,116	4,195	1,164,358
United States	The Bahamas	Canada	Cayman Islands	Curacao	Turks and Caicos Islands	World
	692,281	628,788	305,711	268,298	189,349	2,417,150

Source: United Nations Comtrade Database, Harmonized System Code 440921.

In 2020, the top five importers of wood made of bamboo (including unassembled strips and friezes for parquet flooring) based on available data were France (US$7.8 million), Malaysia (US$7.4 million), the United Kingdom (US$4.4 million), Australia (US$3.5 million) and Germany (US$2.9 million). Together they accounted for 50 per cent of the total value of global imports estimated at US$51.6 million. Figure 17 summarizes this information. The main source of imports by value to the leading importers was China, accounting for almost 40 per cent of overall global supply. Several countries supplied wood made of bamboo to the world in 2020, but in significantly smaller quantities compared to China.

Figure 17 Top five importers of wood made of bamboo (including unassembled strips and friezes for parquet flooring), 2020
(per cent)

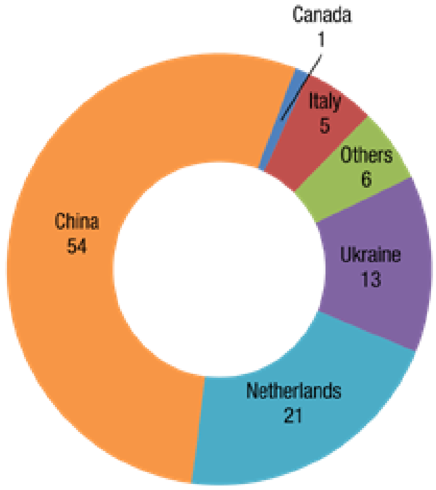


Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

5.6 WOOD MADE OF BAMBOO (ASSEMBLED FLOORING PANELS OF BAMBOO OR WITH AT LEAST A TOP LAYER [WEAR LAYER] OF BAMBOO), HS 441873

In 2020, China was the largest exporter of assembled flooring panels made of bamboo, accounting for 54 per cent of world exports and a trade value of US$28 million. The Netherlands was the second largest exporter with an estimated value of US$10.9 million. Smaller quantities were exported from Ukraine (US$6.9 million), Italy (US$2.8 million) and Canada (US$0.6 million). Figure 18 summarizes this information.

Figure 18 Top five exporters of assembled flooring panels of bamboo or with at least a top layer (wear layer) of bamboo, 2020
(per cent)



Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

The main destinations of exports of assembled flooring panels made of bamboo from the leading exporters in 2020 were the United States, United Kingdom, countries in the European Union (the Netherlands, Sweden, Germany, France, Spain), and Israel. Table 5 provides a summary of the top five destinations of the leading exporters of assembled flooring panels and total exports of each exporter.

Table 5 Leading exporters of assembled flooring panels of bamboo or with at least a top layer (wear layer) of bamboo and destinations, 2020
(U.S. dollars)

Exporting country	Destination of exports and value					Total exports
Canada	United States	n.a.	n.a.	n.a.	n.a.	World
	559,277	n.a.	n.a.	n.a.	n.a.	559,277
China	United States	Netherlands	France	Israel	Spain	World
	10,475,231	7,348,571	2,408,173	1,334,282	1,069,277	28,024,881
Italy	United States	United Arab Emirates	France	Switzerland	United Kingdom	World
	904,401	836,226	310,258	192,391	178,489	2,843,538
Netherlands	United Kingdom	Germany	France	Spain	Belgium	World
	2,434, 317	2,417,431	1,346,880	749,938	649,300	10,875,476
Ukraine	Sweden	Serbia	Poland	Kazakhstan	Italy	World
	5,183,651	1,199,280	270,019	71,671	64,347	6,934,764

Source: United Nations Comtrade Database, HS 441873.

The top five importers of assembled panels of bamboo in 2020 based on available data were the United States (US$17.6 million), United Kingdom (US$7 million), Denmark (US$6.7 million), the Netherlands (US$5.1 million) and New Zealand (US$2.7 million). Figure 19 summarizes this information. Several countries imported smaller quantities, but overall, countries in the European Union accounted for the largest share of total world imports.

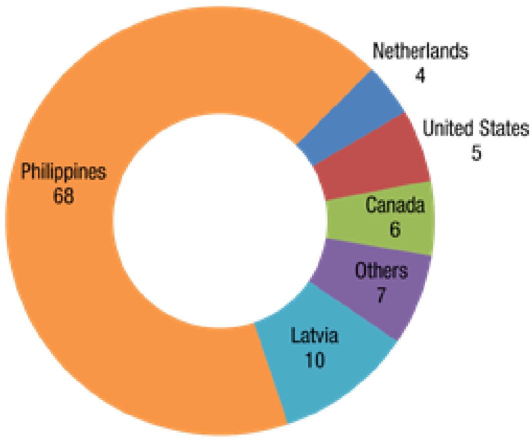
Figure 19 Top five importers of assembled flooring panels of bamboo or with at least a top layer (wear layer) of bamboo, 2020
(per cent)

Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

5.7 WOOD MADE OF BAMBOO (BUILDERS' JOINERY AND CARPENTRY OF WOOD, NOT ELSEWHERE CLASSIFIED UNDER OTHER HS PRODUCT CODES), HS 441891

In 2020, the Philippines was the largest exporter of wood made of bamboo used in builders' joinery and carpentry products that are classified under HS 441891. It accounted for almost 70 per cent of global exports and a trade value of US$113.5 million.[68] The other leading exporters were Latvia (US$17.4 million), Canada (US$9.4 million), the United States (US$9.2 million) and the Netherlands (US$6.7 million). Figure 20 summarizes this information.

Figure 20 Top five exporters of builders' joinery and carpentry of wood products made of bamboo, 2020
(per cent)



Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

[68] Joinery products include, inter alia, doors, windows, shutters, stairs, doors and window frames made of bamboo, while carpentry products include structural members such as beams, rafters and roof struts used as structural components of a roof truss.

The main destination of joinery and carpentry products exported was Japan, accounting for almost all exports from the Philippines. Other destinations include the United States, India, and countries in Europe, but the quantities exported were smaller than that to Japan. Table 6 provides a summary of the top five destinations of the leading exporters of joinery and carpentry products.

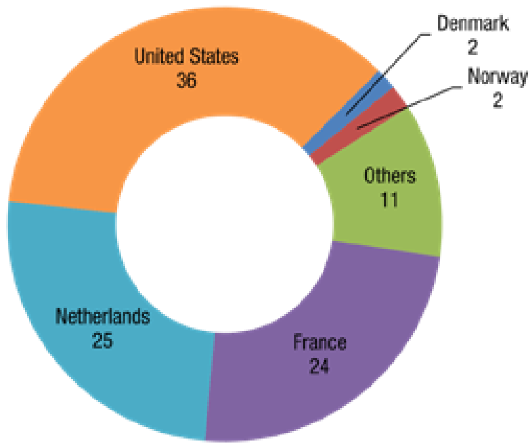
Table 6 Leading exporters of builders' joinery and carpentry of wood products made of bamboo and destinations, 2020
(U.S. dollars)

Exporting country	Destination of exports and value					Total exports
Canada	United States	Saudi Arabia	Saint Pierre and Miquelon	n.a.	n.a.	World
	9,273,006	108,137	7,538	n.a.	n.a.	9,388,683
Latvia	Germany	Denmark	United Kingdom	Sweden	Lithuania	World
	13,295,421	1,737,567	495,571	466,091	400,942	17,419,386
Netherlands	Belgium	Poland	Germany	United States	Norway	World
	5,326,923	848,187	253,520	155,551	80,537	6,743,198
Philippines	Japan	United States	Afghanistan	Papua New Guinea	Jamaica	World
	113,120,062	235,289	61,570	37,421	29,889	113,506,578
United States	India	China	Denmark	Honduras	Spain	World
	6,106,461	644,559	611,102	409,411	362,009	9,206,862

Source: United Nations Comtrade Database, Harmonized System Code 441891.

The top five importers of joinery and carpentry products made of bamboo in 2020 based on available data were the United States and countries in the European Union (the Netherlands, France Norway, Denmark). Together they accounted for 87 per cent of total global imports, with an estimated value of US$138.5 million. Figure 21 summarizes this information. The main sources of imports by value to the leading importers were China and countries in Europe.

Figure 21 Top five importers of builders' joinery and carpentry of wood products made of bamboo, 2020
(per cent)

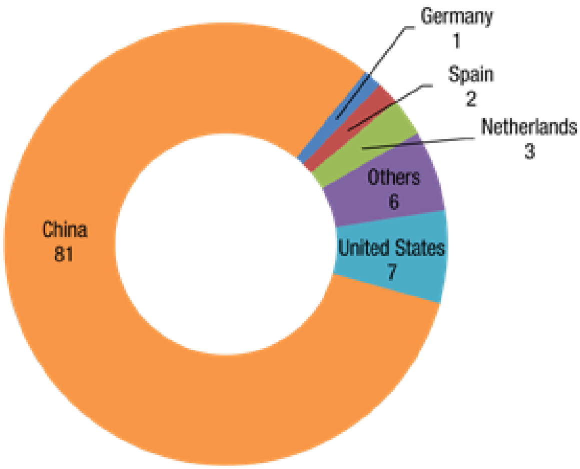


Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

5.8 PLYWOOD, VENEER PANELS AND SIMILAR LAMINATED WOOD MADE OF BAMBOO, HS 441210

International trade in laminated bamboo products is growing fast, largely due to the strength, dimensional stability and rigidity of these products that allow for diverse applications, including beams and columns in construction. In 2020, exports by value of laminated bamboo products were approximately US$87.9 million. The largest exporter was China, accounting for 81 per cent of total laminated bamboo exports and a trade value of US$71.6 million. The other leading exporters were the United States (US$5.9 million), the Netherlands (US$ 2.4 million), Spain (US$1.4 million) and Germany (US$1.2 million). Figure 22 summarizes this information. The value of Chinese exports in laminated bamboo products underscores its position as the major producer of engineered bamboo products.

Figure 22 Top five exporters of bamboo plywood veneer panels and similar laminated timber, 2020
(per cent)



Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

The main destinations by value of the top five exporters of laminated bamboo products are the United States, Malaysia, countries in the European Union, Republic of Korea, Canada and the Dominican Republic. Table 7 provides a summary of destinations for the leading exporters.

Table 7 Leading exporters of plywood, veneer panels and similar laminated wood made of bamboo and destinations, 2020
(U.S. dollars)

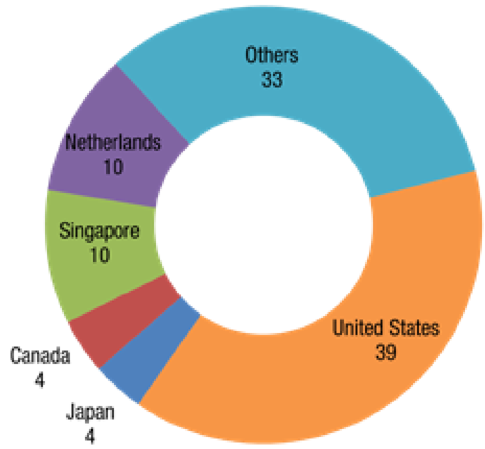
Exporting country	Destination of exports and value					Total exports
China	United States	Malaysia	Netherlands	Canada	Republic of Korea	World
	35,137,043	7,066,446	4,714,014	1,971,166	1,637,991	71,645,304
Germany	Austria	Denmark	Spain	Switzerland	France	World
	219,408	126,980	114,696	100,281	100,047	1,214,090
Netherlands	Germany	United Kingdom	Belgium	France	Austria	World
	687,227	348,352	310,686	258,079	127,508	2,436,320
Spain	France	Morocco	Algeria	Italy	Portugal	World
	1,066,252	177,234	84,911	74,205	23,094	1,448,598

Exporting country	Destination of exports and value					Total exports
United States	Dominican Republic 2,237,219	Canada 1,072,826	Mexico 724,967	Cayman Islands 516,002	Australia 345,905	World 5,930,726

Source: United Nations Comtrade Database, Harmonized System Code 441210.

The top five importers of laminated bamboo products based on available data in 2020 were the United States (US$40.2 million), the Netherlands (US$9.54 million), Singapore (US$10.3 million), Canada (US$4.3 million) and Japan (US$4.02 million). Together they accounted for 67 per cent of total global imports. Figure 23 summarizes this information. The main sources of imports by value of the leading importers were China, Viet Nam, Indonesia, and countries in the European Union (Belgium, Finland). The largest supplier to the leading importers was China, accounting for 49 per cent of overall global supply. Several countries participate in supplying laminated bamboo products, but the quantities are significantly smaller than for China.

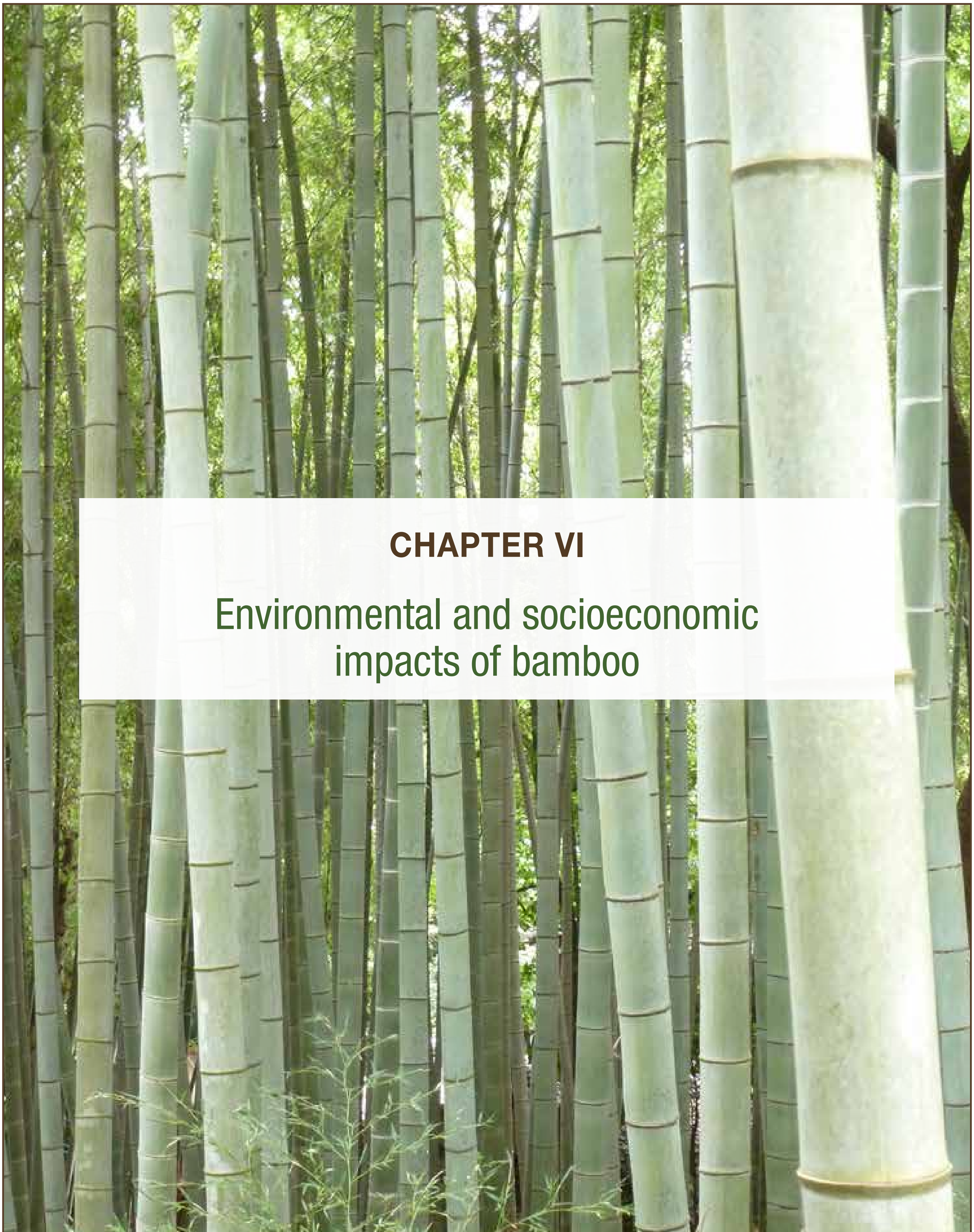
Figure 23 Top five importers of bamboo plywood veneer panels and similar laminated timber, 2020
(per cent)



Source: UNCTAD secretariat calculations based on data from the United Nations Comtrade database.

International trade statistics show that bamboo poles and value-added products made of bamboo for the construction industry are in demand in North America, the European Union, and East Asia. These markets present significant opportunities to bamboo growers to supply quality bamboo products due to demand for substitutes for tropical wood. However, owing to strict market access requirements, exporters must focus on sustainability certifications of their products as well as price competitiveness to gain a competitive advantage in this fast-growing industry. The statistics also highlight the large contribution of China to exports of engineered bamboo products to serve this growing customer base.

The dominance of China in trading engineered bamboo products stems from having abundant resources and species that have good strength properties, and from research and development into new applications of bamboo. Another factor that is contributing to international trade in bamboo products is the growing use of environmentally friendly building materials, as higher standards are set for promoting sustainability in the construction industry. Chapter 6 explores the critical role that bamboo can play in reducing the carbon footprint of the industry. As bamboo grows abundantly in developing countries, the chapter also explores the socioeconomic impact of developing the bamboo sector.



CHAPTER VI

Environmental and socioeconomic impacts of bamboo

6.1 ENVIRONMENTAL BENEFITS

Bamboo has several advantages as a sustainable commodity, but beyond that, it also provides ecosystem services.[69] It is a grass that grows on marginal lands not suitable for agriculture, forestry or any other agroforestry crop. The bamboo plant is resilient. It has high tensile strength. Therefore, it can withstand damage from disasters and other catastrophes. After the nuclear bombings of Hiroshima and Nagasaki, young bamboo shoots were the first plants to reappear (Lobovikov et al. 2007). Bamboo forests are the best land restoration instrument to offset damage to the environment from the extraction of minerals because they grow fast and help stabilize soil fertility (FAO and INBAR 2018). Bamboo flooring panels have already been included in the Asia-Pacific Economic Cooperation (APEC) list of "environmental goods" that benefit from prioritized trade liberalization.[70] Bamboo also contributes to ecotourism, providing producers with supplementary income.

So far only a handful of countries, including China and Ethiopia, have designed strategic environmental plans to promote bamboo plantations and the adding of value to bamboo raw material. They are increasingly joined by others in the design of inclusive environmental policies. For example, on 10 September 2020, Kenya classified bamboo as a "crop" in order to foster the commercialization of bamboo plants as part of a large policy undertaking called the "Greening Campaign." The campaign aims to increase tree cover and endeavours to generate more employment through agroforestry. Before this campaign, bamboo had been classified as a grass plant. In the design of inclusive environmental policies, there are also countries that associate bamboo with rattan, such as India, Japan, Ghana, Nigeria and Cameroon.

6.2 BAMBOO AND THE CIRCULAR ECONOMY

Bamboo is emerging as a promising constituent of the circular economy, which aims to minimize waste and make the most of resources in a sustainable manner. Bamboo plays a crucial role in preventing deforestation and improving forest management. Since bamboo forests grow rapidly, they can quickly replenish deforested areas. Bamboo can also serve as a substitute for materials such as wood. By replacing wood in industrial applications, it can contribute to saving and restoring the world's rainforests, in particular the Amazon, where bamboo is intermingled with other forest species (Phimmachanh et al. 2015). Bamboo is especially viable as a wood substitute where timber is relatively inaccessible or expensive. Bamboo plywood has recently become more economical than other forest products.

The ban on single-use plastics in many developing countries, coupled with increasing deforestation due to timber use, opens possibilities to use bamboo as their substitute. Increased reliance on bamboo as a plastics substitute may also contribute to tackling marine plastic pollution (UNCTAD 2021).[71] However, there are challenges like limited investment and the informality of most activities that preclude bamboo producers from credits or bank loans necessary to access processing equipment and training. Demand-side constraints such as lack of awareness come into play as well. A recent study has identified that 87 per cent of the bamboo potential in eastern Maharashtra in India remains untapped due to both demand and supply constraints (Pijarkar 2019). If properly

[69] Ecosystem services are direct and indirect contributions of ecosystems to human well-being. They directly or indirectly support human survival or quality of life. Ecosystem services can be grouped in four main categories: provisioning services, regulating services, habitat services and cultural services. The most important ecosystem service is climate regulation, and bamboo is part of that.

[70] APEC, "ANNEX C - APEC list of environmental goods," https://www.apec.org/meeting-papers/leaders-declarations/2012/2012_aelm/2012_aelm_annexc.aspx (accessed 6 December 2021).

[71] See UNCTAD (2021) for a more detailed discussion of the circular economy.

funded, the bamboo sector can be as profitable as commercial activities related to wood and wooden products such as Sapele and Okoume.

Producers can increase their income from bamboo by maximizing utilization rates of the plant. This requires a well-organized value chain, with colocation of a tight network of various activities as part of a virtuous cycle within and beyond bamboo enterprises. For example, the bamboo processing industry in China's Anji County has managed to increase its bamboo biomass utilization rate from 20 to 85-90 per cent by fully utilizing the bamboo culm, shoot, sheath, leaves, rhizomes and roots, as well as processing residues (sawdust, slices). The value chain in Anji County is continuously extending to thousands of new products made of bamboo, addressing market needs through innovation and product optimization (Zhaohua and Wei 2018).

6.3 BAMBOO AND CLIMATE CHANGE

Forests, be they bamboo or others, remove, store and sequester more than 70 per cent of global carbon through photosynthesis, whereby carbon is locked in the plant and then transformed into solid biomass (Yiping et al. 2010).[72] Carbon is also stored in the soil where the plant grows.

Bamboo forests have characteristics similar to other types of forests as far as the carbon cycle is concerned and are better reservoirs of carbon sequestration than any other tree, including Sapele and Okoume (Yiping et al. 2010). Bamboo provides approximately 35 per cent more oxygen and absorbs 40 per cent more carbon dioxide than other trees.[73]

Climate change agreements have not yet formally considered bamboo plantations as forests, in contrast to the Food and Agriculture Organization (FAO) definition presented in Chapter 2 of this report. This exclusion prevents many governments from designing climate change mitigation action plans based on bamboo. Meanwhile, INBAR and Ecoplanet Bamboo, a private company, both consider bamboo as one of the solutions to climate change.[74]

Countries must demonstrate additionality in their bamboo projects in order to register them as verified emission reductions with the competent authorities. This means that work on a bamboo plantation is required to show that resulting CO2 emissions are lower than the business-as-usual scenario under which no such project existed. A giant bamboo plantation can store and reduce between 295 and 401 metric tons of carbon per hectare over a period of 30 years (King et al. 2021).

Currently, the only way to earn carbon credits from bamboo is by reapplying forest carbon methodologies to quantify emission reductions for bamboo forestry projects. Therefore, countries need to develop a deep understanding of such methodologies and the certification requirements of international standards. This will allow them to convert their bamboo projects into carbon credits (verified emission reductions) that can be traded on voluntary markets (King et al. 2021). In fact, there may already be many projects that are eligible for carbon credits but that fail to be registered due to the lack of awareness of the methodologies.

For now, there are no dedicated methodologies available to quantify emissions reduction for projects that introduce sustainable management practices for existing bamboo forests (as opposed to planting new bamboo forests). Likewise, it is not yet possible to quantify either the carbon stored in durable bamboo products or the emissions avoided by substituting more carbon-intensive materials with bamboo. More research is needed to develop such methodologies, which

[72] Eliasch Review (2008) assessed that all types of forests store some 77 per cent of global carbon.

[73] Grand View Research, 2021, "Market analysis: Report overview," November, https://www.grandviewresearch.com/industry-analysis/bamboos-market (accessed 6 December 2021).

[74] INBAR, "Climate change," https://www.inbar.int/climate-change/ (accessed 6 December 2021).

would increase the recognition of bamboo as an important carbon sink and open pathways to include it within Nationally Determined Contributions under the Paris Agreement on climate change (King et al. 2021).

The construction industry has high greenhouse gas emissions linked to the production of the raw materials used. For example, the iron and steel sector and the cement sector, account directly for 2.6 and 2.3 gigatons (GtCO2) of carbon dioxide emissions, respectively, from the combustion of fossil fuels and industrial processes, or approximately 8 and 6 per cent of global CO2 emissions, respectively (IEA 2020). Among heavy industries, the iron and steel and cement sectors are the largest emitters of CO2 (IEA 2020). In timber production, the felling of trees removes the ability to absorb existing carbon dioxide from the atmosphere. And as trees are burned, they release carbon dioxide into the atmosphere. Some estimates suggest that between 2015 and 2017, loss of tropical forests accounted for about 8 to 10 per cent of annual human emissions of carbon dioxide (Climate Council 2018). The use of timber, steel and concrete in construction is likely to increase as rapid urbanization and economic development increases demand for new buildings and infrastructure. This, in turn, is likely to increase emissions of greenhouse gases in huge quantities and increase the construction industry's contribution to carbon dioxide emissions at a time when there is a growing need to cut global greenhouse gas emissions to meet the Paris Agreement goal of limiting global warming to well below 2 degrees Celsius and pursuing efforts to limit it to 1.5 degrees Celsius. Bamboo is less used as a building material than concrete, steel and timber, but it has significant environmental benefits that can contribute to reducing emissions.

6.4 BAMBOO AND BIODIVERSITY

Some bamboo species are considered as invasive alien species that can lead to biodiversity loss. This unfounded fear is based on the similarity between oil palm and bamboo. Both plants are widely available in Asia and Africa. Oil palm has been proven to have a detrimental impact on the distribution of primates used as a proxy for biodiversity in most areas (Strona et al. 2018). Therefore, only a tiny area of 3.3 million hectares on the African continent is considered suitable for oil palm cultivation. However, unlike oil palm plantations, bamboo plantations are a bedrock for additional plant and animal biodiversity because bamboo plants nurture microclimates that are favourable for the growth of several bird species and insects that depend on bamboo ecosystems (Phimmachanh et al. 2015). The African Great Green Wall envisages utilizing bamboo as one of the replenishing species in some parts of Africa (Dia and Duponnois 2010).[75]

One example of the increase in animal biodiversity due to bamboo is the giant panda (Ailuropoda melanoleuca) in China. Bamboo shoots are the main feedstock at the Chengdu Research Base for Giant Panda Breeding. Red pandas (Ailurus fulgens) are also dependent on bamboo, with a diet that consists almost exclusively of bamboo shoots and leaves (Phimmachanh et al. 2015). In East Africa, a large forest antelope, the mountain bongo (Tragelaphus euryceros ssp. isaaci), relies on the specific bamboo thickets of Yushania alpina for food and shelter during the dry season. Likewise, mountain gorillas inhabit mountain and bamboo forests in the eastern provinces of the Democratic Republic of the Congo, Rwanda and southwestern Uganda (Bystriakova et al. 2004).

6.5 OTHER SOCIOECONOMIC IMPACTS

Beyond the potential of mitigating greenhouse gas emissions, bamboo farming offers opportunities to improve the livelihoods of communities engaged in this activity. Bamboo farming often represents the leading, or even the only, cash-income-generating prospect in rural areas. In the

[75] The Great Green Wall is a vegetation band from Dakar to Djibouti made of natural and artificial species, accommodation spaces, cropping and cattle rearing zones. Its dimensions are 7,000 km long by 15 km wide.

United Republic of Tanzania, cultivation of bamboo has positively impacted the livelihoods of several thousand people who were without income and has economically empowered women (IFAD 2016). Most of this income is derived from employment generated from low-value-added industries such as bamboo handicrafts and traditional furniture products, and from marketing bamboo shoots. The potential use of bamboo in structural systems as well as in the production of value-added products such as laminated timber, flooring and panels is encouraging farmers to embrace cultivation of specific types of bamboo that are used in the construction industry. This increase in production of specific bamboo species has the potential to generate employment and boost farmers' income from sales of poles to local and international markets, as well as to downstream industries. Increased income is likely to improve and sustain the livelihoods of many households, particularly in rural areas, and reduce poverty. For example, in one of the large bamboo cultivating regions in Southern China, bamboo generates approximately 30 to 40 per cent of a farmer's income, and the development of downstream industries has contributed significantly to rural development and poverty alleviation in the area (Mera and Xu 2014).

Most of the high-quality jobs created in the bamboo construction industry are in the industrial manufacture of value-added bamboo products such as boards and flooring. The market size for these products is expanding due to growing demand for natural materials in infrastructure projects to replace timber-based products as forests get depleted. For example, some forecasts show that the worldwide market for bamboo flooring will grow from US$1.12 billion in 2018 to US$1.53 billion by the end of 2025, at a compound annual growth rate of 3.5 per cent between 2021 and 2025.[76] The economic impact of creating a downstream industry is demonstrated in a multi-stakeholder forestry program funded by the Swiss Agency for Development and Cooperation in Nepal to manufacture value-added products. The agency provided training and equipment to bamboo entrepreneurs in selected producing districts to produce modern bamboo products like bamboo flooring, which were introduced to the international market. This opportunity for low-income rural communities helped them earn a reasonable amount of revenue despite having to purchase the clump from landowners. It also provided jobs that paid equal wages to male and female workers and enabled marginalized households to send their children to good schools (Khanal 2015).

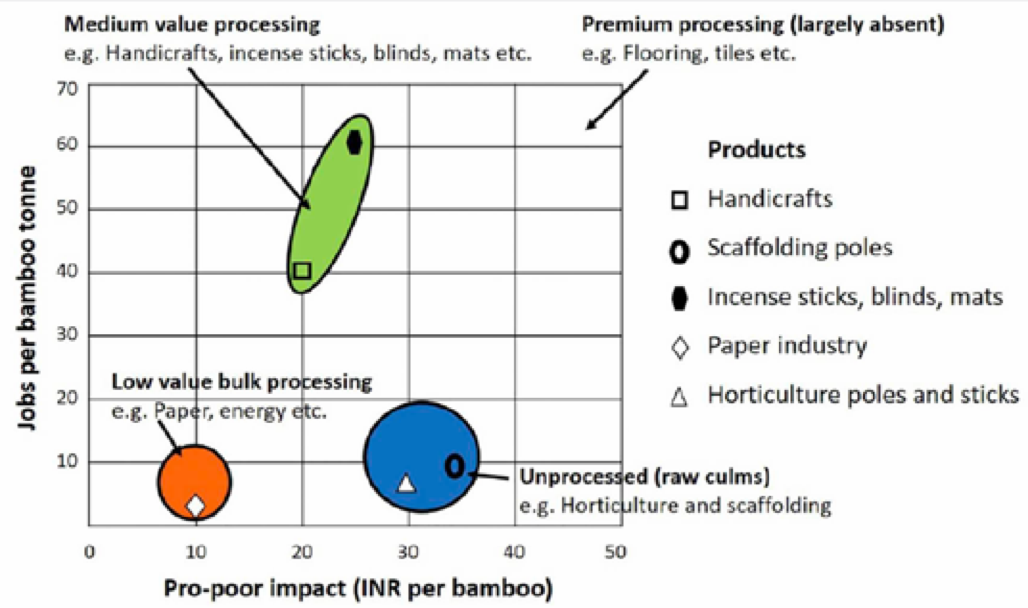
Several countries have plentiful bamboo resources but have been making use of the plant in an isolated or fragmented manner. India has the largest reported bamboo resources in the world, yet has made little use of them to date, mainly due to the different approaches employed by such stakeholders as the state, local communities, artisans, industry and civil society organizations (Gawandi 2021). Hence India is currently reforming its bamboo policy by shifting ownership from the Ministry of Environment to the Ministry of Agriculture. The objective is to increase bamboo supply by scaling up farm production and value addition, while at the same time deregulating bamboo trade and creating demand for medium-to-high-complexity bamboo products (Tambe et al. 2020). Box 2 provides an example of income generation and job creation in India's bamboo industry. About 8.6 million people depend on bamboo industries for their livelihoods in India (INBAR 2014), and the value of associated industries is estimated to have a potential value between US$3.47 billion and US$4.05 billion.[77] Nevertheless, bamboo remains largely underutilized in India, given the wide availability of the resource.

[76] https://www.marketwatch.com/press-release/bamboo-flooring-market-survey-share-and-size-2021-cagr-global-industry-growth-manufacturers-data-latest-updates-business-prospects-demand-progression-status-regional-outlook-2025-covid-19-impact-analysis-by-360-market-updates-2021-12-05 (accessed 6 December 2021).

[77] Ministry of Micro, Small and Medium Enterprises, 2021, **"**Nitin Gadkari : Bamboo industry has potential to be worth Rs.30,000 crore**,** calls for multiple use of bamboo to increase its demand and plantation," press release, 23 March, https://pib.gov.in/PressReleasePage.aspx?PRID=1706862.

Box 2. Farmer income and job creation through bamboo processing in India

In India, the paper industry gradually shifted over the years from bamboo to wood as its raw material. Hence, bamboo production shifted from low-value bulk processing toward the sale of unprocessed raw material, primarily in horticulture. Despite the decrease in complexity, the sale of unprocessed bamboo turned out to be more lucrative, as farmers earned three times more income per culm. The figure below displays the degrees of farmer income and job creation in India based on the processing of bamboo products with different levels of complexity (handicrafts, scaffolding poles, incense sticks, blinds, mats, paper and horticulture poles and sticks). It shows that higher levels of processing do not necessarily have a higher pro-poor impact (Tambe et al. 2020). The objective is to establish premium processing industries that are both employment creators and high-income providers for bamboo farmers, as shown in the top far-right corner of the figure.



Source: Tambe et al. (2020).

Note: INR : Indian rupees.

In Jamaica, where 117,000 hectares of bamboo were available in 2020, one company commercializes bamboo straws as a fully-fledged service. This service includes, in addition to the bamboo straw itself, a care brush, possibility of replacement, and a bag.[78] Considering that a single bamboo straw can replace 360 single-use plastic straws, this has the potential to reduce plastic pollution particularly by companies and hotels. However, although Jamaica has plenty of bamboo, the company sources its raw material from Bali, Indonesia because the local bamboo is not suitable for the production of straws due to its high pulp content and other quality issues.

Viet Nam is another country with significant bamboo resources. It produced high-quality bamboo mats and composite floorings in the late 1990s. However, even though bamboo raw material prices and wages were less than half those in China, Vietnamese bamboo products ended up with a higher price and gradually lost business to Chinese exports. The key reason was the low utilization rate of the bamboo plant, resulting in the need to import additional intermediate

[78] See the Bambusa website at https://www.bambusajamaica.com/ (accessed 6 December 2021).

products and the cost of dealing with wasted materials that caused environmental pollution. Viet Nam gradually increased utilization rates as it imported more than 100 production lines and focused on the strategic development of its bamboo industry. It diversified into bamboo sticks, pressed lumber, engineered boards, shoots, charcoal, construction, furniture and handicrafts, and was able to build a sector valued at US$250 million by 2010 (Zhaohua and Wei 2018).

Globally, China's bamboo sector uses the highest percentage of the plant, and while doing so offers the full spectrum of traditional, hybrid and engineered applications of bamboo products. Box 3 provides an example of bamboo entrepreneurship in China. Anji County has an integrated processing industry with a bamboo biomass utilization rate of between 85 and 90 per cent, resulting in 3,000 different bamboo products in nine categories (Zhaohua and Wei 2018). Employment in the bamboo sector of China is estimated at 8 million people (Shepherd 2019). A system of demonstration sites for the plant ensures participation by multiple stakeholders, the science and technology community, and other groups. Furthermore, the government is committed to increasing the bamboo biomass utilization rate, so it supports the development of a complex supply chain that uses all parts of the plant.

Box 3. Bamboo entrepreneurship in China

Zhou Rong is a bamboo entrepreneur in Chishui, a city in Guizhou province in southern China. She has successfully developed the Guizhou Chishui Zhuyun Bamboo Furniture Co. Ltd. into a US$5 million business since 2015. Her furniture company today employs 60 people, and 2,000 local farmers supply its bamboo. Ms. Rong offers training to her community, which in turn supports her company as customers. She uses 100 per cent of the bamboo plant in her operations and minimizes waste. The business model is based on a set of activities that are mutually supportive and dependent, whereby the company receives raw materials, produces furniture and other products, sells, and gives back to the community in a circular manner by providing training and employment.

Ms. Rong's company grows its own bamboo on 200 hectares, with an additional two hectares for by-products like shoots and fungus. It uses the culm of Moso bamboo for building furniture, and the twigs and culm tips for brooms and charcoal. Leftovers and processing waste from furniture production are converted into charcoal, incense sticks and seedbed for fungus growth, while the bamboo base powers the boilers. The company has introduced poultry farming on the land where it grows Moso bamboo. Chickens consume bamboo weeds as food, and provide natural fertilizer to improve the soil, while their eggs are sold separately to provide additional income.

Source: Pullanikkatil and Shackleton (2019).

CHAPTER VII

Policy recommendations

This report has shown various pathways for developing countries to make use of the economic and environmental qualities of bamboo. There is a wide palette of bamboo products with varying degrees of processing needs and complexity. Countries can benefit most from bamboo through an integrated policy approach that focuses on maximizing the utilization rate of the plant. For instance, if country-wide bamboo plantations were to be established only to harvest shoots for nutrition, this would mean that the rest of the plant would be discarded. Hence it may not be worth the effort to invest and build capacity in raising and harvesting bamboo just for producing shoots. Instead, countries can reap the full benefits of bamboo as a commodity if governments commit to developing a comprehensive bamboo sector.

Bamboo can help developing countries achieve environmental outcomes without sacrificing income or jobs. For this to happen, the bamboo industry has to be seen as an integral part of sustainable development strategies (e.g. circular economy or climate change mitigation plans) and not merely as an export commodity. Achieving such an outcome requires careful preparation and foresight. A long-term view on bamboo should be based on policies, incentives and technical capacity-building (Subramony 2021).

7.1 INCLUDING BAMBOO DEVELOPMENT IN POLICY

Bamboo needs strategic recognition as a non-timber forest product that complements other forestry resources. Countries that have bamboo resources should recognize its strategic status at the highest level. Governments of countries with bamboo resources should take a long-term view and consistently include bamboo as an element of national development plans and other mandates on agriculture-based development. They should also support standard-setting and technical guidelines on products of various complexities that derive from the bamboo plant.

Advocacy groups should campaign through political lobbying to raise awareness and promote the advantages of bamboo over mainstream building materials. Including bamboo in national housing policies and regulations could contribute to meeting Target 11.1 of United Nations Sustainable Development Goal 11 (Ensure access for all to adequate, safe, and affordable housing and basic services and upgrade slums by 2030).

7.2 DEVELOPING DOWNSTREAM INDUSTRIES

Bamboo has great potential as a building material because of its high tensile and compressive strength properties, cost-effectiveness and sustainability. It could also provide a potential solution to greening the construction industry because of its environmental qualities. Considering these attributes, combined with increasing awareness among consumers of bamboo’s economic, commercial and industrial applications, demand for bamboo is expected to grow strongly as investments in infrastructure increase. The choice of bamboo over wood, concrete and steel will be driven largely by the advantages that it offers in terms of strength per unit weight and cost, which make it an attractive building material for affordable housing, long-span open spaces, and structures located on ground with low soil bearing and in areas with high seismic activity.

This expected growth in demand for bamboo has implications for the supply of species frequently used in rudimentary construction (usually species from the Guadua, Dendrocalamus, Bambusa, Gigantochloa and Phyllostachys genera), as well as feedstock in downstream industries that manufacture engineered bamboo products such as bamboo wood and flooring for the modern construction sector. This growing market could create opportunities for bamboo cultivators to boost production of culms and participate in the higher-end markets of engineered bamboo products. To capitalize on the potential economic benefits that could be derived from bamboo, policymakers need to carefully look at ways to encourage the development of bamboo plantations to boost supply and value chains, helping to foster downstream industries where necessary.

7.3 PROVIDING INCENTIVES AND SUPPORT

Governments can provide financial incentives for the sustainable management of bamboo resources, for instance through favourable tax regimes (especially in rural areas and for small and medium-sized enterprises) and grace periods for credit (such as payback periods of a minimum of 10 years). Tax policy should also favour nascent bamboo industries. Governments can put in place a system of demonstration sites at the local level to increase awareness about the uses of bamboo. In terms of support measures for stakeholders, governments can train human resources on bamboo processing techniques, entrepreneurship, and marketing and management of processed products. They can also ensure the provision of adequate equipment and facilities that are needed for modern bamboo processing supply chains.

To encourage local value addition and reap the potential benefits of earning higher revenues, governments should address constraints to the development of bamboo downstream industries by, inter alia, making financing available, attracting quality investment to the sector, and closing the skills gap in value addition. Training in processing could help bring down the cost of production and make companies more competitive. In addition, policymakers could spur development of the local processing industry and value addition by introducing incentives that encourage companies to undertake local processing. Countries that do not have enough bamboo resources could establish free zones where bamboo feedstock for downstream industries could be imported with import-duty exemptions.

7.4 BUILDING CAPACITY

Countries should address technical challenges or weaknesses that impede the development of local bamboo industries. Governments should also provide financial support for research and development and invest in technology application and extension systems to reapply bamboo processing technologies in new areas. Countries should also establish independent platforms where different aspects of bamboo can be discussed by various stakeholders, as is the case of the India Bamboo Forum. Finally, this report has shown that establishing bamboo ecosystems in a specific region where processing industries are colocated can be beneficial to maximize bamboo biomass utilization rates.

As infrastructure demand rises globally, particularly in developing countries, bamboo may provide a cost-effective solution for building affordable structures while contributing less greenhouse gases than conventional building materials. This report demonstrates that bamboo has merits to substitute for conventional building materials because of its mechanical and sustainable properties, but that there are also challenges in building with bamboo. These include joints, poor bonding when bamboo is used in composite materials such as reinforced concrete, and excessive stiffness that could cause structures to fail. Finding innovative solutions to overcome these obstacles would contribute to increasing acceptance of bamboo by engineers and architects as an alternative to conventional building materials in modern construction.

To overcome the challenges in bamboo construction, governments could encourage joint research with the private sector to develop codes of practice to provide practical guidance on specific work tasks to architects, engineers and contractors. For example, research into jointing mechanisms and appropriate long-term bonding solutions in concrete could lead to solutions that would make bamboo an attractive building material in all forms of construction.

7.5 BOOSTING THE SUPPLY OF BAMBOO THROUGH CULTIVATION

Boosting the supply of construction species to meet rising local and foreign demand would require policies that promote bamboo cultivation. Governments can facilitate this process by setting up new nurseries or transplanting existing ones based on the desired species. This will contribute to intensifying cultivation of types of bamboo used in construction that are also feedstock to downstream industries, producing value-added products. Furthermore, governments could consider providing necessary support to farmers in terms of finance, land availability and capacity-building for developing suitable bamboo species for the construction industry.[79] Governments also need to put in place mechanisms to certify that bamboo forests conform with international sustainability standards that guarantee sustainable forest management practices.

7.6 DEVELOPING BAMBOO BUILDING CODES

The widespread use of bamboo as a building material is hindered by the lack of suitable building codes and standards for designing and building with bamboo. International standards developed by the International Organization for Standardization in cooperation with INBAR (ISO 22156:2021) can be applied to the design of bamboo structures whose primary load-bearing structure is made of round bamboo.[80] However, coverage does not include structures made of engineered bamboo products, bamboo-reinforced materials such as bamboo-reinforced concrete, and scaffold structures constructed with bamboo.[81] Convincing engineers and architects to consider bamboo as a building material would be enhanced if the material were to have some degree of standardization and codes of practice to provide a minimum acceptable level of safety. Such codes of practice that cover a wide range of design in wood, steel and concrete are a primary reason for widespread use of these materials in construction and could be the major driver for mainstreaming bamboo in structural applications (Trujillo, undated).

Furthermore, the leading producer of bamboo culms and engineered products used in the construction industry, China, could support INBAR's Bamboo Construction Task Force in developing new international standards on the structural uses of bamboo, reviewing and updating existing international standards, and developing new standards in areas such as bamboo strength grading, connection design, and characterization of bamboo products upon which specifications are based.[82] The development of international bamboo codes equivalent to those used for timber could generate interest globally among architects, engineers and contractors in using more bamboo in construction systems. Additionally, providing more information about bamboo by raising awareness about its economic and ecological benefits in construction could result in widening the range of materials used in the construction sector.

79 https://www.kefri.org/assets/publications/strategy/DRAFT_BAMBOOPOLICY.pdf Kenya National Bamboo Policy, 2019 (accessed 6 December 2021).

80 See the ISO website at https://www.iso.org/standard/73831.html (accessed 6 December 2021).

81 Ibid.

82 See https://www.inbar.int/construction-taskforce/ (accessed 6 December 2021).

ANNEX: STATISTICAL DATA

The tensile test results presented in this table are obtained from experiments conducted by different researchers on selected bamboo species. This table also shows some values obtained for moisture content, density and modulus of elasticity of selected species, factors that impact the tensile strength of the material. For some species different test conditions were applied. Not all tests were guided by the ISO standard for determining mechanical properties of bamboo. The values shown in the table are average values.

Table A1 Tensile Strength of selected bamboo species

Bamboo species	Tensile strength (N/mm2)	Modulus of Elasticity (N/mm2)	Density (kg/m3)	Moisture content (per cent)
Bambusa balcooa	164	n.a.	820	8.5
Bambusa bamboos	121	n.a.	710	9.5
Bambusa nutans	208	n.a.	890	8
Bambusa tulda	207	n.a.	910	8.6
Dendrocalamus giganteus	177	n.a.	740	8
Dendrocalamus hamiltonii	177	n.a.	590	8.5
Dendrocalamus strictus	160	17,500	n.a.	11.4
Gigantochloa apus	294.1	n.a.	n.a.	54.3
Gigantochloa apus	298.9	n.a.	n.a.	15.1
Gigantochloa atroviolacea	237.4	n.a.	n.a.	15/54
Gigantochloa atter	247–332	n.a.	n.a.	14.4
Gigantochloa macrostachya	168	n.a.	960	8
Gigantochloa pseudoarundinacea	177.9	27,631	690	n.a.
Guadua angustifolia	148–384	n.a.	n.a.	n.a.
Guadua angustifolia	162.7	17,900 –24,100	n.a.	n.a.
Phyllostachys bambusoides	140	n.a.	730	8
Phyllostachys edulis	115–309	8,987–27,397	553–1,006	4.9–7.8

Source: Adapted from Bamboo Import Europe (2016b).

Table A2 Tensile strength of selected hard/soft wood species

Species	Average tensile strength parallel to grain (N/mm2)
Hardwoods	
Beech, American	86.2
Elm, cedar	120.7
Maple, sugar	108.2
Oak Overcup	77.9
Pin	112.4
Poplar, balsam	51
Sweetgum	93.8
Willow, black	73.1
Yellow-poplar	109.6
Softwoods	
Baldcypress	58.6
Cedar Port-Orford	78.6
Western redcedar	45.5
Douglas-fir, interior north	107.6
California red fir	77.9
Pacific silver fir	95.1
Hemlock, western fir	89.6
Larch, western fir	111.7
Eastern white pine	73.1
Loblolly pine	80.0
Ponderosa pine	57.9
Virginia pine	94.5
Redwood pine	
Virgin	64.8
Young growth	62.7
Spruce	
Engelmann	84.8
Sitka	59.3

Source: USDA (2010).

The shear strength test results presented in this table are obtained from experiments conducted by different researchers on selected bamboo species. This table also shows values obtained for moisture content and density, factors that impact the shear strength of the material. For some species different test conditions were applied. Not all tests were guided by the ISO standard for determining mechanical properties of bamboo. The values shown in the table are average values.

Table A3 Shear strength of selected bamboo species

Selected bamboo species	Shear strength (N/mm2)	Density (kg/m3)	Moisture content (per cent)
Bambusa balcooa	11.9	820	8.5
Bambusa bambos	9.9	710	9.5
Bambusa nutans	10.5	890	8
Bambusa pervariabilis	8.7/10.3	n.a.	12
Bambusa tulda	9.9	910	8.6
Dendrocalamus giganteus	10.6	740	8
Dendrocalamus hamiltonii	6.7	590	8.5
Gigantochloa apus	6–7.7	n.a.	54.3
Gigantochloa apus	7.5–7.7	n.a.	15.1
Gigantochloa atroviolacea	6.4–11.3	n.a.	54
Gigantochloa atroviolacea	7.9–9.5	n.a.	15
Gigantochloa atter	5.8–10.8	n.a.	72.3
Gigantochloa atter	9.5–10.8	n.a.	14.4
Gigantochloa macrostachya	9.6	960	8.1
Guadua angustifolia	4–5	n.a.	n.a.
Guadua angustifolia	16.7	n.a.	n.a.
Phyllostachys bambusoides	8.7	730	8
Phyllostachys edulis	8.9–12.5	n.a.	12.5
Phyllostachys edulis	8.9	n.a.	Green

Source: Bamboo Import Europe (2016b).

The compressive strength test results presented in this table are obtained from experiments conducted on selected bamboo species by different researchers. This table also shows some values obtained for moisture content, density and modulus of elasticity of selected species, factors that impact the bending strength of the material. For some species different test conditions were applied. Not all tests were guided by the ISO standard for determining mechanical properties of bamboo. The values shown in the table are average values

Table A4 The bending strength of selected bamboo species

Bamboo species	Bending strength (N/mm2)	Modulus of elasticity (N/mm2)	Density (kg/m3)	Moisture content (per cent)
Bambusa balcooa	62.4 –85	7,200–10,300	n.a.	Green
Bambusa balcooa	69.6–92.6	9,300 –12,700	n.a.	Air dry
Bambusa balcooa	151	13,603	820	8.5
Bambusa bambos	143	14,116	710	9.5
Bambusa nutans	52.9	6,700	n.a.	88.3
Bambusa nutans	52.4	10,700	n.a.	14
Bambusa nutans	56 –79	8,800 –10,000	n.a.	Green
Bambusa nutans	76–100	9,300–16,000	n.a.	Air dry
Bambusa nutans	216	20,890	890	8
Bambusa pervariabilis	37	16,400	n.a.	> 20
Bambusa pervariabilis	80	22 ,000	n.a.	< 5
Bambusa polymorpha	28.3	3,100	n.a.	95.1
Bambusa polymorpha	35.5	4,100	n.a.	13.9
Bambusa spinosa	55.4	n.a	n.a.	Air dry
Bambusa spinosa	55	10,300	n.a.	Air dry
Bambusa tulda	51.1	800	n.a.	73.6
Bambusa tulda	66.7	1,000	n.a.	11.9
Bambusa tulda	194	18,611	910	8.6
Dendrocalamus giganteus	193	16,373	740	8
Dendrocalamus hamiltonii	89	9,629	590	8.5
Dendrocalamus membranaceus	26.3	2,400	n.a.	102
Dendrocalamus membranaceus	37.8	3,700	n.a.	7
Dendrocalamus strictus	68	12,000	n.a.	Green
Dendrocalamus strictus	107	15,600	n.a.	Air dry
Dendrocalamus strictus	92–97	13,700–16,000	n.a.	12
Dendrocalamus strictus	105	13,200	n.a.	61
Dendrocalamus strictus	98.5	13,600	n.a.	55
Gigantochloa apus	102	n.a.	n.a.	54.3
Gigantochloa apus	87.5	n.a.	n.a.	15.1

Bamboo species	Bending strength (N/mm2)	Modulus of elasticity (N/mm2)	Density (kg/m3)	Moisture content (per cent)
Gigantochloa atroviolacea	92.3	n.a.	n.a.	54
Gigantochloa atroviolacea	94.1	n.a.	n.a.	15
Gigantochloa atter	87.9–108.1	n.a.	n.a.	72.3
Gigantochloa atter	117.7–127.7	n.a.	n.a.	14.4
Gigantochloa macrostachya	154	14,226	960	8
Guadua angustifolia	53.5	7,400	n.a.	n.a.
Gigantochloa macrostachya	144.8	17,600	n.a.	n.a.
Gigantochloa macrostachya	74–100	17,900	n.a.	15
Gigantochloa macrostachya	46	11,800	n.a.	n.a.
Gigantochloa macrostachya	82	12,500	600	12.6
Gigantochloa macrostachya	72.6	17,608	640	11.4
Melocanna baccifera	57.6	12,900	n.a.	12.8
Phyllostachys edulis	55	9,600	n.a.	> 30
Phyllostachys edulis	51	13,200	n.a.	< 5
Phyllostachys edulis	83	8,400	530	10.3
Thyrsostachys oliveri	61.9	9,700	n.a.	53
Thyrsostachys oliveri	90	12,200	n.a.	7.8

Source: Bamboo Import Europe (2016b).

The compressive strength test results presented in this table are obtained from experiments conducted on selected bamboo species by different researchers. This table also shows some values obtained for moisture content, density and modulus of elasticity of selected species, factors that impact the bending strength of the material. For some species different test conditions were applied. Not all tests were guided by the ISO standard for determining mechanical properties of bamboo. The values shown in the table are average values.

Table A5 Compressive strength of selected bamboo species

Species	Compressive strength (N/mm2)	Modulus of elasticity (N/mm2)	Density (kg/m3)	Moisture content (per cent)
Bambusa balcooa	39.4 - 50.6	n.a.	n.a.	Green
Bambusa balcooa	51 - 57.3	n.a.	n.a.	Air dry
Bambusa balcooa	69	n.a.	820	8.5
Bambusa bambos	61	n.a.	710	9.5
Bambusa bambos	39.1 - 47	n.a.	n.a.	n.a.
Bambusa nutans	75	n.a.	890	8
Bambusa nutans	85	n.a.	n.a.	12
Bambusa nutans	44.7	n.a.	n.a.	88.3
Bambusa nutans	47.9	n.a.	n.a.	14
Bambusa pervariabilis	45.8	15,200	n.a.	-
Bambusa pervariabilis	79	10,300	n.a.	< 5
Bambusa pervariabilis	35	6,800	n.a.	> 20
Bambusa polymorpha	32.1	n.a.	n.a.	95.1
Bambusa spinosa	57	n.a.	n.a.	-
Bambusa tulda	40.7	n.a.	n.a.	73.6
Bambusa tulda	68	n.a.	n.a.	11.9
Bambusa tulda	79	n.a.	910	8.6
Dendrocalamus giganteus	70	n.a.	740	8
Dendrocalamus hamiltonii	70	n.a.	590	8.5
Dendrocalamus membranaceus	40.5	n.a.	n.a.	102
Gigantochloa apus	21.7 - 26.5	n.a.	n.a.	54.3
Gigantochloa apus	27.3 - 48.6	n.a.	n.a.	15.1
Gigantochloa atroviolacea	23.8	n.a.	n.a.	54
Gigantochloa atroviolacea	35.7	n.a.	n.a.	15
Gigantochloa atter	24.8 - 28	n.a.	n.a.	72.3
Gigantochloa atter	31 - 32.9	n.a.	n.a.	14.4
Gigantochloa macrostachya	71	n.a.	960	8
Guadua angustifolia	42	27,000	n.a.	n.a.
Guadua angustifolia	62 - 93	n.a.	n.a.	n.a.
Guadua angustifolia	56	18,400	n.a.	15
Guadua angustifolia	63.3	15,190	n.a.	n.a.
Guadua angustifolia	28	15,000	n.a.	n.a.
Guadua angustifolia	56.2	17,860	n.a.	n.a.

Species	Compressive strength (N/mm2)	Modulus of elasticity (N/mm2)	Density (kg/m3)	Moisture content (per cent)
Guadua angustifolia	38	14,500	n.a.	n.a.
Melocanna baccifera	69.9	n.a.	n.a.	12.8
Phyllostachys babesiosis	51	n.a.	n.a.	n.a.
Phyllostachys babesiosis	63	n.a.	730	8
Phyllostachys babesiosis	44	n.a.	n.a.	64
Phyllostachys babesiosis	40	n.a.	n.a.	61
Phyllostachys babesiosis	71	n.a.	n.a.	9
Phyllostachys babesiosis	74	n.a.	n.a.	9
Phyllostachys babesiosis	54	n.a.	n.a.	12
Phyllostachys edulis	44.6	11,300	n.a.	- n.a.
Phyllostachys edulis	67	n.a.	n.a.	50–99
Phyllostachys edulis	71	n.a.	n.a.	14–7
Phyllostachys edulis	108	n.a.	n.a.	44,017
Phyllostachys edulis	147	n.a.	n.a.	0.1–0.3
Phyllostachys edulis	117	9,400	n.a.	< 5
Phyllostachys edulis	44	6,400	n.a.	> 30
Phyllostachys edulis	60.3	n.a.	603	12.5
Phyllostachys praecox	79.3	n.a.	827	28.5
Thyrsostachys oliveri	46.9	n.a.	n.a.	53

Source: Bamboo Import Europe (2016b).

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Table A6 Mechanical properties of selected wood species

Selected wood species	Density (Kg/m3)	Modulus of elasticity (N/mm2)	Compressive strength parallel to grain (N/mm2)	Shear strength parallel to grain (N/mm2)
Ash - Black, Blue, Green, Oregon, White	490–600	9.4–12	41.2–51.1	10.8–14
Baswood, American	370	10.1	32.6	6.9
Beech, American	640	11.9	50.3	13.9
Birch – Paper, Sweet, Yellow	550–620	11–15	39.2–58.9	8.3–15.4
Butternut	380	8.1	36.2	8.1
Cedar – Atlantic White, Eastern Red, Incence, Northern White, Port-Orford, Western Red, Yellow	310–470	5.5–11.7	27.3–43.5	5.5–9.4
Cherry, black	500	10.3	49	11.7
Chestnut, American	430	8.5	36.7	7.4
Cottonwood – Balam Poplar, Black, Eastern	310–400	7.6–9.4	27.7–33.9	5.4–7.2
Douglas-fir – Coast, Interior West, Interior North, Interior South	460–500	10.3–13.4	43.1–51.2	7.8–10.4
Elm, English	560	11.8	17–32	8-11.3
Fir	320–430	8.9–11.9	33.5–44.2	6.2–8.4
Hackberry	530	8.2	37.5	11
Hemlock – Eastern, Mountain, Western	400–450	8.3–11.3	37.3–49	7.3–10.6
Hickory, pecan – Bitternut, Nutmeg, Pecan, Water	600–660	11.7–13.9	47.6–62.3	14.3
Hickory, true – Mockernut, Pignut, Shagbark, Shellbark	690–720	14.9–15.6	55.2–63.5	12 –16.8
Honeylocust	n.a.	11.2	51.7	15.5
Larch, Western	520	12.9	52.5	
Locust, black	690	14.1	70.2	17.1
Magnolia – Cucumbertree, Southern	480–500	9.7–12.5	37.6–43.5	9.2–10.5
Mahogany	545	8.7	45	6
Maple – Bigleaf, Black, Red, Silver, Sugar	480 –630	7.9–12.6	36–54	11. –16.1
Oak, red – Black, Cherrybark, laurel, Northern Red, Pin, Scarlet, Southern Red, Water, Willow	590–690	10.3–13.1	42 –60.3	9.6–14.3
Oak, white – Bur, Chestnut, Live, Overcup, Post, Swamp Chestnut, Swamp White, White	640–880	7.1–13.7	41.8–61.4	10.3–13.8
Pine – Eastern White, Jack, Loblolly, Lodgepole, Longleaf, Pitch	350–590	8.5–13.7	33.1–49.2	6.1–10.4
Poplar, Yellow	420	10.9	38.2	8.2
Sassafras	460	7.7	32.8	8.5
Spruce – Black, Engelmann, Red, Sitka, White, Norway	350–430	7.9–11	37–44	6.8–9.2
Sycamore, American	490	9.8	37.1	10.1
Tupelo – lack, Water	500	8.3–8.7	38.1–40.8	9.2–11
Walnut, black	550	11.6	52.3	9.4
Willow, black	390	7	28.3	8.6

Source: The Engineering ToolBox, https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html (accessed 6 December 2021).

Table A7 **Bamboo used primarily for plaiting, exports, 2017–2020**
(U.S. dollars)

Country	2017	2018	2019	2020
China	74,848,173	65,616,177	60,764,827	66,905,469
Viet Nam	n.a.	1,486,511	6,922,825	13,395,309
Indonesia	1,628,720	1,443,110	1,390,726	2,370,382
Thailand	1,752,047	3,329,992	3,039,260	2,291,687
Denmark	1,325,457	1,235,763	740,808	2,204,540
Netherlands	4,080,318	2,835,528	3,244,986	1,832,001
Poland	512,838	1,023,872	1,464,311	1,623,200
Germany	1,193,335	1,139,428	1,011,886	1,176,387
Spain	1,332,112	1,248,110	1,071,235	889,221
Other Asia, nes	1,020,052	1,388,261	1,060,017	887,048
Pakistan	1,318,437	1,222,835	1,194,636	824,114
Austria	342,245	442,427	587,911	790,606
Italy	902,489	84,1971	1,036,253	657,832
United States	519,686	458,943	454,076	598,841
India	254,854	886,091	389,810	519,335
Myanmar	547,956	515,513	565,931	502,171
Belgium	183,311	442,119	298,915	411,455
United Kingdom	122,890	184,770	165,519	353,821
Colombia	231,724	377,344	356,527	307,810
Portugal	949,023	1,080,671	723,551	276,822
Sweden	179,407	241,494	212,241	214,177
Hong Kong Province of China	1,199,066	183,878	211,491	158,724
Hungary	28,140	44,810	58,328	144,888
France	296,668	138,070	158,545	133,413
Japan	157,779	85,408	70,235	72,518
Norway	n.a.	n.a.	n.a.	64,604
Canada	18,174	16,658	66,246	57,069
Philippines	n.a.	n.a.	4,866	44,761
Czech Republic	69,378	67,255	88,582	32,775
Turkey	13,213	15,820	44,972	23,064

Source: United Nations Comtrade, Harmonized System Code 140110, 2017.

Note: nes: not elsewhere specified.

Table A8 Bamboo primarily for plaiting, imports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
India	28,683,372	30,739,709	46,744,102	83,992,202
United States	23,578,461	22,183,916	19,952,067	20,361,010
Netherlands	16,404,803	17,813,385	16,285,293	16,444,121
Italy	8,186,937	7,563,915	6,995,020	7,099,478
Spain	10,667,347	10,517,322	8,264,120	6,987,771
Poland	5,242,335	6,751,467	4,842,790	6,185,477
United Kingdom	4,434,365	4,830,134	5,989,596	6,018,285
France	4,623,175	4,352,492	4,084,571	4,960,173
Hong Kong, Province of China	6,027,850	6,097,332	5,174,800	4,543,093
Japan	5,137,927	5,305,601	4,578,585	4,260,374
Germany	3,614,425	3,547,719	3,659,656	3,942,898
Republic of Korea	3,845,625	3,213,033	2,778,120	2,764,805
Portugal	5,607,868	5,022,209	3,223,020	2,224,932
Australia	1,975,928	1,915,648	2,014,708	2,204,105
Canada	1,855,461	1,611,471	1,821,596	2,112,600
China	965,743	842,036	1,619,885	1,846,321
Belgium	1,308,813	1,370,455	1,394,737	1,603,239
Malaysia	929,889	1,371,064	1,060,033	1,527,671
Turkey	1,286,708	1,225,738	936,570	1,321,657
Indonesia	890,293	1,040,572	1,459,617	1,057,532
Pakistan	1,418,382	808,647	1,298,139	1,004,907
Israel	832,000	999,000	1,015,000	995,000
Switzerland	631,422	565,466	692,912	880,280
Denmark	583,864	940,321	787,784	733,970
Austria	512,094	650,778	590,606	733,115
Other Asia, nes	963,181	869,062	784,895	673,605
Czech Republic	359,407	485,641	460,184	606,965
Norway	657,330	561,412	450,599	552,716
Sweden	337,686	359,414	416,566	480,034
Brazil	320,925	296,848	366,123	473,527

Source: United Nations Comtrade, Harmonized System Code 140110, 2017.

Note: nes: not elsewhere specified.

Table A9 Wood made of bamboo (including unassembled strips and friezes for parquet flooring, continuously shaped along any edges, ends or faces, whether or not planed, sanded or end-jointed), exports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
China	212,700,643	151,269,639	100,245,459	88,351,441
United States	1,452,258	733,549	761,085	2,417,150
Netherlands	1,594,637	1,823,665	1,307,557	1,187,380
United Kingdom	1,264,474	933,563	1,075,480	1,164,358
Serbia	997,525	1,182,378	1,140,746	1,004,870
Slovenia	530,005	869,079	927,593	982,024
South Africa	1,571,909	1,203,779	1,096,701	649,052
Germany	474,103	1,040,175	1,006,962	481,357
France	89,998	115,435	105,177	371,603
India	352,285	373,975	252,364	288,337
Denmark	373,467	222,935	193,567	251,932
Australia	223,032	172,219	471,305	161,126
Spain	136,238	54,142	140,634	140,608
Italy	760,289	399,577	349,298	133,883
Pakistan	5,824	44,065	16,939	101,488
Other Asia, nes	n.a.	n.a.	3,818	99,790
Poland	227,903	164,155	108,889	92,434
Georgia	23,429	65,702	98,673	74,977
Canada	26,274	43,397	111,023	59,566
Sweden	81,442	36,834	63,767	55,043
Japan	3,210	3,913	47,321	48,874
Belgium	3,245	36,785	126,143	42,799
Austria	72,143	37,802	19,561	28,220
Thailand	50,740	44,286	186,401	25,648
Malaysia	199,523	18,029	25,053	17,718
Singapore	n.a.	6,519	11,467	10,459
Lebanon	n.a.	4,577	n.a	8,687
Slovakia	40,348	35,548	23,246	4,631
Bosnia Herzegovina	525	817	n.a.	3,443
Indonesia	27,122	n.a.	n.a.	3,376

Source: United Nations Comtrade, Harmonized System Code 440921, 2017.

Note: nes: not elsewhere specified.

Table A10 Wood made of bamboo (including unassembled strips and friezes for parquet flooring), continuously shaped along any edges, ends or faces, whether or not planed, sanded or end-jointed), imports, 2017–2020

(U.S. dollars)

Country	2017	2018	2019	2020
France	5,746,164	7,659,687	5,116,000	7,800,036
Malaysia	8,730,111	12,422,598	8,745,268	7,396,025
United Kingdom	4,950,296	3,304,851	3,362,443	4,361,298
Australia	9,841,530	7,586,166	3,886,532	3,489,371
Germany	3,127,945	3,161,481	4,024,221	2,883,270
Botswana	n.a.	1,904,197	1,952,831	2,153,125
Denmark	1,732,522	1,022,326	2,636,130	1,267,469
Netherlands	1,702,599	1,582,143	1,126,059	1,253,264
Belgium	2,209,939	1,998,937	1,921,319	1,244,160
Canada	1,338,926	1,899,675	1,471,738	1,230,554
Republic of Korea	2,051,650	1,745,881	1,861,138	1,224,600
United States	1,880,685	2,015,940	903,096	1,219,204
Japan	1,272,392	1,586,611	1,660,671	1,143,239
Sri Lanka	1,480,325	n.a.	1,241,520	1,028,640
Portugal	475,180	554,216	692,622	1,023,911
Poland	2,108,124	1,152,210	1,320,708	999,955
India	799,447	851,032	654,416	992,267
Italy	1,104,959	752,758	670,506	961,368
Israel	2,636,000	1,829,000	1,714,000	885,000
Norway	763,726	432,087	548,476	770,102
Spain	458,485	292,766	621,301	649,883
Croatia	536,919	624,471	686,064	550,892
South Africa	1,245,244	1,401,097	1,277,340	541,826
Azerbaijan	n.a.	575,187	629,940	527,712
Hong Kong Province of China	98,669	684,630	180,534	478,888
Austria	184,119	301,508	516,677	475,917
Viet Nam	n.a.	2,532,311	185,294	448,810
Other Asia, nes	601,844	348,321	234,533	411,169
Switzerland	613,125	694,111	351,205	396,312
Philippines	n.a.	n.a.	476,044	317,010

Source: United Nations Comtrade, Harmonized System Code 440921, 2017.

Note: nes: not elsewhere specified.

Table A11 Plywood, veneer panels and similar laminated wood of bamboo, exports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
China	101,388,954	122,848,151	88,666,682	71,645,304
United States	12,625,791	17,001,011	14,837,356	5,930,726
Netherlands	2,472,403	2,076,863	1,803,287	2,436,320
Spain	3,032,162	2,620,862	2,468,890	1,448,598
Germany	515,309	732,633	1,023,909	1,214,090
Uganda	n.a.	534,607	n.a.	1,017,799
United Kingdom	1,551,090	1,290,764	1,483,599	758,423
Portugal	2,334,779	3,366,886	2,020,419	494,813
Indonesia	65,124	490,359	402,204	355,457
Singapore	n.a.	1,005,544	509,324	348,730
Canada	123,909	166,074	393,288	339,908
Italy	653,688	138,104	80,533	327,248
New Zealand	329,287	137,664	285,816	267,852
Viet Nam	n.a	297,409	304,460	191,842
Belgium	1,154,277	1,608,078	167,452	169,075
Sri Lanka	23,798	n.a.	143,055	147,279
Republic of Korea	80,580	105,134	65,241	71,055
Colombia	n.a.	n.a.	n.a.	68,886
Turkey	3,048	14,052	39,562	63,266
India	187,324	108,597	137,287	54,052
South Africa	102,239	170,974	93,522	49,538
Australia	295,452	51,932	195,072	48,780
Philippines	n.a.	n.a.	100	44,855
Czech Republic	330,217	132,830	81,264	44,810
France	75,330	228,801	64,120	41,532
Poland	34,117	3,607	28,243	38,883
Thailand	133,067	36,764	684,395	37,853
Kuwait	590	n.a.	69,903	37,697
Denmark	35,508	287,452	48,893	28,649
Guatemala	30,145	11,329	29	2,6531

Source: United Nations Comtrade, Harmonized System Code 441210, 2017.

Table A12 Plywood, veneer panels and similar laminated wood of bamboo, imports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
United States	68,385,239	74,414,428	46,620,487	40,214,205
Netherlands	34,537,932	25,550,596	15,543,123	11,042,357
Singapore	n.a.	18,096,638	16,582,924	10,264,319
Canada	5,776,460	3,913,492	2,893,233	4,248,589
Japan	4,915,054	4,357,066	4,070,599	4,019,718
Germany	2,427,744	3,421,726	3,089,899	2,975,195
Portugal	1,537,968	1,804,677	1,338,794	2,266,546
Hong Kong Province of China	1,952,312	1,552,737	1,955,723	2,256,731
New Zealand	1,306,762	2,495,016	1,946,782	2,134,877
Indonesia	488,531	1,067,448	362,851	21,247,97
Republic of Korea	1,116,730	986,623	1,241,923	1,904,814
Ireland	1,447,563	1,970,174	1,911,639	1,830,530
Qatar	n.a.	n.a.	n.a.	1,499,996
Australia	2,090,384	1,622,062	1,595,362	1,285,210
Kenya	n.a.	n.a.	918,577	1,223,300
Belgium	1,694,525	1,474,167	1,018,273	1,106,034
France	2,446,487	2,494,935	1,774,383	1,105,839
United Kingdom	1,321,098	2,096,007	1,235,789	1,087,037
Thailand	2,257,019	1,967,349	1,600,658	1,035,577
Philippines	n.a.	n.a.	1,252,899	959,315
China	6,285,220	2,395,009	1,487,507	759,811
Spain	316,292	321,658	488,689	715,078
Hungary	36,389	58,666	1,028,695	680,507
Sweden	415,749	1,117,832	320,354	504,123
Viet Nam	n.a.	219,503	1,773,949	487,750
Denmark	291,014	573,994	506,700	426,202
Lithuania	138,321	351,837	1,162,436	399,060
Italy	1,631,282	1,127,117	710,480	397,419
Brazil	164,415	349,804	241785	310,152
Kuwait	1,468,362	1,089,858	708,524	307,990

Source: United Nations Comtrade, Harmonized System Code 441210, 2017.

Table A13 Assembled flooring panels of bamboo or with at least a top layer (wear layer) of bamboo, exports, 2020
(U.S. dollars)

Country	2017	2018	2019	2020
China	59,689,458	30,009,619	27,057,928	28,024,881
Netherlands	12,673,487	14,471,538	11,032,475	10,875,476
Ukraine	n.a.	n.a.	n.a.	6,934,764
Italy	5,767,450	4,960,271	5,355,521	2,843,538
Canada	1,642,661	1,243,281	220,781	559,277
United States	413,285	815,352	1,319,189	460,362
Slovenia	300,935	78,716	76,003	325,054
United Kingdom	1,871,942	962,472	256,283	324,128
Viet Nam	n.a.	7,532,381	2,014,410	297,924
Germany	718,229	592,992	291,305	190,486
France	238,722	497,685	855,907	179,144
Romania	482,849	406,237	228,710	177,779
Sweden	920,415	561,822	1,006,028	136,043
Croatia	309,950	407,324	120,027	124,003
Spain	1,419,210	165,611	33,110	121,263
Belgium	814,650	84,877	15,941	75,422
Thailand	154,484	171,603	69,350	63,785
Hungary	53,416	4,500	n.a.	47,838
Turkey	591,862	23,596	67,326	41,528
Philippines	n.a.	n.a.	8,194	41,167
Portugal	9,656	164,600	151,861	36,252
Australia	11,981	65,084	16,044	29,499
Denmark	3,396,927	346,834	362,415	27,365
Czech Republic	20,436	18,547	55,634	26,901
Austria	341,760	280,676	12,891	22,576
Malaysia	1,900,706	62,051	232,398	20,737
Greece	n.a.	n.a.	n.a.	16,853
Israel	n.a.	n.a.	n.a.	16,000
Latvia	32,979	19,127	28,507	12,760

Source: United Nations Comtrade, Harmonized System Code 441873, 2017.

Table A14 Assembled flooring panels of bamboo or with at least a top layer (wear layer) of bamboo, imports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
United States	45,001,813	29,882,858	19,290,555	17,555,600
United Kingdom	29,609,989	23,540,675	25,313,378	6,992,586
Denmark	1,8545,068	10,387,575	12,945,757	6,667,946
Netherlands	13,173,367	6,707,452	2,992,875	5,065,172
New Zealand	4,028,385	4,793,598	4,698,230	2,665,795
France	5,046,194	2,909,344	2,264,196	2,492,526
Belgium	1,515,154	1,154,703	824,608	1,994,686
Australia	8,543,545	8,852,421	4,722,766	1,985,629
Germany	3,494,109	2,442,181	1,748,926	1,963,998
Slovenia	1,767,771	3,316,740	1,991,713	1,956,473
Japan	679,326	1,763,326	1,540,454	909,655
Iceland	775,509	814,921	794,625	881,205
Sweden	4,238,141	2,237,402	1,566,826	668,164
Viet Nam	n.a.	344 942	397,178	652,966
Italy	2,109,092	5,283,584	986,138	623,826
Switzerland	1,179,804	446,056	1,577,589	579,175
Spain	1,272,616	1,456,443	992,428	528,828
Philippines	n.a.	n.a.	1,263,127	522,552
Other Asia, nes	79,895	185,382	62,330	419,026
Israel	175,000	484,000	485,000	395,000
Portugal	52,910	88,356	355,823	356,411
Finland	1,429,576	849,084	404,499	342,838
Mauritius	7,081	13,134	n.a.	338,148
Peru	308,938	633,869	456,378	337,944
Cambodia	50,460	84,858	177,102	316,589
Romania	577,973	338,930	186,880	299,227
Ireland	3,594	480	118,918	284,005
Ukraine	n.a.	n.a.	n.a.	281,724
Poland	665,770	667,721	n.a.	262,291
Ecuador	n.a.	14,481	537,740	227,362

Source: United Nations Comtrade, Harmonized System Code 441873, 2017.

Note: nes: not elsewhere specified.

Table A15 Builders joinery and carpentry of wood products made of bamboo, exports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
Philippines	n.a.	n.a.	138,937,815	113,506,578
Latvia	13,512,249	17,476,877	16,143,602	17,419,386
Canada	57,096,932	49,162,098	17,482,203	9,388,683
United States	4,508,046	2,553,278	4,356,105	9,206,862
Netherlands	71,709,71	15,459,365	11,771,829	6,743,198
China	447,119	300,835	542,556	5,295,797
Portugal	2,014,928	3,435,722	1,748,604	1,303,664
Sweden	2,444,869	2,032,347	1,265,867	945,462
United Kingdom	1,571,178	1,804,312	3,007,344	669,930
France	503,329	785,833	880,694	579,052
United Arab Emirates	282,660	956,766	337,337	559,768
Estonia	129,792	431,219	2,079,740	534,677
Denmark	1,054,788	591,478	357,476	278,886
Viet Nam	n.a.	1,850	66,347	207,188
South Africa	247,876	307,999	194,892	171,454
Italy	341,799	144,452	220,329	167,922
Belgium	92,889	70,648	140,720	165,518
Russian Federation	1,823,530	268,963	341,247	147,592
Lithuania	217,438	207,836	147,345	140,811
India	n.a.	119	1,824	113,956
Romania	n.a.	15,005	4,312	62,114
Czech Republic	278,771	29,652	15,000	43,084
Australia	149,149	12,308	55,078	39,413
Germany	63,692	54,359	67,161	37,298
Hungary	10,689	7,122	833	25,151
Norway	165,569	103,605	3,186	23,387
Colombia	n.a.	1,200	n.a.	19,055
Slovakia	284,737	5,008	7,066	14,692
Spain	22,108	12,973	17,871	13,962
Turkey	45,234	77,993	545	13,552

Source: United Nations Comtrade, Harmonized System Code 441891, 2017.

Table A16 Builders' joinery and carpentry of wood products made of bamboo, imports, 2017–2020
(U.S. dollars)

Country	2017	2018	2019	2020
United States	249,680,356	192,949,415	93,126,173	55,991,831
Netherlands	15,673,156	34,747,535	30,947,884	39,480,216
France	44,903,600	36,461,070	35,038,807	37,671,372
Norway	2,013,182	2,485,054	2,896,119	2,847,099
Denmark	3,152,665	1,307,494	1,524,953	2,508,244
Slovakia	1,637,914	1,724,592	1,223,440	1,678,658
United Kingdom	6,276,837	1,937,548	1,480,219	1,325,625
Australia	2,208,364	1,305,939	763,669	1,305,120
Portugal	2,434,224	2,066,053	1,205,304	1,224,955
Spain	1,124,790	492,016	633,069	1,149,440
Finland	2,388,776	1,702,126	1,680,146	1,093,314
Canada	4,600,909	1,749,548	1,483,159	1,036,486
Estonia	1,953,762	1,444,547	1,553,731	1,025,785
Philippines	n.a.	n.a.	977,614	1,013,883
Hungary	1,984,916	1,338,922	1,266,654	997,479
Israel	157,000	29,000	79,000	714,000
Ireland	228,360	28,414	420,605	564,100
Belgium	2,314,816	1,649,762	1,014,566	562,192
United Arab Emirates	1,270,784	1,625,014	1,610,647	517,185
Czech Republic	2,020,897	1,509,664	1,815,530	489,901
Switzerland	873,721	326,925	343,336	468,093
Romania	1,438,384	2,009,204	1,470,139	434,030
Peru	79,312	217,942	209,029	384,040
Italy	3,162,871	555,160	433,897	334,252
Luxembourg	1,316,885	745,280	567,119	308,130
Indonesia	393	n.a.	20,549	276,920
Poland	374,424	59,458	n.a.	269,915
Botswana	n.a.	201,623	421,220	261,748
Sweden	2,306,173	1,194,141	73,205	248,743
Azerbaijan	n.a.	172,559	218,364	237,490

Source: United Nations Comtrade, Harmonized System Code 441891, 2017.

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