Properties and Importance of Various Bamboo Species for Multi-Utility Applications

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Contents

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Abstract

Bamboo, with the potential to grow on wasteland, has emerged as the most appropriate alternative to wood. Low weight to height ratio, high growth rate, tensile strength comparable to materials like steel, and ability to grow on wasteland as well make it a most sought-after material. Bamboo fascinates people by its vivid color and fine particle structure. Easy availability, rapid growing speed, and ability to sustain in wastelands make it most desirable material for building and construction industry. The usage of bamboo varies from household products, handicrafts, and laminated panels to pulp and papermaking industries. Bamboo is available in 90 genera with about 1200 species. The major constituents of bamboo culms are cellulose, hemicelluloses, and lignin (about 90% of the total mass) with resins, tannins, and waxes as the minor amount. Trace amount of inorganic salt is also found in it. Mechanical properties and durability of these species depend on their chemical composition. This chapter presents the information regarding the economic and ecological importance of bamboo species. This chapter tries to assimilate the knowledge about the constituents of various bamboo species available across the globe. In addition to this, factors that affect the quality of bamboo culms in service life are also discussed. Biotic factors include the resistance of culms to various microorganisms and insects attacking the culms alone or in succession. Non-biotic factors like rain, moisture, and weathering are also described here. Knowledge about basic features and properties of these species is required to formulate the strategies for specific uses of these species making it a more valuable product. Livelihood opportunities in the field of bamboo products from Indian perspective are explored. Challenges to wider application of bamboo along with future potential are also discussed here.

Keywords

Bamboo · Constituents · Durability · Bamboo applications · Utilization potential · Rural development

Abbreviations

AC Ash content
C Carbon
CC Cellulose content
LC Lignin content

1 Introduction

Continuous increase in human population coupled with modern lifestyle has generated huge demand for wood and wood-based products in service sector causing severe deforestation. Hence, for achieving sustainable development, non-woody forest products have to be given due attention. Bamboo a unique creation of nature assumes great significance in this context with several environmental benefits. The hollow internal structure makes it lightweight and easy to work with and transport.

Bamboo is a grass belonging to Gramineae family, found in tropical, subtropical, and mild temperate zones (46° north – 47° south latitude). Bamboo exists in about 90 genera divided into about 1200 species (Lobovikov et al. 2005). High growth rate and easy availability make it superior in properties than wood species (Yang et al. 2008).

Most of the properties of bamboo depend on following factors:

- Bamboo species with different age are known to possess different physical as well as chemical properties. As bamboo culm ages, fiber length varies, thus affecting the overall characteristics of the culm (Li et al. 2007; Wang et al. 2016).
- Liese and Kumar (2003) reported that the harvesting time affects durability of bamboo. One week, once moon reaches full moon phase, is known to be related to low capillary water in the bamboo's culms. In addition to this, dry seasons are related to high starch content, and thus greater possibility of microbial attack is there. Rainy seasons are traditionally considered to be ideal time to harvest bamboo species (Kaur et al. 2016d).
- It has been reported in literature that the physicochemical properties grown on different climatic conditions are different. Thus it is essential to know the geographical location of species, where it is grown to know about its specific properties (Kaur et al. 2016c).
- Bamboo culms stored under moist conditions are under ideal conditions for fungi and insects to grow. Traditionally, storing in kitchen over fire place and submerging in running water are considered to be suitable for long-term storage of bamboo species (Liese and Kumar 2003).
- Strength properties of nodal and intermodal sections are reported to be different. The fact is strengthened by studies performed by Ahmad and Kamke (2003), which reported the significant variation of mechanical properties between these two sections. Similarly, Oka et al. (2014) found that the tensile strength parallel to grain varies between nodal and internodal sections. Deng et al. (2016) reported nodal sections are responsible for providing the strength to the culm.
- Strength is known to vary with the height of the culm. While the compressive strength shows a positive correlation with increase in height, the bending strength follows a negative pattern and decreases with height. Literature studies highlight the fact that properties depend on the part of the culm under consideration. It has been found that the shear, compressive, and tensile strength was higher at the top than at the bottom (Oka et al. 2014; Deng et al. 2016; Meena et al. 2016).

Compared to steel, concrete, and timber, less mass of bamboo is able to withstand more loads. The tensile strength of bamboo (28,000 lb./in^2) is much higher than steel (23,000 lb./in^2). It is reported that 50 times less energy is required to generate 1 m^3 per unit stress for bamboo as constructional materials as compared to steel or concrete. This makes bamboo a suitable alternative to steel in load-bearing applications (Rahman et al. 2011). It has been used for household utilities, handicrafts, chairs, etc. (Fig. 1).

Socio-environmental values associated with bamboo make it an alternative material for housing and handicraft, in addition to its wide use in pulp and paper industry. Hollow internal structure of bamboo culms makes it lightweight and easy to work with and transport. Bamboo being easy to split is used in woven industry.

Figure 2 shows the bamboo forests shared by different countries. Asia is the major bamboo-producing continent, with leading countries as India, China, and Indonesia (Lobovikov et al. 2005). In Asia particularly, with large-scale planting of bamboo, the forest area cover has been increased by 10%.

Asia being the biggest grower of bamboo species is the biggest exporter as well. Industrialized bamboo products contributed to 29% and bamboo woven products about 25% to the total share of bamboo export (Fig. 3).

Like wood, the major chemical constituents of bamboo are lignin and cellulose. Although extractives constitute minor proportion of the culm, they significantly affect the pulp making process and cost of bleaching. Bamboo is an extremely diverse plant with around 1200 literature reported the species (Ben-Zhi et al. 2005; Sihag et al. 2015).

Variation of chemical constituents of these species affects the utilization of bamboo resources. Only a few of these species are utilized for specific applications,

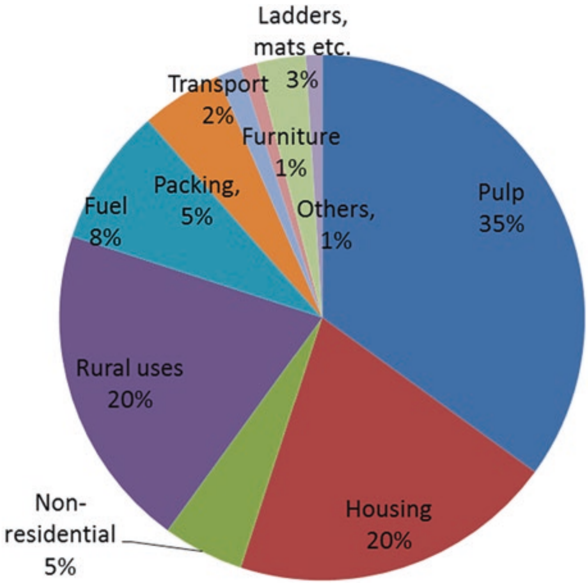

Fig. 1 Different uses of bamboo species. (Adopted: Kaur et al. 2016b)

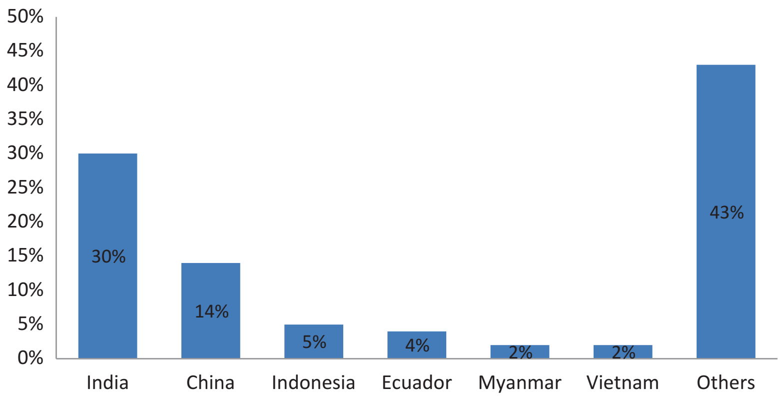

Fig. 2 Worldwide distribution of bamboo. (Adopted: Lobovikov et al. 2005)

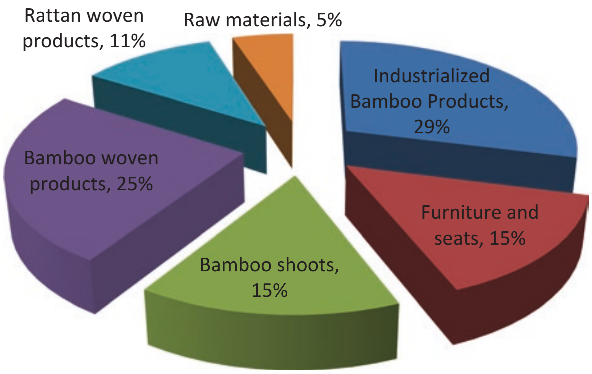

Fig. 3 World trade of bamboo and products. (Adopted: INBAR Report 2012)

while rests of the species are being neglected. Lack of knowledge about total extractive contents and lignocellulosic properties led to their restricted utilization potential. The poor life span of untreated bamboo species (less than 6 months) under field conditions is the greatest hindrance for their wider application (Kaur et al. 2016c, d). Though for timbers, various study documents on specific properties and field of utilization of various species are easy available, the systematic documentation of this information is lacking in literature.

One single parameter is not beneficial to consider a bamboo species for a particular application. For instance, selection of bamboo material requires high physical strength, durability, sustainability, and financial viability. In addition to this low content of water, extractives and starch constituents are desirable factors. Furthermore, pulp and paper industries require species with high CC, long service life with minimum hassles to remove lignin constituents. Species with high lignin content (LC) results in high pulping and bleaching costs. Though high CC is known to be beneficial for pulp making industry as it gives better pulp yield, LC and other extractives are required to be in low amount for the same application.

However, the wide variety of bamboo species give it a significant variation in properties, which affects the quality of finished product. For instance, brightness of pulp and mechanical strength of laminated bamboo boards varies with change in extractive contents. Therefore, the first step toward application of bamboo is the right choice of species for particular application. When it is utilized to produce biomass energy, the effect of various constituents on hydrolysis and fermentation process cannot be ignored. While the chemical constituent of bamboo varies from species to species, there is a significant variation of property in the same species as well. Thus, its evaluation of specific properties is of prime importance, and the effect of geographical location of growth should also be considered.

This chapter aims at the collection of information available in the literature. Ecological importance of bamboo is mentioned here. In review of physicochemical properties, durability of available bamboo species is used to make recommendations for selecting specific species for selected applications (Kaur et al. 2016d). Knowledge gaps in literature have been identified, and future scope for the value addition has been discussed.

2 Ecological Role of Bamboo

Bamboo is a plant, processing of which is simple and requires no special skill and equipment. This leads to low initial investment in bamboo-based industrial ventures. Thus it is a plant with high economic value especially as a furniture and building material. There are numerous ecological benefits as well associated with this plant. Its special properties make it ideal to solve many of the ecological problems facing by the world today such as deforestation, soil erosion, water shortage, landslides, etc. Broad shallow rhizome-root system and its accumulated leaf mulch make it a splendid material to conserve soil and retain moisture, reinforcement of embankments, drainage channels, etc. It is also found to be an excellent source as carbon (C) sink and effective in mitigation of greenhouse effect (Bhalla et al. 2008; Meena and Yadav 2015) (Fig. 4).

2.1 Reduces Deforestation

The high growth rate of bamboo makes it best alternative to wood. Bamboo is considered as fastest-growing, maximum-yielding plant. The high growth rate (30–100 cm daily during the season of growth), which can grow as tall as 36 m and diameter between 1 and 30 cm, makes it a highly renewable resource. The growth rate is so high that it can achieve its full height in a period of only 2 months with low weight and high strength properties (Ribeiro et al. 2017).

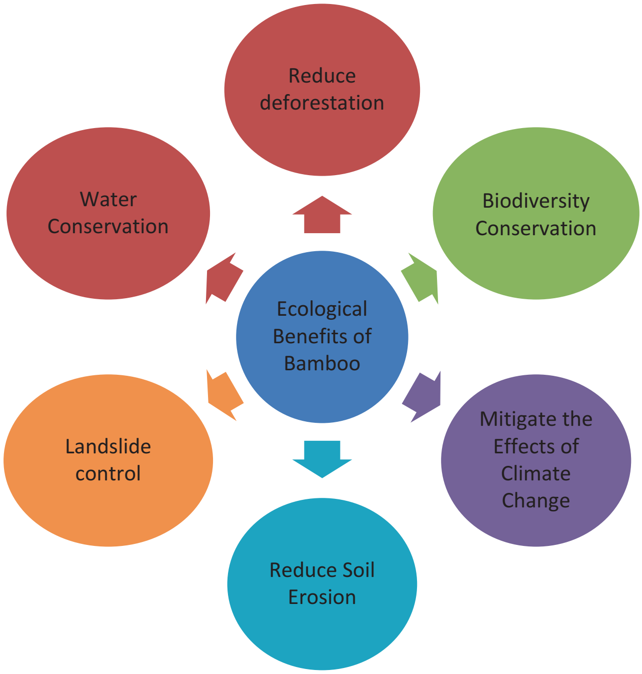

Fig. 4 Ecological benefits of bamboo. (Ben-Zhi et al. 2005)

2.2 Reduces Soil Erosion

Deforestation, overgrazing, tillage, and unsuitable agricultural practices in the past have substantially resulted in degradation in the quality of soil. In the present time, deforestation is a major threat faced by the terrestrial ecosystems, which can lead to loss of soil water holding capacity and thus result in water deficient dry lands (Panagos et al. 2014). It is estimated that the global annual soil erosion rate is 75 billion tonnes (Pg) from arable lands, causing annual loss of US$ 400 billion (FAO report 2017). Bamboo with less maintenance characteristics can grow well on wastelands and steep slopes. The credit of this unique feature of bamboo goes to its extensive fibrous root system and connected rhizome system. It also has leafy mulch and dense foliage, which produces new culms from underground rhizomes. This helps in the harvesting process with minimum disturbance to soil and thus helps in the reduction in soil erosion (Ben-Zhi et al. 2005; Dadhich et al. 2015).

The anti-erodibility of bamboo is reported to be much higher than wood species. For instance, Tardio et al. (2017) performed studies using bamboo plants on the riverbanks to control floods and soil erosion. The case study of Danav Khola River in Nepal involved riverbank protection using bamboo plantation along the shore, which were able to resist the drag of flood water.

2.3 Landslide Control

Landslide is not only a threat to topsoil loss but also dangerous for human and animal life. Bamboo is found to be highly effective in the control of landslide. Usually common bamboo is the most grown on places vulnerable to landslides. The results of studies performed in Japan are very encouraging in this aspect. It was found that *Bambusa multiplex* (hedge bamboo) is able to control erosion for more than 100 years (Shibata et al. 2002).

2.4 Water Conservation

The leafy litter of a plant is related to its ability to retain moisture and prevent soil erosion. The leafy mulch helps to improve the absorption and retention of moisture content more efficiently by reducing the rate of evaporation. Bamboo litter is reported to contain a high water retention capacity. As per literature review, the bamboo plant shed its leaves between the ages of 12 and 18 months to replace it with new leaves. It has been found that a single bamboo strand can hold 5 kg of water, which can strengthen 4 m^2 area of the soil. According to Hui et al. (2003), moso bamboo (*Phyllostachys edulis*) forest (1 ha area) can store up to 4200 tonnes of water before saturation. The relative humidity of bamboo forests is reported to be 5–10% higher than other woody fields during the summer (Xiao 2001).

The bamboo forest is reported to be associated with a higher capacity to conserve water. The studies performed by Wu et al. (1992) elaborated the effect of types of tree grown in a forest the total moisture capacity of forest soil. It was found that when the bamboo forest was mixed with broadleaf, the total moisture capacity of forest soil was very high. Further, it has been reported that pure bamboo forest has the highest non-capillary moisture capacity. It is believed that the high amount of culm stumps, dead rhizomes, and roots of bamboo forest after felling provides this non-capillary pore to absorb sufficient amount of moisture.

2.5 Mitigate the Effects of Climate Change

Bamboo as mentioned above is gifted with rapid growth rate and allows the collection of organic C (Lobovikov et al. 2012). As compared to other plant species, the areal distribution of bamboo is quite high, and it is estimated that it would sequester more C and thereby helps to decrease the severe effects of changing climate (Nath et al. 2015). Moso bamboo forest in China was reported to daily sequester 5.10 Mg ha^{-1} of C, which is 33% and 41% more than a tropical mountain rainforest and *Cunninghamia lanceolata* (Chinese fir) plant species, respectively (Zhou and Jiang 2004; Kuehl et al. 2013).

Because of their environmental benefits, bamboo stands are also known as "natural oxygen bars." A study by Tan et al. (2010) showed that in China, the concentration of negative oxygen ions in bamboo forest is double in amount than an adjacent woody forest. Li et al. (2003) found that rough surface of a bamboo leaf can catch about 4–8 gm^{-2} of dust. It is also found to reduce noise pollution. A reduction in noise levels by 10 to 15 dB was found in a 40-meter-wide land covered with bamboo plants.

2.6 Biodiversity Conservation

The tender shoots and culms of bamboo serve as food for various types of insects, birds, and animals including giant panda (*Ailuropoda melanoleuca*), bears (*Ursus* spp.), and boars (*Sus scrofa*). The presence of starch and other nutrients makes it attractive food for deer and other forest animals (Li et al. 2003). The presence of high bird population of forests of bamboo in China was reported in literature (Li et al. 2003; Song et al. 2011). Similar observations of the presence of variety of bird species were reported in the bamboo forest portion of Chilean forests as well (Reid et al. 2004).

3 Essential Physicochemical Properties of Bamboo

Physical and chemical properties affect seasoning, durability, and utilization potential of the bamboo culm. The bamboo culm consists of nodes, separating the culm into internodal sections. Nodes and internodes are reported to possess no significant variation in chemical composition (Scurlock et al. 2000). The bark of the culm has epidermal cells of waxy layer (cutin). Vascular bundles consist of vessels and sieve tubes.

3.1 Lignocellulosic Content

In bamboo, the broader lamellae consist of the fibrils oriented with very low angle to the axis of fiber. However, the narrow lamellae are known to show a transverse orientation with higher LC. The wall structure of bamboo fiber, which is polylamellate, provides it resistance to tensile forces and thus bestowed it significantly high tensile strength. Natural fibers with competitive specific tensile strength and stiffness are more in demand than glass fiber and synthetic fibers.

Bamboo culms consist mainly of cellulose, hemicellulose, and lignin (approximately 90%). Cellulose is a fundamental material for all plants. Polymers of cellulose (molecular weight 162) are made up of monomer $C_6H_{10}O_5$. The mean degree of polymerization in bamboo is considered as 10,000 (Fig 5).

Chain and layer lattice of cellulose molecules show an isotropic behavior. Cellulose constituents provide mechanical strength to bamboo. Difference in proximate chemical compositions of bamboo and hardwoods is attributed to difference in alkaline components, ash content (AC), as well as silica contents. Mechanical properties and durability of bamboo species depend on chemical composition of species.

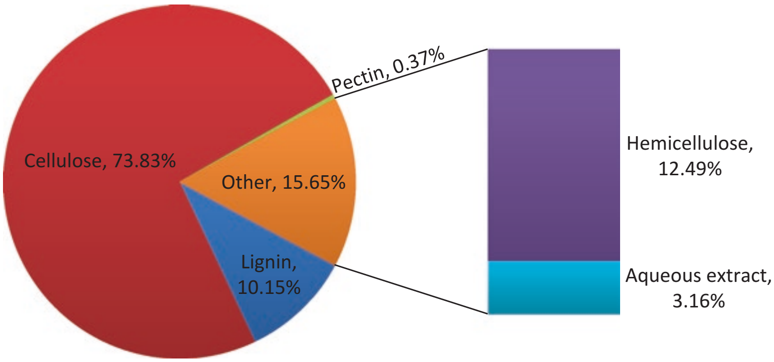

Fig. 5 Constituents of bamboo species. (Wang et al. 2009)

Unlike wood, bamboo lacks rays or knot, beneficial for even distribution of stresses longitudinally (Scurlock et al. 2000).

Chemical extractives of bamboo species are significantly different than wood. Macroscopically graded structure and microscopically graded architecture of fiber distribution provide favorable properties of bamboo.

Literature on chemical constituents of commercially important bamboo species is scanty. Available data of certain bamboo species in this context are compiled in Table 1. The change in geographical conditions and species contributes to difference in properties observed.

3.2 Ash Content

The presence of high amount of silica, calcium, potassium, manganese, and magnesium like inorganic minerals results in high ash content (AC) in bamboo. AC influences the processing of bamboo and has a direct bearing on type and design of processing machinery and tools. AC influences cutting properties, machining operations, and pulp processing properties. Bamboo species investigated in literature were found to have AC between 2.6 and 4.7%. As compared to wood, bamboo is reported to have higher AC. AC of aspen (*Populus* spp.), white oak (*Quercus alba*), and kenaf wood (*Hibiscus*) species contains ash 0.43%, 0.87%, and 1.6–22%, respectively (Ashori 2006). Bamboo species were found to have AC between 3.9 and 5.2%, whereas *Gigantochloa scortechinii* (buluh semantan) species of India contains ash in the range of 1.90– 3.50% (Ganesh 2003). *Bambusa blumeana* (spiny bamboo) species consists of 1.67% AC (Ireana 2010). AC for buluh semantan bamboo, *Gigantochloa levis* (Levis bamboo), *G. brang*, and *G. wrayi* of Malaysia was found to be 2.83%, 1.29%, 1.25%, and 0.88%, respectively (Wahab et al. 2013; Datta et al. 2017). AC was found to be independent of location, nodal and antinodal portions. A positive correlation was found between moisture content and AC. All these studies indicate the range of AC in various bamboo species varied from 0.53 to 4.21%. The lowest AC of *G. wrayi* and *G. brang* makes the processing of bamboo

Table 1 Water, alkali, alcohol-benzene soluble, and AC of various bamboo species

Bamboo species	Ash (%)	Cold-water solubility (%)	Hot-water solubility (%)	Alkali solubility (%)	Alcohol-benzene solubility (%)
Bambusa arundinacea (giant thorny bamboo)	–	9.8 (Kaur et al. 2016a)	11.4 (Kaur et al. 2016a)	27.0 (Kaur et al. 2016a)	3.8[a] (Kaur et al. 2016a)
Bambusa bambos (Indian thorny bamboo)	–	10.0 (Kaur et al. 2016a)	11.2 (Kaur et al. 2016a)	27.4 (Kaur et al. 2016a)	3.6[a] (Kaur et al. 2016a)
Bambusa nutans (Jatia-mokal)	–	7.1 (Kaur et al. 2016a)	8.1 (Kaur et al. 2016a)	28.3 (Kaur et al. 2016a)	4.2[a] (Kaur et al. 2016a)
Bambusa pallida (Jati-banh)	–	11.1 (Kaur et al. 2016)	12.6 (Kaur et al. 2016a)	27.0 (Kaur et al. 2016a)	5.2[a] (Kaur et al. 2016a)
Bambusa tulda (Bengal bamboo)	–	8.1 (Kaur et al. 2016a)	7.8 (Kaur et al. 2016a)	26.1 (Kaur et al. 2016a)	3.2[a] (Kaur et al. 2016a)
Bambusa vulgaris (common bamboo)	4.21 (Subekti et al. 2015)	8.81 (Subekti et al. 2015)	10.22 (Subekti et al. 2015)	23.8 (Subekti et al. 2015)	1.99 (Subekti et al. 2015)
Dendrocalamus asper (solid bamboo)	1.5 (Kamthai 2003); 3.55 (Subekti et al. 2015)	6.4 (Kamthai 2003) 11.34 (Subekti et al. 2015)	9.2 (Kamthai 2003); 9.58 (Subekti et al. 2015)	24.7 (Kamthai 2003; 29.47 (Subekti et al. 2015)	5.5 (Kamthai 2003); 7.49 (Subekti et al. 2015)
Dendrocalamus strictus (male bamboo)	–	6.7 Uttar Pradesh, India; 6.2 Haryana India (Kaur et al. 2016a)	8.4 Uttar Pradesh, India; 8.3 Haryana India (Kaur et al. 2016a)	27.9 Uttar Pradesh, India; 28 Haryana India (Kaur et al. 2016a)	4.2[a] Uttar Pradesh, India; 4.9 Haryana India (Kaur et al. 2016a)
Gigantochloa atter (black bamboo)	1.47 (Subekti et al. 2015)	8.25 (Subekti et al. 2015)	9.63 (Subekti et al. 2015)	24.11 (Subekti et al. 2015)	3.31[a] (Subekti et al. 2015)
Gigantochloa atroviolacea (Java black bamboo)	1.57 (Subekti et al. 2015)	5.91 (Subekti et al. 2015)	7.70 (Subekti et al. 2015)	20.93 (Subekti et al. 2015)	4.51[a] (Subekti et al. 2015)
Gigantochloa apus (string bamboo)	1.57 (Subekti et al. 2015)	7.88	8.18	20.93	3.39[a]
Gigantochloa wrayi	0.53–1.41 (Wahab et al. 2013)	–	–	–	–

(continued)

Table 1 (continued)

Bamboo species	Ash (%)	Cold-water solubility (%)	Hot-water solubility (%)	Alkali solubility (%)	Alcohol-benzene solubility (%)
Pseudosasa amabilis (Tonkin bamboo)	1.38 (Cheng et al. 2015)	–	–	–	–
Pleioblastus chino (Chino bamboo)	1.79 (Cheng et al. 2015)	–	–	–	–

[a]Represents ethanol-toluene solubility

relatively easier. Common bamboo and solid bamboo were found to have relatively higher AC; therefore industrial workers engaged in processing of these bamboo species may encounter problems in processing of the same. Higher AC of these species recommends avoiding the use of these species in industries which require frequent cutting and shaping of the culms.

3.3 Water Solubles

Water solubles are the substances present in cavity cells, fiber cell wall, and cell pores. Cold-water solubility is a measure of the tannins, gums, sugars, and coloring matter in the bamboo. Hot-water solubility provides information about starch content in addition to the above parameters.

Solubility of starch in water at only high temperature makes hot-water-soluble contents higher than cold-water-soluble contents. It is expected that high amount of starch contributes toward higher water-soluble contents. Solid bamboo, *B. pallida*, giant thorny bamboo, and Indian thorny bamboo with higher water solubles may contain higher starch and more vulnerable to degradation (Chew et al. 1992). Cold-water solubility is an indicative parameter for the presence of starch and other sugar components.

Male bamboo species of Uttar Pradesh and Haryana were found to have same cold-water solubility, but hot-water solubility of Haryana species was lower, indicating lower starch content of species in this geographical location (Kaur et al. 2016a). Absorption of water in cement material for production of cement-bonded particle board is affected by chemical content (starch and sugar). The study showed that soaking bamboo chips in water resulted in reduction of its sugar content (less than 0.5%), essential for the manufacture of cement-bonded particle board.

3.4 Alkali Solubility

Solubility in a hot dilute alkali solution (1% solution of NaOH) indicates the extent of decay in a given biomass sample. This includes hemicellulose content and degraded cellulose in biomass sample. Alkali solubility increases in proportion to increase in decay of biomass material. The increased decay results in decreased pulp yield causing severe losses for value-added bamboo products. A few studies are available in literature to evaluate the alkali solubility of bamboo species. Male bamboo species of both Haryana and Uttar Pradesh possessed approximately same alkali solubility. All the bamboo species reported in literature were possessed the alkali solubility between 20.93 and 29.47%. The studies suggest that just after harvesting, the immediate treatment is prerequisite for utilization of bamboo.

Adequate management and efficient storage practices should be followed to avert the degradation of cellulosic material of bamboo caused due to the biotic agents. *G. scortechinii* and Java black bamboo with low alkali solubility are expected to be durable, while solid bamboo and *B. nutans* bamboo species require immediate preservation and treatment.

3.5 Ethanol-Toluene Solubility

The part of material, which is not a part of bamboo's polymeric material, is evaluated using the investigations of the ethanol-toluene extract. Harvesting season and drying affects this constituent of bamboo. Investigation of these extractive contents is highly desirable as they directly affect the quality of pulp produced (Lourenco et al. 2010).

In spite of negative effects associated with higher contents of these extractives on pulp quality and quantity, not much of the studies have been performed to evaluate them. Ethanol-toluene solubility of Indian bamboo species was found in the range of 3.2–5.2%. Solid bamboo was found to possess the highest and lowest alcohol-benzene solubles of 7.49% and 2.5%, respectively (Subekti et al. 2015).

3.6 Starch Content

In general it is believed that the mechanical properties and durability of bamboo species depend on chemical composition of species. Absorption of water in cement material for production of cement-bonded particle board is affected by chemical content (starch and sugar). Starch component in bamboo makes it attractive food for microorganisms like fungi. However investigations performed by Kaur et al. (2016a) on Indian bamboo species revealed no direct correlation between starch content and service life of bamboo culms. Starch content of male bamboo (Uttar Pradesh) was maximum (4.5%), while *B. tulda* (Bihar) has the lowest starch content (1.8%). During decay resistance analysis, all untreated samples exhibited more than 50% of weight loss. *B. tulda* (Bihar) with the lowest starch content (1.8%) was found to be more decayed (weight loss: 57.4%) than male bamboo (Uttar Pradesh) with the highest starch content (4.5%) showing weight loss of 54.3%. *B. pallida* (Karnataka) has 2.8% of starch content, while weight loss by white rot fungi was the maximum for this species.

4 Parameters affecting Physicochemical Properties

The various physicochemical properties of bamboo species vary significantly with change in geographical conditions. Male bamboo species from two different geographical locations was found to have different values of this component solid bamboo species exhibited 5.5% and 7.49% soluble depending on geographical conditions of growth of species (Subekti et al. 2015; Varma et al. 2017).

4.1 Density

Mechanical properties are a function of density. It influences not only shear, compression parallel to grain, but also modulus of elasticity. Decrease in density results in reduced mechanical strength. Bamboo possesses excellent mechanical properties which are correlated with the density. Fiber content and density of bamboo culm varies among different species.

Density is also known to be directly related with tensile strength of species. Scientific investigations on variation of density highlight the variation in property on longitudinal as well as radial basis. Various researches show the variation in density (0.56–0.96 gm/cc) with species was reported in literature (Subekti et al. 2015). Density values of Malaysian bamboo species, common bamboo, *G. scortechinii*, and male bamboo, were reported to be 0.61, 0.63, 0.52–0.67, and 0.65–0.67 gm/cc, respectively (Hamid et al. 2012; Ahmad and Kamke 2003; Hamdan et al. 2009). Solid culm of male bamboo species may provide it more structural strength. This may justify the application of male bamboo species for building and construction industries to bear heavy loads.

4.2 Lignin

Most abundant natural polymer substances present in nature include cellulose, hemicelluloses, and lignin. Plant species like bamboo contains 10–40% of LC on dry weight basis. Lignin is a mononuclear aromatic polymer, often bound to adjacent cellulose fibers to form a lignocellulosic complex, providing strength to the culms. Lignin composed of three units, hydroxyl-phenyl, guaiacyl, and syringyl, which give bamboo a strength in compression, along with structural rigidity and high heating value.

LC of investigated species was found to be in range of 21.5–28.3%. The LC of pine and spruce wood was in the range of 24–27% (Huang et al. 2008). Male bamboo species of both geographical locations, i.e., Haryana and Uttar Pradesh, were found to be rich in LC (Kaur et al. 2016a). Lignin provides resistance against certain microorganisms.

High LC is an undesirable factor in pulp and paper industry as it results in high delignification rates, chemical consumptions, and low pulp yield. Strength of paper produced is directly related to CC of the pulp (Khalil et al. 2010; Kumar et al. 2017).

The carbohydrate content of bamboo is related to durability against microorganisms and service life. Similar to other lignocellulosic materials, cellulose microfibrils of bamboo are embedded in an amorphous matrix of lignin and hemicellulose.

Traditionally quantification of its constituents is performed using wet chemical analysis methods, such as nitrobenzene oxidation, thioacidolysis, derivatization, and reductive cleavage. Although these methods provide valuable and accurate information about these components, they involve long-time duration and many chemical reagents in high quantities, and furthermore they are laborious. Thus, to enhance the large-scale utilization potential of commercial bamboo species, further research for determination of these components in rapid manner is essential. Various sophisticated spectroscopic and chromatographic techniques are used by few researchers to study the detailed structural analysis of type of lignocellulosic components present in species biomass. This includes Fourier-transform infrared spectroscopy as well as nuclear infrared spectroscopic studies (Li et al. 2015). The available studies on quantification of lignin, lignocellulosic, and cellulose components are summarized in Table 2.

4.3 Cellulose

Large variation in cellulose content (CC) is observed in literature. The general range of cellulose in investigated species is between 40.2 and 53.3, maybe because of difference in geographical location, season of harvesting, age, and part of culm investigated.

While Java black bamboo and string bamboo, black bamboo, and male bamboo with high LC are least recommended pulp and paper industry, solid bamboo and common bamboo species with high CC may be considered as the best choice for paper manufacturing industry.

Though pulp and paper industries require information about CC of species selected, very few studies have been found in literature to quantify the same. There is a strong need to quantify extractives and components of bamboo species not reported in these studies.

4.4 Starch

The presence of sufficient quantities of starch is prerequisite for insect and microbial attacks on the bamboo culm. The most appropriate age of harvesting bamboo is reported to be 3 years with the lowest starch content. The study of the radial distribution of starch in the culm shows that the inner portion of the Indian thorny bamboo culm was found to be richer in starch (6.6%) content as compared to the outer portion (4.8%) for the middle section. It is also reported that the variation of starch content from 1.5 to 4.8% and 5.2 to 8.5% bases top portion, respectively.

There exists a negative correlation between extractive contents and pulp yield. Higher starch content of male bamboo species from Allahabad, India, may cause the

Table 2 Starch, density, lignin, lignocellulose, and CC of bamboo species

Bamboo species	Starch (%)	Density (gm/cc)	Lignin (%)	Lignocellulose (%)	Cellulose (%)
B. arundinacea	2.0 (Kaur et al. 2016a)	–	26.5 (Kaur et al. 2016a)	47.7 (Kaur et al. 2016a)	–
B. balcooa	–	0.81 (Naik 2009); 0.8–0.9 (Saikia et al. 2015)	20.5–23.4 (Saikia et al. 2015)	78.69 (Naik 2009)	40.2–44.5 (Saikia et al. 2015)
B. bambos	–	0.71 (Naik 2009)	–	74.96 (Naik 2009)	–
B. bambos	2.0 (Kaur et al. 2016a)	–	21.5 (Kaur et al. 2016a)	50.5 (Kaur et al. 2016a)	–
B. blumeana	–	–	21.6 (Nor-Aziha and Azmy 1991)	–	–
B. nutans	1.9 (Kaur et al. 2016a)	0.89 (Naik 2009)	26 (Kaur et al. 2016a)	51.6 (Kaur et al. 2016a) 69.25 (Naik 2009)	–
B. pallida	2.8 (Kaur et al. 2016a)	–	20 (Kaur et al. 2016a)	46.5 (Kaur et al. 2016a)	–
B. tulda	1.8 (Kaur et al. 2016a)	0.91 (Naik 2009); 0.68–0.8 (Saikia et al. 2015)	24 (Kaur et al. 2016a); 19.8–21.9 (Saikia et al. 2015)	56.2 (Kaur et al. 2016a); 77.14 (Naik 2009)	38.9–42.5 (Saikia et al. 2015)
B. vulgaris	–	–	21.9 (Subekti et al. 2015)	–	53.3 (Subekti et al. 2015)
D. asper	–	–	28.5 (Kamthai 2003); 24.5 (Subekti et al. 2015)	–	51.2 (Subekti et al. 2015)
D. giganteus	–	0.74 (Naik 2009); 0.65–0.87 (Saikia et al. 2015)	18–19.2 (Saikia et al. 2015)	78.27 (Naik 2009)	40.3–42.3 (Saikia et al. 2015)
D. hamiltonii (Hamilton's bamboo)	3.76 (Naik 2009)	0.59 (Naik 2009)	–	79.04 (Naik 2009)	–

(continued)

Table 2 (continued)

Bamboo species	Starch (%)	Density (gm/cc)	Lignin (%)	Lignocellulose (%)	Cellulose (%)
D. strictus	2.5 Haryana (India); 4.5 Uttar Pradesh (UP), India (Kaur et al. 2016a)	–	27.0 Haryana (India) (Kaur et al. 2016); 25 UP (India) (Kaur et al. 2016a)	53.4 Haryana (India) (Kaur et al. 2016a); 53.6 UP (India) (Kaur et al. 2016a)	–
G. apus	–	–	24.8 (Subekti et al. 2015)	–	49.6 (Subekti et al. 2015)
G. atroviolacea	–	–	26.7 (Subekti et al. 2015)	–	49.6 (Subekti et al. 2015)
G. atter	–	–	27.3 (Subekti et al. 2015)	–	49.8
G. macrostachya (Phai bamboo)	0.72 (Naik 2009)	0.96 (Naik 2009)	–	78.07 (Naik 2009)	–
Melocanna bambusoides (Muli bamboo)	0.10 (Naik 2009)	0.72 (Naik 2009)	–	80.80 (Naik 2009)	–
Phyllostachys bambusoides (madake bamboo)	2.1% (Peng et al. 2011)	0.73 (Naik 2009)	–	85.21 (Naik 2009)	–
Phyllostachys pubescens (moso bamboo)	2.12–3.29 (Okahisa et al. 2006)	–	23.6 (Li et al. 2007)	–	–

increased consumption of pulping chemicals, corrosion of handling equipment, low pulp yield, and pulp brightness (Table 2). This discourages the use of the same for pulp and paper industry. A few traces of starch in Bengal bamboo, *B. balcooa* (balcooa bamboo), Indian thorny bamboo, *B. nutans*, *D. giganteus* (dragon bamboo), and madake bamboo species were reported (Liese and Kumar 2003). These species may be recommended for the use of production of paper from pulp.

5 Durability of Various Bamboo Species

Environmental and financial comparison of bamboo with other building material shows its competitiveness. However, in spite of all these advantages, it is still considered as a rural resource. This is because of shorter life span of bamboo and its products. Studies indicate that due to problem of insect-pest attack, steel is

Fig. 6 Decay of untreated bamboo (IIT Delhi, India) in about 5 years of installation

considered over bamboo as choice for building bridges in Europe. Though there are mammoth bamboo forests globally, the resources are exhausting due to excessive harvesting to meet demands of paper-pulp industry. Therefore, in order to achieve the maximum utilization potential for this natural resource, there is a strong need for the active and systematic preservation practice. Along with this, available resources should also be used wisely with minimum wastage (Janssen 2000).

Bamboo with sufficient amount of starch and negligible amount of toxic constituents is susceptible to attack by a variety of organisms including fungi and termites. Natural durability of bamboo species is defined as “the resistance of bamboo to be attacked by bamboo-destroying organisms.” Depending on the species of bamboo, climatic conditions of growth, harvesting season, and duration of storage, its average life span is known to be 1 to 3 years only.

In addition to this, the inherited resistance is affected by temperature, humidity, and the condition of the cell walls. Figure 6 shows degradation of bamboo culms by microorganisms and insects. For efficient utilization, knowledge about its physicochemical constituents and durability is essential.

6 Factors Resulting in Poor Life Span

Type and extent of microbial attack on bamboo are strongly dependent on moisture condition which depends on type of species, conditions of storage, ambient temperature, and humidity (Kaur et al. 2016d). Bamboo is stored outdoors for up to 1 year. Bamboo species are associated with constraints of limited service life, which is even shorter than timber (Subekti et al. 2015). Among these reported species, Bengal bamboo was reported to be most durable with service life less than 2 years. Biotic factors include various microorganisms like fungi and insects like termite. Abiotic factors like weathering, fire, improper handling during storage, cracks, and splits add to deterioration of bamboo culms.

There are basically two types of factors that affect the quality of bamboo culms in service (Fig. 7). Biotic factors include the resistance of culms to various microorganisms and insects attacking the culms alone or in succession. Bamboo is one of the strongest material, but certain non-biotic factors also affect its quality. Abiotic factors of decay of bamboo include climate of the place where bamboo culms are stored. Environmental factors like heat and sunlight (ultraviolet) affect the outdoor service life of bamboo culms. Heat and ultraviolet radiations of sun weather the harvested culm through photooxidation process. Sun-heat causes checks in bamboo leading to development of cracks in culms. Ultraviolet radiations of sun break down the lignocellulosic bond. The surface turns gray and coarse. Rain, abrasion by wind, and fluctuating temperature and moisture accelerate the weathering process and reduce durability of bamboo species. Major chemical constituents of biomass are affected by degradation (Poletto et al. 2012). Cracks and splits may occur due to frequent exposure of culms to wetting and drying cycles of weather conditions.

Under particular conditions, bamboos are targeted by number of organisms. Attack by fungal species is one of the most common reasons of its destruction. Fungi grow in a conducive environment due to specific combinations of moisture, temperature, aerobic conditions, etc. In tropical regions and temperate regions, termites and fungus are the chief destructor, respectively. The decay pattern of fungus follows a completely different mechanism than other insects. Thus the method of control is also dependent on source of decay.

Biotic factors include various types of fungi. Brown rot fungi mainly *Oligoporus placenta* and white rot fungi like *Trametes versicolor*, bacteria, and termites attack bamboo species. Fungi like *T. versicolor* and *P. versicolor* result in more than 50% of destruction of the culm under storage conditions (Schmidt et al. 2011; Kaur et al. 2016a; Yadav et al. 2018).

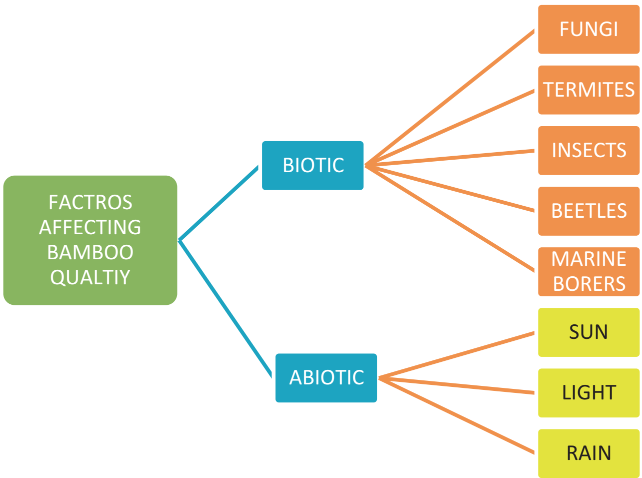

Fig. 7 Factors affecting the quality of bamboo. (Kaur et al. 2016d)

7 Storage and Attack of Fungal Infestation

Decay caused by fungi is the major source of quality loss in both timber and bamboo biomass. Poor natural durability of bamboo against fungi is reported in literature (Xu et al. 2013). Resistance against various kinds of fungi depends on species, culm part, and moisture content of bamboo culm (Schmidt et al. 2013). All fungi produce spores (which are like tiny seeds) that are dispersed by wind and water. The spores can infect moist bamboo during storage, processing, and use. All fungi have certain basic requirements. Optimum conditions for fungi growth include temperature about 20 °C to 30 °C and moisture below 19%. Adequate supply of oxygen and food source like cellulose, hemicellulose, lignin, and starch is required for fungi to grow and multiply.

Fungi consist of a large heterogeneous group of heterothallic organisms living as saprophytes or parasites or in association with other organisms as symbionts. They are ubiquitous, found everywhere in air, soil, water, plant, or animal bodies.

Based on mode of nutrition, fungi are grouped as white rot, brown rot, and soft rot. As the name suggests, the white rot fungal attack causes a bleach appearance because it consumes both lignin and cellulose. Brown rot fungi feed mainly on cellulose. It metabolizes carbohydrate fractions of wood and bamboo, thus affecting the strength. Depolymerization of cellulose fraction takes place, resulting in lower pulp yield. Permanganate number of this type of bamboo is so high that the pulp is different to bleachable (Khalil et al. 2010).

Fungi growth on building materials not only causes material damage but also is hazardous to human health (Li et al. 2015). Fungi mycelial growth causes more damage to buildings than spores. Spores and hyphal fragments, released from fungal biomass, have associated allergies, toxicity, and infections (Torvinen et al. 2006). Contaminated building materials with fungal infestation are a source of contaminated surrounding. The microbially produced volatile organic compounds can also affect the quality of surrounding air, causing sick building symptoms.

There is a large variation in durability reported in the studies. The methods used by these investigators are different. Difference in duration and method of investigation might have contributed to wide variation in durability of these species (Table 3).

Age, height of culm, and period of harvesting also contribute to better service life of the culm. *G. scortechinii* and moso bamboo with weight loss less than 10% against decaying fungi can be considered as highly durable species. The storing and management of these species can be done with ease (Wei et al. 2013).

Bamboo species exhibited less destruction by fungi as compared to wood species. However, *B. nutans*, *B. tulda*, and *B. pallida* bamboo species with loss of more than 55% of weight under fungal infestation conditions are reported to be highly fungal susceptible species.

Table 3 Antifungal decay resistance of a few bamboo species

Species	Fungi	Weight loss %	Test method
B. blumeana	Soft rot fungi	31.9	ASTM D2017 for 8 weeks (Adrianus et al. 2010)
B. blumeana	Soft rot fungi	27.8	ASTM D2017 for 8 weeks (Adrianus et al. 2010)
B. maculate	*T. versicolor*	0.5–1.5	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
B. arundinacea	*P. versicolor*	55.7	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. bambos	*P. versicolor*	56.9	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. nutans	*P. versicolor*	58.2	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. pallida	*P. versicolor*	59.2	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. tulda	*P. versicolor*	57.4	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
D. asper	*T. versicolor*	8.2	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
D. asper	*P. sanguineus*	19.0	Kolle-flask method (Suprapti 2010)
D. strictus	*P. versicolor*	54.1	Haryana species (India) ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
D. strictus	*P. versicolor*	54.3	Uttarakhand species (India) ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
G. angustifolia	*T. versicolor*	2.3	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
G. atroviolacea	*T. palustris*	21.0	Kolle-flask method (Suprapti 2010)
G. atroviolacea	*T. versicolor*	10.4	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
G. apus	*Polyporus* sp.	21.7	Kolle-flask method (Suprapti 2010)
G. atroviolacea	*T. versicolor*	45.7–55.4	EN 113 (1996) (Schmidt et al. 2011)
G. scortechinii	*C. versicolor*	5.3	ASTM D 2017-81 (1986) for 8 weeks (Hamid et al. 2012)
P. pubescens	*T. versicolor*	12.3	Germany species, EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
P. pubescens	*T. versicolor*	15.3	Chinese species, EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
P. pubescens	*C. globosum*	36.9–39.7	EN 113 (1996) (Schmidt et al. 2011)
P. pubescens	*F. palustris*	8.6–9.6	Japanese Industrial Standards (JIS) K-1571-2004 for 12 weeks (Okahisa et al. 2006)

(continued)

Table 3 (continued)

Species	Fungi	Weight loss %	Test method
P. pubescens	*T. versicolor*	10.8–12.0	Japanese Industrial Standards (JIS) K-1571-2004 for 12 weeks (Okahisa et al. 2006)
Malaysian bamboo species	*C. versicolor*	0–36	Incubation with fungi at 22 °C for 8 weeks (Hamid et al. 2012)

8 Resistance to Termites and Insects

Termites are a type of most timber damaging insects (Isoptera) found in 2500 species, with 300 of them labelled as pests. They exist in families and subfamilies, with nests underground, or on hollow of wood or mounds. Past behavior and damaging pattern can help to identify the type of pest species. Harvester termites are found in dry regions, live underground, and are difficult to spot.

Various studies have reported the destruction of bamboo culms because of severe termite infestation. Subterranean termites are major species of termite causing immense destruction during storage. They are social insects, living in colonies of workers, soldiers, and reproductive. The worker termites are whitish in color, are wingless, and are numerous in numbers. Soldiers are also like workers with brown heads and mandibles. They are the protector of colonies. Reproductive function in colony is performed by king and queen termites.

Termites are most successful of all the social insects because of their long life span. They depend entirely over wood and woody tissues for survival. Termite attack is visible on bamboo species, depending on its constituents and properties. Factors like density have a significant effect on bamboo's resistance to fragmentation by termite's attack. Wood and other lignocellulosic biomass are the major food source of termites. The subterranean termite species are the most common species of termite which are most widely distributed and most destructive.

Different physical, mechanical, and chemical properties of wood provide resistance against termite. It is believed that the presence of carbohydrate in wood and bamboo makes it susceptible to termite attack. As termites use cellulose as food, products like paper, fabrics, and woody structures are readily destroyed by them. Hence, a constant effort is being made world over to protect them from destruction.

Termites are destroyers of wood and wooden products in human homes, building materials, forests, and other commercial products (Peralta et al. 2003). Economic losses due to termite attacks include costs of repair and control. Cellulosic materials used in buildings are easy target for termite species. In Indonesia, US $ 200–300 million in 2000 were lost due to termite attack on wood in buildings (Yoshimura and Tsunoda 2004). In India, about 35 species are known to be damaging agricultural crops and buildings (Choudhury et al. 2017; Ashoka et al. 2017).

The termite degradation resistance was found to be independent of season and height of the culm. The yearly average mortalities of the workers and soldiers were 33.2–43.6% and 62.8–69.6% for 2 years old, respectively (Table 4).

Table 4 Termite damage to bamboo species against termite

Bamboo species	Mean percent mass loss (%)	Method
G. angustifolia	24.52	No choice test (Hapukotuwa and Grace 2011)
B. hirose	20.97	
D. latiflorus	21.04	
D. brandisii	16.76	
B. oldhamii	15.73	
G. pseudoarundinacea	12.96	
D. asper	5.3	JIS E1-09 for 3 weeks (Subekti et al. 2015)
B. vulgaris	8.2	
G. atter	8.74	
G. atroviolacea	5.73	
G. apus	6.85	
P. densiflora	12.86	

Studies on the details of weight loss of bamboo species against termites are very limited. Available studies show the bamboo is an easily perishable material. They are able to decompose cellulose, along with lignin, ash, and silica. Termite resistance was found to be independent of oligosaccharide and polysaccharide contents. The presence of nitrogen, ash, silica, and LC may affect the resistance of bamboo against termites. Termite resistance was found to be inversely related to lignin content. It was found that higher LC leads to greater termite resistance. As termites have a substantial preference for nitrogen-rich food, high nitrogen content causes higher damage by termite infestations. Termite durability was found to be independent of AC. The presence of higher silica in bamboo leads to lower termite damage (Dhawan et al. 2007).

Gigantochloa pseudoarundinacea (maxima bamboo) exhibited lowest weight loss of 12.96% against termites using no-choice test (Hapukotuwa and Grace 2011). Three-week termite resistance tests displayed the decay of solid bamboo as the most termite-resistant bamboo species (Subekti et al. 2015).

The investigation also highlighted the negative correlation between the LC and termite resistance. Black bamboo species with LC higher than Java black bamboo, solid bamboo, and common bamboo also reported to exhibit the higher resistance to termite attack. In addition to this, studies also indicated the positive correlation between CCs with termite resistance. Common bamboo samples with higher CC than solid bamboo, black bamboo, Java black bamboo, and string bamboo were heavily damaged by termites.

Resistance to fungi is regarded as absolutely essential to all fields of biomass applications. The strength properties of buildings and pulp obtained from bamboo attacked by decay fungi and termites were lower than those made from stained and decayed bamboo. Hence it is not wise to store these bamboos in areas that are warm and humid.

9 Bamboo as Multipurpose Species

In today's era, global concern for sustainable future is promoting users to switch to bamboo culms for multiple purposes.

9.1 Traditional Uses of Bamboo

Field of applications of bamboo varies from vessels, fences, poles, and musical instruments like flute to food and fodder. Bamboo ropes, mats, baskets, fishing nets, ladders, fans, brooms, lamps, thatching and roofing, bows and arrows, handicrafts, and toys were quite common among rural communities. Chemical products like beer, energy drink, air freshener, and deodorizer add value to bamboo culms.

9.2 Bamboo as Fuel

Biomass is drawing global attention as an attractive alternative renewable energy source, which, using various thermochemical and biochemical conversion techniques, can be easily converted into high-energy content fuel. Combustion, pyrolysis, gasification and liquefaction processes, digestion, and fermentation are the most commonly used conversion techniques to reduce our dependency on fossil fuel. At present, biomass energy shares a significant proportion in total energy generation of the world, which is around 14% of energy supply, after coal, oil, and natural gas (Asif and Muneer 2007). Bamboo, being highly renewable, is the most preferred source for the generation of bioenergy (Scurlock et al. 2000). Since biomass per hectare of bamboo is higher than wood, it has relatively greater potential to substitute wood for bioenergy generation.

There are a few reported case studies, where bamboo is used successfully for power production in many countries (INBAR report 2012), especially in Indian states (Assam, Manipur, and Mizoram) where bamboo is used for electricity generation. Kumar and Chandrashekar (2014) reported balcooa bamboo with high basic density (0.63 g/cm^{-3}), low AC (1.7%), high fixed C content (21.1%), high calorific value (19.6 MJ/kg^{-1}), and low concentrations of potassium (20.6%) and chlorine (0.1%) as the most suitable bamboo species for energy generation.

9.3 Bamboo as Food

Bamboo shoots being rich source of protein, potassium, carbohydrate, dietary fibers, vitamins, and active materials provide nutritious food to the local community. Consumption pattern of bamboo shoots is seasonal and region-specific. Soft, tender bamboo shoots are consumed as vegetables and pickles. Bamboo plays a substantial role to provide the food and nutritional security to the people of bamboo-growing areas. Various traditional techniques are used to ferment bamboo shoots to improve their shelf life and delicacy (Roy et al. 2017). Various medicinal benefits are known to be associated with bamboo shoots. Ethno-pharmacological uses of bamboo include its anticancerous, antidiabetic, and antiulcer activity (Sangeetha et al. 2015).

9.4 Bamboo as Medicine

Bamboo salt, vinegar, and extracts are being used to control diseases like diabetes and cholesterol. Hypertension, sweating, and paralysis can be treated using bamboo. Various parts of giant thorny bamboo (leaf, root, shoot, and seed) are known to have anti-inflammatory, antiulcer, antioxidant, anthelmintic, and astringent activity. Ringworm can be treated using root (burnt root), while skin eruptions can be cured using bark of this tree. Antileprotic and anticoagulation activities of its leaf make it useful for treatment of hemoptysis.

High surface area of bamboo charcoal gives it absorption properties better than wood charcoal, which can be used for numerous biomedical applications including absorption of toxin from blood. Nanoparticles ($NiO.5ZnO.5Fe_2O_4$) that coated bamboo charcoal was found to possess microwave and infrared energy absorption properties. Bamboo charcoal's amalgamation with long with silver nanoparticle resulted in microwave absorption properties. The bamboo charcoal was found to be better adsorbent as well. Bamboo charcoal also has antimicrobial and antifungal activities. It can also be used to protect neurons from oxidative stress. Indian thorny bamboo leaves extract can be used for the most common bacterial diseases (Poletto et al. 2012). Bamboo shoots also help to reduce weight loss and are anti-inflammatory (Hossain et al. 2015).

9.5 Bamboo as Structural Element

Bamboo is a unique creation of nature. The lightweight functionally graded structure composite nature of bamboo culm, made up of axial cellulose fibers, makes it ideal for earthquake-resistant structures. Bamboo with compressive strength double than concrete, shear stress higher than wood, and tensile strength equal to steel is one the strongest building material. Specific properties of bamboo are given in Table 5.

Table 5 Specific properties of bamboo (Shah et al. 2013)

Property	Value
Specific gravity	0.57–0.65
Bond stress	5.6 kg/cm^2
Safe working stress in shear	115–180 kg/cm^2
Safe working stress in compression	105 kg/cm^2
Ultimate compressive stress	794–864 kg/cm^2
Modulus of elasticity	1.5–1.0 × 105 kg/cm^2

Certain added advantages of bamboo as building material include wider span and ease of curvability without breaking (Nurdiah 2016). It is reported in literature that the buildings with bamboo as construction material for the roof top are energy efficient. This reduces the temperature of top floor of building and makes it a comfort zone during hot months of summer. Hoang et al. (2010) reported the effectiveness of bamboo buildings to provide better inside air quality with less ozone level indoors.

9.6 Pulp and Paper

Increasing human population, documentation, rising literacy rate, and improving economic resources have resulted in the rapid growth of pulp and paper industry. Traditionally, wood and timbers were generally used for the manufacture of pulp for the production of paper worldwide. However, the severe problem of deforestation and agricultural waste disposal problems has prompted researchers to look for the alternatives. Non-woody plants like bamboo hold a good opportunity in this field.

About 18 species of bamboo are reported to useful for pulp and paper industry. Bamboo is used for the preparation of printing and writing paper, newsprint substitute, wrapping, bag paper, etc. (Hammett et al. 2001). CC in bamboo (40–50%) is comparable to softwoods (40–52%) and hardwoods (39–56%). Thus cellulosic fibers for paper industry can be obtained from it. In addition to this, it is also useful for the production of ethanol and starch granules for saccharification.

One of the latest studies performed by Sugesty et al. (2015) showed that dragon bamboo and *Gigantochloa robusta* (tropical timber bamboo) are highly suitable for the production of pulp for rayon fiber. *D. brandisii* (velvet leaf bamboo) culms are also reported to be suitable for production of pulp fibers.

10 Bamboo and Livelihood Opportunities: Indian Perspective

Bamboo has been used by mankind since ancient times and now holds a strong capacity to provide income for billions of people every day, particularly in rural areas (Lobovikov et al. 2005; Song et al. 2011).

In fact, with wide range of applications, bamboo species specifically favored for reforestation and forest rehabilitation. Given the fact that manufacturing different products using bamboo can be a zero waste process, they have 100% utilization capability, which is only 20% in case of a wood species (Lobovikov et al. 2012). Processing of bamboo being simple requires no special skill and equipment, leading to low initial investment. Hollow internal structure of bamboo culms makes it lightweight, easy to work with, and easy to transport. Bamboo plant is also found to be an excellent source as C sink and effective in mitigation of greenhouse effect (Bhalla et al. 2008; Ram and Meena 2014).

Table 6 Market demand of bamboo in various applications in India

Bamboo item	Market size 2003 (Rupees crore)	Market potential 2015 (Rupees crore)
Shoots	5	300
Timber substitution	10,000	30,000
Plyboard	200	500
Plyboard for truck, railways	1000	3400
Bamboo mat boards	–	3908
Bamboo flooring	100 for export, 100 for domestic	1950
Pulp	100	2088
Furniture	380	3265
Scaffolding	–	861
Housing	–	1163
Road	–	274
Miscellaneous (pencil, match box, etc.)	394	600

Adopted: Kumar and Tanya (2015)

With about 1500 commercial applications mentioned in literature (Scurlock et al. 2000), it captures a significant share in global market about US $7 billion (Lobovikov et al. 2012). Bamboo is commonly found in Africa, Asia, some parts of Europe, and America. India is rich in bamboo resources accounting 13.96 million hectares forest area with 123 species in 23 genera (FSI report 2011). In India, they are widely distributed, especially in semidry and dry zone along plains and hilly tracts, usually up to an altitude of 1000 meters. North-Eastern Indian states covering a major portion and diversity of bamboo species are also popularly known as "Bamboo Paradise of India" (Goyal and Brahma 2014). It has been reported that in the state of Assam, bamboo forest occupies an area of 1813 km^2 out of total geographical area of 78,438 km^2 (Sharma et al. 2010).

India, China, and Myanmar together constitute ~ 80% world's bamboo forest. Although 45% of the world's bamboo production is shared by India, its share in global market is only 4.5% (Mehra and Mehra 2007). This is mainly due to lack of proper postharvest management and preservation techniques of bamboo culms. Table 6 shows market share of various categories of bamboo products.

India being a developing country has vast potential to utilize bamboo for multiple applications. Bamboo can help to provide not only food security but also employment opportunities to people of India. The wide distribution of Indian bamboo species shows the enormous potential it possesses to develop bamboo-based industries in India. Application of property-specific bamboo species can help to achieve the maximum utilization capability to the Indian bamboo species. Socio-environmental values associated with bamboo make it an alternative material for housing. Excellent flexibility makes it ideal for earthquake-resistant structures. Building bamboo houses in earthquake prone areas of Gujarat and landslide-affected areas of hilly region can provide economically feasible safe houses to the society.

Providing training on advanced equipment, making finance easy to the viable projects, and linking these projects to the markets can help in creation of employment opportunities to the bamboo artisans and improve their socioeconomic status. Development of new products using engineered bamboo may give rise to new dimension of rural economy from abundantly available and lying unused bamboo biomass in rural areas.

11 Conclusion

Bamboo with capability to grow effortlessly on wasteland is emerging as a more suitable alternative to wood, metal, steel, and plastic. Considering the fast growth rate, high tensile strength, and low weight to height ratio, the highest emphasis should be given to its wider utilization. Major bamboo-producing countries include Asian countries, mainly India, China, and Indonesia. Present chapter highlights the variation in not only major constituents like lignin and cellulose but also minor constituents like ash, starch, alkali, and water-soluble contents. These studies emphasize the fact that male bamboo species with solid culm and relatively high lignin density is the most suitable for load-bearing applications especially in building and construction industries. Starch content varies significantly with species from 1.5 to 4.8%. Bamboo species like *B. nutans*, *B. tolda*, and *B. pallida* were reported to be highly fungal susceptible species, with the loss of more than 55% of total weight under fungal attack. The studies urge the necessity of preservation and treatment of bamboo under storage conditions to pave the way forward for efficient resource utilization from the bamboo forests available on all continents.

12 Future Prospects

Bamboo no doubt is a very promising material with numerous species found all over the world. The engineering properties of bamboo have helped it to emerge as a "Material of Future." It is a unique creation of nature with lightweight functionally graded structure composite nature, made up of axial cellulose fibers in a lignin matrix, resulting in high strength both in tension and compression with good laminar shear. However, short life span of bamboo (1–3 years) and fast deterioration under storage conditions put serious constraints on bamboo utilization as structural elements.

Studies on the physicochemical properties are important for the selection of suitable bamboo for its multiple purpose uses. Most of the studies that have been reviewed depict the fact that the distribution and contents of extractives, cellulose, hemicellulose, and lignin remarkably affect its processing properties. Complete characterization of any bamboo species is not available in literature. The review of properties of bamboo species recommends the choice of bamboo species according to the end use. Unavailability of characterization data is a major hindrance to enhance utilization potential of bamboo species.

A significant variation of some properties exists among species. Male bamboo species from different geographical locations have marked differences in their properties. Bamboo species showed marked difference in AC, viz., male bamboo (Haryana) 2.6% and giant thorny bamboo (Uttar Pradesh) (8.1%). Density of all the species reported in literature was found to vary the most. Male bamboo species were found to be rich in LC. Both these factors make this species the righteous material for building and construction applications. *B. pllaida* was low in lignin (20%) and ligno-CC (46.5%), which can be considered as a good choice for paper industry. Characterization of commercially important bamboo species would help in preparing guidelines to choose species as per requirement. Decay resistance analysis showed loss of strength by fungi and termites the most. It is expected that in addition to starch other factors like storage conditions, moisture content, and geographical conditions have contributed toward fungal decay resistance of these species. These studies may give rise to a new dimension of economy from abundantly available and lying unused bamboo biomass globally.

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