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Recent Advancement in Physico-Mechanical and Thermal Studies of Bamboo and Its Fibers

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Abstract

Bamboo has its own role in the development of society. It is widely used as a support tools for sustainable farming and being exceptional resource for variety of income and employment-generating systems. This overlooked biomass provides food, raw material, shelter, medicine for large part of world's population. Bamboo has given a great support to mankind by providing building materials that are extensively used for household products. It has found a good place for industrial applications due to advances in processing technology and increased market demand. Numerous fundamental studies were carried out to highlight their fundamental characteristics prior to industrial exploitation or high end bamboo-based biomaterials. The mechanical and physical properties of bamboo have noteworthy effects on their durability and strength. Thermogravimetry is one of the key sensitive technique that characterizes the mechanical responses of materials by monitoring property changes with respect to the temperature. Comprehensive review and study on thermal analysis are useful for quantitative determination of the degradation behaviour and the composition of the material. The magnitude and location of the derivative thermogravimetric curve also provides information of the interaction between the material components at various temperature scales. Therefore, these studies can be focused to evaluate the basic fundamental problems faced and thus, a well-designed research and development towards sustainability can be achieved.

Keywords: physico-mechanical, thermal properties, thermogravimetry, bamboo

1. Introduction and global scenario

Bamboos are an extremely multipurpose and most beneficial group of plants. Bamboos are found in almost all continents of the world. Both common people and researchers have utilized bamboo in a variety of ways and have played an important role in today's life. At present, bamboos are considered as highly renewable resources [1, 2]. The development and exploration of bamboo eventually depends, not only on scientific community, but on urban and rural people who are largest utilizers (buyers, sellers and processors) of bamboo. Bamboo has played an important role in the lives of people in South and Southeast Asia [3]. Being an essential natural resource, "sustainable development" is a critical concern of the bamboo economy. The development of bamboo is a concern of both enhancing the supply and ensuring productivity, which leads to development and needs of present and future. Presently non-profit organizations like American Bamboo Society, International Network for Bamboo and Rattan (INBAR) Latin America, INBAR West Africa, European Bamboo Society, INBAR East Asia, INBAR West Asia and Bamboo Society of Australia have clear objectives to promote all aspects of bamboo interest in respective countries [4].

These organizations promote opportunities for sharing information and education, and awareness among common people. The role of bamboo in plantations and sustainably have achieved forests in providing economically possible environmental services. Different resource inventory methods and technical manuals have been considered by these organizations to improve criteria and indicators for sustainable resource management along with income generation for local people, particularly for bottom billion people. In addition to these societies, researchers are contributing to make a connection of sustainability with the world growing population, average welfare rate and environmental impact of welfare commodities, demonstrating the need of achieving a factor 20 environmental improvement by the year 2040. The material scientists and engineers [5–8] can take up the responsibility to contribute to sustainable development by finding more environmentally benign ways of research in material sciences and engineering applications. One of the ways for solutions is to be found in new material applications: improving the dimensional stability of bamboo products, providing practical methods and procedures in determining the strength and thermal stability of bamboo and their products.

The use of bamboo can be explored for various purposes depending upon its properties. It plays an important role for house construction, agricultural tools and implements, as food material, weaponry, bicycles, etc. [9, 10]. The traditional cottage industry has been greatly benefited and it is also an appropriate source of cellulose for paper production and rayon [11]. Bamboo craft is one of the known of traditional cottage industries. Since early ages the baskets, mats and many other products of household use were fabricated from bamboo as it is available in vicinity of nearby forests. Later, tribal and rural people took up bamboo as a means of livelihood. Now bamboo craft is well established in all rural areas of the country and it feeds millions of traditional workers [12].

Bamboo is mainly grown in tropical regions of Asia, Latin America and Africa. Bamboo can be called as a collective name for different species of giant grasses [13]. It has been estimated

Use of bamboo as plant	Use of bamboo as material
Ornamental horticulture	Local industries
Ecology	Artisanat
Stabilize of the soil	Furniture
Uses on marginal land	A variety of utensils
Hedges and screens	Houses
Minimal land use	Wood and paper industry
Agroforestry	Strand boards
Natural stand	Medium density fiberboards
Plantation	Laminated lumber
Mixed agro-forestry system	Paper and rayon
	Parquet
	Nutritional industries
	Young shoots for human consumption
	Fodder
	Chemical Industries
	Biochemical products
	Pharmaceutical industry
	Energy
	Charcoal
	Pyrolysis
	Gasification

Table 1. Various uses of bamboo [16].

that 60–90 genera of these species are available in different sizes and forms. Nature has given bamboo special structural design. Due to the direction of fibers and hollowness of bamboo less material is needed as compared to materials with high mass content e.g. wood. This unique property has led a world class revolution in bamboo both in cultivation and utilization. A comprehensive range of bamboo products are available in variety of styles and design patterns in the form of furniture, decorative products, wall hangings, basket, lamp shade, and table top items. The mostly rural people have used bamboo crafting as a tool for designing such products. In comparison to ancient era where it has been used as household purposes for keeping goods, the modern scenario is different as the demand of bamboo is persistently growing in the domestic as well as international markets due to its varied design patterns as well as its eco-friendly features.

It has been estimated that at global level about 2.5 billion people use bamboo in different forms with an annual turnover of 10 billion USD and the figures will be doubled by 2015. China is the largest among the bamboo exporting countries. The total export value of bamboo products of the country is \$550 billion per annum [14]. Moreover, advanced research activities have been carried out for efficient fuel generating systems. The international network for

bamboo and Rattan (INBAR) are functioning at the international level. A well mechanized mode has been adopted at global level, for primary processing and product manufacturing. A collective effort by Choudhury and Sharma [15] to summarize the uses and importance of bamboo shoots on global level has provided enough knowledge to researchers associated with development and utilization of bamboo. The authors provided a global scenario of marketing the bamboo and earnings from it although considering it as underestimated natural resources at international level, even being found naturally or cultivated. The market value of bamboo in China and America is worth of millions dollars in terms of import and export marketing. USA imports tones of bamboo from many Asian countries for food items. India, an economically superpower country is alone doing bamboo marketing in millions of rupees. As summary, various uses of bamboo are presented in **Table 1**.

2. Role of bamboo in sustainable economic viability

World bamboo sector in different countries are unique in terms of their scale and level of organization. Bamboo in many countries follows the global constraints on forests and timber, and the ongoing need to develop rural industries and improve poverty. Policies in the forest sector are critical in ensuring the healthy development of the bamboo. Depending on the particular condition, bamboo is treated as tree or agriculture crop. To avoid hindrance to sustainable development, this tree or crop is fitted in such policies to pose least threat to sustainable sector. Therefore, clear classification had been designed by different countries, which are well recognized and made in accordance with ecological conditions of bamboo. Bamboo has been recognized as multifunction species and single purpose for bamboo has been avoided by developing countries. In economically sound countries with significant bamboo sectors, different agencies and societies are working specifically on bamboo are playing an important role in formulating policies to ensure healthiness of agro-forestry and natural resources. For example, model systems opted by China should be utilized where there is strict need of it. Presently, the farmers are investing in the bamboo industry with making secure their right of uses manage and transfer resources.

The restricted use of bamboo in some contents of the world has provided limited knowledge about the economic feasibility of bamboo. To acquire more knowledge into building and maintenance costs of the initially described bamboo applications have been compared to more common building materials such as steel, timber and concrete taking environmental assessment and the same structural elements into account [17]. Some buildings have been executed in European countries with bamboo as the main structural material. Although, there are problems some of which had direct consequences of the use of bamboo. This influence of working with bamboo has been analyzed. Therefore, studies on critical factors of failure and success of the application of bamboo in Western European building projects have been carried out to provide solutions as to preventing measures or reduce the negative impacts of their causes [17].

No.	Species	Local name	Uses
1	<i>Bambusa blumeana</i>	Buluh duri	Chopstick, tooth picks, furniture, musical instrument, poles, shoot as food
2	<i>Bambusa heterostachya</i>	Buluh galah/tilan/pering	Poles, frames, tooth picks, blinds, skewer sticks
3	<i>Bambusa vulgaris</i>	Buluh minyak/aao/ aro/gading/ tamalang	Ornamental, tooth picks, chopsticks, skewer sticks, shoot as food
4	<i>Bambusa vulgaris var. striata</i>	Buluh gading	Ornamental
5	<i>Dendrocalamus asper</i>	Buluh betong/pering	Shoots as food, chopsticks
6	<i>Dendrocalamus pendulus</i>	Buluh akar/belalai	Handicraft, basket
7	<i>Gigantochloa brang</i>	Buluh brang	Shoots as food, chopsticks, skewer sticks, tooth picks
8	<i>Gigantochloa levis</i>	Buluh beting/bias	Shoots as food, chopsticks
9	<i>Gigantochloa ligulata</i>	Buluh tumpat/tikus belalai	Frames, shoots as food, poles for vegetable support
10	<i>Gigantochloa scortechinii</i>	Buluh semantan	Handicraft, small scale industries, incense sticks
11	<i>Gigantochloa wrayi</i>	Buluh beti/raga	Handicraft, small scale industries, incense sticks
12	<i>Schizostachyum brachycladum</i>	Buluh nipis/lemang	Handicraft, rice vessels (lemang)
13	<i>Schizostachyum grande</i>	Buluh semeliang/ semenyeh	Frames, leaves used for wrapping Chinese glutinous rice dumpling
14	<i>Schizostachyum zollingeri</i>	Buluh dinding/kasap/ telur/nipis	Handicraft, tooth picks, skewer stick
15	<i>Bambusa multiplex</i>	—	Fishing rods
16	<i>Bambusa tuldoidea</i>	—	Ornamental
17	<i>Gigantochloa balui</i>	—	Handicrafts, sailing masts
18	<i>Schizostachyum pilosum</i>	—	Flooring and basketry
19	<i>Dinorchloa darvelana</i>	—	Pests species
20	<i>Dinorchloa obclavata</i>	—	Pests species
21	<i>Dinorchloa prunifera</i>	—	Pests species
22	<i>Dinorchloa robusta</i>	—	Pests species
23	<i>Dinorchloa scabrida</i>	—	Pests species
24	<i>Dinorchloa sipitangensis</i>	—	Pests species
25	<i>Dinorchloa sublaevigata</i>	—	Pests species
26	<i>Dinorchloa trichogona</i>	—	Pests species

Table 2. Commonly available bamboo species in Malaysia [20].

In Malaysia, government has classified bamboo as a non-timber forest and is next in importance to rattan. It has been used as food as well as traditional and commercial products since ages. There are more than 50 species of bamboo reported in Malaysia, an integral part of forestry, but it is also commonly spread outside forests including farmlands, riverbanks, roadsides and urban areas. Based on Fourth National Forest Inventory, bamboo occupies about 7% of the total forest area in Peninsular Malaysia (the total area of Peninsular Malaysia is 131,600 km²). The list of bamboo species available in Malaysia with proper uses is given **Table 2**. The genera found in the country are *Bambusa*, *Dendrocalamus*, *Dinochloa*, *Gigantochloa*, *Racemobambos*, *Schizostachyum*, *Thyrsostachys*, *Chusqua*, *Phyllostachys* and *Yushania* [18]. Among all the species available, 14 Malaysian bamboo have been identified as commercial species [19]. To maximize the exploration of bamboo industry in Malaysia, bamboo resources are needed to be maintained for industries particularly for joss sticks, chopsticks, basket-making, toothpicks and joss-papers. A systematic policies for the production bamboo is the need of present economic scenario of Malaysia, otherwise there will be depletion in demand of bamboo. The sustainable future of bamboo in Malaysia needs sustainable plantation of bamboo resources. In context to this, Malaysian government has disseminated trial of Malaysian commercial bamboos at few sites but not on the whole Peninsular Malaysia.

3. Physico-mechanical properties of bamboo for commercial utilization

The advancement of science and technology has led to new methods to make bamboo more durable and usable in terms of building materials. Bamboo has helped to uplift the rural economy through the establishment of industries and opportunities of employment. Bamboo based industries could be a sustainable option to ease the domestic demand and bring foreign currency by exporting newly designed products to international markets. The use of bamboo can be exploited to greater extent as it is cheap and found in abundance. The properties like rapid growth rate, short rotation age, excellent flexibility and high tensile strength has transformed bamboo into a wide variety of products ranging from domestic household products to industrial applications [21]. The uses in platforms (floors for transport vehicles such as trucks, busses and rail coaches), concrete molding boards (in building industries), flooring, furniture, pulp and handicraft works has provided new dimensions to bamboo utilization [22–24]. To elevate the utilization of bamboo, its fundamental physical and mechanical properties must be fully understood [25]. Researchers have proved that physical and mechanical properties of bamboo vary with respect to position in the bamboo. Lee et al. [26] found that the physical and mechanical properties of bamboo are affected by height location. Xian and Ye [27] studied the variation in mechanical properties of bamboo and established an equation for predicting the tensile modulus of elasticity from the radial position. Li [28] investigated the variation of the specific gravity and bending properties of bamboo and found that the specific gravity and bending properties decrease from the outer to inner layers of the bamboo culms.

3.1. Physical properties

3.1.1. Moisture content

Utilization of bamboo has now advanced from traditional to structural applications such as composites and advanced materials [29, 30]. The advancement in usage of bamboo needs further understanding of the material characteristics such as the physical properties. Terminology of a bamboo culm is illustrated in **Figure 1**. Physical properties of the node and internode positions of bamboo have been investigated by Tamizi [31] with small size specimens (strips of bamboo). The statistical data obtained showed a great variation according to the sources and position of the samples obtained from the bamboo. It was observed that moisture content was higher at the inner layer and reduced in the outer layer of the bamboo culm. Liese [32] claimed that different bamboo species showed different moisture values which can be attributed to difference in some inherent factors such as age, anatomical features and chemical composition. But in this case, the age factor is not involved since all samples were taken from 3 years bamboo culms. In this chapter, discussion is focusing on moisture content, specific gravity, shrinkage and fracture roughness.

The higher moisture content could be influenced by the anatomical structure of bamboo. The inner layer contains lower vascular bundles concentration which leads to higher moisture content as compared to outer layer as shown by Li [28]. This phenomenon is similar to non-wood plant, i.e., oil palm trunk which shown higher content of parenchyma in core part. Engler et al. [34] has reported the relation between moisture content and thermal use of one of the bamboo species. Authors stated that moisture content is one of the most relevant characteristics, which significantly influences the thermal use and efficiency. A comparison study with other species of wood has been done and authors revealed that the moisture content of bamboo was higher at an average of 136.9% and spreading widely. Related to the ages, the

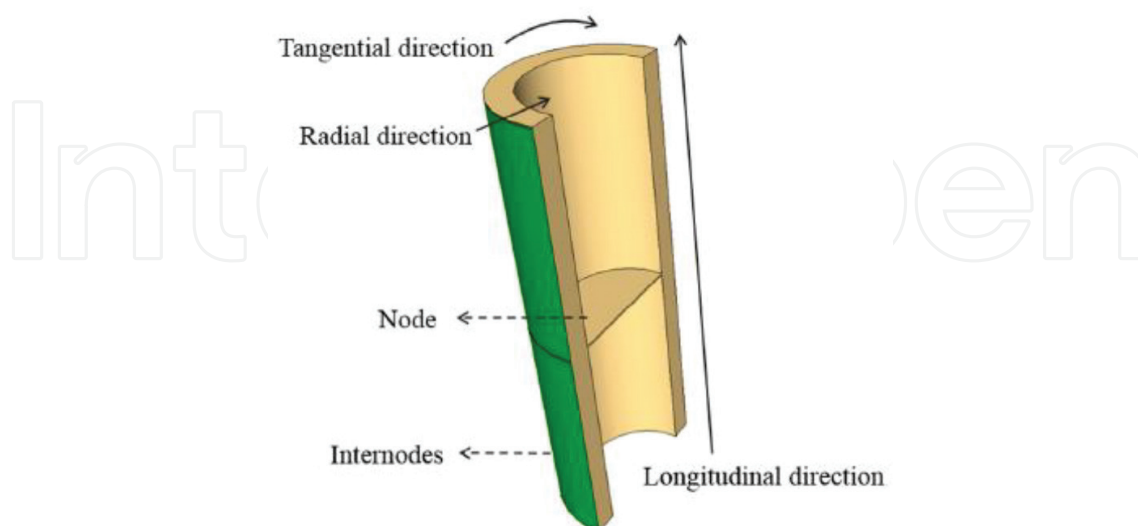


Figure 1. Terminology of a bamboo culm [33].

young culms in general show significant higher moisture contents, compared to the older culms. It was also found that moisture content at the bottom of bamboo culm was higher as compared to the top.

Studies by Kamthai [35] on different physical and mechanical properties of sweet bamboo found that the moisture content was 60.2%. On the other hand, Chen et al. [36] investigated the moisture content of modified bamboo strips. Alkaline treatment enhanced the moisture absorption, while esterification treatment, oxidation and silane treatments has reduced the moisture content. The results revealed that moisture content directly affects the other properties like interfacial shear strength.

3.1.2. Specific gravity

Different observation by various researchers has been put forward in order to get in-depth knowledge about the specific gravity of bamboo, for example a study on nodes and internodes of *Gigantochloa* has been carried out by Tamizi [31]. The specific gravity of samples from outer layer was higher compared to middle and inner layer for both internodes and nodes of all the *Gigantochloa* species. *G. levis* node recorded the highest specific gravity value among all of the species while *G. wrayi* node gave the least values. The bamboo density has a close relation with vascular and ground tissues percentages as proposed by Janssen [37] and Espiloy [38]. It was revealed that specific gravity of internode and node part of each bamboo species was marginally different. In contrast to report by Hamdan et al. [39], it was found that the nodes present along the culms height generally have higher density than the internodes due to lesser presence of parenchyma as well as lower moisture content and volumetric shrinkage.

3.1.3. Shrinkage and fracture toughness

Shrinkage is a characteristic property of bamboo which describes tendency of bamboo towards shrinkage under different conditions. Unlike wood, bamboo has a tendency to shrink from the very beginning of drying. The elimination of moisture in the cell wall that is hygroscopic or bound water leads to shrinkage as a result of the contraction of microfibrillar net in proportion to the amount of liquid evaporated [40]. Yu et al. [22] reported a study on shrinkage at different locations of Moso bamboo (*Phyllostachys pubescens*). The results revealed that both height and layer had a substantial effects on tangential and longitudinal shrinkages, but the interaction between height and layer had no significant effect on shrinkage. It was observed that tangential and longitudinal shrinkages appeared to be divided into two 3-layer zones (i.e., outer 3-layers consisting of layers 4, 5 and 6 and inner 3-layers consisting of layers 1, 2 and 3). It was found that tangential shrinkage was slightly greater at 4.0 m and longitudinal shrinkage was slightly greater at 1.3 m.

Amda and Untao [41] studies about the physical properties such as fracture toughness and tensile tests of bamboo culm and nodes. Authors reported that fracture toughness of bamboo culms depends on the volume fraction of fibers. It was observed that bamboo culm has a high value of fracture toughness for outer surface layer and decreases towards the inner surface, meaning that bamboo offers a greater fracture toughness on the outer surface where the most

dangerous and external force is exerted. Authors also explained that fracture toughness distribution with radius was in accordance to the values obtained for volume fraction of fibers, which means the proportionality depends directly to each other. The value of fracture toughness is increased at outer surface while moving towards outer surface. Moreover, it was found that fracture toughness of bamboo was higher than aluminum alloy and way better than other wood species.

3.2. Mechanical properties

Bamboo is known for its orthotropic character meaning, it has specific mechanical properties in x, y, z directions i.e., longitudinal, radial, and tangential. A pool of knowledge of the mechanical properties of bamboo helps in safe design as bamboo responses in the same manner as other building materials do. However, being a natural composite or biological material like wood, it is exposed to greater variability and complexity, due to various growing conditions as availability of moisture and soil conditions. Preparation of bamboo samples prior to mechanical testing is presented in **Figure 2**.

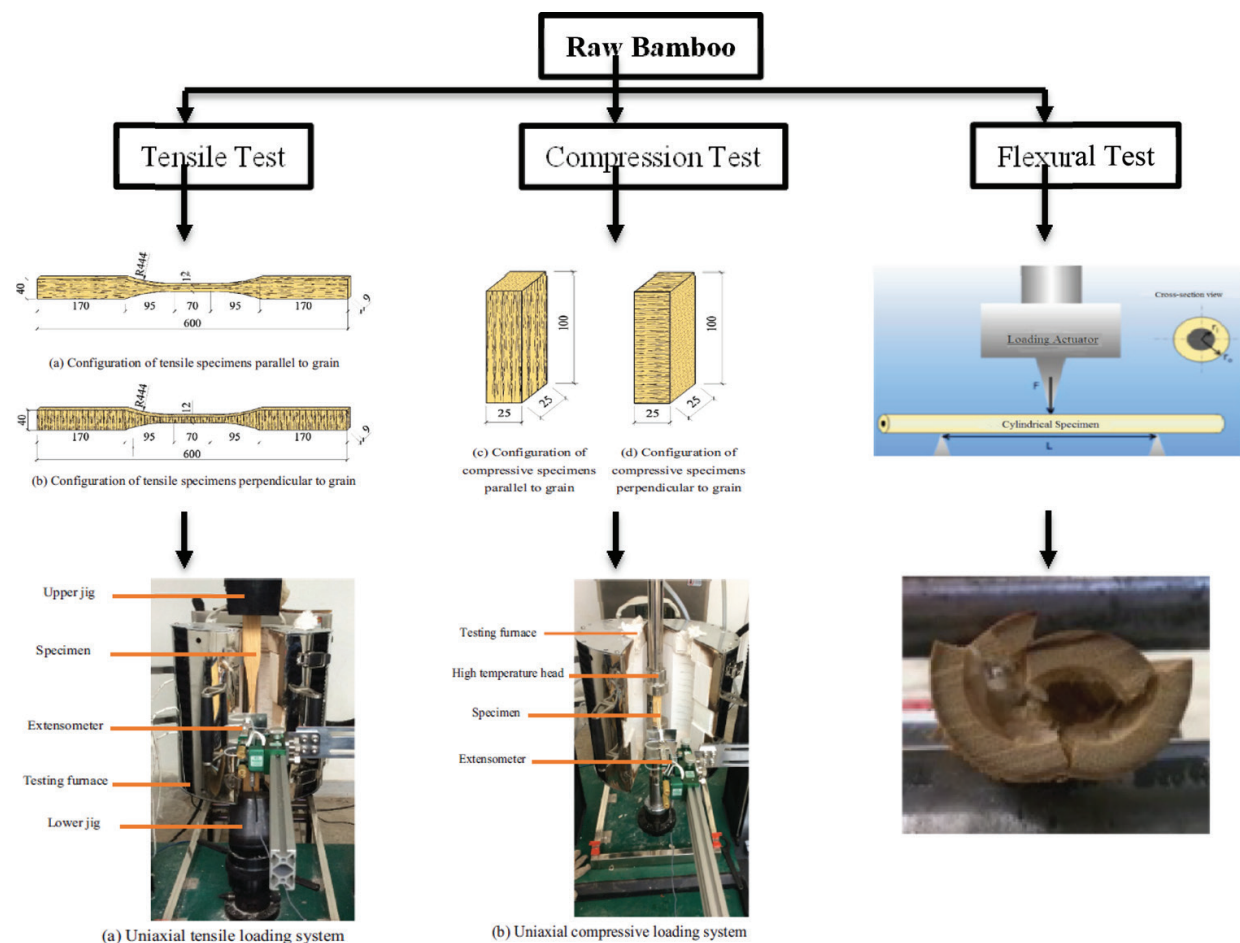


Figure 2. Preparation of bamboo samples for mechanical testing including tensile test, compression test and flexural test [9, 42].

3.2.1. Tensile strength and modulus

Studies have been carried out to investigate the variation of mechanical properties as well as between the internodes and nodes, and the variation between different locations in the bamboo culm [43, 44]. Researchers have conducted studies on the mechanical behavior of both full size culm (round form) [45, 46] and small specimens [47, 48]. Lakkad and Patel [49] revealed that the specific strength of bamboo is greater than that of the most thermosetting resins. It was observed that bamboo is stiffer and stronger than other woods. Therefore, authors hypothesized that bamboo has remarkable potential as a structural material when considering the mechanical properties of bamboo together with its low cost properties.

Defoirdt et al. [50] assessed the tensile properties of bamboo fibers to understand, how they go well as starting material for composite material. They reported that decreasing trend in strength of bamboo fiber was observed as length was increased justifying that, with higher test lengths there are more drawbacks in the fibers that increases the chances of failure. They compared the tensile strength of bamboo with other fibers and found that tensile strength of bamboo is higher in contrast to other fibers even though the bamboo fibers were damaged during extraction process. In other study, Tan et al. [51] revealed that the tensile strength degradation of bamboo corresponds to the fiber density degradation. Authors reported the highest strengths were found to be in the regions nearer outer surfaces with higher fiber densities. However, lowest strengths correspond to the regions away from the outside surfaces with the lowest fiber densities whereas in between regions shown intermediate tensile strengths.

Li [28] also stated that tensile strength and mean Young's modulus increases with increase of cellulose content and decreasing microfibrillar angle. Rao and Rao [52] carried out a study on tensile strength as well as tensile modulus of bamboo. They reported that bamboo fibers possess highest tensile modulus as compared to other fibers viz., palm coconut and sisal fibers. In our recent work carried out on *Gigantochloa* spp, we observed that the higher tensile modulus group was *G. levis* (3793 MPa), followed by *G. wrayi* (3670 MPa) and *G. scortechinii* (3456 MPa) and the lower was *G. brang* (2661 MPa); (*G. levis* > *G. wrayi* > *G. scortechinii* > *G. brang*). There was a noteworthy difference between green and air dry sample. This might due to the fact that bamboo behaves as similar to wood whereby the mechanical properties increases with the decrease in moisture content [39]. The analysis of variance for tensile modulus at different locations exhibited a significant difference between the internode strips and node strips.

3.2.2. Static bending (modulus of rupture and modulus of elasticity)

Modulus of rupture is the maximum flexural stress sustained by the specimen during bending test or in other words can be defined as the maximum stress in bending that can be withstood by the outer fibers of a specimen before rupturing. Tamizi [31] reported the comparative results of modulus of rupture with reference to different position of different species of bamboo. Both dry and green sample exhibited different values of modulus of rupture. The order was (*G. scortechinii* > *G. wrayi* > *G. levis* > *G. brang*). It was reported that air dry samples showed

better modulus of rupture (30–40%) compared to green samples. This can be ascribed to the fact that bamboo behaves similar to wood whereby the mechanical properties increases with decrease in moisture content. The data presented that results at inner surface (130.71 MPa) direction were higher compared to the outer surface direction (111.07 MPa). The difference in MOR showed that the outer layer has less than 5% stronger from the middle layer, and the middle layer has less than 5% stronger than inner layer. Difference in MOR, the outer layer strength was less than 10% higher than the inner layer. The value for MOR (green) at the node is relatively higher than the internode. This is reflected due to the density of the node are higher compared to the internode as node contain lesser presence of parenchyma. This is similar to the earliest report mentioning that the strength properties in bending of bamboo are greatly correlated with specific gravity [53].

Biswas et al. [54] reported utilized wastes from two species of bamboo viz. *B. balcooa* and *B. vulgaris*. The waste was a type of shavings acquired during planning operation of bamboo splits for production of rectangular strips of constant thickness. This raw material was utilized for the formation of particle board. The modulus of rupture (MOR) values of boards made from planer waste was 15.7 N/mm² and 17.7 N/mm² for *B. balcooa* and *B. vulgaris*, respectively. Varied results were obtained and particle geometry had significant influence on modulus of rupture in both species. The bamboo planer waste had no definite pattern of particle geometry with light and curly shape with good tendency to fold. Authors revealed that based on modulus of elasticity a significant effect was observed on the particle board geometry.

Based on modulus of elasticity Li et al. [55] published an interested report that bamboo has high modulus of elasticity as compared to human bones. The average modulus of elasticity across the thickness of bamboo culm can be 18 GPa, equivalent to that of human cortical bone. Ghavami et al. [56] studied the modulus of elasticity of bamboo with some degree of precision. Authors stated that fiber distribution in bamboo follows an organized pattern with an increased amount of fibers on the outer surface of the culm. While proving how this variation occurs, the basic equations from the bamboo approach can be changed in order to model the mechanical behavior of bamboo. Yu et al. [22] revealed that modulus of elasticity of bamboo varied greatly from the inner layer outwards. Modulus of elasticity at 1.3 m was less than those at 4.0 m from the base. This report suggests that layer had important effect on the modulus of elasticity. It was observed that modulus of elasticity decreased as the layer decreased from the outer (layer 6) to the inner (layer 1) layers, but the difference between layers 3 and 4, and between layers 1 and 2 were not considerably less.

4. Thermogravimetric studies of bamboo

4.1. Thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG)

Thermogravimetric analysis (TGA) is a useful method for the quantitative determination of the degradation behaviour and the composition of particular material. The magnitude and location of the curve in thermograms provides the information of the component and the

interaction between the components at various temperature scales [57]. The chemistry of bamboo is complex and has been divided by analytical methods into major components including cellulose, hemicellulose and lignin like several other lignocellulosic materials [58, 59]. Under these circumstances, the thermal decomposition is somewhat similar to the combination of those of the constituents pyrolyzed at the same conditions.

In a study by Tamizi [31] on different species of bamboo (*Gigantochloa*), viz., *G. brang* and *G. levis*, TGA studies were carried out at different positions which designated as outer, middle and inner layer. The shape of thermograms in these two species revealed quite similar characteristics. The behavior was in agreement with the data obtained by other researchers. Xie et al. [60] and Mui et al. [61] reported that the temperature range, weight losses and the rates of thermal degradation at different stages (devolatilization and combustion steps) changes with each different fiber at any specific location of the plant [62]. Thermal stability was observed up to 210°C in *G. brang* and thereafter started to decompose.

The initial degradation temperature between 210 and 390°C are linked to decomposition of bamboo constituents, which are mainly cellulose and hemicellulose [63, 64]. The second stage degradation between 390 and 800°C in the entire sample corresponds to decomposition of lignin. Previous studies have shown that the thermal stability is determined by the chemical composition of any biomass as various components of lignocellulosic materials have different thermal behaviors [62, 65]. Also, several studies on the thermal decomposition of the individual components of lignocellulosic materials indicated that decomposition of hemicellulose starts first, followed by the cellulose and finally, the lignin [65–68]. Similarly, in the thermograms of *G. levis*, samples gave an initial weight loss below 100°C attributed to the loss of moisture. Thereafter, the thermal degradation of the bamboo samples starts to decompose near 200°C at both internode and nodes. A distinct weight loss was observed between 230–400 and 230–390°C at the internode and node, respectively.

Differential thermograms revealed that different mass losses due to different constituents present at different positions. From DTG curves, it can be concluded that two major processes took place when *G. brang* decomposed. It was observed that a minor weight loss occurred below 100°C, with peaks between temperatures of 25 and 105°C. These weight losses have been reported to be associated loss of water as a moisture evaporation process [65]. The main DTG peak was assigned to the decomposition of hemicellulose and cellulose [69]. The decomposition of lignin is indicated by clear wide tail due to devolatilization process [63]. In presence of nitrogen, it has been observed that mass loss of small biomass samples at lower heating rates usually produce one to two major distinct DTG peaks, corresponding to hemicellulose and cellulose pyrolysis. For example, Font et al. [70] inspected the thermal decomposition of almond shells at 10°C min⁻¹ in the inert atmosphere, resulting in two not completely separate DTG peaks, with one centering at around 310°C and other at 368°C.

In another study, one major peak was recorded for degradation of cotton stalk, sugarcane bagasse, rice straw, EFB, etc., under nitrogen while two peaks were reported by the same author for the degradation of these bioresources under oxygen. Thus, changes in the parameters like heating rate and atmospheric condition can sometimes merge the two peaks into

one very broad peak [70, 71]. Other study has reported thermogravimetric study on alkaline treated *Bamboosa balcua* both in strip and dust form. They observed that thermograms of untreated bamboo exhibited two steps of degradation in wide range between 50–150 and 426–150°C, respectively. The first step of degradation, 7.65% weight loss was assigned to moisture evaporation and variation in trend in weight loss was observed in treated samples depending upon concentration of alkaline used. It was found that with increase in concentration of alkaline the amount of moisture absorbed was decreased, which was evident from TGA curves. This observation was supported on the basis of crystallinity index [72]. The tendency to release absorbed moisture upon heating will decrease as water is strongly attached in a well packed structure leading to higher finished temperature.

Typical TGA curves determined and reported by researchers can be illustrated by **Figure 3**. Apart from this, the thermal degradation process of bamboo fiber reinforcement was studied by Rajulu et al. [73] and it was stated that the thermal degradation of the fibers follow a two stage process. The TGA curves obtained might due to the fact that bamboo is composed of a strong composite network, which is interlinked through inter and intramolecular hydrogen bonding between polyphenolic groups lignin, hemicelluloses and α -cellulosic components of this network. The second degradation temperature region corresponds to hemicellulose degradation present in bamboo fiber.

A study on different hemicellulosic subfractions of *Phyllostachys bambusoides* by Peng et al. [76] to explore the mass loss and compare thermal behavior of different fraction was carried out. It was observed that weight loss of among two isolated fractions (HA and H₄₅) mainly occurred in the range of 200–320°C and was found that HA fraction was more thermally stable than H₄₅, indicating that hemicelluloses exhibited more thermal stability than branched hemicelluloses. This observation was supported by DTG studies, where the DTG curves exhibited

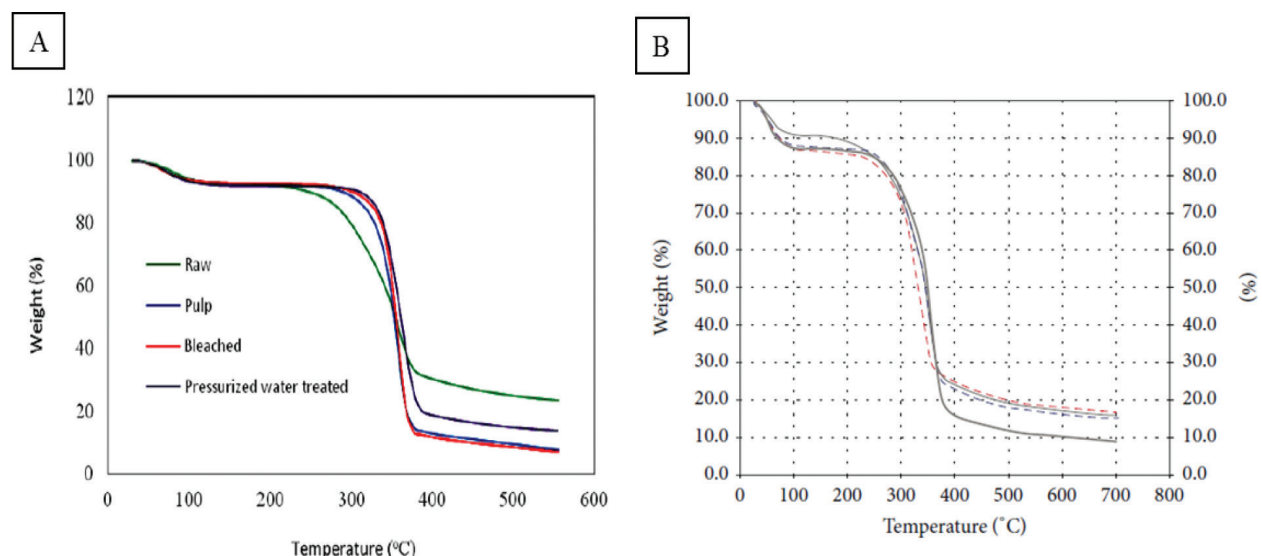


Figure 3. TGA thermograms of (A) raw, pulp, bleached, and pressurized enzyme hydrolysis bamboo fibers [74]; and (B) thermal analysis of green bamboo fiber, dewaxed bamboo fiber, delignified bamboo fiber and cellulose fiber [75].

the maximum peak at 296 and 293°C with shoulders at 242 and 237°C, respectively for H₄₅ fraction. These results were justified by different researchers with different view of explanation. Nowakowski et al. [77] corroborated the first peak with reduced temperature polymerization process leading to the formation of char, carbon monoxide, carbon dioxide and water. Meanwhile, the second peak was assigned to generation of volatile anhydrosugars and related monomeric compounds.

Mui et al. [61] reported that three key components of bamboo namely, xylan, cellulose, and lignin has one major decomposition step to volatiles and a minor decomposition to which leads to the formation of char. A well model theory was presented to explain the decomposition of these components from bamboo to volatiles and chars called as five component and six component systems. Different thermo-parameters were obtained by these model systems. Moreover, Krzesinska et al. [78] conducted the thermal studies on solid iron bamboo (*Dendrocalamus strictus*), a bamboo with unique properties. The thermal decomposition of *Dendrocalamus strictus* was studied at different temperatures varying from 300 to 600°C. It was found that in the case of both raw and pre-charred *Dendrocalamus strictus*, poor thermal decomposition is completely absent. These carbonized samples of *Dendrocalamus strictus* would be a bonus for manufacturing of thermally stable composites.

5. Conclusion

The foregoing discussions have explored the broader aspects of bamboo, cast as it were within the discourse on sustainable development. To conclude, the above findings of pertinence are worth reiterating here in debating the future challenges confronting the bamboo industry, even though the bamboo industry has contributed a lot to Malaysia's economy. Land use policy choice is becoming more concerned as conservation groups have asserted that much of the land is being cleared to grow bamboo, while increasing the carbon dioxide content of the atmosphere, bamboo is the best plant to utilize this carbon dioxide. There is still considerable scope for increased utilization and value added products from bamboo. Malaysia stands to benefit from such a policy turn as bamboo industry is able to participate in cutting edge agricultural research and innovation. To get in-depth knowledge about the structural use of bamboo the study on fundamental properties is a necessary step towards the effective utilization of bamboo in market. With more research, a large number of value-added bamboo products for higher profitability could be made available in the market. If implemented effectively, the policy turn to diversify bamboo products will reflect the bamboo industry's green revolution effort towards a sustainable future.

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