Monopodial and Sympodial Bamboos Grown in Tropic and Sub-tropic Countries – A Review

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Bamboo belongs to the grass family and is an important non-timber forest product in tropic and sub-tropic countries. The global trade of bamboo products is worth billions of dollars and is mainly dominant with monopodial bamboo grown in sub-tropic countries such as China and Japan. Many researchers globally discuss that in addition to species and region, bamboo quality can differ based on its rhizome types because the physiology is different for both monopodial and sympodial bamboo. However, there is a massive competition within the yearly forest products due to the challenges posed by underground root system in agroforestry. This review studied the properties of bamboo with regards to their differences in terms of monopodial and sympodial types of rhizomes. It was found that most of the structural, chemical organic, and mechanical properties are higher in monopodial bamboo, but there is a greater fibre morphology and decay resistance in the sympodial bamboo.

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INTRODUCTION

Bamboo is a monocotyledon plant and is classified as sub-family of Bambosoidea in the family of Graminae. Worldwide, bamboo consists of 119 genera and 1500 species under three main tribes, namely, Arundinarieae (temperate woody bamboo), Bambuseae (tropical woody bamboo), and Olyreae (herbaceous bamboo). They are distributed within the tropic and sub-tropic regions from sea level to the alpine, with the altitude or from 47° S° to 50° 30’ N and latitude from sea level to 4300 m (Clark *et al.* 2015). Bamboo stands exist in all continents except for Europe and Antarctica (Ram *et al.* 2010; Hagarth and Belcher 2013; Mera and Xu 2014).

Bamboo culms cover about 3.2% (37 million hectares) of the world forest area. Approximately 80% of the bamboo stand and species are distributed in the Asia and pacific regions (Mera and Xu 2014). China owns the largest bamboo forest area (601,000 km^2) followed by India (108,630) and Myammar (8950 km^2) (Fei *et al.* 2016). The deforestation that occurs in these countries is relieved by the emergence of bamboo forests and in turn this balances the ecosystem.

A bamboo forest is part of the forest ecosystem, and it acts as an important source of carbon and carbon sink (Li *et al.* 2003). Bamboo possesses a great advantage of reducing global warming by utilizing the carbon dioxide emission produced from modern vehicles, industries, and population growth. One hectare of bamboo culms is able to absorb more than twelve tons of carbon dioxide per year (Raka *et al.* 2011), while the dicotyledon trees only absorb slightly lower carbon dioxide, ranging from 1.1 to 9.5 tons per year (Chasan 2019). This is due to the fact that bamboo achieves its maximum growth within a one year and matures within 3 to 4 years for sympodoal bamboo and 7 to 8 years for monopodial bamboo (Razak *et al.* 2010; Fangchun 2001a,b). Depending on the bamboo culm, the photosynthesis process that produces carbohydrates for the growth and maturation is also involved in nutrient uptake from soils.

The bamboo culm grows toward maturation, and when it gets old, it loses its ability to uptake nutrients from soil. The amount of nutrients or inorganic contents in *Gigantochloa scortechinii* culm declines from a young age (6 months), toward its old age of 6.5 years (Norul Hisham *et al.* 2006). The oldest bamboo culm experiences an insufficiency in nutrients and will produce flowers and then die if it is not being utilised for any purpose. Therefore, mature bamboo culm needs to be harvested to allow a new shoot to emerge from the rhizome to produce a new culm. The age-maturation of bamboo culm is important to determine the harvesting cycle of each bamboo culm for production, propagation, and its overall sustainability for further utilization. The making of a specific bamboo product depends on the culm age for its maximum quality. Bamboo shoot as a food is best when it emerges less than 3 weeks from soils (Fangchun 2001b). The quality of bamboo higo products, such as barbeque and chop sticks, are maximum for the bamboo culm aged 1 to 2 years (Hamdan and Mohmod 1992). While the most suitable age for bamboo timber and flooring ranges from 3 to 4 years for sympodial bamboo to achieve its maximum strength (Sattar *et al.* 1994; Mohmod and Phang 2001; Banik 2015).

A mature bamboo culm as a biological material for human products evolved from traditional to a modern application parallel to human civilization. Historical records show that bamboo was used as fire work and in rockets during the Chinese dynasties (Deluca 2016). Indigenus people in Southeast Asia used bamboo as a rice cooker and in weapons in their daily life. Fei *et al.* (2016) mentioned that half of the world population utilizes bamboo products such as in housing, biocomposites, mats, chopsticks, charcoal, activated carbon, pulp, shoot, and other applications.

Medicine is another category of a small amount of bamboo products. The *Pleioblastus amarus* leaves can remedy fever, fidgeting, and lung inflammation (Kiruba *et al.* 2007). The extracts of *Sasa senanensis*, *Bambusa caulis*, and *Pseudosasa japonica* have anti-cancer activity (Panee 2009; Seki *et al.* 2010; Kim *et al.* 2013). In addition, bamboo is reported to have great potential for soil erosion control, water conservation, land rehabilitation, and carbon sequestration (Zhou *et al.* 2005).

The bamboo industry has evolved from being used as basic tools for domestic requirement to world commodities for international markets. The global bamboo market was about USD 68.8 billion in 2018 (Market Research Report 2019). The most popular product, woven bamboo, represents the largest proportion of global exports, estimated at USD 380 million in 2017 (Inbar 2020). China with the largest bamboo forest area is a main exporter for bamboo products. China's bamboo industry success is not only related to its culture that has been ever expanding, but the proper selection of bamboo species for a specific product for optimum qualities is the main contribution for success. Norul Hisham *et al.* (2006) explained that there are thousands of bamboo species worldwide and their properties differ by species, age, location, and other external factors. According to the phenotype, bamboo can be divided into three types of rhizomes, namely monopodial (leptomorph), sympodial (pachymorph), and amphipodial. The different rhizome structure possibly influences its growth, development, and maturation (Fangchun 2001a; Fei *et al.* 2016).

Despite being in the same tribe, the growth and development phases in monopodial and sympodial bamboo culms may be different due to different rhizome structures. Zhao *et al.* (2014) made comparison between the micro Ribonuleic acid (mRNA) of monopodial bamboo (*Phyllostachys pubescens*) and sympodial bamboo (*Dendrocalamus latiflorus*). In their reports, the rhizome of monopodial bamboo can spread laterally while grown in soil, and can also be separated from the mother plant, while sympodial bamboo grows in clusters within a relatively small range. The result indicates that there are 19,295,759 and 11,513,888 raw sequence reads, in which 92 and 69 conserve miRNAs, as well as 95 and 62 novel miRNAs are identified in *P. pubescens* and *D. latiflorus*, respectively. The ratio of high conserved miRNA families in *D. latiflorus* is more than that in *P. pubescens*. In addition, a total of 49 and 106 potential targets are predicted in *P. pubescens* and *D. latiflorus*, respectively, in which several targets for novel miRNAs are transcription factors that play important roles in plant development. Experiments show that miR397, miR1432, and miR7748 are specifically conserved in the leaf sample of *P. pubescens*.

Taken together, the comparison between *P. pubescens* and *D. latiflorus* indicate that monopodial and sympodial bamboo may share different miRNAs and target genes to have a better adaption for their development in different stages, and stress response in their diverse course of evolution. Therefore, monopodial bamboo requires more self-regulation to adapt to the environment than sympodial bamboo, which might be consistent with the generation of lower conserved miRNAs families. Fangchun (2001a) investigated the physical properties of 96 bamboo species and the mechanical properties of 65 bamboo species from both monopodial and sympodial bamboo. The moisture content, density, shrinkage, tensile, and compression properties vary by species, which originated from different rhizome type. The growth, development, and properties of some bamboo species either from monopodial and sympodial rhizomes may also be influenced by the site condition and climate of a specific area.

The International Network for Bamboo and Rattan (INBAR) proposed priority species of bamboo and rattan that include 20 taxa (species and genera) of particular economic importance and another important 18 taxa (Rao *et al.* 1998). In this context, the priority is based on its specific uses, and the main criteria for the classification of species-usage is general characteristics, such as diameter, wall thickness, internode length, and overall culm height. The priority species by the culm physical properties, *P. pubescens*, is categorized as medium to large monopodial bamboo with 10 to 20 m height, 18 to 20 cm diameter, internodes up to 45 cm long, and thick wall up to 2 cm (Rao *et al.* 1998). The *P. pubescens* is the most successful bamboo species in China for manufacturing glue-laminated timber flooring.

A similar characteristic in sympodial bamboo such as *Dendrocalamus asper* with up to 20 to 30 m height, internodes 20 to 45 cm long, diameter of 8 to 20 cm, and thick walls up to 2 cm, is that they are only used as furniture, musical instruments, chopsticks, household utensils, and handicrafts (Rao *et al.* 1998). The thick wall of *D. asper* does not give advantage for manufacturing glue-laminated board or flooring in Asian countries. The examples of end products from monopodial and sympodial bamboo species are shown in Table 1 and 2.

Table 1. Example of the Utilization of Monopodial and Sympodial Bamboo in China (Liu *et al.* 2018)

Value	Utilization	Product	Bamboo Species
Economic	Timber	Bamboo flooring; Pulp and paper; Construction material; Bamboo chopsticks	*P. edulis* (monopodial) *D. giganteus* (sympodial)
	Shoot	Fresh shoot Drying shoot Canned shoots Flavored shoot	*P. edulis* (monopodial) *D. brandisii* (sympodial) *D. latiflorus* (sympodial) *P. praecox* (monopodial)
	Skin/Bark	Tables and chairs Basket Wall of house	*Neosinocalamus affinis* *B. textilis* (sympodial) *B. chungii* (sympodial)
	Artistic	Musical instruments Bonsai Root carving	*Qiongzhuea tumidissinoda* *Chimonobambusa quadrangularis* *Pseudosasa amabilis* *P. nigra* (monopodial)
Ecological	Water conservation	Water conservation forest	*P. edulis* (monopodial) *D. giganteus* (monopodial)
	Ecotourism	Scenic spot	*P. aurea* (monopodial) *B. ventricosa* (sympodial) *Thyrsostachys siamensis*

Table 2. Example of the Utilization of Sympodial Bamboo in Malaysia

Value	Utilization	Product	Bamboo Species
Economic	Timber	Structure Parquet Furniture	*Gigantochloa thoii* *G. scortechinii* *D. asper ; G. ligulata* *G. wrayi ; G. brang* *B. vulgaris ; B. blumeana* *B. heterostachya* *B. vulgaris* cv. *vittata*
	Shoot	Fresh shoot Canned shoot	*B. vulgaris* *B. vulgaris var striata* *D. asper ; D. gigantues* *G. levis ; G. ligulata* *G. wrayi* *Schizostachyum brachycladum* *Trametes siamensis*
	Skin	Basketry Blind Craft	*G. brang* *S. brachycladum* *S. grande* *S. zollingeri* *B. vulgaris* *B. blumeana* *B. heterostachya* *B. vulgaris* cv *vittata*
	Art and Craft	Cooking vessel	*S. zollingeri*
	Utencil	Chopstick Tooth pick Barbeque stick	*D. asper* *G. scortechinii* *Gigantochloa* sp.

Another example is the trial of glue laminated bamboo board and flooring from sympodial bamboo *G. scortechinii* in Peninsular Malaysia during 1998 to 2001. The *G. scortechinii* culm has an internode ranging 32 to 50 cm long, 11 to 18 cm in diameter, and 6 to 9 mm in wall thickness (Norul Hisham *et al.* 2006), which is similar to *P. pubescens* grown in China. However, after two decades of trial, the quality appearance and marker acceptance of laminated bamboo flooring from *G. scortechinii* was not comparable to *P. pubescens*. In the period of 1998 to 2015, two laminated bamboo board factories in Malaysia were closed down due to lack of quality appearance for the local market. Another contributing factor is unsustainability of the material, as most of the stock is obtained in the natural forest and the bamboo plantation is not established at the beginning. This indicates that the quality of laminated bamboo flooring and other biocomposites is not only dependent on the basic and physical characteristics. Other properties, such as chemical, mechanical, machining, and appearance that vary between monopodial and sympodial bamboos, are a collective factor for optimum quality. In view of the above, this review aims to elaborate the properties characterization in monopodial and sympodial bamboos.

RHIZOME

The monopodial rhizome has a long and slender culm with a cylindrical or sub-cylindrical form. Its diameter usually is less than that of the culm coming from it (Fig. 1).

Its internode is longer, relatively uniform in length, rarely solid, typically hollow with interruptions at each node by a diaphragm; nodes in some genera usually elevated or inflated, in others no lateral buds in the dormant state are boat-shaped (McClure 1966). The monopodial bamboo is characterized as having strong frost resistance and is distributed in area of higher latitudes, such as Japan, Korea, Yellow River, and Yangtze Valley where there is a slight winter (Fangchun 2001a).

The sympodial rhizome has 6 to 7 large lateral buds on either side of the thick rhizome proper, and the buds grow up to new bamboos with a short rhizome neck (Fig. 1). The rhizome internodes are broader, long, solid, and asymmetrical, while the nodes are not elevated. The underground rhizome consists typically of two parts: the rhizome proper and the rhizome neck. The neck is basal to the rhizome proper, generally shorter in length and obconical in shape. It connects the new rhizome to the mother rhizome. Rhizomes are usually more or less curve-shaped and rarely straight, with maximum thickness, typically somewhat greater than that of the culm (Liese and Kohl 2015).

Being morphologically different, the monopodial bamboo rhizome can be extended horizontally under the soils depending on the species, and its length ranges from 50 to 70 m for *P. heteroxyxla*, 90 to 250 m for *P. viridis*, and 200 to 350 m for *P. niagra* (Jinghua 2000). Sympodial bamboo rhizome, such as *B. tulda*, can only be extended under the soils, up to 5.2 m (White and Childers 1945). Due to this capability, monopodial and sympodial bamboo rhizomes are commonly referred to as running and clumping bamboos, respectively. Amphipodial, which is a combination of monopodial and sympodial rhizomes, belongs to the genera including Bashania and Shibataea (Maoyi 2007). These genera originated from Japan.

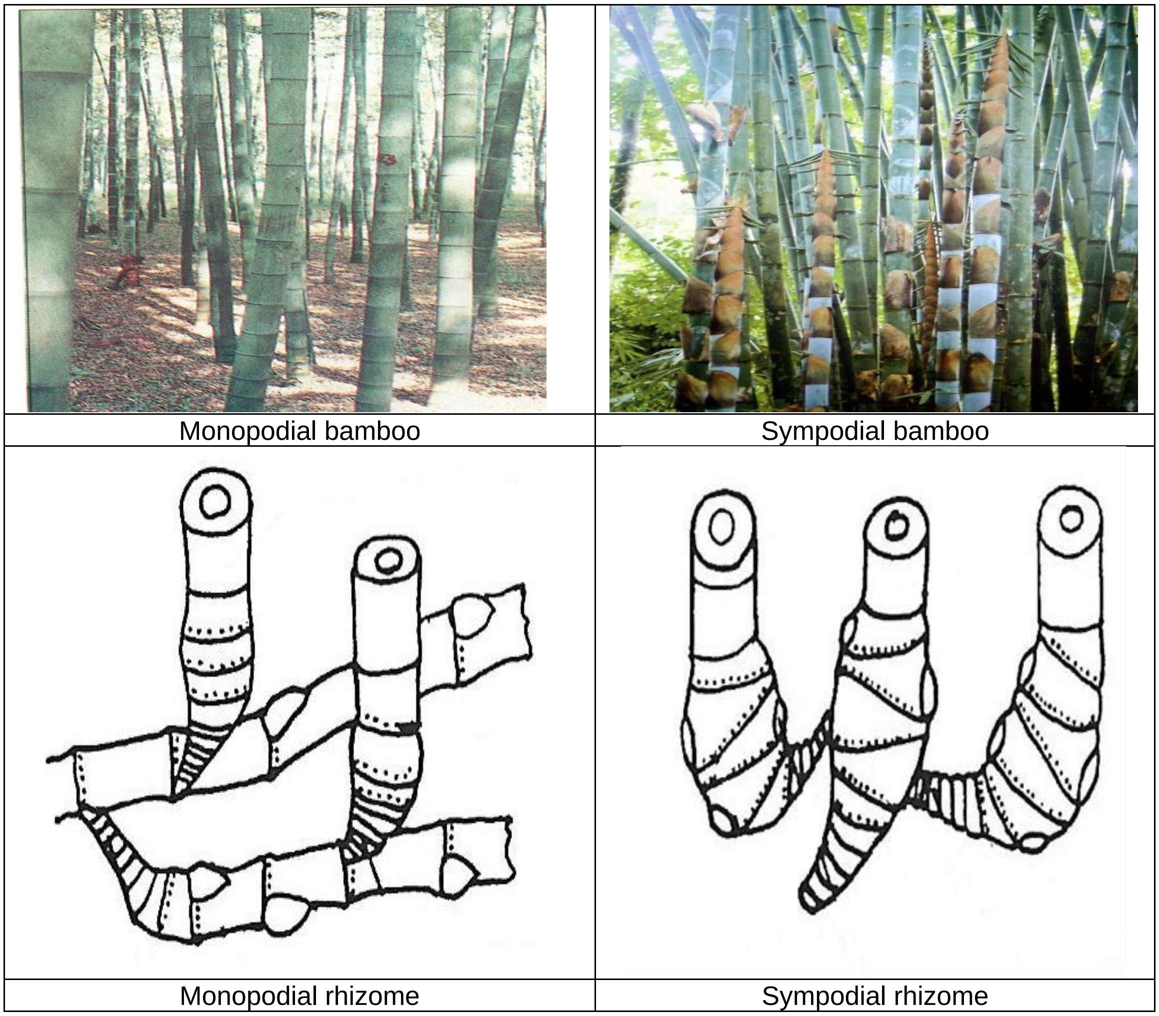

Fig. 1. Monopodial bamboo and rhizome and sympodial bamboo and rhizome (Redrawn with inspiration from Banik *et al.* 2015)

SPROUT AND GROWTH

Monopodial Bamboo

The *P. nigra* var. henosis has the shortest sprouting phase (19 days), followed by *P. nidularia* (20 days), and *P. makinio* (25 days) as shown in Table 2. The *P. heteroclade* has the longest sprouting phase (45 days) among the *Phyllostachys* genera. The sprouting phase of *P. pubescence* grown in China (28 days) is quicker than those grown in the USA (44 days). This is reflected by the different site and climate between these countries. The growth phase is quickest for *P. nigra* (24 days) followed by *P. pubescens* (31 days) and *P. makinoi* (32 days) in China (Hwang and Ma 1994; Zhang *et al.* 1997; Li *et al.* 2005).

Sympodial Bamboo

The *Fargesia spathecea* has the earliest sprouting phase (59 days) amongst the sympodial bamboo, followed by *F. robusta* (80 days) and *F. denudate* (90 days). *D. latiflorus* has the longest sprouting phase (180 days) amongst the sympodial bamboo. The growth phase is the quickest for *Fargesia robusta* (70 days) followed by *Dendrocalamopsis oldhani* (80 days) and *D. latiflorus* (90 days) in China (Zhou 1999; Qin *et al.* 1993; Gao *et al.* 2000).

Overall

The sprouting and growth phases are significantly shorter in monopodial bamboo (32.7 and 33.2 days) compared to the sympodial bamboo (105.8 and 102.6 days), respectively, from further analysis of the statistical data (Table 3). The bamboo shoot elongation rate within 24 h depends on the genera, species and rhizome. *P. reticulate* records the fastest growth rate (maximum 120 cm/day) for monopodial bamboo (Ueda 1960), and the rate is same as *D. asper* for sympodial bamboo (Subsansenee 1994). The growth rate of *B. balcooa*, *D. gigantus*, and *B. vulgaris* are recorded as 77 cm/day, 58 cm/day, and 44 cm/day, respectively (Osmastos 1918; Banik 1993).

Table 3. Sprouting and Growth Phases of Monopodial and Sympodial Bamboos

Species	Rhizome	Location	Sprout (days)	Growth (days)	Source
Arundinaria amabilis	Mono	S.E China	38	44	Fangchun (2001a)
A. fargesii	Mono	N. China	46	41	Fangchun (2001a)
Brachyschyum densiflorum	Mono	S. China	28	27	Fangchun (2001a)
Indocalamus barbatus	Mono	S. China	67	66	Fangchun (2001a)
Indosasa crassiflora	Mono	S. China	40	32	Fangchun (2001a)
P. august	Mono	S. China	22	26	Fangchun (2001a)
P. bambusoides f. Tanakae	Mono	C. China	26	27	Fangchun (2001a)
P. bambusoides Youngii	Mono	S. China	28	26	Fangchun (2001a)
P. bissetii	Mono	S.W China	35	29	Fangchun (2001a)
P. decora	Mono	E. China	22	24	Fangchun (2001a)
P. glauca	Mono	E. China	29	31	Fangchun (2001a)
P. glauca f. Yunzhu	Mono	C. China	30	28	Fangchun (2001a)
P. parvifolio	Mono	E. China	32	30	Fangchun (2001a)
P. praecox	Mono	S. China	29	28	Fangchun (2001a)
P. meyeri	Mono	E. China	53	36	Fangchun (2001a)
P. nigra	Mono	S. China	30	25	Fangchun (2001a)
P. nigra var. henonis	Mono	S. China	26	27	Fangchun (2001a)
P. nuda	Mono	S. China	28	33	Fangchun (2001a)
P. pubescens	Mono	E. china	30	40	Fangchun (2001a)
P. pubescens f. grammica	Mono	E. China	37	31	Fangchun (2001a)
P. rubella	Mono	E. china	38	37	Fangchun (2001a)
P. spextabilis	Mono	S. china	26	29	Fangchun (2001a)
P. viridis f. houzeauana	Mono	S. china	29	28	Fangchun (2001a)
P. vivax	Mono	S. China	28	28	Fangchun (2001a)
Sinobambusa laeta	Mono	S.E. China	54	50	Fangchun (2001a)
P. pubescens	Mono	S. China	31	NA	Zheng *et al.* (1998)
P. pubescens	Mono	E. China	28	33	Zhang *et al.* (1995)
P. pubescens	Mono	USA	44	70	Lee and Addis (2001)
P. nigra	Mono	E. China	27	24	Zhang *et al.* (1997)
P. makinoi	Mono	E. China	25	32	Huang and Ma (1994)

P. heteroclada	Mono	E. China	45	39	Jin et al. (1999)
P. nidularia	Mono	W. China	20	45	Zhang *et al.* (1995)
P. nigra var. *henonis*	Mono	C. China	19	34	Li *et al.* (2005)
F. robusta	Sym	W. China	80	70	Qin *et al.* (1993)
F. denudate	Sym	W. China	90	163	Wang *et al.* (1991)
F. spathacea	Sym	C. China	59	110	Li (2003)
Dendrocalamopsis oldhami	Sym	S. China	120	80	Gao *et al.* (2000)
D. latiflorus	Sym	E. China	180	90	Zhou (1999)

Mono – monopodial, Sym – sympodial, S.E – South east, N – North, S.W – South west, C- central, W – West, E- East, S – South

Table 4. Statistical Analysis of Sprouting and Growth Phases for Monopodial and Sympodial Bamboos

Phase	Monopodial	Sympodial	DF	F	Significance
Sprout (days)	32.7 (10.77)	105.8 (49.94)	1	16.3	0.000***
Growth (days)	33.2 (8.94)	102.6 (36.86)	1	20	0.000***

*** Significant at $P < 0.01$. The value in the parenthesis is standard deviation.

CULM DIAMETER AND HEIGHT

Most bamboo culm achieves maximum height within one year, without showing any further growth for subsequent years (Liese 1985). The classification of culm diameter and height is useful in helping to identify the growth factors for individual species in different site location, topography, climate, and other conditions (Fangchun 2001a). It is also commonly used to classify bamboo according to its suitable usage (Benton 2015; Liese and Kohl 2015). Fangchun (2001a) classified the bamboo growth according to the average diameter namely: Class 1 (diameter more than 12 cm), Class 2 (10 to 12 cm), Class 3 (8 to 10 cm), Class 4 (6 to 8 cm), and Class 5 (less than 6 cm).

Monopodial Bamboo

The *P. nigra* var. *henonis* grown in Central China achieves a maximum height of 400 cm in only 34 days (Li *et al.* 2005). The culm diameter and height vary with genera and species in different site locations (Table 4). The *P. makinoi* grown in the Dasi site, West Taiwan records the highest diameter at breast height (DBH), height, and point density (5.9 cm, 11.1 m, and 18767 culm/ha) compared to Jhudong site, West Taiwan (4.7 cm, 10.7 m, and 17567 culm/ha), respectively. The *P. pubescence* is grown in the Shi Zhua site, Taiwan with a lower temperature (11.5 °C), and higher elevation that has a significantly higher DBH, height, and culm density (10.6 cm, 21.4 m, and 8344 culm/ha) compared to the Hui sun site (6.8 cm, 10.3 m, and 7933 culm/ha), which has temperature and elevation of 20.3 °C and 667 m, respectively (Wang and Chen 2015). This indicates that the *P. pubescens* prefers the mountain climate with elevation of 1000 to 1500 m.

The majority of the monopodial bamboo (Table 5) species is classified as class 4 and 5, with exception of *P. pubescens* (Class 2). Physically, *P. pubescens* is selected for manufacturing laminated flooring and other composite board in China. The quantity of bamboo strips is proportional to the culm diameter. The *P. pubescens* records the longest culm (21.4 m) for monopodial bamboo. Other monopodial bamboo species produce a culm length less than 12 m (Table 4).

Sympodial Bamboo

Clump size also influences the culm DBH and height as in sympodial bamboo. Generally, the culm's DBH and height increases with increasing clump size (Table 5). The small (4.5 m^2), medium (7.13 m^2), and large (9.3 m^2) clump sizes of *B. stenostachya* produce the DBH (8.7 cm, 9.3 cm and 10.2 cm) and height (15.3 m, 17.4 m, and 20.3 m) respectively (Chen *et al*. 2012). The sympodial bamboos have all the classes as shown in Table 5. The species with diameter class 1 including *D. asper*, *D. latiflorus*, *G. levis*, *Melocanna bambusoides*, and *Oxytenanthera abyssinica*. Others, including *B. vulgaris* var. *striata*, *B. stenostachya*, *Gigantochloa scortechinii*, *G. wrayi*, and *S. grande* are classified as class 2, the same as *P. pubescens*. The *D. latiflorus* and *T. oliveri* are recorded as the longest culm (25 m) for sympodial bamboo. This is followed by *B. vulgaris* var. *striata*, *D. asper*, and *M. bambusoides* (23 m), and lastly, by *B. stenostachya*, *G. ligulata*, and *S. funghomii* (20 m).

Overall

The sympodial bamboo (9.3 cm and 17 m) has a significantly higher DBH and height than monopodial bamboo (5.6 cm and 10.8 m), as shown by the statistical analysis of the data (Table 5). This factor may be due to the fact that most sympodial bamboo are grown in tropical countries that are rich in sunlight and rain for photosynthesis. The starch stored in parenchyma is used for the culm growth. By contrast, most monopodial bamboo is grown in temperate countries with less sunlight, and the starch are stored in the parenchyma that are later used for their sustenance during winter and snow.

Table 5. DBH and Maximum Height of Monopodial and Sympodial Bamboo

Species	Diameter		Max. Height (m)	Reference
	Max. DBH (cm)	Class		
Monopodial				
P. pubescens	10.8	2	14.6	Inove *et al.* (2009)
P. bambusoides	6.8	4	14.9	Inove *et al.* (2009)
P. nigra var. *henonis*	2.3	5	5.9	Inove *et al.* (2009)
P. nigra Munro	1.2	5	3.3	Inove *et al.* (2009)
P. bambusoides f. Castillon	0.7	5	2.3	Inove *et al.* (2009)
P. virida-glaucescens	3.9	5	10.1	Gratani *et al.* (2008)
P. pubescens	10.7	3	14.3	Gratani *et al.* (2008)
P. bambusoides	4.4	5	6.0	Gratani *et al.* (2008)
P. pubescens	6.8	4	10.3	Wang *et al.* (2009)
P. pubescens	10.6	2	21.4	Wang *et al.* (2009)
P. makinoi	5.2	5	10.2	Wang and Shen (1987)
P. makinoi	5.0	5	10.7	Wang and Shen (1987)
P. makinoi	4.7	5	10.7	Wang and Shen (1987)
P. makinoi	5.9	5	11.1	Wang and Shen (1987)
P. makinoi	5.4	5	10.8	Wang and Shen (1987)
P. makinoi	5.2	5	11.3	Wang and Shen (1987)
Sympodial				
B. blumeana	9	3	13	Azmy and Razak (1991)
B. heterostachys	5	5	18	Azmy and Razak (1991)
B. vulgaris	9	3	18	Azmy and Razak (1991)
B. vulgaris var. *striata*	10	2	23	Azmy and Razak (1991)
B. stenostachya	8.7	4	15.3	Chen *et al.* (2012)

B. stenostachya	9.3	4	17.4	Chen *et al.* (2012)
B. stenostachya	10.2	2	20.3	Chen *et al.* (2012)
D. asper	13	1	23	Azmy and Razak (1991)
D. latiflorus	20	1	25	Lu (2001)
G. levis	13	1	10	Azmy and Razak (1991)
G. ligulata	3.5	5	20	Azmy and Razak (1991)
G. scortechinii	11	2	18	Azmy and Razak (1991)
G. wrayi	10	2	12	Azmy and Razak (1991)
S. brachycladum	7	4	21	Azmy and Razak (1991)
S. grande	11	2	12	Azmy and Razak (1991)
S. zollingeri	7	4	15	Azmy and Razak (1991)
Guadua augustifolia	8.41	3	16.7	Riano *et al.* (2002)
M. bambusoides	15	1	23	Liese (1985)
Ochlandra travancorica	5	5	6	Liese (1985)
Ox. abyssinica	15	1	15	Liese (1985)
O. albociliata	3	5	10	Liese (1985)
O. nigro-ciliata	10	3	15	Liese (1985)
S. brachycladum	7	4	13	Liese (1985)
S. funghomii	10	3	20	Inbar (2010)
Teinostachym dulloa	10	3	23	Liese (1985)
T. oliveri	8	4	25	Liese (1985)
T. siamensis	6	4	13	Liese (1985)

Table 6. Statistical Analysis of Basic Characteristics of Monopodial and Sympodial Bamboos

Characteristic	Monopodial	Sympodial	DF	F	Significance
DBH (cm)	5.6 (3.1)	9.3 (3.7)	9	1.93	0.09*
Height (m)	10.8 (4.7)	17.0 (5.0)	9	2.06	0.07*

*****Significant at P < 0.1

The application of NPK (the proportion of three plant nutrients in order: nitrogen (N), phosphorus (P) and potassium (K)) fertilizer of 0.75 to 0.93 kg/clump at 2 or 3 times per year could increase the bamboo production for *Neosinocalamus affinis* (Long and Jiang 1996). The *G. levis* clump applied with 12 kg chicken manure gives the highest shoot sprouting. The fertilization using cow dung, chicken manure, and rusk husk ash at 0.5, 1, and 2 kg per clump during growth and development in *G. leavis* and *D. asper* were only important at the first year of plantation establishment (Fernandez *et al.* 2003). The average DBH of *P. pubescens* clump aged more than one year fertilized with N:P:K (244 kg N ha/year, 196 kg P/ha, 196 kg K ha/year) for 30 years is identical with the unfertilized clump (10.1 cm). This shows that the bamboo achieves its maximum growth in one year, as mentioned by Liese (1985) and Banik (2015).

ANATOMY

Microstructure

In the transverse section, the microstructure of monopodial and sympodial bamboo is the same as they are both covered by epidermis, hypodermis, and cortex in the outermost zone. The epidermis consists of axially elongated cells, shorter cork, silica cells, and stomata. The epidermis cells are always covered on the outside by a cutinized layer of cellulose and pectin with tangential lamellation. Its main function is for water blockage and tissue protection. The hypodermis is the next layer, and it consists of several layers of thick-walled scerenchymatous cells. This is followed by the pith ring or pith periphery, in which a non-vascular tissue is composed of layers of parenchyma cells, and often heavily thickened and lignified. They are commonly long in tangential direction, but small in radial and longitudinal directions. The ground tissue is next to the pith ring. The ground tissue contains parenchyma cells with embedded vascular bundle (Grosser and Liese 1971).

Table 7. Vascular Bundle Type Classification by Grosser and Liese (1971, 1973)

Type	Characteristic	Occurrence
I Open-type	Consisting of one part (central vascular strand) with supporting tissue as sclerenchyma sheaths; intercellular space with tyloses. Type I is also called 'open-type'	All species with leptomorph rhizomes (*Arundinaria, Phyllostachys*)
II Tight-waist type	Consisting of one part (central vascular strand); supporting tissue as sclerenchyma sheaths; sheath at the intercellular space (protoxylem) strikingly larger than the two lateral ones and extends in a fan-like shape; intercellular space without tyloses. Type II is also called 'tight-waist type'.	In species with pachymorph rhizomes growing either in single culm formation (*Melocanna*) or in clumps (*Cepha- lostachyum, Schizostachyum*, and *Teinostachyum*). In *Cephalostachyum*, as only type throughout the culm; in *Melocanna, Schizostachyum,* and *Teinostachyum* in the base internodes often together with type III.
III	Consisting of two parts (central vascular strand and one fibre strand); fibre strand inside the central strand; sheath at the inner cellular space (protoxylem) generally smaller than the other ones.	In dump-forming species with pachymorph rhizomes (*Bambusa*, *Dendrocalamus*, *Gigantochloa*, and *Thyrsostachys*); at the base internodes combined mostly with type IV, in the middle and upper parts as only type. In *Melocanna*, *Schizostachyum*, and *Teinostachyum* combined at the base internodes with type II. In some *Oxytenanthera* spp. as only type throughout the culm
IV	Consisting of three parts (central vascular strand and two fibre strands); fibre strands outside and inside the central strand.	In clump-forming species with pachymorph rhizomes (*Bambusa*, *Dendrocalamus*, *Gigantochloa*, and *Thyrsostachys*); mostly at the base internodes, seldom at the middle part; always combined with type III

The thin walls of parenchyma cells are connected to each other by numerous simple pits. The cell is thinner than the fibre wall, and they are located mainly on the longitudinal walls, while the horizontal walls are scarcely pitted. The parenchyma tissue is lignified during the sprouting of the culm and the cells may store a certain amount of starch. A small and elongated parenchyma cell, like a cubic cell, appear and are interspersed between the long cells. The cubic-like cell is characterized with a denser cytoplasm and thin walls, it is not lignified even in mature culm (Grosser and Liese 1971).

Vascular Bundle

The bamboo vascular bundle consists of two metaxylem vessels, phloem, and protoxylem attached to the fibre bundle. The size and shape vary with genera and species, as well as along the internode height and across the culm wall in transverse direction. The classification of vascular bundle was slightly different between European and Chinese researchers. Grosser and Liese (1971, 1973) on their detailed analysis of 52 species in 14 genera classified the vascular bundle to four different classes as shown in Table 7.

Types I, II, III, and IV of the vascular bundles obtained from sympodial bamboo are reported by researchers (Suzuki and Itoh 2001; Sharma *et al.* 2017; Nordahlia *et al.* 2019). In contrast to the vascular bundle classified by Grosser and Liese (1971), Xin and Qion (1983) classified vascular bundles into four different classes using 10 genera and 45 species belonging to monopodial bamboo natively from China (Table 8).

Table 8. Classification of Vascular Bundle Type According to Xin and Qion (1983)

Type	Characteristic	Occurrence
I	Vascular bundles are separated by parenchyma. No air canals in cortex.	Bamboo with the following species: *Phyllostachys arcana*, *P. aurea*, *P. aureosulcata*, *P. bambusoides*, *P. bambusoides* var. *tanakae*, *P. bambusoides* var. *castilloni*, *P. bambusoides* var. *castilloni-inverssa*, *P. besseti*, *P. decora*, *P. dulcis*, *P. flexsuosa*, *P. glauca*, *P. glauca f. Yunzu*, *P. meyeri*, *P. nigra*, *P. nigra* var. *henonis*, *P. nuda*, *P. nuda f. Localis*, *P. viridis*, *P. platyglossa*, *P. praecox*, *P. Prapinqua,* and *P. pubescen*s.
II	Vascular bundles are isolated. Between them, there are fibre cell groups in rectangular, round, or variant forms, and they are never linked. These are mostly peripheral in position. No air canals in cortex	Bamboo with the following species: *Indocalamus longiauritus*, *I. victorialis*, *Pleioblastus amarus*, *Pl. gramineus*, *Pl.* sp., *Psudosasa amabilis*, and *Sinobambusa tootsik*
III	Vascular bundles are linked, occasionally with very narrow gaps of parenchyma interrupting air canals in cortex	Bamboo with the following species: *Phyllostachys heteroclada* and *Ph. nidularia*
IV	Vascular bundles are connected in the form of a ring enclosing stele. No air canals in cortex	Bamboo with the following species: *Arundinaria fargesii, Chimonobambusa utilis, Ch. quadrangular, Ch. purpurea, Qionzbuea lumidinoda, Sasa unbigena*, and *Sinarundinaria fangiana*

Vascular bundle classification made by Grosser and Liese (1971) is mostly used and referred to by many researchers worldwide. In an anatomical structure point of view, the sympodial bamboo has more fibre strands or island at the bottom (Type III), and both bottom and top (Type IV) of vascular bundle. This generally gives additional support and strength to the culm. The monopodial bamboo is structured by only a central vascular bundle (Type I) and surrounded with sclerenchyma sheaths. Therefore, the monopodial bamboo, such as *P. pubescens*, is more pliable and softer, which is advantageous during processing such as cutting, splitting, moulding, and sanding. The type of vascular bundle may be the same or differ within the individual culm of each species. In monopodial bamboo, the *S. manii* grown in India has vascular bundle Type I, as classified by Grosser and Liese (1971), along its culm height (Naithani *et al.* 2010). In contrast, Sharma *et al.*

(2017) found a Type III vascular bundle at the basal and middle portions, while the Type II of vascular bundle was at the top portion of *S. manii*. The *P. pubescens*, *P. nigra*, and *P. bambusoides* grown in South Korea have vascular bundle Type 1 with tylosoid in the intercellular space (Jeon *et al.* 2018).

Monopodial Bamboo

The vascular bundle dimension and shape vary with genera, species, site location, culm height, and diameter in transverse section (Mohamed *et al.* 2019). In monopodial bamboo (Table 9), the vascular bundle frequency differs across the transverse and longitudinal directions. The frequency of vascular bundle in 12 China bamboo species is biggest at the outer zone ($14/mm^2$), followed by the middle zone ($4.8/mm^2$), and smallest at the inner zone ($2.9/mm^2$). The frequency is also increased with the internode height in *P. pubescens* (Fangchun 2001a). The frequency of vascular bundle is highest in order of *Arundinaria japonica* ($7/mm^2$), *Brachystachyum densiflorum* ($7/mm^2$), and *Indocalamus mingoi* ($6.67/ mm^2$).

Sympodial Bamboo

In sympodial bamboo, the *S. pergracile* has Type II vascular bundle along the culm height (Sharma *et al.* 2017). The *B. rigida* grown in Sichuan, China has vascular bundle Type III at the middle zone of the transverse direction, while Type I and II are located at inner and outer zone, respectively (Huang *et al.* 2015). In the transverse direction, the *D. brandisii* grown in China has vascular bundle Type II, Type III, and Type V at the periphery, middle, and outer zones, respectively (Wang *et al.* 2016). The vascular bundle of bamboo grown in Malaysia is dominated with Type II, III, and IV. The species with Type II includes *S. brachycladum* and *S. zollingeri*. The Type III includes *G. thoii*, *G. scortechinii*, *G. ligulata*, *G. wrayi*, *G. brang*, *S. grande*, *B. heterostachyum*, and *B. vulgaris* cv. *vittata*. Type IV includes *B. vulgaris*, *B. blumeana*, and *D. asper*. In all cases, the vascular bundle Type IV is mostly classified as a thick-walled and large-diameter bamboo species (Nordahlia *et al.* 2019). This indicates that the vascular bundle type may be similar to or different from each of the individual culm of the same species.

The vascular bundle dimension for radial/tangential (R/T) in sympodial bamboo, *G. scortechinii* increases from the inner zone to the outer zone, and it significantly differed at the middle portion with age. A smaller vascular bundle tends to be denser than a bigger one (Norul Hisham *et al.* 2006). The R/T ratio of vascular bundle increases from inner zone toward the outer zone in basal, middle, and top portion of *B. rigida* aged 1, 3, and 5 years. Overall, the R/T ratio of vascular bundle is not significantly different with culm height for all ages (Huang *et al.* 2015). The radial length and tangential diameter of vascular bundle in *G. scortechinii* is longer at the nodal portion compared to the internode portion (Table 10). In the internode, the vascular bundle is longest in descending order of *G. levis* (1171.14 µm), *G. scortechinii* (787.2 µm), and *G. wrayi* (754.1 µm). In the node, the vascular bundle length in descending order is *G. levis* (1193.2 µm), *G. scortechinii* (1078.2 µm), and *G. wrayi* (963.4 µm). In the internode, the vascular bundle width is highest in *G. levis* (798.3 µm), followed by *G. scortechini* (544.6 µm), and *G. wrayi* (532.9 µm). In the node, the vascular bundle width in descending order is *G. levis* (720.4 µm), *G. scortechinii* (587.9 µm), and *G. wrayi* (685.8 µm) (Mohd Tamizi *et al.* 2011).

The metaxylem vessel diameter increases from the outer zone toward the inner zone in all age classes of *G. scortechiii* (0.5, 1.5. 3.5, 5.5, and 6.5 years) (Table 11). Vessel diameter is significantly bigger with age at the outer and inner zones, but this is not the same at the middle zone. The diameter gradually increased from the youngest age of 0.5 years (0.51 μm) to a maximum diameter at the age of 5.5 years (0.62 μm). The vessel diameter in *G. scortechinii* is also smaller than *P. pubescens*, which has an average of 0.98 μm (Fangchun 2000a). A smaller metaxylem vessel diameter is reported in *D. brandisii* (Wang *et al.* 2016), where it slightly increases with age from 139.4 μm (aged 1 year) to 162.0 μm (aged 3 years). The metaxylem vessel is slightly elliptical in *B. rigida* due to the radial length is longer than the tangential diameter (Table 9). The metaxylem vessel diameter is not significantly different with age but it tends to be slightly smaller from the basal portion toward the top. The diameter also significantly increases from outer part of the vessel towards the inner in all ages. The metaxylem diameter ranges from 112.3 μm to 127.4 μm, 97.8 μm to 127.5 μm, and 104.6 μm to 129.2 μm for bamboo aged 1, 3, and 5 years, respectively (Huang *et al.* 2015). Liu *et al.* (1998) mentioned that larger vessel diameter in laminated bamboo of *D. latifflorus* could probably cause its lower glue bond strength compared to *P. edulis*.

Table 9. Vascular Bundle Frequency in Monopodial and Sympodial Bamboos

Species	Vascular Bundle Frequency (mm^2)	Reference
Monopodial		
A. japonica	7.00	Fangchun (2001a)
Brachystachyum densiflora	7.00	Fangchun (2001a)
C. quadrangularis	5.00	Fangchun (2001a)
I. migoi	6.67	Fangchun (2001a)
P. bambusoides	3.67	Fangchun (2001a)
P. glauca	5.67	Fangchun (2001a)
P. pubescens	3.00	Fangchun (2001a)
Pleioblatus amarus	4.67	Fangchun (2001a)
S. manii	3.93	Fangchun (2001a)
Sympodial		
S. pergracile	3.27	Fei *et al.* (2016)
S. munroi	2.91	Fei *et al.* (2016)
D. giganteus	1.13	Fei *et al.* (2016)
B. sinospinosa	1.06	Fei *et al.* (2016)
D. farinosus	3.08	Fei *et al.* (2016)
B. rigida	1.69	Fei *et al.* (2016)
B. pervariadilis	1.51	Fei *et al.* (2016)
B. rigida (1 years)	4.98	Huang *et al.* (2015)
B. rigida (3 years)	5.04	Huang *et al.* (2015)
B. rigida (5 years)	5.04	Huang *et al.* (2015)
G. brang	6.38	Mohd. Tamizi *et al.* (2011)
G. levis	4.33	Mohd. Tamizi *et al.* (2011)
G. scortechinii	7.73	Mohd. Tamizi *et al.* (2011)
G. scortechinii (one month)	0.64	Mohamed *et al.* (2019)
G. scortechinii (1 year)	0.64	Mohamed *et al.* (2019)
G. scortechinii (2 years)	0.64	Mohamed *et al.* (2019)
G. scortechinii (3 years)	0.64	Mohamed *et al.* (2019)
G. wrayi	6.84	Mohd. Tamizi et al (2011)
B. blumeana (1 year)	0.84	Mohmod *et al.* (1993)
B. blumeana (2 years)	0.66	Mohmod *et al.* (1993)
B. blumeana (3 years)	0.82	Mohmod *et al.* (1993)
B. blumeana	2.89	Espiloy (1987)
G. levis	1.56	Espiloy (1987)

Table 10. Radial Length, Tangential Diameter, and R/T Ratio of Vascular Bundle in Monopodial and Sympodial Bamboos

Species	Vascular Bundle (µm)			Reference
	Radial (R)	**Tangential (T)**	**R/T**	
Monopodial				
A. japonica	0.40	0.36	1.11	Fangchun (2001a)
Brachystachyum densiflora	0.34	0.31	1.10	Fangchun (2001a)
C. quadrangularis	0.29	0.25	1.16	Fangchun (2001a)
I. migoi	0.20	0.27	0.74	Fangchun (2001a)
P. bambusoides	0.54	0.48	1.13	Fangchun (2001a)
P. glauca	0.45	0.35	1.29	Fangchun (2001a)
P. pubescens	0.50	0.49	1.02	Fangchun (2001a)
Pleioblatus amarus	0.42	0.43	0.98	Fangchun (2001a)
Sympodial				
G. scortechinii (0.5 year)	-	-	1.25	Norul Hisham *et al.* (2006)
G. scortechinii (1.5 years)	-	-	1.28	Norul Hisham *et al.* (2006)
G. scortechinii (3.5 years)	-	-	1.20	Norul Hisham *et al.* (2006)
G. scortechinii (5.5 years)	-	-	1.20	Norul Hisham *et al.* (2006)
G. scortechinii (6.5 years)	-	-	1.22	Norul Hisham *et al.* (2006)
G. brang	0.79	0.51	1.55	Mohd Tamizi *et al.* (2011)
G. levis	1.17	0.80	1.46	Mohd Tamizi *et al.* (2011)
G. scortechinii	0.79	0.50	1.58	Mohd Tamizi *et al.* (2011)
G. wrayi	0.75	0.53	1.42	Mohd Tamizi *et al.* (2011)
D. giganteus	0.86	0.70	1.43	Fei *et al.* (2016)
B. sinospinosa	0.71	0.74	0.96	Fei *et al.* (2016)
D. farinosus	0.66	0.55	1.20	Fei *et al.* (2016)
B. rigida	0.76	0.64	1.19	Fei *et al.* (2016)
B. pervariadilis	0.79	0.70	1.13	Fei *et al.* (2016)
B. rigida (1 year)	-	-	1.25	Huang *et al.* (2015)
B. rigida (3 years)	-	-	1.18	Huang *et al.* (2015)
B. rigida (5 years)	-	-	1.16	Huang *et al.* (2015)
B. blumeana (1 year)	-	-	1.00	Mohmod *et al.* (1990)
B. blumeana (2 years)	-	-	0.91	Mohmod *et al.* (1990)
B. blumeana (3 years)	-	-	0.95	Mohmod *et al.* (1990)
B. vulgaris (1 year)	-	-	1.38	Mohmod *et al.* (1990)
B. vulgaris (2 years)	-	-	1.33	Mohmod *et al.* (1990)
B. vulgaris (3 years)	-	-	1.33	Mohmod *et al.* (1990)
G. scortechinii (1 year)	-	-	0.84	Mohmod *et al.* (1990)
G. scortechinii (2 years)	-	-	1.36	Mohmod *et al.* (1990)
G. scortechinii (3 years)	-	-	1.11	Mohmod *et al.* (1990)

Overall Features

The radial length and tangential diameter of the vascular bundle is significantly higher in monopodial bamboo (0.39 µm and 0.37 µm) than sympodial bamboo (0.28 µm and 0.22 µm), respectively, as shown in the statistical reanalysis results (Table 12). While the R/T ratio of vascular bundle is significantly higher in sympodial bamboo (1.23) than the monopodial bamboo (1.07), the metaxylem vessel diameter is significantly higher in sympodial (127.97 μm) than the monopodial bamboo (72.38 μm). In contrast, the vascular bundle frequency is significantly higher in monopodial (5.18/mm^2) than the sympodial bamboo (2.80/mm^2).

Table 11. Metaxylem Vessel Diameter in Monopodial and Sympodial Bamboos

Species	Metaxylem Vessel Diameter (μm)	Reference
Monopodial		
A. japonica	54.0	Fangchun (2001a)
Brachystachyum densiflora	76.3	Fangchun (2001a)
C. quadrangularis	57.3	Fangchun (2001a)
I. migoi	45.3	Fangchun (2001a)
P. bambusoides	109.7	Fangchun (2001a)
P. glauca	78.3	Fangchun (2001a)
P. pubescens	98.0	Fangchun (2001a)
P. b.f zitchiku	58	Fangchun (2001a)
P. congesta	65	Fangchun (2001a)
P. nuda	68	Fangchun (2001a)
Pleioblatus amarus	91.0	Fangchun (2001a)
A. amabiris	89	Fangchun (2001a)
Chimonobambusa marmorea	73	Fangchun (2001a)
C. quadragularis	62	Fangchun (2001a)
C. utilis	77	Fangchun (2001a)
S. manii	56.2	Sharma *et al.* (2017)
Sympodial		
B. rigida (1 year)	121.4	Huang *et al.* (2015)
B. rigida (3 years)	113.2	Huang *et al.* (2015)
B. rigida (5 years)	117.0	Huang *et al.* (2015)
D. brandisii (1 year)	139.4	Wang *et al.* (2016)
D. brandisii (2 years)	147.1	Wang *et al.* (2016)
D. brandisii (3 years)	162.0	Wang *et al.* (2016)
G. scortechinii (0.5 year)	51.0	Norul Hisham *et al.* (2006)
G. scortechinii (1.5 years)	54.0	Norul Hisham *et al.* (2006)
G. scortechinii (3.5 years)	57.0	Norul Hisham *et al.* (2006)
G. scortechinii (5.5 years)	62.0	Norul Hisham *et al.* (2006)
G. scortechinii (6.5 years)	50.0	Norul Hisham *et al.* (2006)
Neosinocalamus affinis	191.5	Luo *et al.* (2019)
B. intermedia	168.7	Luo *et al.* (2019)
B. multiplex	170.4	Luo *et al.* (2019)
B. rigida	185.1	Luo *et al.* (2019)
B. blumeana	165.5	Espiloy (1987)
G. levis	220.2	Espiloy (1987)

Table 12. Statistical Reanalysis of the Vascular Bundle Elements in Monopodial and Sympodial bamboos

Characteristic	Monopodial	Sympodial	DF	F	Significance
Radial length	0.39 (0.11)	0.28 (0.40)	1	0.08	0.44[NS]
Tangential diameter	0.37 (0.09)	0.22 (0.25)	1	0.14	0.20[NS]
R/T	1.07 (0.16)	1.23 (0.19)	1	0.16	0.04**
Vascular bundle frequency	5.18 (0.69)	2.80 (0.43)	1	8.47	0.000**
Metaxylem vessel diameter	72.38 (17.69)	127.97 (49.92)	1	14.6	0.001**

DF– Degree of freedom, F– F ratio, NS is not significant at $P > 0.1$, * is significant at $P < 0.1$, ** is significant at $P < 0.05$. The value in parentheses is standard deviation.

The proportion of metaxylem vessel diameter is significantly higher in sympodial (6.40%) than the monopodial bamboo (5.21%), but not for fibre and parenchyma proportions. The proportion of fibre and parenchyma are not significantly different for monopodial (40.92% and 45.56%) and sympodial (53.00% and 53.38%) bamboos, respectively.

Fibre Morphology

Monopodial bamboo

In monopodial bamboo (Table 13), *I. migoi* and *P. pubescens* growing in China have the longest fibre (2250 μm), while the *Indocalamus tessellatus* grown in China has the shortest fibre (1435 μm). The *Brachycladum densiflorus* grown in China records the widest fibre (16.9 μm), while the *Arundinaria amabilis* also grown in China has the thickest fibre wall, and the *P. viridis* grown in USA has the widest fibre lumen (5.63 μm). The fibre of the three monopodial bamboos grown in Taiwan is the longest, when ranked in descending order of *Phyllostachys bambusoides* (2033 to 2239 μm), *P. nigra* (1934 to 2199 μm), and *P. pubescens* (1375 to 1573 μm). The outer zone has a longer fibre than the inner zone for all species (Jeon *et al.* 2018).

Table 13. Fibre Morphology in Monopodial and Sympodial Bamboos

Species	Origin	FL (μm)	FD (μm)	FLD (μm)	FWT (μm)	References
Monopodial						
A. amabilis	China	2338	15.3	3.81	5.23	Fangchun (2001a)
A. japoniea	China	1990	15.8	2.57	6.18	Fangchun (2001a)
Brachystachyum densiflorum	China	2175	16.9			Fangchun (2001a)
C. quadrangularis	China	1700	14.8	3.48	3.63	Fangchun (2001a)
C. utilitis	China	2230	11.9	4.67	2.41	Fangchun (2001a)
I. migoi	China	2250	14.0			Fangchun (2001a)
I. tessellatus	China	1435	13.5			Fangchun (2001a)
P. congesta	China	1784	12.7	2.82	4.02	Fangchun (2001a)
P. flexuosa	USA	1540	9.6	4.09	3.28	Fangchun (2001a)
P. heterocycle	Brasil	1690	8.7	3.17	3.94	Fangchun (2001a)
P. pubescens	China	2250	13.6	3.12	3.75	Fangchun (2001a)
P. viridis	China	1886	14.3	4.14	2.87	Fangchun (2001a)
P. viridis	USA	1690	11.4	5.63	2.10	Fangchun (2001a)

Pleioblastus amarus	China	2129	14.4	2.49	5.78	Fangchun (2001a)
P. pubescens	Korea	1474				Jeon *et al.* (2018)
P. nigra	Korea	2066				Jeon *et al.* (2018)
P. bambusoides	Korea	2136				Jeon *et al.* (2018)
Sympodial						
B. basihirsuta	China	1667	14.4	2.35	2.14	Fangchun (2001a)
B. boniopis	China	1788	14.2	4.24	1.44	Fangchun (2001a)
B. corginera	China	2482	16.3	2.50	2.56	Fangchun (2001a)
B. dessimulator	China	1861	18.0	3.38	2.13	Fangchun (2001a)
B. eutuldoides	China	1993	16.9	1.66	4.08	Fangchun (2001a)
B. glaucescens	China	2115	14.9	2.13	3.39	Fangchun (2001a)
B. glaucescens	China	2079	15.9	2.49	2.85	Fangchun (2001a)
B. gibboides	China	2135	16.8	2.65	3.16	Fangchun (2001a)
B. lapidea	China	2390	10.8	5.59	2.05	Fangchun (2001a)
B. lapidea	China	2363	13.5	3.23	2.23	Fangchun (2001a)
B. longiflora	China	1806	16	2.05	3.61	Fangchun (2001a)
B. multiplex	China	2385	13.1	2.78	4.68	Fangchun (2001a)
B. pervariabilis	China	2036	14.1	3.71	2.83	Fangchun (2001a)
B. rigida	China	2230	13.7	5.77	1.22	Fangchun (2001a)
B. sinospinosa	China	2450	16.2	7.34	1.37	Fangchun (2001a)
B. spinosa	China	2270	14.7	5.28	1.94	Fangchun (2001a)
B. textillis	China	2480	14.9	3.37	4.63	Fangchun (2001a)
B. textillis	China	2236	14.4	2.68	4.10	Fangchun (2001a)
B. textillis var. *a*	China	1968	16.1	2.68	2.54	Fangchun (2001a)
B. textillis var. *g*	China	1842	14	4.08	1.42	Fangchun (2001a)
D. gigantus	Thai	2487	18.5	5.26	1.00	Fangchun (2001a)
D. Oldhami	China	2334	15.0	4.30	2.16	Fangchun (2001a)
D. strictus	China	2236	15.3	3.69	2.05	Fangchun (2001a)
D. strictus	China	2800	9.9	3.69	2.05	Fangchun (2001a)
Dinochlua utilitis	China	2340	16.3	5.48	1.26	Fangchun (2001a)
Lignalia chungii	China	2507	13.2	4.09	1.36	Fangchun (2001a)
L. remotiflora	China	2071	15.2	3.28	2.51	Fangchun (2001a)
L. surectta	China	2186	17	2.98	2.11	Fangchun (2001a)
S. dumetorum	China	2446	15	4.83	1.80	Fangchun (2001a)
S. fungnomii	China	2840	13.7	4.74	2.03	Fangchun (2001a)
S. nalhannense	China	2444	13.8	1.62	4.69	Fangchun (2001a)
S. lima	China	3190	15.2	5.04	2.05	Fangchun (2001a)
S.pseudolima	China	2135	17.8	3.22	2.43	Fangchun (2001a)
Sinarundinaria chungii	China	2260	11.7	1.59	4.53	Fangchun (2001a)
Sinocalamus affinis	China	2220	15	4.43	1.75	Fangchun (2001a)
Sn. affinis	China	2710	13.6	4.82	1.90	Fangchun (2001a)
Sinocalamus pubescens	China	1938	15.3	2.40	2.70	Fangchun (2001a)
Sn. bicicatricatus	China	2008	15	2.35	3.33	Fangchun (2001a)
Sn. farinosus	China	2670	16.9	3.28	5.03	Fangchun (2001a)
Sn. latiflorus	China	2880	14	4.74	2.62	Fangchun (2001a)
Sn. latiflorus	China	1830	14.5	3.78	3.01	Fangchun (2001a)
Sn. minor	China	2297	17.8	4.39	1.56	Fangchun (2001a)
Sn. minor	China	2920	10	3.28	3.00	Fangchun (2001a)
Sn. oldhamii	China	2480	13.8	4.46	2.69	Fangchun (2001a)
Sn. stenoauritus	China	1976	16.9	2.42	2.52	Fangchun (2001a)
Sn. vario-striatus	China	2198	16.5	3.2	1.94	Fangchun (2001a)
Thamnocalamus siamensis	China	2006	16.8	2.21	2.94	Fangchun (2001a)
B. blumeana (1 year)	Msia	1940	18	10	5	Mohmod *et al.* (1990)
B. blumeana (2 years)	Msia	1870	20	9	5	Mohmod *et al.*

						(1990)
B. blumeana (3 years)	Msia	1950	20	9	5	Mohmod *et al.* (1990)
B. vulgaris var. *striata* (1 year)	Msia	3340	17	2	7	Mohmod *et al.* (1990)
B. vulgaris var. *striata* (2 years)	Msia	3300	17	3	7	Mohmod *et al.* (1990)
B. vulgaris var. *striata* (3 years)	Msia	3760	17	2	6	Mohmod *et al.* (1990)
G. scortechinii (1 years)	Msia	3500	16	2	7	Mohmod *et al.* (1990)
G. scortechinii (2 years)	Msia	3800	17	2	7	Mohmod *et al.* (1990)
G. scortechinii (3 years)	Msia	4240	17	3	8	Mohmod *et al.* (1990)
G. scortechinii (0.5 year)	Msia	2230	26	10	8	Norul Hisham *et al.* (2006)
G. scortechinii (1.5 years)	Msia	2500	26	8	9	Norul Hisham *et al.* (2006)
G. scortechinii (3.5 years)	Msia	2500	26	8	9	Norul Hisham *et al.* (2006)
G. scortechinii (5.5 years)	Msia	2380	26	9	8	Norul Hisham *et al.* (2006)
G. leavis	Msia	2040	23.7	4.00	9.34	Razak *et al.* (2013)
G. scortechinii	Msia	1745	17.3	8.66	4.30	Razak *et al.* (2013)
G. wrayi	Msia	1799	17.9	3.83	7.02	Razak *et al.* (2013)
G. brang	Msia	1910	22.8	4.75	9.02	Mohd Tamizi *et al.* (2011)
G. thoii	Msia	4071	25.5	5.0	12.2	Nordahlia *et al.* (2019)
G. ligulata	Msia	3930	22.6	4.3	9.2	Nordahlia *et al.* (2019)
G. wrayi	Msia	2753	24	10.3	7.0	Nordahlia *et al.* (2019)
G. brang	Msia	3543	21.4	6	7.7	Nordahlia *et al.* (2019)
S. brachycladum	Msia	2840	22.2	6.4	7.9	Nordahlia *et al.* (2019)
S. grande	Msia	2451	15	3.1	6.1	Nordahlia *et al.* (2019)
S. zollingeri	Msia	2326	14.8	8.1	3.3	Nordahlia *et al.* (2019)
B. vulgaris	Msia	2494	14.1	3.5	7.1	Nordahlia *et al.* (2019)
B. blumeana	Msia	2905	18.9	7.6	5.7	Nordahlia *et al.* (2019)
B. heterostachya	Msia	3764	26.8	5.8	10.5	Nordahlia *et al.* (2019)
B. vulgaris cv. *Vitta*	Msia	3592	20.3	6.9	6.3	Nordahlia *et al.* (2019)
D. asper	Msia	2998	23.3	6.1	8.6	Nordahlia *et al.* (2019)

FL: Fibre length; FD: fibre diameter; FLD: fibre lumen diameter; FWT: fibre wall thickness

Sympodial bamboo

In sympodial bamboo (Table 14), the longest and shortest fibres are recorded for *G. scortecinii* (4240 μm) grown in Malaysia and *B. basihirsuta* (1667 μm) grown in China, respectively. The fibre is widest in *B. heterostachya* (26.8 μm) grown in Malaysia and narrowest in *D. striticus* (9.9 μm) grown in China. The fibre wall is thickest in *G. thoii* (12.2 μm) grown in Malaysia and thinnest in *D. gigantus* (1 μm) grown in Thailand. The fibre lumen is largest in *B. blumeana* (10 m) grown in Malaysia and smallest in *Sinarundina chungi* (1.59 μm) grown in China. The fibre wall diameter, thickness, and lumen diameter of *B. blumena*, *B. vulgaris*, and *G. scortechinii* are not significantly different with culm aged one to three years. The fibre length ranges from 1.89 μm to 1.99 μm in *B. blumeana*, from 3.30 μm to 3.76 μm in *B. vulgaris*, and from 3.50 μm to 4.24 μm in *G. scortechinii*. The fibre diameter ranges from 0.018 μm to 0.02 μm in *B. blumeana*, 0.017 μm in *B. vulgaris* and *G. scortechinii*. The fibre wall thickness is 0.05 in *B. blumeana*, ranges from 0.06 to 0.07 in *B. vulgaris*, and 0.07 to 0.08 in *G. scortechinii*. The fibre lumen diameter ranges from 0.009 to 0.010 in *B. blumana*, from 0.002 to 0.003 in *B. vulgaris*, and *G. scortechinii* (Mohmod *et al*. 1990).

In the *G. scortechinii* aged 0.5 to 6.5 years grown in the same clump, the youngest culm aged 0.5 years had the shortest fibre (2.23 μm). Culm aged 1.5 years had the longest fibre, but the fibre tends to be shorter with ageing. The fibre diameter does not differ by age, and the mean is 26 μm. The widest fibre lumen diameter is recorded in the youngest culm aged 0.5 years (10 μm) and the diameter remains unchanged beyond age 1.5 years. The fibre wall is thinner at the early age of 0.5 years (8 μm) but thickens as much as 1 μm at age of 1.5 years (Norul Hisham *et al.* 2006). The fibre length is significantly higher for the internode than the node with an average of 2074.2 μm and 1672.6 μm in *G. brang*, *G. levis*, *G. scortechinii*, and *G. wrayi*. The fibre is longest in the middle section (2064.4 μm), followed by the inner (1861.4 μm) and outer (1698.5 μm) for the above three species. The fibre is wider in the node (22.0 μm) than the internode (18.2 μm). It is the widest in descending order of *G. brang* (22.8 μm), *G. levis* (22.7 μm), *G. wrayi* (17.9 μm), and *G. scortechinii* (17.3 μm), respectively. The fibre is also widest at the middle section (22.4 μm), followed by the inner (19.6 μm) and outer sections (18.5 um) across the culm wall.

The fibre lumen is widest in descending order of *G. scortechinii* (8.60 um), *G. brang* (4.75 um), *G. levis* (4.75 um), and *G. wrayi* (4.75 um). The lumen is also larger in node compared to the internode. The lumen diameter is largest at the inner section (5.96 um) and smaller toward the outer section (5.44 um). The fibre wall is thickest in descending order of *G. levis* (9.34 μm), *G. brang* (9.02 μm), *G. wrayi* (7.02 μm), and *G. scortechinii* (4.30 μm). The node has a thicker fibre wall than the internode. The fibre wall is also thickest in the middle zone (8.43 μm) followed by the outer (7.03 μm) and inner (6.80 μm) zones (Mohd Tamizi *et al.* 2011). The fibre length in *Schizostachyum manii*, *Scizostachyum munroi*, and *Schizostachyum pergracile* grown in India increased from the inner zone and reached a maximum at the middle zone but further decreased toward the inner zone in the transverse section of all culm height. The fibre characteristics, such as diameter, lumen diameter, and wall thickness decreased along the culm height (Sharma *et al.* 2017). Amongst the 4-year-old *G. scortechinii*, *G. thoii*, *G. ligulate*, *G. wrayi*, *G. brang*, *S. brachycladum*, *S. grande*, *S. zollingeri*, *B. vulgaris*, *B. blumeana*, *B. heterostachya*, *B. vulgaris* cv *Vittata*, and *D. asper* grown in Malaysia, *G. thoii* has the longest fibre (4070 μm) and the fibre length for all species are ranged from 2330 μm to 4070 μm (Norhadlia *et al.* 2019).

Table 14. Statistical Reanalysis of the Fibre Morphology in Monopodial and Sympodial Bamboos

Fibre	Monopodial	Sympodial	DF	F	Significance
Length	1929.7(273.6)	2494.8 (6.09)	1	9.08	0.00***
Diameter	12.95 (2.33)	17.06 (3.92)	1	11.34	0.00***
Lumen diameter	3.64 (0.96)	4.49 (2.25)	1	1.52	0.22^{NS}
Wall thickness	3.93 (1.32)	4.39 (2.72)	1	0.31	0.58^{NS}

DF– Degree of freedom, F– F ratio, NS is not significant at P > 0.1, *** is significant at P < 0.01.
The value in parentheses is standard deviation

The statistical reanalysis of the fibre morphology data shows that the fibre length and diameter are significantly longer and wider in sympodial bamboo (2494.8 μm and 17.06 μm) than the monopodial bamboo (1929.7 μm and 12.95 μm), respectively. In contrast, fibre lumen diameter and wall thickness are not significantly different in monopodial (3.63 μm and 3.93 μm) and sympodial (4.49 μm and 4.39 μm) bamboos, respectively.

PHYSICAL PROPERTIES

Basic Density and Volumetric Swelling

The density is closely related to the mechanical properties of bamboo and it differs by species, age, culm height, and portion. The density increases from the basal portion towards the top as well as from inner to the outer culm wall. The main reason for this trend is that the top and outer portion are heavily distributed by vascular bundles and a thinner vessel diameter.

Monopodial Bamboo

The density progressively increases with age as occurs in *P. pubescens* and *S. affinis* aged 1 (0.43 g/cm^3 to 0.49 g/cm^3) to 7 years (0.62 g/cm^3 and 0.63 g/cm^3), respectively, but it tends to decrease beyond 8 years (Table 16). The density is higher for bamboo grown in drought and low temperature areas, as it has compact tissue. In contrast, the bamboo density is lower in warm, moist climates and nourishing soil because its thick culm wall tissue is loose (Fangchun 2001a).

The same trend occurs for *N. affinis* grown in China, for which the density significantly increases with age for 1 year (0.56 g/m^3), 2 years (0.68 g/m^3), and 3 years (0.77 g/m^3). However, all bamboo age classes fertilized with potassium, calcium, and nitrogen show a lower density than the unfertilized bamboo especially with a higher dose of nitrogen (Xie *et al.* 2019). These results are in a good agreement with the findings of Yang *et al.* (2014), in which the long-term nitrogen fertilization significantly decreased the basic density of *P. pubescens*. The density increases from basal portion (0.60 g/m^3) toward the middle (0.69 g/m^3) and top (0.79 g/m^3) portions of *B. vulgaris* aged 4 years grown in China (Huang *et al.* 2014). The volumetric swelling is highest and lowest in *B. sinospinosa* (32.8%) and *P. glauca* F. Youzhu (7.4%).

Sympodial Bamboo

The density decreases with age for 1-year (1.10 g/m^3), 2-years (1.04 g/m^3), and 3-years-old (1.00 g/m^3) wild *B. blumeana* culms. In contrast, the density increases with ages in 1-year (0.29 g/m^3), 2-years (0.51 g/m^3), and 3-years-old (0.54 g/m^3) wild *B. vulgaris* var. *striata*. The same trend occurs in wild *G. scortechinii*, where the density increases with age in 1-year (0.47 g/m^3), 2-years (0.53 g/m^3), and 3-years-old (0.56 g/m^3) culms. Overall, *B. blumeana* has the highest density follow by *G. scortechinii* and, lastly *B. vulgaris* (Abdul Latif *et al.* 1990). The density of wild *G. scortechinii* grown in the same clump also increased with age for 0.5 (0.53 g/m^3), 1.5 (0.59 g/m^3), 3.5 (0.61 g/m^3), 5.5 (0.63 g/m^3), and 6.5 years (0.68 g/m^3). Along the internode height, the density trends are also slightly increased from the bottom portion toward the top portion along the sixth internode, for all age classes (Norul Hisham *et al.* 2003; Norul Hisham *et al.* 2006).

The densities of 4-year-old Malaysian bamboo, as reported by Nordahlia *et al.* (2019) in descending order, are *G. thoii* (0.75 g/m^3), *G. scortechinii* (0.64 g/m^3), *G. wrayii* (0.63 g/m^3), *S. grande* (0.63 g/m^3), *B. vulgaris* (0.61 g/m^3), *S. brachycldum* (0.59 g/m^3), *D. asper* (0.56 g/m^3), *B. vulgaris* cv *vittata* (0.55 g/m^3), *G. brang* (0.54 g/m^3), *B. heterostachya* (0.53 g/m^3), *B. blumeana* (0.48 g/m^3), *G. ligulata* (0.44 g/m^3), and *S. zollingeri* (0.36 g/m^3). Within the culm region, the node density is not significantly different from internode density either at basal or top portions for *D. asper* grown in Thailand. The density at basal portion of culm without node (0.71 g/m^3) is not significantly different from the one with node (0.69 g/m^3). The density at the top portion of culm without node (0.90 g/m^3) is not significantly different from the one with node (0.92 g/m^3). The same trend is reported for *P. bambisoides* (monopodial type) by Tomak *et al.* (2012) as well as for *Guadua angustifolia* (sympodial type) by De Vos (2010).

Overall Analysis

The statistical reanalysis of the density in monopodial and sympodial bamboos shows that there is no significant different of density (0.58 g/cm^3 and 0.59 g/cm^3) for both types of bamboo. In contrast, the volumetric shrinkage is significantly higher for sympodial (16.92%) than the monopodial (12.63%) bamboos.

Table 15. Basic Density and Shrinkage Properties of Monopodial and Sympodial Bamboo

Species	Basic Density (g/cm^3)	Shrinkage (Volume, %)	Reference
Monopodial			
Arundinaria			
A. amabilis	0.63	10.2	Fangchun (2001a)
A. fargesii	0.54	15.2	Fangchun (2001a)
A. japonica	0.63	-	Fangchun (2001a)
A. spongisa	0.50	22.4	Fangchun (2001a)
Chimonobambusa			
C. marmorea	0.60	-	Fangchun (2001a)
C. quadrangularis	0.51	-	Fangchun (2001a)
C. utilis	0.58	-	Fangchun (2001a)
Indosasa			
I. longspicta	0.51	15.4	Fangchun (2001a)
Phyllostachys			
P. angusta	0.49	-	Fangchun (2001a)
P. aurea	0.91	-	Fangchun (2001a)
P. spec bilis	0.51	-	Fangchun (2001a)
P. bambusoidea	0.72	10.4	Fangchun (2001a)
P. bambusoidea f. Tanaka	0.51	13.6	Fangchun (2001a)

P. bambusoidea. f. Zitchiku	0.53	10.3	Fangchun (2001a)
P. congesta	0.65	-	Fangchun (2001a)
P. decora	0.55	-	Fangchun (2001a)
P. filifera	0.63	-	Fangchun (2001a)
P. flexuosa	0.57	-	Fangchun (2001a)
P. gluaca	0.68	10.4	Fangchun (2001a)
P. glauca f. Youzhu	0.63	7.4	Fangchun (2001a)
P. glauca f. variabilis	0.66	9.2	Fangchun (2001a)
P. decora	0.55	-	Fangchun (2001a)
P. heteroclada	0.52	-	Fangchun (2001a)
P. iridensclada	0.43	-	Fangchun (2001a)
P. kwangsinsis	0.59	-	Fangchun (2001a)
P. meyeri	0.43	12.4	Fangchun (2001a)
P. nidularia	0.45	-	Fangchun (2001a)
P. nigra	0.72	-	Fangchun (2001a)
P. nigra var. *henosis*	0.44	-	Fangchun (2001a)
P. nuda	0.64	-	Fangchun (2001a)
P. parvifloria	0.59	-	Fangchun (2001a)
P. platyglossa	0.47	-	Fangchun (2001a)
P. praecox	0.66	-	Fangchun (2001a)
P. pubescens	0.66	14.7	Fangchun (2001a)
P. viridi-glaucessens	0.50	-	Fangchun (2001a)
P. viridis	0.62	-	Fangchun (2000)
P. vivax	0.64	-	Fangchun (2000)
Pleioblastus			
P.amarus	0.57	-	Fangchun (2001a)
Sympodial			
Bambusa			
B. badihirsuta	0.67	18.5	Fangchun (2001a)
B. breviflora	0.57	10.2	Fangchun (2001a)
B. cornigera	0.60	15.1	Fangchun (2001a)
B. dissemualator	0.60	-	Fangchun (2001a)
B. dissimilis	0.60	-	Fangchun (2001a)
B. dolichoclad	0.73	-	Fangchun (2001a)
B. eatuldoies	0.57	14.2	Fangchun (2001a)
B. e. var. *basistriata*	0.77	17.2	Fangchun (2001a)
B. flexuosa	0.45	13.8	Fangchun (2001a)
B. gibba	0.57	18.1	Fangchun (2001a)
B. gibboides	0.54	18.6	Fangchun (2001a)
B. lapidea	0.50	18.7	Fangchun (2001a)
B. longiflora	0.57	20.2	Fangchun (2001a)
B. multiplex cv.	0.50	-	Fangchun (2001a)
B. multiplex f. lutea	0.55	18.4	Fangchun (2001a)
B. pervarialis	0.58	22.0	Fangchun (2001a)
B. p. var. *viridi-st*	0.52	15.9	Fangchun (2001a)
B. rigida	0.55	16.0	Fangchun (2001a)
B. rigida	0.69	14.2	Huang *et al.* (2014)
B. rutita	0.61	11.1	Fangchun (2001a)
B. sinospinosa	0.50	32.8	Fangchun (2001a)
B. stemostachy	0.64	23.1	Fangchun (2001a)
B. spimosa	0.36	-	Fangchun (2001a)
B. textilis	0.69	-	Fangchun (2001a)

B. t. var. *sracillis*	0.58	-	Fangchun (2001a)
B. tulda	0.65	13.0	Fangchun (2001a)
B. tubdoides	0.59	14.3	Fangchun (2001a)
B. ventricosa	0.42	10.5	Fangchun (2001a)
B. vulgaris	0.68	10.2	Fangchun (2001a)
B. vulgaris	0.61	-	Nordahlia *et al.* (2019)
B. vulgaris cv *vittata*	0.55	-	Nordahlia *et al.* (2019)
B. vulgaris var. *striata*	0.65	13.7	Fangchun (2001a)
B. vulgaris var. *striata*			
1 year	0.30	-	Mohmod *et al.* (1990)
2 years	0.51	-	Mohmod *et al.* (1990)
3 years	0.54	-	Mohmod *et al.* (1990)
B. bambos	0.87	-	Srivaro and Jakranod (2016)
B. longispiculata	0.80	-	Srivaro and Jakranod (2016)
B. blumeana	0.77	-	Srivaro and Jakranod (2016)
B. blumeana			
1 year	1.03	-	Mohmod *et al.* (1990)
2 years	1.04	-	Mohmod *et al.* (1990)
3 years	1.00	-	Mohmod *et al.* (1990)
B. blumeana	0.48	-	Nordahlia *et al.* (2019)
B. heterostachya	0.53	-	Nordahlia *et al.* (2019)
Dendrocalamus			
D. beecheyanus	0.59	26.7	Fangchun (2001a)
D. beecheyanus var. *pubuscens*	0.72	9.6	Fangchun (2001a)
D. bicicatriatus	0.53	16.0	Fangchun (2001a)
D. gigantens	0.55	19.6	Fangchun (2001a)
D. gromdis	0.48	21.8	Fangchun (2001a)
D. hamilthonii	0.69	20.3	Fangchun (2001a)
D. mino var. *pubencen*	0.56	14.3	Fangchun (2001a)
D. stenoauritus	0.74	14.0	Fangchun (2001a)
D. stricticus	0.50	-	Fangchun (2001a)
D. validus	0.47	24.4	Fangchun (2001a)
D. vario-striatus	0.75	11.8	Fangchun (2001a)
Gigantochloa			
G. scortechinii			
1 year	0.47	-	Mohmod *et al.* (1990)
2 years	0.53	-	Mohmod *et al.* (1990)
3 years	0.56	-	Mohmod *et al.* (1990)
G. scortechinii	0.64	-	Nordahlia *et al.* (2019)
G. thoii	0.75	-	Nordahlia *et al.* (2019)
G. ligulata	0.44	-	Nordahlia *et al.* (2019)
G. wrayi	0.63	-	Nordahlia *et al.* (2019)
G. brang	0.54	-	Nordahlia *et al.* (2019)
G. brachycladum	0.59	-	Nordahlia *et al.* (2019)
G. atter			
0.3 year	0.35	-	Marsoem *et al.* (2015)
1.3 years	0.43	-	Marsoem *et al.* (2015)
3.3 years	0.59	-	Marsoem *et al.* (2015)
Lignania			
L. cerosissina	0.69	-	Fangchun (2001a)
L. chungii	0.42	-	Fangchun (2001a)
L. papilata	0.77	16.9	Fangchun (2001a)

Schizostachyum			
S. fungbomii	0.50	-	Fangchun (2001a)
S. hainanense	0.46	-	Fangchun (2001a)
S. pseudolima	0.48	-	Fangchun (2001a)
S. manii	0.50	-	Nordahlia *et al.* (2019)
S. munroi	0.57	-	Nordahlia *et al.* (2019)
S. pergracile	0.64	-	Nordahlia *et al.* (2019)
S. grande	0.63		Nordahlia *et al.* (2019)
S. zollingeri	0.36	-	Nordahlia *et al.* (2019)
Sinobambusa			
S. laeta	0.45	-	Fangchun (2001a)

Table 16. Basic Density and Volumetric Shrinkage of Monopodial and Sympodial Bamboos

Fibre	Monopodial	Sympodial	DF	F	Significance
Basic density (g/cm^3)	0.58 (0.10)	0.59 (0.14)	1	0.11	0.74^{NS}
Volumetric shrinkage (%)	12.63 (3.99)	16.92 (5.10)	1	6.93	0.01***

DF– Degree of freedom, F– F ratio, NS is not significant at P > 0.1, *** is significant at P < 0.0. The value in parentheses is standard deviation

MECHANICAL PROPERTIES

Bamboo has high mechanical and workability properties and is a preferable material for many uses in agricultural, industrial, building, and architecture sectors. The flexural ductility of bamboo (*Ph. pubescens*) is 3.06 times that of wood (*Tectona grandis*). The bending MOR of bamboo (*P. pubescens*) is 1.72 times that of wood (*Tectona grandis*), while its MOE is 0.84 higher than wood at similar density. High length-to-width ratio, density, and strength of bamboo fibers, as well as their parallel orientation all contributed to the excellent ductility and strength properties of bamboo (Chen *et al.* 2020). The mechanical properties differ with the bamboo culm position, portion, and section. Generally, it is higher at the upper position than the lower position, and higher at the outer section of the culm wall than the inner section. This gives rise to a denser and larger vascular bundle in the outer section than at the inner section (Fangchun 2001b).

Monopodial Bamboo

The effect of age on the mechanical properties of bamboo is significantly important for choosing an optimum harvesting age, the quality of end products, and service life (Norul Hisham *et al.* 2006). The compression and tensile strengths of *Ph. pubescence* gradually increase from one to five years but are almost constant from six to eight years before slightly declining from nine to ten years. Therefore, it is assumed that the best harvesting age for *P. pubescens* ranges from six to eight years (Fangchun 2001b). The mechanical properties of bamboo are clearly influenced by the species seen as shown in Table 17. The highest compression, tensile, and modulus of rupture for monopodial bamboo grown in China are *P. pubescens* (86.5 MPa), *P. decora* (310.8 MPa) and *P. glauca* (213.4 MPa).

Sympodial Bamboo

The highest compression, tensile, and modulus of rupture strenghts for sympodial bamboo species grown in China are *B. rigida* (79.8 MPa), *D. latiflorus* (199.1 MPa), and *B. rigida* (196.4 MPa). It is *G. scortechinii* (59.1 MPa), *D. asper* (222 MPa) and *G. wrayi* (201 MPa) for Malaysia bamboo respectively. The *B. bambos* has a highest tensile (260 MPa) and modulus of rupture (225 MPa) for the Thailand bamboo (Table 17).

In contrast, the lowest compression, tensile and modulus of rupture strengths for sympodial bamboo grown in China is recorded in *D. beecheyanis* and the values are 19.4 MPa, 92.9 MPa and 40.5 MPa respectively. In Malaysia bamboo, the lowest is *B. blumeana* (27.1 MPa), *D. asper* (222 MPa) and *B. heterostachya* (120 MPa) respectively. The lowest tensile (110 MPa) and modulus of rupture (145 MPa) is recorded in *B. longispiculata* for Thailand bamboo.

The shear, compression, and static bending strength of *B. blumeana*, *B. vulgaris* var. striata and *G. scortechinii* aged 1, 2 and 3 years are significantly increased with age (Mohmod et al. 1990). Nordahlia *et al.* (2019) also found that the MoR and MoE of 13 Malaysian bamboos are increased with the culm height and the trend is the same for *G. scortechinii* (Shahril and Mansur 2009), *D. latiflorus*, *D. meerrillanus*, *B. vulgaris* (Leoncio 2017) and *D. strictus* (Bhonde *et al.* 2014). The increment of MoR and MoE along the culm height is accompanied by the higher number of vascular bundles (Nordahlia *et al.* 2019).

Hamdan *et al.* (2009) reported that the MoR of bamboo without node is significantly higher at the top (258 MPa) than the basal (140 MPa) portions. The MoR at the top portion (147 MPa) is also significantly higher than at the basal portion (95 MPa) for the bamboo with node. A higher MoR at the internode portion is also contributed to its longitudinal straight cells as compared to the partially interrupt of radial cells at the node region. Bamboo with node fails quickly at the node region itself as compared to bamboo with internode. This trend is the same for sympodial bamboo, *Guadua angustifolia* (De Vos 2010) and *Gigantochloa scortechinii*. However, it is contradicted with monopodial bamboo, *P. pubescens* (Shoa *et al.* 2010; De Vos 2010), which the MoR is not significantly different in bamboo with and without the node. The MoR of bamboo with node is 32% (basal portion) and 43% (top portion) lower than bamboo without node in *D. asper* (Srivaro and Jakronod 2016), 20% lower than bamboo without node in *G. angustifolia* (De Vos 2010) and 27% lower for bamboo without node in *G. scortechinii* (Hamdan *et al.* 2009).

There is no significant difference of the MoE for *D. asper* with or without node (Srivaro and Jakronod 2016), as well as in *P. pubescens* and *G. angustifolia* (De Vos 2010); *P. bambusoides* (Lee *et al.* 1994; Tomak *et al.* 2012). The mechanical properties are higher at the top portion in the same or different species due to a higher volume fraction of vascular bundles and density (Amada *et al.* 1996; Malanit 2009; Dixon and Gibson 2014). The shear strength of *D. asper* aged 10 years without node are not significantly different for basal (12.3 MPa) and top (14.2 MPa) portions. The same trend occurs for *D. asper* with node for basal (11.9 MPa) and top (13.1 MPa) portions. The shear strength is higher at the top portion than the lower portion regardless of node or internode as the shear strength is mostly influenced by both density and culm height. This demonstrates that failure occurs by slipping of two shearing planes and a tearing failure of the soft parenchyma ground tissue as a result of the shear force (Srivaro and Jakronod 2016).

In the same study, Srivaro and Jakronod (2016) reported that the tensile strength of *D. asper* without node is significantly higher at the top (299 MPa) than the basal (165 MPa) portions. The same trend for the *D. asper* with node for the top (145 MPa) and basal (73

MPa) portions. A higher tensile strength at the internode than the node of the region for all culm heights is also obtained in *P. bambusoides* and *P. pubescens* (Lee *et al*. 1994; Shao *et al*. 2010). A higher tensile strength at the internode region is due to its longitudinal straight cell as compared to partly radial aligned cells at the node of the region, which is likely a loose compact structure (Wang *et al*. 2014).

Overall

The monopodial bamboo (207.18 MPa and 160.66 MPa) has a significantly higher tensile and modulus of rupture than the sympodial bamboo (122.27 and 72.63 MPa), respectively, as shown in the statistical reanalysis of the data. However, the compression strength is not significantly different from the rhizome as shown in Table 17.

Table 17. The Compressive, Tensile and Modulus of Rupture for Monopodial and Sympodial Bamboos

Species	Origin	Compressive (MPa)	Tensile (MPa)	MoR (MPa)	References
Monopodial					
Arundinaria					
A. amabilis	China	82.5	-	-	Fangchun (2001a)
A. amabalis	China	80.8	280	-	Fangchun (2001a)
A. fergesia	China	41.4	-	-	Fangchun (2001a)
A. spongiosa	China	64.5	169	-	Fangchun (2001a)
Indosasa					
I. crassiflora	China	50.8	-	-	Fangchun (2001a)
I. longispicata	China	54.6	139.7	-	Fangchun (2001a)
Chimonobambusa					
C. quadragularis	China	65.9	-	-	Fangchun (2001a)
Phyllostachys					
P. angsiensis	China	60.0	171.4	-	Fangchun (2001a)
P. angusta	China	63.1	177.0	-	Fangchun (2001a)
P. aureosulcata	China	72	252.4	-	Fangchun (2001a)
P. bambusoides	China	64.3	239.8	-	Fangchun (2001a)
P. decora	China	77.5	310.8	-	Fangchun (2001a)
P. frimbrigula	China	52.4	189	-	Fangchun (2001a)
P. flexxuosa	China	70.8	278.3	-	Fangchun (2001a)
P. glauca	China	76.0	255.3	-	Fangchun (2001a)
P. glauca	China	-	185.9	213.4	Fangchun (2001a)
P. heteroclada	China	65.4	250.2	-	Fangchun (2001a)
P. iridenscens	China	57.6	185.6	-	Fangchun (2001a)
P. makinoi	China	55.8	-		Fangchun (2001a)
P. meyeri	China	68.8	203.5	-	Fangchun (2001a)
P. nidularia	China	57.9	176.2	-	Fangchun (2001a)
P. nigra	China	40.7	-	-	Fangchun (2001a)
P. nigra. var. *henonis*	China	59.6	267.8	-	Fangchun (2001a)
P. nuda	China	75.7	262.1	-	Fangchun (2001a)
P. platyglossa	China	60.5	227.3	-	Fangchun (2001a)
P. praecox	China	59.2	166.2	-	Fangchun (2001a)
P. pubescens	China	71	198.4	-	Fangchun (2001a)
P. pubesces	China	61.1	185.4	136.9	Fangchun (2001a)
P. pubescens	China	61.1	186	131.9	Fangchun (2001a)
P. pubescens (1	China	49	135		Fangchun (2001b)

year)					
P. pubescens (2 years)	China	61	175		Fangchun (2001b)
P. pubescens (3 years)	China	65	200		Fangchun (2001b)
P. pubescens (4 years)	China	69	186		Fangchun (2001b)
P. pubescens (5 years)	China	68	184		Fangchun (2001b)
P. pubescens (6 years)	China	70	181		Fangchun (2001b)
P. pubescens (7 years)	China	67	192		Fangchun (2001b)
P. pubescens (8 years)	China	76	215		Fangchun (2001b)
P. pubescens (9 years)	China	65	185		Fangchun (2001b)
P. pubescens (10 years)	China	63	186		Fangchun (2001b)
P. fimbriligula (1 year)	China	46	117		Fangchun (2001b)
P. fimbriligula (2 years)	China	48	133		Fangchun (2001b)
P. fimbriligula (3 years)	China	49	149		Fangchun (2001b)
P. fimbriligula (4 years)	China	50	163		Fangchun (2001b)
P. fimbriligula (5 years)	China	52	177		Fangchun (2001b)
P. fimbriligula (6 years)	China	52	189		Fangchun (2001b)
P. fimbriligula (7 years)	China	53	201		Fangchun (2001b)
P. fimbriligula (8 years)	China	54	212		Fangchun (2001b)
P. pubescens	China	86.5			Li (2004)
P. (Se.) pubescens	China	65	189.5	127	Fangchun (2001a)
P. (uns.) pubescens	China	71.2	175.6	-	Fangchun (2001a)
P.viridi-glaucescen	China	67.2	230.7	-	Fangchun (2001a)
P. viridi	China	48.1	158.2	-	Fangchun (2001a)
P. viridi	China	-	289.1	194.1	Fangchun (2000b)
P. vivax	China	50.2	146.8	-	Fangchun (2001a)
Pleioblatus					
P. amara	China	66	173.4	-	Fangchun (2001a)
Sympodial					
Bambusa					
B. breviflora	China	58.0	-	-	Fangchun (2001a)
B. corginera	China	50.6	136	-	Fangchun (2001a)
B. lapidea	China	44	-	-	Fangchun (2001a)
B. flexuasa	China	38.9	-	-	Fangchun (2001a)
B. gibba	China	31.3	-	-	Fangchun (2001a)
B. pervariabilis	China	34.8	-	-	Fangchun (2001a)
B. pervariabilis	China	48.5	191.2	-	Fangchun (2001a)

B. rigida	China	51	-	-	Fangchun (2001a)
B. rigida	China	79.8		196.4	Huang *et al.* (2014)
B. rutila	China	43.6	-	-	Fangchun (2001a)
B. spp	China	46	-	-	Fangchun (2001a)
B. textilis	China	58.7	-	-	Fangchun (2001a)
B. textilis var. *fusca*	China	36.7	123.4	63.3	Fangchun (2001a)
B. textilis var. *gracilis*	China	54.1	-	-	Fangchun (2001a)
B. tulda	China	43	-	-	Fangchun (2001a)
B. tuldoides	China	46.3	-	-	Fangchun (2001a)
B. ventricosa	China	33.7	-	-	Fangchun (2001a)
B. ventricosa var. *striata*	China	54.8	-	-	Fangchun (2001a)
B. vulgaris	Malaysia			172	Nordahlia *et al.* (2019)
B. blumeana	Malaysia			116	Nordahlia *et al.* (2019)
B. blumeana	Malaysia	27.1			Mohmod *et al.* (1990)
B. blumena (without nodes)	Thailand		170	128	Srivaro and Jakranod (2016)
B. blumena (with nodes)	Thailand		100	100	Srivaro and Jakranod (2016)
B. heterostachya	Malaysia			120	Nordahlia *et al.* (2019)
B. vulgaris cv. *vittata*	Malaysia			176	Nordahlia *et al.* (2019)
B. vulgaris	Malaysia		232.1		Awalludin *et al.* (2017)
B. vulgaris	Malaysia	28.2			Mohmod *et al.* (1990)
B. longispiculata (without nodes)	Thailand		180	175	Srivaro and Jakranod (2016)
B. longispiculata (with nodes)	Thailand		110	145	Srivaro and Jakranod (2016)
B. bambos (without nodes)	Thailand		260	225	Srivaro and Jakranod (2016)
B. bambos (with nodes)	Thailand		125	150	Srivaro and Jakranod (2016)
Dendrocalamus					
D. beecheyanus	China	19.4	92.2	40.5	Fangchun (2001a)
D. gigantens	China	41.6	161.7	-	Fangchun (2001a)
D. hamiltonii	China	47.5	170.5	-	Fangchun (2001a)
D. latiflorus	China	19.7	-	-	Fangchun (2001a)
D. latiflorus	China	-	199.1	-	Fangchun (2000b)
D. asper	Malaysia			150	Nordahlia *et al.* (2019)
D. asper	Malaysia		222		Awalluddin *et al.* (2017)
Lingnania					
L. chungii	China	27.3	-	-	Fangchun (2001a)
L. chungii	China	47.8	173.4	119.3	Fangchun (2001a)
L. fimbrigulata	China	55	-	-	Fangchun (2001a)
L. spp.	China	69.1	-	-	Fangchun (2001a)
L. wenchouensis	China	46.6	103	76.1	Fangchun (2001a)
Schizostachyum					
S. funghoamii	China	40.3	-	-	Fangchun (2001a)
S. affinis	China	-	227.6	-	Fangchun (2000b)
S. brachycladum	Malaysia			263	Nordahlia *et al.* (2019)
S. grande	Malaysia			184	Nordahlia *et al.* (2019)
S. zollingeri	Malaysia			143	Nordahlia *et al.* (2019)

Sinobambusa					
S. laeta	China	40.9	-	-	
Sinocalamus					
S. beecheyana	China	38.9	-	-	Fangchun (2001a)
S. beecheyana var. *pubescens*	China	22.1	-	-	Fangchun (2001a)
S. farinosus	China	48.5	187.9	-	Fangchun (2001a)
S. latiflorus	China	48.6	141.3	-	Fangchun (2001a)
S. latiflorus	China	28.8	85.3	65.1	Fangchun (2001a)
S. oldhamii	China	39.3	156.3	71.5	Fangchun (2001a)
S. oldhamii	China	42	-	-	Fangchun (2001a)
S. sffinis	China	30.7	-	-	Fangchun (2001a)
S. spp.		38	-	-	Fangchun (2001a)
Gigantochloa					
G. thoii	Malaysia			163	Nordahlia *et al.* (2019)
G. scortechinii	Malaysia			125	Nordahlia *et al.* (2019)
G. scortechinii	Malaysia	28.9			Mohmod *et al.* (1990)
G. scortechinii (with node)	Malaysia	39.6			Noor Zuraida *et al.* (2013)
G. scortechinii (with internode)	Malaysia	51.9			Noor Zuraida *et al.* (2013)
G. ligulata	Malaysia			180	Nordahlia *et al.* (2019)
G. wrayi	Malaysia			201	Nordahlia *et al.* (2019)
G. brang	Malaysia			159	Nordahlia *et al.* (2019)
Guadua					
G. angustifolia	Columbia	30.7			Camargo (2006)
G. angustifolia (2 years)	Columbia	28.6		95.8	Correal and Camargo (2010)
G. angustifolia (3 years)	Columbia	41.0		92.7	Correal and Camargo (2010)
G. angustifolia (4 years)	Columbia	40.4		103.8	Correal and Camargo (2010)
G. angustifolia (5 years)	Columbia	35.2		107	Correal and Camargo (2010)

Table 18. Statistical Reanalysis of the Compressive, Tensile and Modulus of Rupture in Monopodial and Sympodial Bamboo

Property	Rhizome		DF	F	Significance
	Monopodial	Sympodial			
Compression	37.44 (34.21)	36.43 (10.86)	1	0.05	0.95^{NS}
Tensile	207.18 (45.82)	122.27 (35.82)	1	11.95	0.007***
MoR	160.66 (40.08)	72.63 (25.95)	1	19.42	0.002***

DF– is degree of freedom, F– is F ratio, NS is not significant at P > 0.1, *** is significant at P < 0.0. The value in parentheses is the standard deviation.

CHEMICAL PROPERTIES

Bamboo tissue consists of cellulose, hemicellulose, lignin, extractives, ash, silica (as a component of ash), starch, as well as various sugars akin to other monocotyledon and dicotyledon plants. The bamboo cellulose is composed of a longer chain of $C_{12}H_{10}O_{15}$, and its molecular weight is approximately 1,500,000 g/mol. The cellulose in bamboo can be further separated into 70% to 80% alpha cellulose, 25% beta cellulose, and 1% to 5% gamma cellulose (Fangchun 2001a). The bamboo hemicellulose is mainly composed of pentosane with a small quantity of hexoan. About 90% of bamboo hemicellulose is made from xylan. The bamboo xylan is made up of D-glucuranate arabinoxylan, which comprises 4-oxygen-methyl-D-glucuranate, L-arabinose, and D-xylose. The composition of bamboo arabinoxylan is different from conifers and broad-leaved trees. The polymerized molecules of bamboo xylan are more than that of trees. The content of pentose in bamboo ranges from 19% to 23%, which is close to broad leaves and much higher than that of conifers, which is 10% to 15% (Maoyi *et al.* 2007).

The structure of hemicellulose is determined by mainly arabinoxylans linked *via* (1-4)-ß-glycosidic bonds with branches of arabinose and 4-O-methyl-D-glucuronic acid (Lou *et al.* 2012). The bamboo lignin is a typical herbaceous lignin, consisting of three phenyl propane units, *i.e.*, paradinum, guaiacyl, and mauve in the ratio of 5:34:11. The specific features of bamboo lignin lie in the presence of dehydrogenated polymerides and 5% to 10% of acrylic ester. The lignin content of one-year-old bamboo ranges from 20% to 25%, approaching a broad-leaved wood and some grass (such as wheat straw 22%), and lower than that of conifers. The specific features of bamboo lignin lie in the existence of dehydrogenated polymerides and 5% to 10% of acrylic ester (Maoyi *et al.* 2007). Information on the content and distribution of lignin at each developmental stage is crucial for the exploitation of bamboo biomass (Chang and Holtzapple 2000; Shimokawa *et al.* 2009).

The lignin and the process of lignification in bamboo cells are used by researchers to study the earliest growth of bamboo cells toward its maturation. In bamboo, lignification in the culm proceeds acropetally, whereas lignification in each internode proceeds basipetally (Itoh 1990). Fibres and parenchyma cells of bamboo develop thick secondary walls that are composed of polylamellate structures containing broad and narrow lamellae (Parameswaran and Liese 1976; 1980). The deposition of lignin is much denser in the narrow lamella, and the distribution of the lignin-rich layers in bamboo fibres shows concentric rings in cross-sectioned walls (Parameswaran and Liese 1976). The pores of cell walls and cell corners are filled with lignin as seen in rapid-freezing and deep-etching (RFDE) electron microscopy (Nakashima *et al.* 1997; Fujino and Itoh 1998; Hafrén *et al.* 1999). In contrast to the findings made by Itoh (1990), the lignification of bamboo cells in various age classes of bamboo *P. pubescens* still occurred after the first growing season.

The protoxylem vessels are lignified in the early stage of vascular bundle differentiation. Upon completion, metaxylem vessel and fibre walls initiate lignification from the middle lamella and cell corners. Most of the parenchyma cell walls are lignified after the stem reaches its full height, while a few parenchyma cells remain non-lignified even in the mature culm. The cell walls of fibres and most parenchyma cells are further thickened during the stem growth to form polylamellate structure and the lignification process of these cells may last even up to 7 years. The fibre walls are rich in guaiacyl lignin in the early stage of lignification, and lignin rich in syringyl units are deposited in the later stage. Vessel walls mainly contained guaiacyl lignin, while both guaiacyl and syringyl lignin are present in the fibre and parenchyma cell walls (Lin *et al.* 2002). The unlignified primary wall (ULP) of *P. pubescens* is characterized by the narrow spacing between the cellulose microfibrils in fibres, but not in parenchyma cells. The unlignified secondary wall (ULS) largely consisted of dense cellulose microfibrils with narrow spacing or “slit-like” pores.

The cell wall architecture of the delignified secondary wall (DLS) in fibres showed porosity similar to that of ULS. Pores in the middle lamella and secondary walls of ULS in fibres are reduced significantly or disappear immediately after lignification. However, the pores reappear following delignification. The deposition of lignin in ULS immediately proceeds in the pores during maturation to LS. The pore sizes of primary and secondary fibre walls are significantly smaller in bamboo than in either *Eucalyptus* or *Pinus*, suggesting a denser arrangement of cellulose microfibrils in bamboo fibre walls than in either tree species. The narrow spacing between cellulose microfibrils in bamboo fibres may be one of the reasons for the deposition of less lignin in bamboo than in tree species (Suzuki and Itoh 2001).

In *Sinobambusa tootsik* (Tsuyama *et al.* 2017), the content of monolignol glucosides is maximum during the early stages of lignification, whereas the contents of monolignols peak at later stages of lignification. Elongation growth is ended by the culm lignin content, which is approximately half that of mature culms.

Monopodial Bamboo

In relation to species (Table 19), the α-cellulose, hemicellulose, and lignin contents in monopodial bamboo *P. heterocycla* (*Carr*.) Mitford cv. *Pubescens* aged 4 years are 42.7%, 25.52%, and 21.15%, respectively (Wang *et al.* 2021). The *Melocacna baccifera* contains 52.78% α-cellulose, 21.1% hemicellulose, 25.2% lignin, 4.13% hot water soluble, 3.24% hot water soluble, 2.45% ash, 19.5% NaOH, and 3.48% ethanol/toluene extractives (Tripathi *et al.* 2018). In relation to the culm age (Table 20), the holocellulose, lignin, ethanol/toluene extractive of monopodial bamboo *P. edulis* are not significantly different with age (1, 2, and 3 years) ranging from 65.97% to 67.24%, 30.48% to 32.09%, and 4.59% to 5.11%, respectively. The ash content is significantly lower in the oldest culm (0.89%), and it is not significantly different for culm aged 1 (1.83%) and 2 years (1.68%). In contrast, the silica content is significantly high for the oldest culm (0.30%), while it is not significantly different for culm aged 2 (0.28%) and 3 years (0.21%) (Ju *et al.* 2021).

In relation to the culm portion (Table 20), the holocellulose, ethanol/toluene, ash, and silica contents in monopodial bamboo *P. edulis* aged 1, 2, and 3 years are not significantly different with the culm height ranging from 65.77% to 67.69%, 4.58% to 4.85%, 1.36% to 1.72%, and 0.23 to 0.33%, respectively, with the exception of the lignin content. The lignin content is significantly highest at the middle portion of the culm (32.92%), while it is not significantly different at the basal (31.01%) and top portions (30.67%), regardless of age (Zhan *et al.* 2021).

Sympodial Bamboo

The chemical composition of cultivated sympodial bamboos *G. brang, G. levis, G. scortechinii*, and *G. wrayi* varies by species, portion (node or internode), and section (outer, middle, or inner) of the culm (Table 20). The α-cellulose is highest in descending order of *G. brang* (51.58%), *G. scortechinii* (46.87%), *G. wrayi* (37.66%), and *G. leavis* (33.81%). Regardless of species, the α-cellulose is not significantly different with node (42.74) and internode (42.22), but the outer culm layer has a significantly highest α-cellulose (49.07%), followed by middle (41.28%), and inner (37.09%) layers. The holocellulose is highest in *G. wrayi* (84.53%) but it is not significantly different from *G. levis* (84.52%). The *G. brang* (79.70%) has a significantly higher holocellulose content than the *G. scortechinii* (74.63%). Overall, the node (81.66%) has a significantly higher holocellulose than the internode (80.03%) and it is significantly in descending order of outer (82.99%), middle (80.89%), and inner (78.65%) layers of the culm wall.

The lignin is significantly highest in *G. scortechinii* followed by *G. wrayi* (37.66%), but it is not significantly different for *G. brang* (24.83%) and *G. levis* (26.50%). Overall, the lignin content is significantly higher in internode (32.295) than the node (24.76%) portions, and it is significantly highest at the outer (33.43%), followed by inner (30.03%) and middle (21.98%) culm wall layers. The ash content is significantly highest in *G. scortechinii* (2.84%) followed by *G. levis* (1.30%), *G. brang* (1.26%), and *G. wrayi* (0.88%). Overall, the ash is significantly higher at the node (1.6%) than the internode (1.54%) portions. Opposite of α--cellulose and lignin, the ash is significantly highest at the inner (1.89%) culm wall, followed by the outer (1.52%) and lastly middle (1.28%) culm wall layers. The ethanol/toluene extractive is significantly highest in *G. levis* (9.23%), followed by *G. wrayi* (8.62%). The extractive content is not significantly different for *G. brang* (8.30%) and *G. scortechinii* (8.00%). The node (8.63%) has a significantly higher extraction content than the internode (8.46%), while it is significantly highest in the inner (13.42%) culm wall followed by the middle (7.21%) and lastly the outer (4.99%) layers of the culm wall (Razak *et al.* 2013).

In seven sympodial bamboo species grown in India, *B. nutan* Dehradun has 51.6% cellulose, 26% lignin, 8.1% hot water soluble, 7.1% cold water soluble, 28.1% NaOH soluble, and 4.2% ethanol/toluene extractive contents. The *B. tulda* has 56.2% cellulose, 24% lignin, 7.8% hot water soluble, 5.5% cold water soluble, 26.1% NaOH soluble, and 3.2% ethanol/toluene extractive. The *B. arundinacea* Allahabad has 47.7% cellulose, 26.5% lignin, 11.4% hot water soluble, 9.8% cold water soluble, 27.0% NaOH soluble, and 3.5% ethanol/toluene extractives. The *B. pallida* IWST, Bangalore has 46.5% cellulose, 20% lignin, 12.6% hot water soluble, 11.1% cold water soluble, 27% NaOH, and 5.2% ethanol/extractive contents. The *B. bambos* IWST, Bangalore has 50.5% cellulose, 21.5% lignin, 11.2% hot water soluble, 10% cold water soluble, 27.4% NaOH soluble, and 4.2% ethanol/toluene extractive.

The *D. strictus* Alalhabad has 53.6% cellulose, 25% lignin, 8.4% hot water soluble, 6.7% cold water soluble, 27.9% NaOH soluble, and 4.2% ethanol/toluene extractives. The *D. strictus* Teri has 53.4% cellulose, 27% lignin, 8.3% hot water soluble, 6.2% cold water soluble, 28.0% NaOH soluble, and 4.9% ethanol/toluene extractive contents (Kaur *et al.* 2016ab). The chemical composition of sympodial bamboo *B. garuchokua*, *B. pallida*, and *B. assamica* aged 3 years grown in India behave differently (Brahma and Brahma 2018). The α-cellulose is highest in *B. pallida* (38.29%), followed by *B. garachokua* (36.75%) and *B. assamica* (31.37%). Regardless of species, the α-cellulose content is highest at the outer culm all section followed by the middle (37.31%) and inner (35.90%) sections. In contrast, the holocellulose is highest in ascending order of *B. assamica* (60.18%), *B. pallida* (65.92%), and *B. garuchokua* (68.86%).

Overall, the holocellulose content is highest at the outer section (69.63%), followed by the middle (62.81%, and inner (62.51%) sections. The lignin content is highest in ascending order of *B. assamica* (18.29%), *B. pallida* (22.42%), and *B. garuchokua*

(23.03%). Overall, the outer section has the highest lignin content (23.98%) and it is not much different with the inner (22.23%) and lastly the middle (17.78%) sections. The ash content is increased in ascending order of *B. garachukua* (0.99%), *B. pallida* (1.08%), and *B. assamica* (1.12%), while it is increased from the outer wall section (0.95%) toward the middle (1.04%) and inner (1.20%) sections. The hot water soluble is highest in *B. garuchokua* (5.90%) followed by *B. pallida* (5.70%) and lastly *B. assamica* (4.24%), while it gradually increases from outer section (4.43%) toward the middle (5.32%) and inner (6.09%) sections. The alcohol/toluene content is almost identical for *B. garuchokua* (4.12%) and *B. pallida* (4.37%), but it is lowest in *B. assamica* (3.44%). Across the culm wall, the extractive content is gradually decreased from the inner (4.55%) section toward the middle (4.02%) and outer sections (3.36%).

In relation to the culm section (Table 19), the contents of holocellulose, α-cellulose, lignin, ash, hot water soluble, cold water soluble, and 1% NaoH soluble are not significantly different with node or internode regions at the basal, middle, and top portions of sympodial bamboo *D. asper* aged 3 years ranging from 75.65% to 77.36%, from 67.07% to 69.64%, from 26.47% to 30.86%, from 0.92 to 2.29%, from 6.47 to 9.63%, from 4.23 to 14.05%, and from 23.40 to 26.78% (Kamthai and Puthson 2005). Almost all major chemical constituents in sympodial bamboo *G. scortechinii* aged 0.5, 1.5, 3.5, 5.5, and 6.5 years are relatively low at the youngest age of 0.5 years (Table 18). The starch content is low at the age of 1.5 years (0.6%) but increases to 3.5% at the age of 3.5 years and remain unchanged toward the later years. This is probably because no further increase of parenchyma length and lumen diameter occurred beyond the age of 3.5 years. The starch granule is situated or stored in vertically elongated cells of ground parenchyma (Liese and Weiner 1996).

The authors reported that younger 1-year-old bamboo culms do not contain any starch during the growing phase, because all the nutrients must be utilized immediately for metabolic processes. However, Mohmod *et al.* (1992) reported minor trace of starch content (0.8%) at the basal portion of 1-year-old *G. scortechnii*. Lignin content drastically increased at the age of 1.5 years (14.5%) and then gradually increased thereafter. No specific trend for alcohol/toluene extractive was observed, but it was high at age of 0.5, 3.5, and 6.5 years. The α-cellulose content remained unchanged, but the holocellulose content slightly increased beyond 3.5 years. The α-cellulose, holocellulose, hot water soluble, NaOH soluble, and ash contents in *G. scortechinii* are not significantly different with bamboo aged 1, 2, and 3 years (Table 20). The averages are 40.7%, 41.41%, and 40.49% for α-cellulose; 66.7%, 67.8%, and 67.9% for holocellulose; 6.3%, 5.9%, and 5.4% for hot water soluble; 19.6%, 19.2%, and 19.6% for NaOH soluble; and 11.0%, 11.1% and 11.4% for ash contents, respectively (Mohmod *et al.* 1994).

The lignin content is not significantly different in culm aged 1 (25.7%) and 2 years (24.9%), but significantly highest in the oldest culm (28.0%). The same trend occurs for cold water soluble and ethanol/toluene extractive. The average cold water soluble is 4.3%, 4.4%, and 5.5% in culm aged 1, 2, and 3 years, while it is 3.2%, 3.2%, and 3.5% for the ethanol/toluene extractives. Zhang *et al.* (2015) examined the chemical composition of *F. fungosa* aged 1, 2, and 3 years. The holocellulose content is not significantly different, with age ranging from 69.86% to 70.77%. Regardless of age, the holocellulose content is also not significantly different at the basal (70.11%), middle (69.99%), and top (70.56%) portions of the culm. Same as holocellulose, the lignin is not significantly different with age ranging from 22.66% to 24.21%. The alcohol/toluene extractive is significantly highest for the oldest culm (4.14%) and it is not significantly different for culm aged of 1 year (3.01%) and 2 years (3.22%). The ash content is significantly highest at a youngest age of 1 year (2.88%) but declines toward 2 (1.51%) and 3 years (1.40%). The silica content is significantly decreased in descending order of 1 year (0.48%), 2 years, (0.38%) and 3 years (1.40%).

In sympodial bamboo of *D. hamiltonii* (Zhan *et al*. 2016), the holocellulose content is significantly increased at the youngest age of 1 year toward the older age of 2 (68.7%) and 3 (76.7%) years. In contrast, the lignin content is not significantly different with ages ranging from 21.4% to 23.6%, but it is significantly different with the culm portion. The ethanol/toluene extractive content is significantly increased at the youngest age of 1 year (0.9%) toward the older aged of 2 years (1.2%) and 3 years (1.9%). The ash content is not significantly different with age ranging from 2.0% to 2.9%. In contrast to *F. fungosa* (Zhan *et al.* 2015), the silica content is significantly increased with age from 1 year (0.3%), 2 years (0.7%), and 3 years (2.1%) (see Fig. 2).

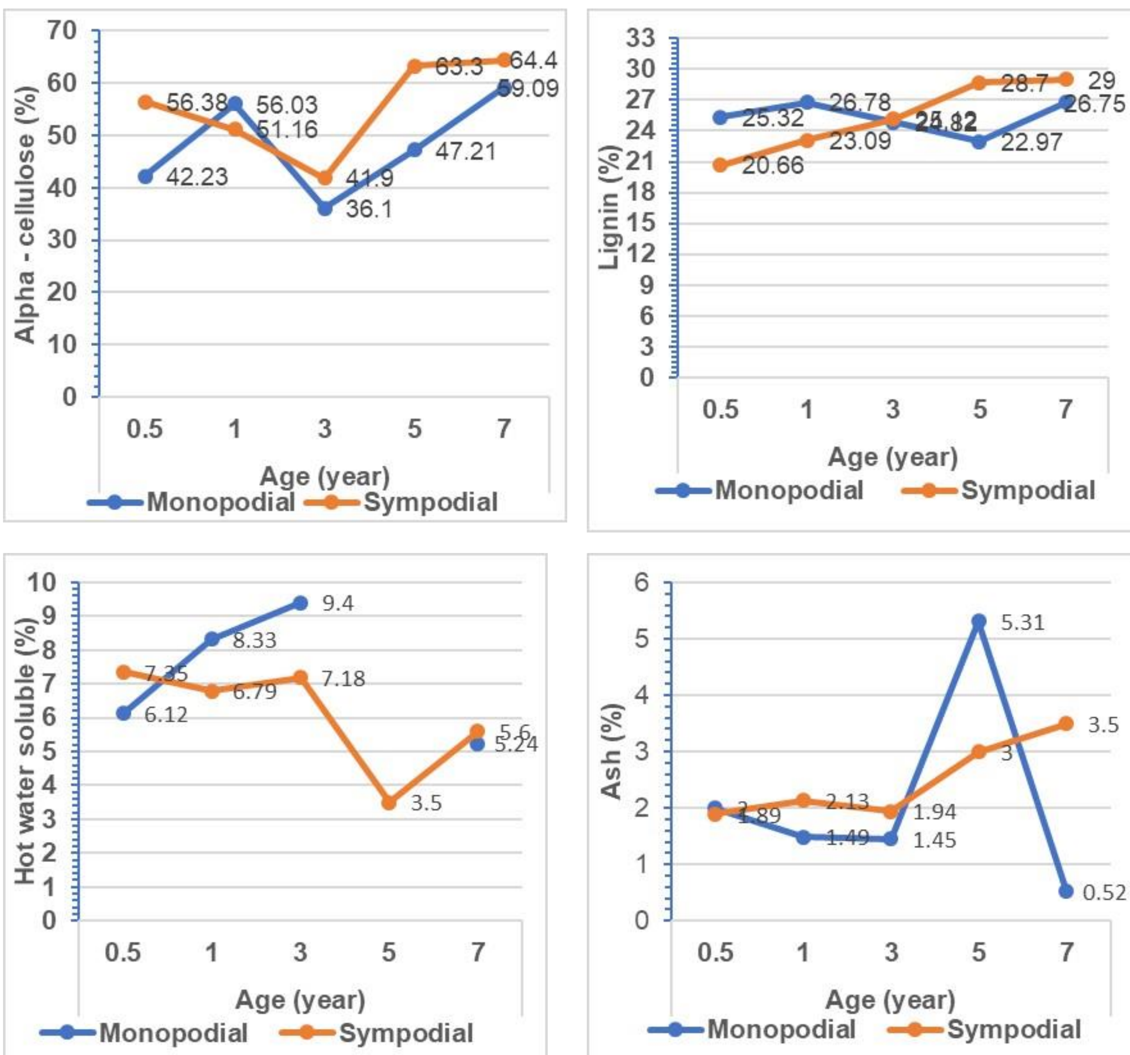

Fig. 2. The effect of ageing on the chemical properties in monopodial and sympodial bamboos

In relation to the culm portion (Table 19), the α-cellulose, lignin, holocellulose, cold water soluble, and ash contents in *G. scortechinii* aged 1, 2, and 3 years are not significantly different with the culm height (basal, middle, and top portions); ranging from 40.3% to 41.1%, 25.5% to 26.6%, 67.2% to 68.90%, 4.4% to 4.9%, and 1.10% to 1.13%, respectively. The hot water soluble is significantly increased at the basal (5.3%) toward the middle (6.0%) and top (6.5%) portions. A same trend occurs for NaoH soluble and ethanol/toluene extractives. The average NaoH soluble is 18.49% (basal), 19.8% (middle), and 20.1% (top), while it is 3.0% (basal), 3.3% (middle), and 3.6% (top) for the ethanol extractive contents (Mohmod *et al.* 1994). The holocellulose content in *D. hamiltonii* (Zhan *et al.* 2016) is not significantly different with portions ranging from 69.2% to 73.4%. The lignin content is significantly decreased in descending order of top (24.8%), middle (22.4%), and basal (21.60%) portions. Within the culm height, the extractive content is not significantly different with the culm portion ranging from 1.1% to 1.5%. The ash and silica contents are not significantly different with the culm portion ranging from 1.8% to 3.1% and 0.4% to 1.6% respectively.

The lignin content of *F. fungosa* aged 1, 2, and 3 years is significantly highest at the top (24.66%) but not significantly different from the basal (23.76%) portions. The middle portion has the lowest lignin content (21.86%). The ash content is not significantly different from the culm portion, ranging from 1.90% to 1.96%. Within the culm wall section, the silica content is significantly decreased in descending order of top (0.43%), middle (0.39%), and basal (0.33%) portions (Zhan *et al.* 2015). The maximum cellulose, hemicellulose, lignin, ash, silica, hot water soluble, cold water soluble, NaOH soluble, and ethanol/toluene extractive contents in monopodial bamboo are recorded for *P. heterocycle* (75.30%), *P. edulis* (29.66%), *Sasa albomarginate* Makin (39.76%), *S. albomarginate* Makin (3.38%), *P. sp* (0.13%), *P. heterocycla* (15.94%), *P. heteroclada* (13.57%), and *P. mayeri* (35.31%). While the minimum contents in monopodial bamboo are obtained in *P. bambusoides* (12.02%), *M. baccifera* (15.03%), *P. bissetii* McClure (14.69%), *C. utilis* (0.74%), *B. garuechokua* (0.99%), *S. affinis* (0.17%), *P. bisseti* McClure (1.68%), *P. pubescens* Mazel (2.38%), *P. bambusoides* (14.60%), and *P. pubescens* (1.60%) (Table 20).

In contrast, the maximum cellulose, hemicellulose, lignin, ash, silica, hot water soluble, cold water soluble, NaOH soluble, and ethanol/toluene extractive contents in sympodial bamboo are recorded by *D. striticus* (68.00%), *S. affinis* (25.41%), *D. striticus* (32.20%), *D. sp* (4.39%), *S. funghpmii* McClure (3.76%), *B. sinaspinosa* (9.91%), *B. sinaspinsa* McClure (10.53), *B. textilis* (32.27), and *B. sinaspinosa* (28.02%); while, the minimum contents for sympodial bamboo are recorded in *B. sinanpinosa* (17.10%), *D. striticus* (15.05%), *D. sp* (17.62%), *B. garuechokua* (0.99%), *S. affinis* (0.17%), *O. travancorica* (3.13%), *T. sp* (1.61%), *D. hamiltonii* (13.81%), and *D. hamiltonii* (0.9%).

Overall

Regardless of the rhizome, the overall monopodial type of bamboo has a significantly higher cellulose, hemicellulose, lignin, hot water soluble, cold water soluble, and 1% NaOH soluble (47.63%, 20.81%, 25.57%, 6.97%, 6.89%, and 28.09%) contents compared to the sympodial type of bamboo (40.42%, 14.24%, 24.33%, 5.75%, 5.61%, and 24.69%), respectively. In contrast, the sympodial type of bamboo has a significantly higher ash content (2.06%) compared to the monopodial type of bamboo (1.54%). Both the silica (0.27% and 0.92%) and ethanol/toluene extractive (4.72% and 7.20%) are not significantly different in monopodial and sympodial types of bamboo (Table 21).

Table 19. Chemical Properties in Monopodial and Sympodial Bamboos

Species	Percentage										References
	Origin	Cel	Hemi	Lig	Ash	Sil	Hw	Cw	NaOH	Eth/Tl	
					Monopodial						
					Arundinaria						
A. fargesii	*China*	45.10	21.8	25.26	1.54	-	-	-	24.35	-	Fangchun (2001a)
A. murielea Gamble	China	61.06	-	21.18	2.92	-	-	-	-		Fangchun (2001a)
					Chimonobambusa						
C. quadragularis	China	50.53	18.47	20.78	2.97	0.59	-	4.18	-	-	Fangchun (2001a)
C. utilis Keng F.	China	55.07	22.25	26.08	*0.74*	-	-	-	29.14	-	Fangchun (2001a)
C. delicatus Hsu et	China	48.34	17.58	20.01	2.68	0.51	-	6.61	-	-	Fangchun (2001a)
					Indocalamus						
I. farinosus Keng et K	China	57.02	18.67	24.69	2.03	-	-	-	27.06	-	Fangchun (2001a)
					Melocanna						
M. baccifera	China	62.25	15.13	24.13	1.87	-	6.48	3.26	18.97	-	Fangchun (2001a)
M. baecifera	China	75.30	*15.03*	23.20	1.74	-	-	-	17.13	-	Fangchun (2001a)
M. baccifera	India	52.78	21.1	25.2	2.45		4.13	3.24	19.5	3.48	Tripathi *et al.* (2018)
					Phyllostachys						
P. bambusoides Seib	China										Fangchun (2001a)
P. bambusoides	China	55.7	-	15.84	-	-	-	-	17.02	-	Fangchun (2001a)
P. bambusoides	China	37.51	-	39.51	-	-	-	-	*14.60*	-	Fangchun (2001a)
P. bambusoides (0.5 year)	China	48.92		24.51	2.22	-	5.93	4.62	27.60	1.81	Jiang (2002)
P. bambusoides (1 year)	China	56.74		29.93	1.25	-	8.97	10.49	29.93	7.34	Jiang (2002)
P. bambusoides (3 years)	China	***12.02***	-	25.15	0.98	-	7.32	6.11	31.33	5.86	Jiang (2002)
P. meyeri (0.5 year)	China	49.97	-	23.58	1.68	-	5.15	3.60	27.27	1.81	Jiang (2002)
P. meyeri (1 year)	China	57.88	-	23.62	1.29	-	8.91	10.70	34.28	7.04	Jiang (2002)
P. meyeri (3 years)	China	39.95	-	23.35	1.85	-	12.71	8.81	35.31	7.52	Jiang (2002)
P. bissetii McClure	China	52.14	19.26	24.02	0.89	-	*1.68*	-	31.05	-	Fangchun (2001a)
P. bissetii McClure	China	55.53	20.11	25.36	1.07	-	8.50	-	27.35	-	Fangchun (2001a)
P. bissetii McClure	China	55.38	19.88	25.60	1.41	-	8.03	-	26.91	-	Fangchun (2001a)
P. bissetii McClure	China	69.25	25.31	*14.69*	2.78	-	8.58	-	30.21	-	Fangchun (2001a)

P. glauca	China	-	22.64	33.46	1.43	-	5.24	-	28.96	-	Fangchun (2001a)
P. makinoi Hayata	China	50.55	24.79	30.88	-	-	-	-	-	-	Fangchun (2001a)
P. nidularia Munro	China	54.83	21.39	25.58	0.87	-	-	-	26.69	-	Fangchun (2001a)
P. nigra var. *Menoni*	China	51.34	19.76	33.45	1.38	-	5.84	-	33.07	-	Fangchun (2001a)
P. nigra (0.5 year)	China	45.38	-	28.94	1.98	-	8.30	6.72	31.83	4.12	Jiang (2002)
P. nigra (1 year)	China	58.85	-	23.90	1.81	-	8.53	10.69	32.24	5.29	Jiang (2002)
P. nigra (3 year)	China	13.79	-	25	1.71	-	8.36	6.50	33.65	5.58	Jiang (2002)
P. nigra	Japan	42.3	-	23.80	2.0		-	-	-	3.4	Higuchi (1958)
P. pubescens	China	-	21.12	30.67	1.10	-	5.96	-	30.98	-	Fangchun (2001a)
P. pubescens Mazel	China	45.94	18.81	27.83	0.81	0.17	-	4.17	-	-	Fangchun (2001a)
P. pubescens Mazel	China	45.50	21.12	30.67	1.10	-	5.96	*2.38*	30.98	-	Fangchun (2001a)
P. sp.	China	45.80	18.39	23.06	1.73	*0.13*	-	3.91	-	-	Fangchun (2001a)
P. pubescens (0.5 year)	China	61.97	-	26.36	1.77	-	3.26	5.41	27.34	*1.60*	Jiang (2002)
P. pubescens (1 year)	China	59.82	-	34.77	1.13	-	6.31	8.13	29.34	3.67	Jiang (2002)
P. pubescens (3 years)	China	60.55	-	26.20	0.69	-	5.11	7.10	26.91	3.88	Jiang (2002)
P. pubescens 7 years)	China	59.09	-	26.75	0.52	-	5.17	7.14	26.83	4.78	Jiang (2002)
P. pubescens (1 year)	U.S.A	47.11	-	21.78	1.90	-	5.56	-	-	3.22	Li (2004)
P. pubescens (3 years)	U.S.A	46.63	-	23.62	1.36	-	6.89	-	-	4.73	Li (2004)
P. pubescens (5 years)	U.S.A	47.21	-	22.97	1.30	-	5.31	-	-	6.92	Li (2004)
P. heteroclada (1 year)	China	58.15	-	22.42	1.24	-	9.60	13.57	30.89	5.38	Jiang (2002)
P. heteroclada (3 years)	China	38.96	-	22.75	1.27		15.94	9.68	34.84	9.11	Jiang (2002)
P. heterocycla	Japan	49.1	-	26.1	1.3	-	-	-	-	4.6	Higuchi (1958)
P. heterocycla	China	42.7	25.52	21.15	-	-	-	-	-	-	Wang *et al.* (2020)
P. praccox (0.5 year)	China	42.23	-	26.74	3.24	-	8.57	6.72	33.36	2.25	Jiang (2002)
P. praccox (1 year)	China	56.03	-	21.68	1.96	-	7.68	11.21	32.84	3.80	Jiang (2002)
P. praccox (3 years)	China	40.81	-	25.65	2.26	-	9.09	7.18	23.26	5.64	Jiang (2002)
P. reticulata	Japan	25.30	-	25.3	1.9	-	-	-	-	3.4	Higuchi (1955)
P. edulis	Taiwan	45.39	29.66	21.51	1.48	-	-	-	-	6.39	Li *et al.* (2018)
Sasa											
S. albomarginate Makin	China	-	-	39.76	3.38	-	-	-	-	-	Fangchun (2001a)
Sympodial											
Bambusa											
B. arundinacea	China	57.56	19.62	30.90	3.26	-	5.25	4.59	19.35	-	Fangchun (2001a)
B. breviflora Munro	China	-	20.80	24.20	-	-	-	-	-	-	Fangchun (2001a)
B. nutans	China	-	-	21.70	-	-	-	-	-	-	Fangchun (2001a)

B. pervariabilis McCl	China	55.77	16.19	23.28	3.00	-	5.30	4.29	29.12	-	Fangchun (2001a)
B. pervariabilis McCl	China	48.51	15.81	23.98	1.56	0.54	-	8.03	-	-	Fangchun (2001a)
B. polymor pha	China	-	18.50	24.70	-	-	-	-	-	-	Fangchun (2001a)
B. polymor pha Munro	China	46.90	17.05	23.86	2.10	0.21	-	5.00	-	-	Fangchun (2001a)
B. rigida Keng et Keng	China	46.71	18.78	22.16	1.20	0.54	-	6.98	-	-	Fangchun (2001a)
B. rigida Keng et Keng	China	56.98	19.19	23.51	1.49	-	-	-	-	25.44	Fangchun (2001a)
B. sinaspinosa McClure	China	47.50	16.14	24.35	3.72	2.26	-	10.53	-	-	Fangchun (2001a)
B.sinaspinosa McClure	China	55.46	20.30	23.17	2.86	-	-	-	-	28.02	Fangchun (2001a)
B. sinaspinosa (0.5 year)	China	52.58		19.90	2.69		8.23	7.29	29.98	4.23	Jiang (2000)
B. sinaspinosa (1 year)	China	49.45		20.51	1.92		9.91	8.08	30.25	5.49	Jiang (2000)
B. sinaspinosa (3 years)	China	*17.10*		24.17	1.84		9.27	9.07	26.92	5.88	Jiang (2000)
B. sterstachya Hacel	China	52.20	19.61	30.88	2.45	-	-	-	-	-	Fangchun (2001a)
B. textilis McClure	China	58.48	18.87	20.19	2.24	-	7.60	4.88	25.11	-	Fangchun (2001a)
B. textilis (0.5 year)	China	51.96		18.67	2.39	2.39	8.03	6.64	32.27	-	Jiang (2002)
B. textilis (1 year)	China	50.40		19.39	2.08	2.08	7.55	6.30	30.57		Jiang (2002)
B. textilis (3 years)	China	45.50		23.81	1.58	1.58	8.75	6.84	28.01		Jiang (2002)
B. tulda	China	64.36	18.42	24.16	2.02	-	4.97	2.64	21.89	-	Fangchun (2001a)
B. tulda	China	-	18.10	23.10	-	-	-	-	-	-	Fangchun (2001a)
B. vulgaris	China	41.00	21.00	28.10	1.70	0.71	-	4.60	21.50	-	Fangchun (2001a)
B. vulgaris	China	43.00	22.50	25.80	-	-	-	3.70	20.20	-	Fangchun (2001a)
B. vulgaris	China	-	21.00	22.90	-	-	-	-	-		Fangchun (2001a)
B. vulgaris	China	43.80	20.60	27.90	1.88	0.57	-	3.00	-		Fangchun (2001a)
B. sp	China	-	19.19	23.51	1.49	-	8.22	-	25.44		Fangchun (2001a)
B. sp	China	-	18.17	22.71	1.14	-	8.45	-	25.27		Fangchun (2001a)
B. sp	China	61.79	21.48	21.99	1.67	-	6.88	2.93	18.39		Fangchun (2001a)
B. sp	China	45.03	17.64	23.04	2.42	1.19	-	14.34	-		Fangchun (2001a)
B. sp	China	47.62	15.68	26.41	1.30	0.25	-	6.53	-	-	Fangchun (2001a)
B. garuchokua	India	36.75		23.03	*0.99*		5.90			4.12	Brahma and Brahma (2018)
B. pallida	India	38.29		22.42	1.08		5.70			4.37	Brahma and Brahma (2018)
B. assamica	India	31.37		18.29	1.12		4.24			3.44	Brahma and Brahma (2018)
				Cepholostachyum							
C. fuchsiamum Gamb	China	56.12	17.45	22.15	-	-	-	4.84	-	-	Fangchun (2001a)

C. pergracila Munro	China	49.05	17.55	22.44	2.67	1.31	-	7.05	-	-	Fangchun (2001a)
C. pergracile	China	-	18.40	24.90	-	-	-	-	-	-	Fangchun (2001a)
Dendrocalamus											
D. giganteus	China	51.49	17.83	24.44	2.16	0.96	-	5.65	-	-	Fangchun (2001a)
D. giganteus	China	39.40	18.40	25.30	2.87	0.37	-	5.10	24.40	-	Fangchun (2001a)
D. hamiltonii	China	63.26	21.49	26.21	1.80	-	4.42	2.47	20.81	-	Fangchun (2001a)
D. hamiltonii	China	-	16.90	22.40	-	-	-	-	*13.81*	-	Fangchun (2001a)
D. hamiltonii (1 year)	China	-	-	23.5	2.3	0.3	-	-	-	*0.9*	Zhan *et al.* (2016)
D. hamiltonii (2 years)	China	-	-	23.6	2.0	0.7	-	-	-	1.2	Zhan *et al.* (2016)
D. hamiltonii (3 years)	China	-	-	22.9	2.9	2.1	-	-	-	1.9	Zhan *et al.* (2016)
D. latiflorus Munro	China	52.84	19.78	26.25	3.03	-	-	-	21.81	-	Fangchun (2001a)
D. longispathus	China	-	18.60	25.00	-	-	-	-	-	-	Fangchun (2001a)
D. membranaceus Munro	China	47.61	16.60	26.59	1.83	0.87	-	6.54	-	-	Fangchun (2001a)
D. sericeus Munro	China	50.34	16.27	23.50	1.94	0.77	-	5.63	-	-	Fangchun (2001a)
D. sinicus Chia	China	47.53	15.97	26.59	3.44	2.07	-	6.40	-		Fangchun (2001a)
D. strictus	China	*68.00*	19.56	32.20	2.10	-	5.93	4.20	15.00	-	Fangchun (2001a)
D. strictus	China	66.40	*15.06*	27.87	2.32	-	-	-	30.61		Fangchun (2001a)
D. strictus	China	-	23.20	26.00	-	-	-	-	-	-	Fangchun (2001a)
D. sp	China	53.46	16.13	19.61	4.39	1.11	-	6.48	-		Fangchun (2001a)
D. sp	China	44.01	19.79	23.54	3.63	0.55	-	8.74	-		Fangchun (2001a)
D. sp	China	50.07	13.57	24.80	2.14	0.61	-	5.79	-	-	Fangchun (2001a)
D. sp	China	50.25	16.56	18.67	2.55	***0.17***	-	5.58	-		Fangchun (2001a)
Dinochloa											
D. sp	China	54.04	17.99	*17.62*	2.89	1.13	-	5.52	-	-	Fangchun (2001a)
Ochlandra											
O. travancorica	China	61.76	17.84	26.91	2.60	-	*3.13*	3.59	19.98		Fangchun (2001a)
Schizostachyum											
S. fumghpmii McClure	China	52.49	16.76	23.90	5.73	3.76	-	3.44	-		Fangchun (2001a)
S. affinis McClure	China	63.98	-	22.08	1.85	*0.17*	-	-	24.93	-	Fangchun (2001a)
S. affinis	China	-	25.41	31.28	1.20	-	9.78	-	31.24		Fangchun (2001a)
S. affinis Keng	China	59.06	18.88	28.96	1.62	-	7.10	-	26.20		Fangchun (2001a)
S. affinis Keng	China	60.68	18.15	24.27	2.47	-	7.75	-	25.31	-	Fangchun (2001a)
S. affinis Keng	China	57.07	18.03	23.11	2.51	-	8.68	-	26.89		Fangchun (2001a)
S. affinis Keng	China	62.57	19.17	21.35	1.69	-	7.52	-	27.82		Fangchun (2001a)
S. distegius Keng et K	China	50.84	17.74	22.65	1.79	0.51	-	5.56	-	-	Fangchun (2001a)

S. distegius Keng et K	China	59.07	19.00	23.31	1.13	-	-	-	27.71	-	Fangchun (2001a)
S. farinosus Keng	China	51.47	16.11	24.22	2.78	1.84	-	3.39	-	-	Fangchun (2001a)
S. farinosus Keng et K	China	58.11	19.20	25.25	2.63	-	-	-	27.37		Fangchun (2001a)
Thyrsostachys											
T. oliveri	China	-	18.50	20.90	-	-	-	-	-	-	Fangchun (2001a)
T. oliveri Gamble	China	51.16	16.31	23.92	2.49	0.63	-	4.44	-	-	Fangchun (2001a)
T. siamensis Gamble	China	48.83	15.72	21.19	3.80	0.98	-	9.33	-	-	Fangchun (2001a)
T. sp.	China	51.37	16.25	24.55	3.64	2.08	-	3.73	-	-	Fangchun (2001a)
T. sp.	China	66.72	17.41	27.09	1.25	-	3.39	*1.61*	17.11	-	Fangchun (2001a)
Fargesia											
F. fungosa (1 year)	China	-	-	22.66	2.88	0.48	-	-	-	3.01	Zhan *et al.* (2015)
F. fungosa (2 years)	China	-	-	24.21	1.16	0.38	-	-	-	3.22	Zhan *et al.* (2015
F. fungosa (3 years)	China	-	-	24.04	1.40	0.30	-	-	-	4.14	Zhan *et al.* (2015
Gigantochloa											
G. brang	Malaysia	51.58	-	24.83	1.26	-	-	-	-	8.30	Razak *et al.* (2013)
G. levis	Malaysia	33.81	-	26.50	1.30	-	-	-	-	9.23	Razak *et al.* (2013)
G. scortechinii	Malaysia	46.87	-	32.55	2.84	-	-	-	-	8.00	Razak *et al.* (2013)
G. wrayi	Malaysia	37.66	-	30.04	0.88	-	-	-	-	8.62	Razak *et al.* (2013)
G. scortechinii (0.5 year)	Malaysia	64.6	-	23.4	1.9	0.6	5.8	-	-	-	Norul Hisham *et al.* (2006)
G. scortechinii (1.5 y)	Malaysia	64.1	-	26.8	2.5	1.1	3.4	-	-	-	Norul Hisham *et al.* (2006)
G. scortechinii (3.5 y)	Malaysia	64.6	-	27.8	2.8	1.7	5.3	-	-	-	Norul Hisham *et al.* (2006)
G. scortechinii (5.5 y)	Malaysia	63.3	-	28.7	3.0	2.2	3.5	-	-	-	Norul Hisham *et al.* (2006)
G. scortechinii (6.5 y)	Malaysia	64.4	-	29.0	3.5	2.0	5.6	-	-	-	Norul Hisham *et al.* (2006)

Table 20. Statistical Reanalysis of the Chemical Properties in Monopodial and Sympodial Bamboos

Chemical	Rhizome		DF	F	Significance
	Monopodial	Sympodial			
Cellulose	47.63 (15.20)	40.42 (20.38)	1	3.73	0.06*
Hemicellulose	20.81 (3.41)	14.24 (7.92)	1	14.29	0.00***
Lignin	25.57 (4.83)	24.33 (3.10)	1	3.29	0.07*
Ash	1.54 (0.80)	2.06 (1.06)	1	8.89	0.00***
Silica	0.27 (0.21)	0.92 (0.55)	1	1.71	0.20NS
Hot water	6.97 (2.95)	5.75 (2.84)	1	2.93	0.09*
Cold water	6.89 (2.94)	5.61 (2.52)	1	3.52	0.07*
NaoH soluble	28.09 (5.30)	24.69 (4.91)	1	7.25	0.01**
Ethanol/toluene extractive	4.72 (1.94)	7.20 (7.54)	1	2.59	0.12NS

NS –Not significant at P > 0.1, * - significant at P < 0.1, **- significant at P < 0.05, and ***- significant at P < 0.01

SUSCEPTIBILITY AND RESISTANCE TO FUNGI

Akin to other monocotyledon and dicotyledon plants, bamboo contains structural organic chemicals, inorganic chemicals, and extractives. It is easily decayed by micro-organisms, such as mold, fungi, and insects, under appropriate conditions. Although it is well known that the bamboo has been used by human and animals, a few hundred years ago both in tropic and temperate climate, minimal information is known regarding its susceptibility to different fungi, mode of attack, resistance, and the classes. In the earliest research on susceptibility of bamboo to micro-organism, Liese (1985) reported that it is attacked especially by insects at ambient temperature; while the white, brown, and soft rot fungi are able to attack above the bamboo fibre saturation point. Liese (1985) and George (1985) both agree that the bamboo service life is estimated between 6 months to 3 years when in contact with soils. This finding is in a good agreement with Kaur *et al.* (2016b), which reveals that the untreated *D. strictcus* damages at 60% within 3 months and is completely destroyed within 6 months of exposure to termites.

The soft rot decay on the different ages of *Sinobambusa tootsik* (Makino) is characterized by cavities only in the fibre cell walls, but parenchyma and vessel components are unattacked. The rate of decaying is influenced by the location of the fibre, culm age, and the degree of lignification of individual fibers (Murphy *et al.* 1991). In bamboo, the brown rot fungi consume the carbohydrate fraction of the walls and modifying lignin during the process. The white rot is able to consume both the carbohydrate and lignin fraction of the walls, while the soft rot consumes the carbohydrate fraction but probably not the lignin. Each fungal type gives its own microscopic characteristics at the cell wall levels after the decaying process. Brown rot gives indication of widespread amorphous degradation of the bulk cell wall, and white rot gives indication of localized degradation adjacent to the hyphae (bore holes and erosion troughs). The soft rot shows indication of discrete cavities within the secondary wall, erosion of the wall from the lumen, and possibly, a generalized dissolution of the wall (Sulaiman and Murphy 1994).

The compound middle lamellae (CML) encompassing the cell corner regions are preferentially degraded in *P. pubescens* at an early stage of decaying process by white rot *Lentinus edodes*. The fibre secondary walls remain largely intact during this period. The preferential degradation of the CML compared to the fiber secondary walls strongly involves not only enzyme systems of the white rot fungus, but also a relationship to physicochemical properties of bamboo cell walls, particularly the influence of lignin composition and distribution (Kim *et al.* 2008). Same as the mode of white rot attacks, the CML in *P. pubescens* fibers are degraded at an early stage of decaying process by the *G. trabum*, which is confirmed by the distribution of H-unit lignin in the middle lamella. The absorbance bands assigned to lignin are decreased in the Fourier transform infrared spectra. The decay of bamboo fiber walls by *G. trabeum* is influenced by lignin distribution in the fiber walls. Polylaminate layers in bamboo fibers had an influence on cell wall degradation, with the narrow layers showing greater resistance than the broad layers (Cho *et al.* 2008).

In *G. scortechinii* decayed by white rot (*Coriolus versicolor*) and brown rot (*Coniophora puteana*) fungi, the mode of hyphae attacks is penetration of the larger methaxylem vessel cell and further to the neighbor parenchyma and fibre cells through small pit membrane cells (Norul Hisham *et al.* 2012). Similarly, the hyphae of white rot *P. chrysosporium* and brown rot *G. trabum* attack the *P. edulis* through the parenchyma cells. Places near the inner skin are the most frequently attacked, and the vessels are the primary paths for the spread of mycelium. The bamboo crystalline structure decreases after being decayed by both fungi and the crystalline cellulose in bamboo is well deteriorated. The white rot strongly degrades the lignin component, then the hemicellulose and cellulose components. The brown-rot selectively degrades the hemicellulose fraction over cellulose and lignin. The decaying process is accompanied by oxidation and hydrolysis surface reactions, but the reaction rates behave differently for cellulose and lignin (Xu *et al.* 2013).

In the decay resistance class of several bamboo species (Wei *et al.* 2013), the *G. angustifolia* is rather resistant to *Trametes versicolor* and same with *D. asper* against *Chaetomium globosum*. For brown-rot fungi, the *Coniophora puteana* and *Gloeophyllum trabeum* produce a low mass loss (maximum 2.9%). In contrast, the white-rot, *T. versicolor* yields the highest decay (max. 15.3%), while the *Schizophyllum commune* is considered as inactive (max. 3.2%). For soft-rot fungi, *Ch. globosum* gives a medium degradation (max. 9.6%) and *Paecilomyces variotii* exhibits low degradation (max. 3.1%). The decay resistance depends on the bamboo species, type of fungi, the standard of testing, incubation period, and its environmental conditions. The deterioration is always expressed in percentage weight loss of oven-dried specimen before and after the exposure. For instance, the *G. scortechinii* exposed to brown rot *Coniophora puteana* showed 8.90% of weight loss after 8 weeks incubation period (Norul Hisham *et al.* 2012), while it was 18.70% weight loss after 52 weeks of incubation (Schmidt *et al.* 2013). The *D. asper* recorded 15.3% weight loss after it was exposed to *Schizosphyllum commune* for 12 weeks (Suprapti 2010), and it was only 4.3% weight loss after it was exposed to the same fungus for 52 weeks (Schmidt *et al.* 2013). The *P. pubescens* showed only 5.3% weight loss after 52 weeks was exposed to *Gloeophyllum trabeum* (Schmidt *et al.* 2011), and it recorded 54.36% of weight loss after it was exposed for 8 weeks (Li *et al.* 2020). The weight loss of *P. pubescens* decayed by brown rot *Coniophora puteana* contact with soil was 6.3% compared to without soil contact, 25% (Schmidt *et al.* 2011)

Overall

Regardless of fungi (Table 22), the decay resistance is not significantly different for both monopodial (16.72%) and sympodial (14.22%) bamboo. The resistance is also not significantly different with fungi, either white, brown, or soft rot for both monopodial (19.06%, 15.92%, and 11.05%) and sympodial (14.03%, 12.88%, and 17.38%) bamboos, respectively. Generally, in all type of fungus, the monopodial bamboo is less resistant toward white, brown, and soft rot compared to the sympodial bamboo.

Table 21. Weight Loss of Monopodial and Sympodial Bamboos Decayed by Fungi

Species	Week	Fungi	Strain	% WL	References
Monopodial					
P. pubescens	52	WR	*Pleurotus ostreatus* 11	21.0	Schmidt *et al.* (2011)
P. pubescens	52	WR	*Schizophyllum commune* 87	5.2	Schmidt *et al.* (2011)
P. pubescens	52	WR	*Schizophyllum commune* 98	4.4	Schmidt *et al.* (2011)
P. pubescens	52	WR	*Trametes versicolor* 63	47.8	Schmidt *et al.* (2011)
P. pubescens (with soil contact)	52	WR	*Schizophyllum commune* 87	6.3	Schmidt *et al.* (2011)

P. pubescens (without soil contact)	52	WR	*Schizophyllum commune* 87	5.8	Schmidt *et al.* (2011)
P. pubescens	8	WR	*Coriolus versicolor*	60.48	Li *et al.* (2020)
P. pubescens	52	BR	*Coniophora puteana* 167	4.7	Schmidt *et al.* (2011)
P. pubescens	52	BR	*Gloeophyllum trabeum* 183	5.3	Schmidt *et al.* (2011)
P. pubescens (with soil contact)	52	BR	*Coniophora Puteana 167*	6.3	Schmidt *et al.* (2011)
P. pubescens (without soil contact)	52	BR	*Coniophora Puteana 167*	25.0	Schmidt *et al.* (2011)
P. pubescens	52	SR	*Chaetomium globosum* 10	38	Schmidt *et al.* (2011)
P. pubescens	52	SR	*Paecilomyces variotii* 13	3.9	Schmidt *et al.* (2011)
P. pubescens	8	BR	*Gloeophyllum trabeum*	54.36	Li *et al.* (2020)
P. pubescens	52	BR	*Schizophyllum commune* 87	5.7	Schmidt *et al.* (2013)
P. pubescens	52	BR	*Coniophora puteana* 167	38.3	Schmidt *et al.* (2013)
P. nigra	52	BR	*Coniophora puteana* 167	32.6	Schmidt *et al.* (2013)
P. nigra	52	WR	*Schizophyllum commune* 87	9.1	Schmidt *et al.* (2013)
P. nigra (with soil contact)	52	BR	*Coniophora puteana* 167	15.5	Schmidt *et al.* (2011)
P. nigra (without soil contact)	52	BR	*Coniophora puteana* 167	40.3	Schmidt *et al.* (2011)
P. nigra (with soil contact)	52	WR	*Schizophyllum commune* 87	16.4	Schmidt *et al.* (2011)
P. nigra (without soil contact)	52	WR	*Schizophyllum commune* 87	7.4	Schmidt *et al.* (2011)
P.nigra Boryana (with soil contact)	52	BR	*Coniophora puteana* 167	35.3	Schmidt *et al.* (2011)
P. nigra Boryana (without soil contact)	52	BR	*Coniophora puteana* 167	38.5	Schmidt *et al.* (2011)
P. nigra Boryana (with soil contact)	52	WR	*Schizophyllum commune* 87	19.7	Schmidt *et al.* (2011)
P. nigra Boryana (without soil contact)	52	WR	*Schizophyllum commune* 87	5.8	Schmidt *et al.* (2011)
P. edulis	12	WR	*Phanerochaete chrysosporium*	40.0	Xu *et al.* (2013)
P. edulis	12	BR	*Gloeophyllum trabeum*	34.6	Xu *et al.* (2013)
Phyllostachys vivax	16	WR	*Trametes versicolor*	19.0	Xu *et al.* (2013)
Phyllostachys vivax	16	WR	*Xylaria polymorpha*	17.5	Xu *et al.* (2013)
Phyllostachys vivax	16	BR	*Coniophora puteana*	9.2	Xu *et al.* (2013)
Phyllostachys vivax	16	BR	*Oligoporus placenta*	6.9	Xu *et al.* (2013)
Phyllostachys vivax	16	SR	*Xylaria longipes*	18.2	Xu *et al.* (2013)
P. bambusoides (top with node)	8	BR	*Coniophora puteana*	6.9	Tomak *et al.* (2013)
P. bambusoides (top with internode)	8	BR	*Coniophora puteana*	7.9	Tomak *et al.* (2013)
P. bambusoides (middle with node)	8	BR	*Coniophora puteana*	6.4	Tomak *et al.* (2013)

P. bambusoides (middle with internode)	8	BR	*Coniophora puteana*	7.1	Tomak *et al.* (2013)
P. bambusoides (basal with node)	8	BR	*Coniophora puteana*	4.1	Tomak *et al.* (2013)
P. bambusoides (basal with internode)	8	BR	*Coniophora puteana*	6.1	Tomak *et al.* (2013)
P. bambusoides (top with node)	8	BR	*Poria placenta*	6.5	Tomak *et al.* (2013)
P. bambusoides (top with internode)	8	BR	*Poria placenta*	2.7	Tomak *et al.* (2013)
P. bambusoides (middle with node)	8	BR	*Poria placenta*	3.4	Tomak *et al.* (2013)
P. bambusoides (middle with internode)	8	BR	*Poria placenta*	0.5	Tomak *et al.* (2013)
P. bambusoides (basal with node)	8	BR	*Poria placenta*	6.2	Tomak *et al.* (2013)
P. bambusoides (basal with internode)	8	BR	*Poria placenta*	1.8	Tomak *et al.* (2013)
A. amabilis	52	BR	*Coniophora puteana* 167	38.6	Schmidt *et al.* (2013)
A. amabilis	52	BR	*Schizophyllum commune* 87	10.8	Schmidt *et al.* (2013)
Sympodial					
G. atroviolacea	52	WR	*Pleurotus ostreatus* 11	10.6	Schmidt *et al.* (2011)
G. atroviolacea	52	WR	*Schizophyllum commune* 87	6.7	Schmidt *et al.* (2011)
G. atroviolacea	52	WR	*Schizophyllum commune* 98	5.6	Schmidt *et al.* (2011)
G. atroviolacea	52	WR	*Trametes versicolor* 63	51.6	Schmidt *et al.* (2011)
G. atroviolacea	12	WR	*Coriolus versicolor* 1030	7.7	Suprapti (2010)
G. atroviolacea	12	WR	*Phanerochaete chrysosporium* HHBI-320	7.6	Suprapti (2010)
G. atroviolacea	12	WR	*P. sordida* HI IBI-321	5.4	Suprapti (2010)
G. atroviolacea	12	WR	*Phlebia brevispora* Mad.	4.1	Suprapti (2010)
G. atroviolacea	12	WR	*Postia placenta* Mad- 696	5.1	Suprapti (2010)
G. atroviolacea	12	WR	*Pycnoporus sanguineus* FIHBI-324	14.4	Suprapti (2010)
G. atroviolacea	12	WR	*P. sanguineus* HHBI-8149	3.8	Suprapti (2010)
G. atroviolacea	12	WR	*Schizophyllum commune* FIHBI-204	5.8	Suprapti (2010)
G. atroviolacea	12	WR	*S. commune* HHBI-222	2.8	Suprapti (2010)
G. atroviolacea	52	BR	*Coniophora puteana* 167	5.6	Schmidt et al. (2011)
G. atroviolacea	52	BR	*Gloeophyllum trabeum* 183	5.7	Schmidt et al. (2011)
G. atroviolacea	12	BR	*Dacryopinax*	3.4	Suprapti (2010)

			spathularia HHBI-145		
G. atroviolacea	12	BR	*D. spathularia* HHBI-223	7.7	Suprapti (2010)
G. atroviolacea	12	BR	Lentinus lepideus Mad-534	3.9	Suprapti (2010)
G. atroviolacea	12	BR	*Polyporus* sp. HHBI-209	20.9	Suprapti (2010)
G. atroviolacea	12	BR	*Tyromyces palustris* FRI Japan-507	21.0	Suprapti (2010)
G. atroviolacea	12	SR	*Chaetomium globosum* FRI Japan 5-1	4.6	Suprapti (2010)
G. atroviolacea	52	SR	*Chaetomium globosum* 10	9.4	Schmidt *et al.* (2011)
G. atroviolacea	52	SR	*Paecilomyces variotii* 13	3.6	Schmidt *et al.* (2011)
B. maculate	52	WR	*Pleurotus ostreatus* 11	28.2	Schmidt *et al.* (2011)
B. maculate	52	WR	*Schizophyllum commune* 87	2.8	Schmidt *et al.* (2011)
B. maculate	52	WR	*Schizophyllum commune* 98	1.8	Schmidt *et al.* (2011)
B. maculate	52	WR	*Trametes versicolor* 63	62.5	Schmidt *et al.* (2011)
B. maculate	52	WR	*Schizophyllum commune* 87	5.1	Schmidt *et al.* (2013)
B. maculate	52	BR	*Coniophora puteana* 167	3.6	Schmidt *et al.* (2011)
B. maculate	52	BR	*Gloeophyllum trabeum* 183	1.9	Schmidt *et al.* (2011)
B. maculate	52	BR	*Coniophora puteana* 167	20.4	Schmidt *et al.* (2013)
B. maculate	52	SR	*Chaetomium globosum* 10	31.8	Schmidt *et al.* (2011)
B. maculate	52	SR	*Paecilomyces variotii* 13	1.2	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	WR	*Schizophyllum commune* 3	7.4	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	WR	*Schizophyllum commune* 3	6.9	Schmidt *et al.* (2011)
M. bambusoides (2 years)	24	WR	*Schizophyllum commune* 3	5.0	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	WR	*Schizophyllum commune* 3	4.6	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	WR	*Schizophyllum commune* 4	9.1	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	WR	*Schizophyllum commune* 4	6.4	Schmidt *et al.* (2011)
M. bambusoides (2 years)	24	WR	*Schizophyllum commune* 4	5.6	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	WR	*Schizophyllum commune* 4	4.8	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	WR	*Trametes versicolor* 63	28.3	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	WR	*Trametes versicolor*	16.9	Schmidt *et al.*

			63		(2011)
M. bambusoides (2 years)	24	WR	*Trametes versicolor* 63	12.5	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	WR	*Trametes versicolor* 63	14.7	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	BR	*Coniophora puteana* 1	11.2	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	BR	*Coniophora puteana* 1	13.7	Schmidt *et al.* (2011)
M. bambusoides (2 years)	24	BR	*Coniophora puteana* 1	8.4	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	BR	*Coniophora puteana* 1	9.9	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	BR	*Oligoporus placenta* 120	5.6	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	BR	*Oligoporus placenta* 120	6.8	Schmidt *et al.* (2011)
M. bambusoides (2 years)	24	BR	*Oligoporus placenta* 120	5.4	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	BR	*Oligoporus placenta* 120	6.0	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	SR	*Chaetomium globosum* 76	52.7	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	SR	*Chaetomium globosum* 76	31.4	Schmidt *et al.* (2011)
M. bambusoides (2 years)	24	SR	*Chaetomium globosum* 76	32.3	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	SR	*Chaetomium globosum* 76	27.9	Schmidt *et al.* (2011)
M. bambusoides (0.5 year)	24	SR	*Paecilomyces variotii* 92	19.7	Schmidt *et al.* (2011)
M. bambusoides (1 year)	24	SR	*Paecilomyces variotii* 92	9.6	Schmidt *et al.* (2011)
M. bambusoides (2 years)	24	SR	*Paecilomyces variotii* 92	8.2	Schmidt *et al.* (2011)
M. bambusoides (3 years)	24	SR	*Paecilomyces variotii* 92	7.5	Schmidt *et al.* (2011)
B. polymorpha (Top)	24	WR	*Schizophyllum commune* 4	5.9	Schmidt *et al.* (2011)
B. polymorpha (Basal)	24	WR	*Schizophyllum commune* 4	4.1	Schmidt *et al.* (2011)
B. polymorpha (Top)	24	BR	*Coniophora puteana* 1	12.1	Schmidt *et al.* (2011)
B. polymorpha (Basal)	24	BR	*Coniophora puteana* 1	15.5	Schmidt *et al.* (2011)
B. polymorpha (Top)	24	BR	*Oligoporus placenta* 120	12.8	Schmidt *et al.* (2011)
B. polymorpha (Basal)	24	BR	*Oligoporus placenta* 120	5.7	Schmidt *et al.* (2011)
B. polymorpha (Top)	24	SR	*Chaetomium globosum* 76	33.7	Schmidt *et al.* (2011)
B. polymorpha (Basal)	24	SR	*Chaetomium globosum* 76	23.3	Schmidt *et al.* (2011)
B. polymorpha (Top)	24	SR	*Paecilomyces variotii* 92	14.1	Schmidt *et al.* (2011)
B. polymorpha (Basal)	24	SR	*Paecilomyces*	9.4	Schmidt *et al.*

			variotii 92		(2011)
D. strictus (Top)	24	WR	*Schizophyllum commune* 4	2.7	Schmidt *et al.* (2011)
D. strictus (Basal)	24	WR	*Schizophyllum commune* 4	4.7	Schmidt *et al.* (2011)
D. strictus, Teri	12	WR	*Polyporus versicolor*	54.1	Kaur *et al.* (2016b)
D. strictus, Allahabad	12	WR	*Polyporus versicolor*	54.3	Kaur *et al.* (2016b)
D. strictus (Top)	24	BR	*Coniophora puteana* 1	38.2	Schmidt *et al.* (2011)
D. strictus (Basal)	24	BR	*Coniophora puteana* 1	12.7	Schmidt *et al.* (2011)
D. strictus (Top)	24	BR	*Oligoporus placenta* 120	11.3	Schmidt *et al.* (2011)
D. strictus (Basal)	24	BR	*Oligoporus placenta* 120	9.8	Schmidt *et al.* (2011)
D. strictus (Top)	24	SR	*Chaetomium globosum* 76	28.2	Schmidt *et al.* (2011)
D. strictus (Basal)	24	SR	*Chaetomium globosum* 76	6.7	Schmidt *et al.* (2011)
D. strictus (Top)	24	SR	*Paecilomyces variotii* 92	9.3	Schmidt *et al.* (2011)
D. strictus (Basal)	24	SR	*Paecilomyces variotii* 92	2.1	Schmidt *et al.* (2011)
O. nigro-ciliata (Top)	24	WR	*Schizophyllum commune* 4	2.1	Schmidt *et al.* (2011)
O. nigro-ciliata (Basal)	24	WR	*Schizophyllum commune* 4	2.8	Schmidt *et al.* (2011)
O. nigro-ciliata (Top)	24	BR	*Coniophora puteana* 1	38.5	Schmidt *et al.* (2011)
O. nigro-ciliata (Basal)	24	BR	*Coniophora puteana* 1	4.0	Schmidt *et al.* (2011)
O. nigro-ciliata (Top)	24	BR	*Oligoporus placenta* 120	7.4	Schmidt *et al.* (2011)
O. nigro-ciliata (Basal)	24	BR	*Oligoporus placenta* 120	1.6	Schmidt *et al.* (2011)
O. nigro-ciliata (Top)	24	SR	*Chaetomium globosum* 76	41.1	Schmidt *et al.* (2011)
O. nigro-ciliata (Basal)	24	SR	*Chaetomium globosum* 76	21.1	Schmidt *et al.* (2011)
O. nigro-ciliata (Top)	24	SR	*Paecilomyces variotii* 92	7.4	Schmidt *et al.* (2011)
O. nigro-ciliata (Basal)	24	SR	*Paecilomyces variotii* 92	6.0	Schmidt *et al.* (2011)
T. oliveri (Top)	24	WR	*Schizophyllum commune* 4	6.8	Schmidt *et al.* (2011)
T. oliveri (Basal)	24	WR	*Schizophyllum commune* 4	3.2	Schmidt *et al.* (2011)
T. oliveri (Top)	24	BR	*Coniophora puteana* 1	18.5	Schmidt *et al.* (2011)
T. oliveri (Basal)	24	BR	*Coniophora puteana* 1	8.2	Schmidt *et al.* (2011)
T. oliveri (Top)	24	BR	*Oligoporus placenta* 120	6.4	Schmidt *et al.* (2011)
T. oliveri (Basal)	24	BR	*Oligoporus placenta* 120	2.3	Schmidt *et al.* (2011)
T. oliveri (Top)	24	SR	*Chaetomium*	47.2	Schmidt *et al.*

			globosum 76		(2011)
T. oliveri (Basal)	24	SR	*Chaetomium globosum* 76	27.2	Schmidt *et al.* (2011)
T. oliveri (Top)	24	SR	*Paecilomyces variotii* 92	7.7	Schmidt *et al.* (2011)
T. oliveri (Basal)	24	SR	*Paecilomyces variotii* 92	5.2	Schmidt *et al.* (2011)
B. vulgaris	12	WR	*Coriolus versicolor* 1030	7.2	Suprapti (2010)
B. vulgaris	12	WR	*Phanerochaete chrysosporium* HHBI-320	8.7	Suprapti (2010)
B. vulgaris	12	WR	*P. sordida* HI IBI-321	5.4	Suprapti (2010)
B. vulgaris	12	WR	*Phlebia brevispora* Mad.	4.8	Suprapti (2010)
B. vulgaris	12	WR	*Postia placenta* Mad-696	4.5	Suprapti (2010)
B. vulgaris	12	WR	*Pycnoporus sanguineus* FIHBI-324	22.5	Suprapti (2010)
B. vulgaris	12	WR	*P. sanguineus* HHBI-8149	5.0	Suprapti (2010)
B. vulgaris	12	WR	*Schizophyllum commune* FIHBI-204	8.8	Suprapti (2010)
B. vulgaris	12	WR	*S. commune* HHBI-222	4.6	Suprapti (2010)
Bambusa vulgaris Schrad.	3	WR	*Trametes versicolor*	48.09	Poonia *et al.* (2021)
B. vulgaris	12	BR	*Dacryopinax spathularia* HHBI-145	5.2	Suprapti (2010)
B. vulgaris	12	BR	*D. spathularia* HHBI-223	4.7	Suprapti (2010)
B. vulgaris	12	BR	Lentinus lepideus Mad-534	4.1	Suprapti (2010)
B. vulgaris	12	BR	*Polyporus* sp. HHBI-209	36.2	Suprapti (2010)
B. vulgaris	12	BR	Tyromyces palustris FRI Japan-507	37.4	Suprapti (2010)
Bambusa vulgaris Schrad.	3	BR	*Rhodonia placenta*	47.65	Poonia *et al.* (2021)
B. vulgaris	12	SR	*Chaetomium globosum* FRI Japan 5-1	7.0	Suprapti (2010)
B. nutans, Dehradun	12	WR	*Polyporus versicolor*	58.2	Kaur *et al.* (2016b)
B. arundinacea, Allahabad	12	WR	*Polyporus versicolor*	55.7	Kaur *et al.* (2016b)
B. tulda, Bihar	12	WR	*Polyporus versicolor*	57.4	Kaur *et al.* (2016b)
B. bambus, IWST, Bangalore	12	WR	*Polyporus versicolor*	56.9	Kaur *et al.* (2016b)
B. *pallida*, IWST, Bangalore	12	WR	*Polyporus versicolor*	59.2	Kaur *et al.* (2016b)
D. asper	12	WR	*Coriolus versicolor* 1030	15.2	Suprapti (2010)
D. asper	12	WR	*Phanerochaete*	7.2	Suprapti (2010)

			chrysosporium HHBI-320		
D. asper	12	WR	*P. sordida* HI IBI-321	7.5	Suprapti (2010)
D. asper	12	WR	*Phlebia brevispora* Mad.	11.1	Suprapti (2010)
D. asper	12	WR	*Postia placenta* Mad-696	3.7	Suprapti (2010)
D. asper	12	WR	*Pycnoporus sanguineus* FIHBI-324	19.0	Suprapti (2010)
D. asper	12	WR	*P. sanguineus* HHBI-8149	8.9	Suprapti (2010)
D. asper	12	WR	*Schizophyllum commune* FIHBI-204	15.0	Suprapti (2010)
D. asper	12	WR	*S. commune* HHBI-222	4.6	Suprapti (2010)
D. asper	52	WR	*Schizophyllum commune* 87	4.3	Schmidt *et al.* (2013)
D. asper	12	BR	*Dacryopinax spathularia* HHBI-145	6.7	Suprapti (2010)
D. asper	12	BR	*D. spathularia* HHBI-223	8.8	Suprapti (2010)
D. asper	12	BR	*Lentinus lepideus* Mad-534	5.8	Suprapti (2010)
D. asper	12	BR	*Polyporus* sp. HHBI-209	21.0	Suprapti (2010)
D. asper	52	BR	*Coniophora puteana* 167	29.3	Schmidt *et al.* (2013)
D. asper	12	BR	*Tyromyces palustris* FRI Japan-507	16.5	Suprapti (2010)
D. asper	12	SR	*Chaetomium globosum* FRI Japan 5-1	8.0	Suprapti (2010)
D. gigantues	12	BR	*Gloeophyllum trabeum*	13.36	Brito *et al.* (2020)
D. gigantues	12	BR	*Postia placenta*	22.47	Brito *et al.* (2020)
G. apus	12	WR	*Coriolus versicolor* 1030	4.8	Suprapti (2010)
G. apus	12	WR	*Phanerochaete chrysosporium* HHBI-320	6.5	Suprapti (2010)
G. apus	12	WR	*P. sordida* HI IBI-321	5.4	Suprapti (2010)
G. apus	12	WR	*Phlebia brevispora* Mad.	3.8	Suprapti (2010)
G. apus	12	WR	*Postia placenta* Mad-696	4.8	Suprapti (2010)
G. apus	12	WR	*Pycnoporus sanguineus* FIHBI-324	9.0	Suprapti (2010)
G. apus	12	WR	*P. sanguineus* HHBI-8149	4.0	Suprapti (2010)
G. apus	12	WR	*Schizophyllum commune* FIHBI-204	4.5	Suprapti (2010)

G. apus	12	WR	*S. commune* HHBI-222	3.2	Suprapti (2010)
G. apus	12	BR	*Dacryopinax spathularia* HHBI-145	5.80	Suprapti (2010)
G. apus	12	BR	*D. spathularia* HHBI-223	5.9	Suprapti (2010)
G. apus	12	BR	*Lentinus lepideus* Mad-534	4.3	Suprapti (2010)
G. apus	12	BR	*Polyporus* sp. HHBI-209	21.7	Suprapti (2010)
G. apus	12	BR	*Tyromyces palustris* FRI Japan-507	23.8	Suprapti (2010)
G. apus	12	SR	*Chaetomium globosum* FRI Japan 5-1	7.5	Suprapti (2010)
G. pseudoarundinacea	12	WR	*Coriolus versicolor* 1030	20.7	Suprapti (2010)
G. pseudoarundinacea	12	WR	*Phanerochaete chrysosporium* HHBI-320	16.6	Suprapti (2010)
G. pseudoarundinacea	12	WR	*P. sordida* HI IBI-321	5.3	Suprapti (2010)
G. pseudoarundinacea	12	WR	*Phlebia brevispora* Mad.	10.3	Suprapti (2010)
G. pseudoarundinacea	12	WR	*Postia placenta* Mad-696	13.0	Suprapti (2010)
G. pseudoarundinacea	12	WR	*Pycnoporus sanguineus* FIHBI-324	32.6	Suprapti (2010)
G. pseudoarundinacea	12	WR	*P. sanguineus* HHBI-8149	8.7	Suprapti (2010)
G. pseudoarundinacea	12	WR	*Schizophyllum commune* FIHBI-204	26.6	Suprapti (2010)
G. pseudoarundinacea	12	WR	*S. commune* HHBI-222	4.0	Suprapti (2010)
G. pseudoarundinacea	12	BR	*Dacryopinax spathularia* HHBI-145	4.1	Suprapti (2010)
G. pseudoarundinacea	12	BR	*D. spathularia* HHBI-223	3.3	Suprapti (2010)
G. pseudoarundinacea	12	BR	*Lentinus lepideus* Mad-534	11.0	Suprapti (2010)
G. pseudoarundinacea	12	BR	*Polyporus* sp. HHBI-209	27.4	Suprapti (2010)
G. pseudoarundinacea	12	BR	*Tyromyces palustris* FRI Japan-507	26.9	Suprapti (2010)
G. pseudoarundinacea	12	SR	*Chaetomium globosum* FRI Japan 5-1	9.3	Suprapti (2010)
G. scortechinii (0.5 year)	8	WR	*Coriolus versicolor*	9.90	Norul Hisham *et al.* (2012)
G. scortechinii (3.5 years)	8	WR	*Coriolus versicolor*	9.24	Norul Hisham *et al.* (2012)
G. scortechinii (6.5 years)	8	WR	*Coriolus versicolor*	5.30	Norul Hisham *et al.* (2012)

G. scortechinii (0.5 year)	8	BR	*Coniophora puteana*	9.95	Norul Hisham *et al.* (2012)
G. scortechinii (3.5 years)	8	BR	*Coniophora puteana*	9.49	Norul Hisham *et al.* (2012)
G. scortechinii (6.5 years)	8	BR	*Coniophora puteana*	8.90	Norul Hisham *et al.* (2012)
G. scortechinii	52	BR	*Coniophora puteana* 167	18.7	Schmidt *et al.* (2013)
G. scortechinii	52	BR	*Schizophyllum commune* 87	4.7	Schmidt *et al.* (2013)

Table 22. Statistical Analysis of Weight Loss of Decayed Monopodial and Sympodial Bamboo

Fungus	Rhizome		DF	F	Significance
	Monopodial	Sympodial			
White rot	19.06^{X} (17.21)	14.03^{X} (16.49)	1	0.02	0.08^{NS}
Brown rot	15.92^{X} (15.55)	12.88^{X} (10.57)			
Soft rot	11.05^{X} (10.11)	17.38^{X} (13.98)			
Average	16.72 (15.77)	14.22 (14.25)			

DF– Degree of freedom, F– F ratio, NS is not significant at P > 0.1, *** is significant at P < 0.0.
The value in parentheses is standard deviation.

CONCLUSIONS

1. The bamboo properties are not only different with genera, species, and site location, but also with rhizome type. The monopodial bamboo has shorter sprouting time, growth phase, diameter breast height, and overall height than the sympodial bamboo.
2. Anatomically, the monopodial bamboo contains a higher radial length and tangential diameter, but its radial length/tangential diameter is smaller than the sympodial bamboo. The vascular bundle frequency is higher in monopodial bamboo.
3. The monopodial bamboo contains higher α-cellulose, hemicellulose, lignin, hot water soluble, cold water soluble, and 1% NaOH soluble contents. Monopodial bamboo has a higher tensile and modulus of rupture but there is not much difference in the compression strength.
4. The fibre length and diameter are longer and wider in sympodial bamboo, but the fibre lumen diameter and wall thickness are not different in either monopodial or sympodial bamboos.
5. The proportion of metaxylem vessel diameter is higher in sympodial bamboo but the proportion of fibre and parenchyma are not much different for monopodial and sympodial bamboos. The volumetric shrinkage is higher in sympodial bamboo, but the density is not much different for both rhizome types.

6. Sympodial bamboo has a significantly higher ash content, but both the silica and ethanol/toluene extractive contents are not much different from either monopodial or sympodial bamboo. Overall, the sympodial bamboo is more resistant toward white, brown, and soft rot compared to the monopodial bamboo.

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