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A REVIEW OF THE FACTORS AFFECTING THE PROPERTIES OF BAMBOO FIBER BIO-COMPOSITE MATERIALS

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ABSTRACT

The increasing demand for eco-friendly, sustainable, biodegradable natural fiber reinforced composites is a direct result of an increase in environmental awareness and a shift away from traditional material sources that are in favour of composites which derived from renewable green resources. Natural fiber composites have garnered significant interest due to their abundance. Among other advantages, natural fiber composites are inexpensive, biodegradable, and renewable. As a result, bamboo fiber has recently received a great deal of attention, and it has been extensively utilised in the production of bio-composite materials to replace or reduce the use of nonrenewable or synthetic fiber. The quality of bamboo fiber composites is largely determined by factors such as the selection of an appropriate bamboo fiber, preparation and extraction methods, and resin. Inappropriate selection of these factors may have a negative impact on the quality of bamboo fiber composites. Therefore, the purpose of this study is to provide a comprehensive review of these factors, which may aid in the selection process. In this study, the properties of fibers, moisture content, orientation and length of fibers, matrix, and fiber extraction processes are described in detail. Thiese findings can serve as a reference for future research on bamboo fiber composites and promote their use.

Keywords: *Bamboo fiber, Bio-composite, Properties of fiber*

INTRODUCTION

Increasing consciousness and awareness of sustainable development has stimulated research into the creation of new materials for the construction, furniture, packaging, aerospace, automotive, and many other industries. Thus, there is increasing research and development interest in the creation of new materials derived from renewable resources. In addition, the rising costs of raw materials for engineering and standard plastics, the future viability of natural reservoirs, and the environmental threat have prompted the development and production of polymer composites that incorporate natural recyclable materials (Ortega et al., 2021). In recent years, synthetic fibre reinforcement has dominated the market; however, natural fibre reinforcement has gained significant traction to replace this synthetic fibre in a variety of applications (Sanjay et al., 2019). As a viable alternative to traditional petroleum-based materials and for the development of novel applications, the use of renewable raw materials such as plant fibres and bio-based polymers has become widespread in this field. Existing synthetic fibres such as glass, carbon, and aramid are being supplanted by naturally occurring natural fibres that can be used as reinforcements. Due to their low density, mechanical sturdiness, low cost, durability, sustainability, and biodegradability, natural fibres provide applications in structural and environmental construction that are both functional and cost-effective (Karimah & Rasyidur, 2021). However, the greatest challenge in working with natural fiber reinforced plastic composites is their large variation in properties and characteristics.

There are three types of composite materials. These three types of composite materials are polymer matrix composite (PMC), metal matrix composite (MMC), and ceramic matrix composite (CMC). Green composites are a subset of bio-composite materials that include both reinforced and polymer matrix phases produced from biological or renewable sources (Saba et al., 2017; Varis et al., 2019). The term "bio-composites" refers to: petroleum-derived, nonbiodegradable polymers reinforce with biofibers such as polypropylene (PP), polyethylene (PE), polyester, epoxy, or vinylester; (ii) biopolymers reinforce with biofibers such as PLA, PHA; and (iii) biopolymers reinforced with synthetic fibers such as glass or carbon. Biopolymers reinforced with biofibers are sometimes referred to as "green composites" since they are thought to be more environmentally friendly (Faruque & Bilisik, 2020; Yatim et al., 2010).

Amongst the natural fiber plants, bamboo is considered as essential plant fiber and has great potential in bio-composite industry. Sun et al., (2020) stated that in Asian countries' bamboo is considered as natural engineering material. Bamboo is fast growing grass up 15-30m full height within 2-4 months period of times and daily growth rates about 20cm up to 100cm. Overall, mechanical characteristics of naturally grown bamboo vary greatly due to variations in species, growth pattern, and grown features, limiting their wide structural uses (Sun et al., 2020). Bamboo fiber is considered attractive due to its low density, high mechanical characteristic, and low cost as a sustainable structural material that can be used for a variety of applications such as building construction, housing, and flooring (Bahari & Krause, 2016). According to Khalil et al., (2012), bamboo fiber is known to have the mechanical toughness, thermal stability, and ease of bamboo fiber extractions, as well as its ease of chemical modification that has made it adaptable in composite sector. The most appealing and well-known qualities of bamboo fibers is their economic values, lightweight, high specific strength, and nonhazardous nature. From the previous study, some species of bamboo fiber can reach a massive tensile strength of 100 MPa, while constructional bamboo species could reach up to 400 MPa tensile strength (Gao et al., 2022; F. Wang et al., 2015). As a result, constructional bamboo fibers have the superior prospective in mechanical behavior if used properly. Aside from bamboo strip-based composites, to regulate the extraction of bamboo fibers from bamboo trees, the fabrication of bamboo-based composites is compulsory (Khalil et al., 2012). Bamboo fibers possessed finer mechanical distinctive than other natural fibers. However, it is brittle due to additional lignin content that covered the bamboo fibers. Thus, there are varieties of method that have been developed to extract bamboo fiber for reinforcement of composites such as alkaline treatment. The treatment was used for simplification of the bamboo fiber extraction and also enhancement for the separation of bamboo fiber to formulate bamboo fiber (Yang et al., 2010).

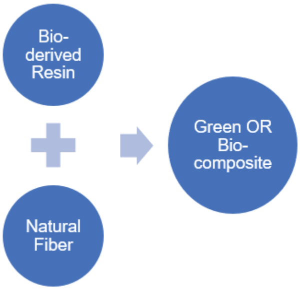


Figure 1. Fabrication of Bio-composite
Source: Saba et al., (2017)

For clearer and safer environment there are some new ideas by researchers towards a new direction in eco-composite, which is to provide the benefits to ecological and environmental over the synthetic or conventional composites. Bamboo fibers has qualities like economic value, lightweight, high specific strength, and non-hazardous nature As a result, this has prompted researchers to study in the direction of composite technology. Thus, it is clear that bamboo fiber-based composites have the potential to replace non-renewable, expensive synthetic fibers in composite materials, particularly in the construction industries. Therefore, in this paper, a

systematic review of the bamboo fiber as bio composites along with the physicochemical properties and polymer matrices were included. The factors affecting the mechanical properties of the bamboo fiber were also summarized.

TYPES OF NATURAL FIBERS

Natural fiber has been proposed as a replacement for synthetic fiber because of its benefits, which include light weight, biodegradability, low cost, low energy needs, plentiful availability, high strength, and elasticity modulus. Kenaf, jute, flax, sisal, coir, and bamboo fiber are some of the most widely researched plant fibers as shown in Table 1. Bamboo fiber has received a lot of attention because of its low density, high stiffness, and high strength, as well as the fact that bamboo grows quickly, making it readily available (Chin et al., 2020). Research was conducted utilizing the G. Scortechinii

(Buluh Semantan) bamboo species, which is common in Southeast Asia and it has good mechanical characteristics. Bamboo that is 3–5 years old is generally suggested for use in the building sector.

Table 1. The Important Properties of Natural Fibers

Fiber/ Property	Abaca	Bamboo	Banana	Coir	Cotton	Flax	Hemp	Jute	Kenaf
Density (g/cc)	1.5	0.85	1.35	1.2	1.21	1.38	1.47	1.23	1.2
Diameter (μm)	20	56.5	21	18.5	23.5	21.5	30.5	15	24
Length (mm)	4.9	2.75	0.65	1.65	35.5	37.5	30	3.4	6.2
Tensile strength (MPa)	621.5	566	721.5	175	442	689	845	480	612.5
Young's Modulus (Gpa)	32.35	53	29.5	6	8	60	45	37.5	41
Elongation at break (%)	2.9	4.65	5.5	20	6	2.1	3.05	2.3	4.8
Moisture content (%)	14	14	10.5	10	33.5	7	8	12	9.1

Source: Dasore et al., (2021)

Table 2. The Chemical Composition of Natural Fibers

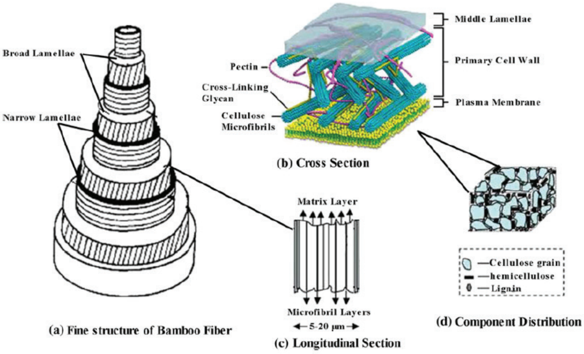
Fiber/Property	Abaca	Bamboo	Coir	Cotton	Hemp	Jute
Cellulose (%)	60.8-68.0	36.1-54.6	32.0-43.4	82.7-98.0	55-90	58.0-71.5
Hemicellulose (%)	17.5-21	11.4-16.6	0.3	4.0-5.7	12	13.6-24.0
Lignin (%)	5-15.1	20.5-28.5	40-45.8	0.7	2-5	11.8-16
Pectin (%)	<1	<1	3	4	3	2
Fat and wax (%)	<1	1-4	0-6	2-3	1.7	<1

Source: Bourmaud et al., (2018)

Bamboo fibers with a low density (1.4 g/cm3) have superior mechanical properties, including higher specific stiffness and bending load strength than synthetic glass fibers (Jawaid et al., 2021). Bamboo that is made up of cellulose, hemicellulose and lignin contribute a major part which is 95% of total mass of bamboo as mentioned in Table 2. Moreover, the cellulose content has higher percentages about 73.83% compared to oil palm (44.20-49.60), coir (36.62-43.21), corn stalks (38.33-40.31), jute (69.21-72.35), kenaf (3750-63.00) and sisal (43.85-56.63) (Rasheed et al., 2020). A lower content of holocellulose and alpha-cellulose would lead to higher moisture content (Wahab et al., 2013).

FACTORS INFLUENCING THE PROPERTIES OF BAMBOO FIBER

Bamboo has great mechanical properties because its main component is fiber and the tissues in the fibers are all arranged in the same direction (Liu et al., 2012). The mechanical qualities of fiber species differ from one another. This is based on its function and it is reflected in their physical, chemical, and morphological features. For example, according to Liu et al., (2012), the tensile strength is mostly provided by cellulose content, and the microfibrillar angle is proportional to the strain-to-failure due to irreversible deformation of the cell wall. The modulus of elasticity is proportional to the cellulose concentration and inversely proportional to the microfibrillar angle. The bamboo cellulose fibrils in the walls of the fibers are almost aligned in the same direction. This makes the fibers longitudinal elasticity the best, while their lignification makes them more rigid across their width (X. Wang et al., 2012).



(a) Fine structure of Bamboo Fiber (b) Cross Section (c) Longitudinal Section (d) Component Distribution

Figure 2. Bamboo Fiber Structure

Source: Liu et al., (2012)

There are many factors that influence the mechanical properties of bamboo fibers, including the chemical makeup and structure of the bamboo fibers, moisture content, bamboo age, and so on (Chen et al., 2022). Moreover, Chen et al., (2022) mentioned that the tensile modulus of bamboo was reduced when hemicellulose was removed. However, this did not alter when lignin was removed. In addition, the tensile strength of bamboo fiber dropped, when the chemical elements were removed. Nonetheless, with the removal of lignin the ductility declined marginally, but rose with the removal of hemicellulose.

Table 3 shows the composition and mechanical properties of a few natural fibers. Bamboo contains a high amount of lignin (32%), and a small microfibrillar angle (2–10), when compared to other lignocellulosic fibers (Liu et al., 2012). These elements contribute to the fiber's polylamellate wall structure's extraordinarily high tensile strength, flexural strength, and stiffness. The reported mechanical properties of bamboo fiber vary due to the various testing methodologies and samples evaluated. Amada et al., (1997), for example, assessed the original bamboo fiber tensile strength and modulus to be 600 MPa and 46 GPa, respectively, but when lignin was removed from the fresh bamboo fiber using alkali pretreatment, the strength and modulus were considerably increased.

Table 3. Natural Fibers Chemical Composition and Mechanical Properties

Fibers	Density (Kg/m3)	Microfibril angle	Cellulose (%)	Lignin (%)	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (GPa)
Bamboo	0.6–0.8	2–10	60.8	32.2	140–800	1.3	11–30
Banana	1.4	11	65	5	500	5.9	12
Coir	1.1–1.5	30–49	32–43	40–45	131–220	15–40	4–6
Flax	1.5	5–10	64–71	2	345–1100	2.7–3.2	27.6

Source: Liu et al., (2012)

The structure of bamboo fiber cells is complex, with a multi-layered middle layer of the cell's secondary wall (Osorio et al., 2011). As a result, the lignification of the thin and thick layers varies, as does the orientation of the microfibrils, resulting in a relatively considerable change in mechanical properties between adjacent wall layers (Pramudi et al., 2021). The multi-layered cell wall construction improves fracture resistance and encourages internal sliding between cell wall layers during tension (Fig. 2) (Chen et al., 2022). The microfibril angle also has an impact on the mechanical characteristics of the fiber; typically, the tensile strength and modulus of the fiber improve as the microfibril angle decreases (Chen et al., 2022). As a result, the decreased microfibril angle is a key feature that contributes to bamboo fiber exceptional mechanical qualities.

Table 4. Bamboo Fibril Mechanical Testing Findings

Sample	Equipment	Strength (MPa)	Strain (%)	Modulus (GPa)
Fiber bundle	Tensile tester	387	16.7	2.7
Single fiber	Micro-tensile tester	916	12.6	13.6
Regenerated fiber	Tensile tester	290	71.2	1.8
Single fiber	Nanoindenter	N/A	N/A	13
Bamboo nanofibril	AFM	N/A	N/A	40

SourceL: Liu et al., (2012)

The strength of bamboo fiber bundles was 387 MPa, with an average elastic modulus of 2.7 GPa, as indicated in Table 4. Single bamboo fibers had three times the strength. This divergence can be explained by bamboo fiber non-uniform diameter or the presence of weak places in the fibers. The average elastic modulus of a single fiber was roughly 13 GPa, which was comparable to the nanoindentation result but significantly greater than that of fiber bundles. The difference in mechanical properties between fiber bundles and single fibers is due to the fact that the strength of the bamboo fiber is greater than the bonding between the bamboo fiber and the matrix. Due to the size impact, the AFM testing findings revealed that a nanofibril had a higher modulus than a single bamboo strand. When the fiber size is lowered to the nanoscale, the fibril can prevent the existence of flaws, and the strength is more likely to exceed the theoretical strength of covalent bonds (Liu et al., 2012). The mechanical properties of bamboo entities have a significant size influence. Regenerated bamboo fiber has lower strength and modulus than the original fiber but it has higher strain, that is most likely due to crystalline structural conversion.

Moisture Content of Bamboo Fiber

Moisture content is an important factor that influences the mechanical characteristics of wood. The necessary moisture content of wood and lumber as a construction material ranges from 6% to 8% for indoor use and from 9% to 14% for exterior wood or building envelope components inside completed assemblies (Chen et al., 2022). Bamboo is a hygroscopic substance that may absorb or expel water to maintain equilibrium with its surroundings. The moisture content or equilibrium moisture content of the bamboo species was determined after conditioning at 27°C and 70% relative humidity. The findings also showed that bamboo samples conditioned at 27°C and 70% relative humidity were not infested with fungi. Fungi started to break down bamboo when the amount of water in it was more than 15% (Chaowana et al., 2021). Wang et al., (2013) investigated the effect of moisture content on the mechanical properties of bamboo at the macroscopic and cell wall scales and found that at the fiber saturation point, the compressive modulus of elasticity, indentation modulus of elasticity, and hardness of bamboo fiber decreased as moisture content increased. Chen et al., (2022) studied the effect of moisture content changes on the mechanical properties of bamboo fibers using tensile tests of single fiber and nanoindentation and discovered that as moisture content increased, the tensile modulus and tensile strength of bamboo fibers decreased significantly, while elongation at break increased.

Liu et al., (2012) explains that moisture can cause substantial damage to the fiber-matrix interface, which can result in the inefficient stress transfer from the matrix to the reinforcement. This is in addition to the fact that moisture can alter the properties of both the polymer matrix and the natural fibers themselves. The process of degradation begins with the swelling of cellulose fibers, which creates stress at the interface and leads to the formation of microcracks in the matrix around the swelled fibers. The cracks make water absorption and its subsequent attack on the interface even worse. The absorbed water begins to create intermolecular hydrogen bonding with the fibers, which in turn decreases the interfacial adhesion between the fiber and the matrix. Additionally, water-soluble compounds begin to leach out of the fibers as a result of the absorbed water. In the end, this resulted in the fiber and the matrix becoming unbonded from one another. The bamboo fiber became more pliable after it absorbed moisture, which resulted in an increase in extensibility and a decrease in the elastic modulus. However, the bamboo fiber tensile strength was not considerably impacted by this change. When it comes to the interfacial strength of the finished composites, it is possible that exposure to excessive humidity during material storage and composite formation can be significantly more detrimental than exposure to moisture after fabrication. Therefore, the relative humidity that is present during the manufacturing process of composites has a significant effect on the interfacial shear strength (IFSS) of the composites that are ultimately produced. This was supported by Liu et al., (2012) that potentially destructive effects of moisture on the interface between natural fibers and resin could be mitigated, at least partially, by a variety of fiber treatments.

Degree of Cure

Bamboo is an excellent choice for the development of natural fibre composites due to its excellent mechanical properties. Bamboo is capable of producing natural honeycomb fiber-reinforced composite materials. This paper includes mechanical properties of bamboo such as tensile strength, elongation at break, and Young's Modulus based on previous literature. According to J. Huang and Young (2019), bamboo fibre was manufactured using resins that was transferred into the moulding process and then treated with alkaline. The bamboo was cured with epoxy adhesive and the tensile strength being measured in Table 5. The result is shown decreasing in tensile strength from 717.53 MPa to 473.05 MPa for the alkali treated and untreated bamboo fibers as well as for the young's modulus showing a decreasing value from 43.34 GPa to 33.31 GPa. From the outcome, it revealed that alkaline-bamboo fiber (ALK-BF) has higher tensile strength due to better interface shear strength.

Table 5. The Mechanical Properties of Bamboo Fiber

	Density (g/cm3)	Equivalent Diameter (μm)	Tensile Strength (MPa)	Elongation At Break (%)	Young's Modulus (GPa)
BF	0.93-0.04+0.06	643.15-66.15+81.00	717.53-188.67+176.87	2.03-0.38+0.56	43.34-8.55+8.66
ALK-BF	1.29-0.07+0.05	583.80-33.93+38.20	473.05-52.63+101.12	2.05-0.39+0.53	33.31-1.92+3.09

Source: J. Huang & Young, (2019)

Table 6. The Mechanical Properties of Treated and Untreated Bamboo Layer

Bamboo Layer	Tensile Strength (MPa)		Ultimate/Break Load (kN)		Impact Test (J)	
	Treated	Untreated	Treated	Untreated	Treated	Untreated
1	7.81	6.74	0.930	0.265	1.5	1
2	9.51	4.35	0.150	0.205	2.5	1.5
3	18.07	16.51	0.180	0.045	3	1.8

Source: Lokesh et al., (2020)

The mechanical behavior of natural fiber polymer composite (NFPC) is primarily determined by a large number of characteristics, including the volume percentage of fibers, fiber length, the quantitative relationship between fibers and matrix, fiber–matrix adhesion, fiber orientation, and stress transmission at the interface (Lokesh et al., 2020). According to Lokesh et al., (2020), the excessive fiber content in composite materials degrades the mechanical characteristics of the composite due to a lack of adequate bonding between the matrix and fiber at their interface. As a result, the load transmission to the bonding fibers is disrupted as shown in Table 6. This might explain why greater compositions of bamboo fibers have lower impact and flexural strength values. The current study shows that increasing the treated content of fiber in composite materials enhances impact strength, tensile strength, and flexural strength.

Method Extraction of Bamboo Fiber

Bamboo culm strength is derived from multiple bamboo fibers that are oriented longitudinally along its length. Bamboo fiber is a natural bio-composite with the primary chemical elements of cellulose, hemicellulose, and lignin as shown in Table 7. Bamboo fibers are derived from bundles, which are vascular bundle components scattered within the culm's diameter. With an increasing percentage of fiber bundles, the size of the vascular bundle decreases from bottom to top. However, the fraction of fibers does not change greatly with age. Additionally, bamboo fibers have a significantly higher amount of lignin than other natural fibers, resulting in their exceptional strength (Shah et al., 2016). Stronger fibers are resulted from more robust culm structures. Excessive lignin, on the other hand, impedes the extraction process, preventing the separation of individual fibers. The lignin that remains on the fiber surface after extraction may result in increase in strength, but the fibres are brittle (Zakikhani et al., 2014).

Table 7. Bamboo Fibers Mechanical and Physical Properties Based on Extraction Methods

Extraction Procedure	Tensile Strength (MPa)	Young's Modulus (GPa)	Fibre Length (mm)	Fibre Diameter (μm)	Density (g/cm3)
Mechanical					
Steam explosion	516	17	-	-	-

Steam explosion	441±220	36±13	-	15 to 210	-
Steam explosion	383	28	-	-	-
Steam explosion	441	35.9	-	0.8 to 125	-
Steam explosion	615 to 862	35.45	-	-	-
Steam explosion	308±185	25.7±14.0	-	196±150	-
Rolling mill	270	-	220 to 270	100 to 600	-
Grinding	450 to 800	18 to 30	-	-	1.4
Retting	503	35.91	-	-	0.91
Crushing	420±170	38.2±16	-	262±160	-
Chemical					
Chemical	341	19.67	-	-	0.89
Chemical	450	18	10	270	1.3
Chemical	329	22	-	-	-
Alkaline	419	30	-	-	-
Alkaline	395±155	26.1±14.5	-	230±180	-
Combined Mechanical and Chemical					
Chemical + Compression	645 Max: 1000	-	> 10	50 to 400 HC: 150 to 250	0.8 to 0.9
Chemical + Roller mill	370 Max: 480	-	120 to 170	HC: 50 to 100	-

Source:Zakikhani et al., (2014)

Bamboo fibers can be removed mechanically, chemically, or by a combination of the two methods as shown in Table 7. Tensile testing of single bamboo fiber suggests that steam explosion is the best method of extraction to create high-strength bamboo fiber (Shah et al., 2016). After the rolling mill process, bamboo fiber has the lowest tensile strength of 270MPa. Besides, bamboo fiber has a somewhat lower strength than kenaf, ramie, and flax. However, bamboo fibers range of 615 to 862 MPa is included among natural fibers. Even though they all come from the same species, natural fibers, like bamboo fibers, have very different microstructures as they all grow from the same plant. Nonetheless, several parameters are required further consideration in order to make a better comparison between natural fibers such as the type of chemical used, controlled temperature for the dying process, selected single fiber's length for tensile testing and single fiber density.

Orientation and Fiber Length

An experiment was carried out to investigate the mechanical properties of bamboo fiber reinforced epoxy composites along with the effect of fiber orientation by Rao et al. (2020). Table 8 shows that the orientation of fiber could affect the mechanical properties of bamboo fiber and reinforced epoxy composites. The maximum tensile strength is observed with 0° orientation for bamboo fiber reinforced composites as 125 MPa and the minimum reading recorded with 90° orientation is 122 MPa.

Table 8. Maximum Tensile Strength and Impact Strength for Different Orientations

Fiber Orientation	Fiber Loading (Wt.%)	Tensile Strength (MPa)	Impact Strength (J/M)
0°	24	125	250
90°	24	112	230

Source: Rao et al., (2020)

Table 9. The Tensile Properties of Alkali-Treated Bamboo Fiber Reinforced Epoxy Composite with Different Fiber Aspect Ratios

Average of Equivalent Diameter (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
719.33–15.46+14.31	213.47–7.15+11.27	11.96–0.87+0.41	1.76–0.16+0.13
583.80–33.93+38.20	222.71–21.30+15.52	13.10–1.65+1.36	2.01–0.19+0.14
340.76–25.53+98.00	269.05–20.43+22.62	16.43–1.38+1.59	2.23–0.31+0.27

Source: Huang & Young, (2019)

A test made by Huang and Young (2019) resulted in three batches of alkali-treated bamboo fiber reinforced epoxy composites. They are of different fiber diameters, tensile strength and modulus had slightly increased for smaller fiber diameter as demonstrated in Table 9. However, the rising tendency is not as clear due to the significant variation. The tensile strength and modulus of composites with a smaller fiber diameter of 340.76 m are dramatically increased when compared to composites with a greater fiber diameter. It may be deduced that while bamboo fiber length is constant, the tensile strength and Young's modulus of bamboo fiber composites increase when bamboo fiber diameter decreases.

Bamboo Fiber Matrix Adhesion

A few chemical methods can improve the mechanical properties of bamboo fiber-reinforced composites, especially the interfacial adhesion between the fibers and the matrix, such as sodium hydroxide (NaOH), nitric acid-potassium chlorate (HNO3–KClO3), sodium hypochlorite (NaClO), and benzoate (Noori et al., 2021). Among the several chemical treatments given to bamboo fibers, the most common is alkaline treatment, also known as mercerization. Alkaline treatment is a chemical technique that can enhance the characteristics of composites reinforced with lignocellulosic fibers (Hassan et al., 2020). The alkaline treatment is a very successful and relatively inexpensive procedure that involves immersing the bamboo fibers in a specific concentration of aqueous sodium hydroxide (NaOH) for a certain duration and temperature (Ouarhim et al., 2018).

Table 10. Properties of Typical Thermoplastic and Thermoset Polymers Used in Fabrication of Bamboo Fiber Compositions

Property/ Thermoplastic	Polypropylene (PP)	Polyvinyl Chloride (PVC)	Polylactic Acid (PLA)	Polystyrene (PS)	High-density Polyethylene (HDPE)
Density (g/cm3)	0.899 -0.920	1.42 – 1.81	1.26	10.4 – 10.6	0.94 – 0.96
Tensile strength (MPa)	26.0 – 41.4	15 - 52	25 – 30	25 - 69	14.5 – 38.0
Elongation (%)	15 - 700	20 - 40	1.8	1.0 – 2.5	2.0 - 130
Young modulus (GPa)	0.95 – 1.77	1.12 – 3.66	2.34	4 - 5	0.4 – 1.5
Property/ Thermoset	Epoxy	Polyester	Elastomer (natural rubber)		
Density (g/cm3)	1.1-1.4	1.2-1.5	0.91-0.93		
Tensile strength (MPa)	35-100	30.9	20-30		
Elongation (%)	1-6	2	750-850		
Young modulus (GPa)	3-6	3.1	0.001-0.005		

Source: Shah et al., (2016)

A study found that bamboo fiber reinforced PVC thermoplastic composites have a substantial potential for application as alternative fillers in the development of sustainable biobased composites with greener and cleaner credentials (Bahari & Krause, 2016). The properties of the polymeric matrix (thermoplastic or thermoset) also affect how well a bio-composite works mechanically. Thermosetting matrices are more commonly used for high-performance advanced composites than thermoplastic matrices (reversible process). Polyethylene (PE), polystyrene (PS), nylons, polycarbonate (C), polyactals, polyamide-imide, polyether-ether kenote (PEEK), polysulphone polyphenylene sulphide, and polyether imide are examples of thermoplastic polymers.

As shown in Table 10, the mechanical properties of thermosetting polymers have substantially higher strength and stiffness values than thermoplastic polymers. Because of this, thermosetting polymers are used and thought of more often than thermoplastic polymers as structural bio-composites for building materials and structures. The numerous fiber bundles that are still bound together in the natural lignin of the bamboo strip contribute to the strip's durability as a type of fiber. The process of fabricating composites is made simpler by the fiber alignment in a unidirectional direction within the bamboo strips. The strips of bamboo were first impregnated with an epoxy matrix before being arranged in a unidirectional alignment in the mould of the hot press. Following the application of hot pressing to the sample, a post-curing process consisting of 12 hours at 40°C was completed (Hebel et al., 2014). Nevertheless, the design of the composites is constrained by this type of fiber since bamboo strips are unable to deform or bend easily, which makes it difficult to set certain designs of the composite mould.

Bamboo fiber reinforced polymer composites (BFPC) are a lightweight bio-composite with similar strength to conventional materials (Khalil et al., 2012). Based on the tensile strength of polymer matrices in Table 10, the tensile strength of its composites can be deemed (Shah et al., 2016). Commonly, the result of tensile properties in composites is better when the fiber is higher in content. Nevertheless, at some point, as aptly put by Shah et al., (2016) the matrices are unable to completely bind all the fibers, resulting in a reduction in tensile strength as fiber loading rises. A research made by Thwe and Liao, (2002) showed that by increasing the percentage of bamboo fiber reinforced polypropylene (BFRP), it merely increased the tensile strength of the composites and raised the percentage. This may have a negative effect on tensile strength. Moreover, more void formations in the composite resulting from inadequate handling during fabrication. This may lead to micro crack formation under loading and reduce tensile strength.

The outcome of the research optimum percentage of fiber content by mass is 30% for BRFP involves both tensile strength and tensile modulus.

DISCUSSION FOR MECHANICAL PROPERTIES OF BAMBOO FIBER COMPOSITE MATERIALS

The mechanical properties of bamboo fiber bio-composites are influenced by a variety of elements, including the type of polymer matrix, the related fiber types, processing, and morphologies of the fibers, as well as their dispersion, distribution, orientation, and interfacial interactions (Kumar et al., 2019). Additionally, a bamboo fiber bio composite's strength is more dependent on the fiber than the matrix because the strength of reinforcing fiber is higher than that of the matrix material. As a result, the bamboo fiber bio composite strength can be increased to a certain extent by adding more fiber to the composite structure (Abdellaoui et al., 2019). However, as the amount of bamboo fiber exceeds the limit, the amount of porosity in the composite increases, and the load transferred via the interface decreases, which causes a greater reduction in the strength and stiffness of the composite material (Faruque & Bilisik, 2020).

Additionally, when the amount of fiber in a composite structure rises, the material absorbs more water, which frequently compromises the mechanical properties of the composite (Faruque & Bilisik, 2020). The length of the reinforcement bamboo fiber also has a significant impact on the mechanical properties of the composite (Pickering et al., 2016). The bamboo fiber's load-bearing capacity improves with increasing aspect ratio. It should be observed that an extremely long bamboo fiber can tangle and cause an uneven distribution of the reinforcement and the fiber. The composite matrix, which shields the surface of the bamboo fiber from external stresses is another crucial component. The polymer matrix increases the composite durability by transferring forces applied externally to the reinforcement materials. The strength of the bio composites increases with the amount of interfacial interaction between the bamboo fibers and matrix. The interfacial bonding is crucial and the real indication of the composite qualities when the applied load is passed from the matrix to the reinforcing components (Ferreira et al., 2017). The hydrophobicity of the bamboo fibers, the interfacial bonding between matrix and fiber, and the roughness all need to be improved in order to increase the interfacial bonding between the bamboo fiber and the matrix. Several processes, including mechanical interlocking, chemical bonding, electrostatic bonding, and inter-diffusion bonding, are typically used to strengthen the link between the fiber and matrix (Gholampour, 2020).

CONCLUSION

From the discussion, it can be concluded that bamboo fibers bio-composite can potentially replace synthetic fibers as reinforcement in polymer composite due to their excellent properties, including low density, low cost, high impact resistance, and high flexibility, low specific gravity, less abrasiveness to equipment, biodegradability, biocompatibility, and renewability. Although it is clear that bamboo fibers have significant shortcomings, such as higher moisture content, these can be fixed by implementing various physical and chemical changes. Bamboo fibers poor wettability and lower moisture resistance limit their use in composites to some extent. However, chemical treatment can fix these issues. Some techniques for processing natural fiber reinforced polymer composite include hand lay-up, injection molding, and compression molding. The amount of cellulose and hemicellulose has a significant impact on these composites mechanical characteristics. The diameter, length of the fiber, fiber content, and manufacturing method are a few more elements that influence the mechanical properties of composites. In addition, the tribological characteristics of a composite are affected by the different fiber orientations. By increasing the fiber loading, composite materials resistance is improved, and with an increase in fiber loading, these composites coefficient of friction may fluctuates between rise and fall.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception, analysis, and interpretation of the data, drafting or revising the article for significant intellectual content, and approval of the final manuscript.

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