Design of green laminated composites from agricultural biomass

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14.1 Introduction

The indigenous plant such as oil palm (*Elaeis guineensis*), bamboo (*Bambusa*), coconut (*Cocos nucifera*), rattan (*Calamus*), and date palm (*Phoenix dactylifera*) thrives in tropical and subtropical regions worldwide. Along with agricultures mentioned above, the influence in human life is numerous, and mostly, people use them to make many of their necessary tools and food. In Malaysia, the oil palm residual such as oil palm trunk (OPT), empty fruit bunch (EFB), and oil palm fronds (OPF) has become top-ranking precious commercial crash crops compared with other agricultural biomass raw materials [1–4]. Alternative materials with low cost and that are sustainable and easily available due to the initiative to produce natural fiber from agricultural biomass materials of various plants and fruits such as oil palm, date palm, bamboo, rattan, coconut, kenaf, and pineapple.

Therefore, the countries such as Malaysia and Indonesia are aggressively trading lignocellulosic fibers to produce wise material for product and applications. Besides, local farmers will generate their income, and yet, countries' economic conditions will increase the agricultural industries. Recently, some effort focused on research related to agricultural biomass raw materials to tackle environmental problems due to overflow of biomass waste material. Agricultural waste biomass has become an important research and development in science and technology field because the effect from the creation of new solutions is able to give positive impact to our life. In order to meet increasing demands for laminated composite-based products, many woods have been overharvested in recent years and need long terms to grow again. Therefore, developing nontree wood alternatives is one means of solving the wood problem [5,6].

Laminated composites are formed when the fibers are reinforced by matrix, which consists of several layers of fibers. Advances in science and technology enable the world's manufacturing industry to manipulate matter at the policy level to improve the overall properties of alternative materials to replace conventional materials.

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Technology-based research with a focus on agricultural biomass species variety with high potentialities can be grown and be applied in many applications [7]. The research became important for producing and providing an innovative composite especially in laminated composite products to improve the quality and sustainability of the features [8]. The effect from this activity can make a high impact to the laminated composite manufacturers to enhance the cell structure using physical or mechanical methods.

Nowadays, laminated composites from agricultural biomass have been rapidly applied in various manufacturing industries such as furniture, building and construction, interior, automotive components, sport equipments, and various more [9,10]. Consumers all over the world, which concern the environmental issue, have accepted products made with natural fibers compared with wood. This is because in their everyday usage, they appreciated not only the sustainability of the product and the benefits to environment and ecology but also the increase economic returns. Not only these commercial cash crops can be transferred into a value-added product, but also the transformation of technology development will give benefits to the community.

14.2 Classification and properties of agricultural biomass raw materials

Billions of tons of agricultural biomass are released around the world through agriculture industry annually. Bamboo, oil palm, coconut, rattan, and dates are listed among the potential candidate as agricultural biomass raw materials that can be utilized in various applications. Generally, this biomass from residual crops is found in the form of stalks, roots, seeds shells, leaves, etc. All can be divided into several groups depending on the part of the plant, which can be extracted, that is, bast (stem), leaf, fruit (seed), and straw [9], as illustrated in Fig. 14.1. The properties of mentioned biomass differ depending on types of plants and parts of the plant itself. These agricultural biomasses exhibit a variety of properties, differences in chemical composition, and morphology of the matrix. Cellulose, hemicelluloses, lignin, extractives, and pectin are believed to be responsible for the chemical, physical, and mechanical properties of biomass. Besides fiber diameter, cell wall structure, microfibril angle, and chemical constituents,

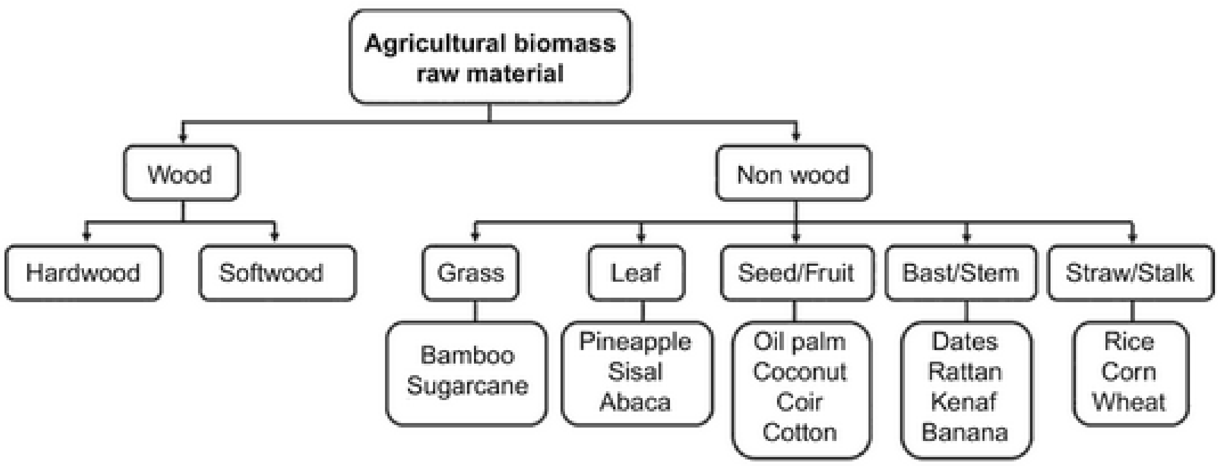

Fig. 14.1 Classification of agricultural biomass raw materials.

researchers also concluded that the overall properties of agricultural biomass also vary according to location, geography, plant age, climate, and soil conditions [11,12].

14.2.1 Chemical properties of agricultural biomass raw materials

Plant fiber is a three-dimensional, natural polymer composite consisting of cellulose, hemicelluloses, lignin, pectin, extractive, and other organic constituents [13]. Cellulose and hemicelluloses combined to form the microfibrils that build up lamella, and the whole components are bind together with lignin to form the cell walls. Cellulose is a semicrystalline polysaccharide composed of a linear chain of D-anhydroglucose ($C_6H_{11}O_5$) units. D-anhydroglucose is the cellulose monomer, which linked together by β-(1, 4)-glycosidic bonds to form the repeating units of cellulose chain, known as dimer cellobiose. Cellulose plays an important role in maintaining the plant structure and influences its mechanical properties by providing structural stability, strength, and stiffness to the plant cell wall.

Hemicelluloses, which are also known as polyoses, are heteropolymers that present in almost all plant cell walls. It is a branched polymer, which has a random and amorphous structure with some strength. Unlike cellulose, hemicellulose is made up of shorter chains of sugar units. The sugar monomers in hemicellulose include xylose, mannose, rhamnose, galactose, and arabinose. In addition to carbohydrates, most plant tissues contain a compound called lignin. Lignin is defined as amorphous, complex hydrocarbon polymer that contains both aromatic and aliphatic constituents formed from units of phenylpropane and has a high degree of polymerization. It serves as a support to the mechanical strength of the plant. It is associated with the hemicelluloses in plant cell wall, where it strengthens and assists the connection of hemicelluloses to microfibrils. Besides, lignin also acts as a natural decay resistance of the plant biomass [14].

Apart from cellulose, hemicelluloses, and lignin, plants also contain other elements that are present in small quantities. Most of these elements can be dissolved in neutral organic solvent. These elements are known as extractives. It influences the physical properties of plant biomass. Extractive can be considered as unstructured biomass substance and only consists of compounds outside the cell and has low molecular weight. Different parts of the plant like stem, branch, root, bark, and leaves have different amount and different types of extractive. The variability in cell wall composition of selected agricultural biomass, focusing on bamboo, oil palm, coconut, rattan, and dates, is shown in Table 14.1. The content of the polymers varies depending on the plant species. Plant age, growth condition, soil, and other environmental factors such as temperature, stress, and humidity influence the composition, structure, and properties of plant biomass [15].

14.2.2 Physical properties of agricultural biomass raw materials

Table 14.2 provides an overview of physical properties of selected agricultural biomass. Biomass fiber properties that receive crucial concern include fiber length, fiber diameter, cell wall dimension, microfibril angle, and lumen diameter [1]. The single cell dimension of biomass fibers is determined by the species, origin, sources, and maturity of the fibers itself [39]. Basically, cell wall structure of biomass fiber is predominantly

Table 14.1 Chemical composition of selected agricultural biomass

Type of agricultural biomass	Composition (%)				Source
	Cellulose	Hemicellulose	Lignin	Extractives	
Bamboo	73	12	10	3	[15]
	55	26	22	–	[16]
	52	–	33	9	[17]
Oil palm EFB	50	30	17	3	[18]
	38	35	23	3	[19]
Oil palm trunk	31	33	25	4	[19]
	47	–	23	–	[4]
Oil palm frond	56	27	20	4	[15]
	40	30	21	2	[19]
Coconut coir	44	20	45	–	[20]
	43	4	48	–	[21]
	21	13	47	–	[22]
Rattan	41	30	25	5	[23]
Date trunk	32	–	37	–	[24]
Date frond	49	23	31	24	[25]
Date leaf	35	28	27	8	[26]

Table 14.2 Physical characteristics of selected agricultural biomass

Type of agricultural biomass	Fiber length (mm)	Fiber diameter (μm)	Cell wall thickness (μm)	Lumen width (μm)	Source
Bamboo	2.0–3.0	14.0–17.8	3.0–9.0	3.8–8.6	[15,27–29]
Oil palm EFB	0.6–1.4	8.0–25.0	2.0	6.9–9.8	[15,29–31]
Oil palm trunk	0.6–1.2	29.6–35.3	8.0	17.6	[4,30,32]
Coconut coir	0.3–1.0	12.0–19.3	0.06–8.0	10.4–12.5	[22,33–35]
Rattan	1.2–2.0	10.3–15.9	5.4–6.4	11.0–15.3	[23,36,37]
Date trunk	1.0–1.3	12.5–41.0	4.0–6.0	4.5–28.0	[24]
Date frond	1.1–1.2	12.5–17.5	4.0–4.5	4.5–9.0	[24,25,38]

composed of polysaccharide-rich primary (P) and secondary wall layers (S1, S2, and S3) [30]. Strength, toughness, and collapse resistance of the cell wall structure are provided by the sandwich-like and thick multilayered structure of the cell wall layers [40].

On the other hand, the bulk density of fibers is influenced by lumen structure. The size of lumen also affects acoustic factor and thermal conductivity of fiber in final product [33]. Structural characteristic of fiber such as fiber length, fiber width, and thickness of cell wall will determine the properties and performance of final products in terms of tensile strength, bonding, tear strength, stress distribution, and drainage. Furthermore, length over width, which represents as fiber aspect ratio, is also essential in deciding the suitability of fiber for a specific application to fully utilize its maximum potential [41,42]. Hence, when considering biomass materials in multidisciplinary applications, its individual fiber characteristic plays an important factor, which strongly influence the final properties of biomass fibers.

Table 14.3 Mechanical properties of selected agricultural biomass

Type of agricultural biomass	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Source
Bamboo	0.9	35	503	1.4	[43,44]
Oil palm EFB	0.7	3.2	248	2.5	[15]
Oil palm trunk	1.1	45	600	5	[4]
Coconut coir	1.2	44	500	2	[45,46]
Rattan	0.6	10	566	17	[47,48]
Date leaf	0.9	11	309	2.7	[15,49]

14.2.3 Mechanical properties of agricultural biomass fibers

Mechanical properties of biomass fibers are important in order to produce various types of value-added product. In plant cell walls, microfibrils are sorted by layer. Plant cells are usually stronger and hard when subjected to mild stress because of the existence of lumen, lamella, and microfibril structure. Microfibril orientation affects the mechanical properties. For example, the high tensile strength and tensile modulus in biomass fiber are closely related with high cellulose content and low microfibril angle. Overview of the mechanical properties of selected agricultural biomass is presented in Table 14.3.

Different sources of plant biomass exhibited different mechanical properties. The large variations in the mechanical properties determine the suitability of the plant biomass to be commercialized. Moreover, factors that influence plant growth including species, fiber structure, and environmental conditions also resulted in large variation in tensile properties of the plant biomass. Study on the relationship between plant structure and its mechanical properties shows that the tensile properties of the biomass fibers are dominantly influenced by the cellulose content and microfibril angle. Reduction in microfibril angle has improved in both tensile strength and tensile modulus whereas decreasing in elongation at break.

14.3 Design of agricultural biomass raw materials

14.3.1 The availability of agricultural biomass raw materials

Various studies on potential utilization of natural fibers like bamboo strip, coir, kenaf bast, and pineapple fibers showed that the presence of these fibers in different composites is advantageous to industry and consumers [50–52]. In order to assess the sustainability of present usage patterns and introduce alternative agricultural biomass raw materials for product and applications, an assessment of the resources and its availability for manufacturing industry has to be made. Below, an overview of the resource based from different types of residues is given. This biomass is included in a form of fiber, solid, hybrid with natural fiber, and hybrid with nonnatural fiber. The various advantages of agricultural biomass are abundant, low cost, biodegradable, and comparable mechanical properties of wood. Fig. 14.2 showed the design of fiber agricultural

Fig. 14.2 The availability of various types of agricultural biomass.

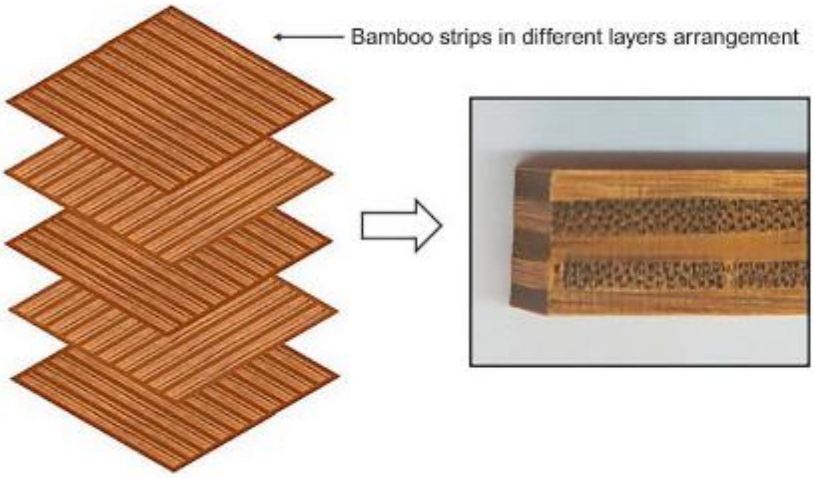

Fig. 14.4 Laminated bamboo strips biocomposites in different layers arrangement.

several applications such as furniture, building, and automobile industries. The present work characterizes the mechanical properties of date laminated composites [10,60]. Meanwhile, the laminated solid composite from bamboo strips arranged in many different orientations may indicate an improvement toward its mechanical strength to its density ratio and has a similar specific modulus compared with timber as shown in Fig. 14.4. Rattan is from tropical grasses having hollow stems and more flexible compared with bamboo, which usually rattan and bamboo are habitually confused to consumers. Rattan stems are originally solid and tough suitable to produce a solid composite. The thickness of the stem varies from ¼ to 2 in. The outer skin needs to be removed before the stems are made into products.

14.3.2.3 Hybrid—Natural fiber hybrid with natural fiber

Merging the two types of fibers into a single matrix has produced the development of hybrid biocomposites. The advancement of laminated composite production from natural fiber hybrid with natural fiber (Fig. 14.5) has increase value-added bamboo and oil palm trunk (OPT) materials to produce green composites obtained from renewable sources. The research of hybrid is to determine the eventual forms of composites that are being designed in laminated bamboo strip hybrid with OPT veneer biocomposites (LBHC). The research successfully has indicated bamboo strips, and OPT veneer has potential to give advantage as alternative material for furniture applications. The advantage of merging these two biomasses will give benefits as their low cost, low energy inputs, low density, and biodegradability also performed better in mechanical properties. Optimum elasticity of composites reinforced with natural fibers was proved to increase the strength, especially when modified with crushed fibers and embroidered fibers. Results revealed that LBHC has excellent mechanical properties compared with plywood structure.

While woven banana fiber, kenaf fiber, and banana/kenaf hybrid fiber composites were studied, it was found that mechanical strength of woven banana/kenaf fiber hybrid composites exhibits the enhancement due to the hybridization. Sodium

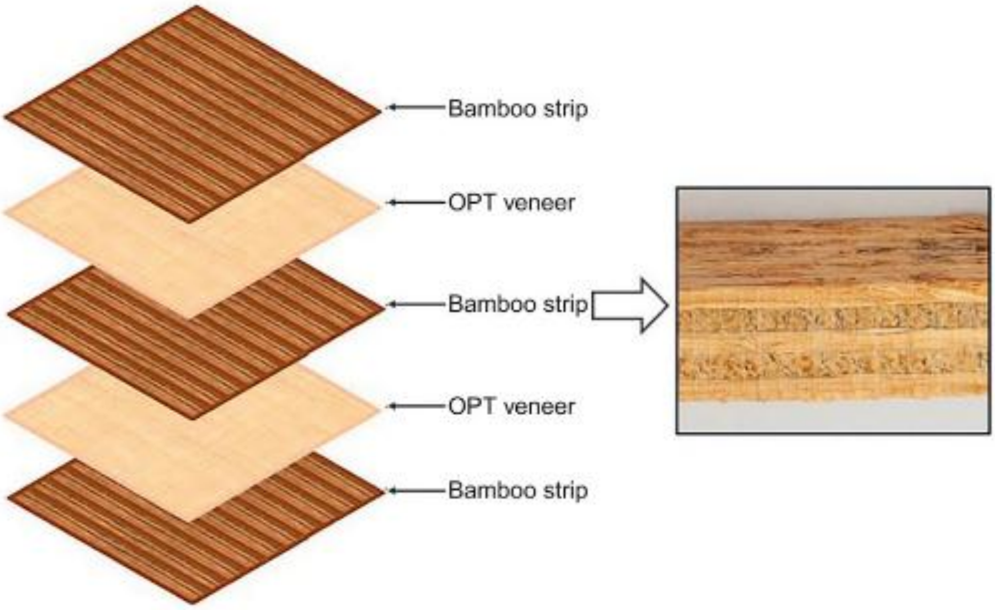

Fig. 14.5 Laminated bamboo strips hybrid with OPT veneer biocomposites (LBHC).

lauryl sulfate (SLS) treatments provide an additional improvement in mechanical strength through enhanced interfacial bonding [61]. The comparison and potentiality of jute and banana fiber composites were done to stressing both mechanical and physical properties and their chemical composition [62]. Samivel et al. [63] have done the experiment in the effect of hybridization of banana and kenaf fiber-reinforced hybrid composites, and results proved that hybrid composites are able to offer better resistance to water absorption as compared with nonhybrid composites.

14.3.2.4 Hybrid—Natural fiber hybrid with non-natural fiber

Natural fibers have been approved as main acts in the new economy-based sustainability on the use of renewable materials in polymer products. Taking all these factors into account, researchers and scientists are interested to investigate more about natural fibers as an alternative method for fiber-reinforced composites. Within a few years, natural fiber-reinforced composites are categorized as wise material in different applications due to its excellent properties. Therefore, many good achievements are based on natural fiber hybrid with nonnatural fiber. For example, fiber glass has excellent properties and a strong and lightweight material very popular in manufacturing industries. The strength properties are slightly lower than carbon fiber and less stiff; the material is typically far less brittle and low cost. Natural fibers such as pineapple leaf, OPT, and bamboo have the potential and can be used as a replacement for general reinforcement materials in composites for applications requiring high strength-to-weight ratio and further weight reduction.

Hybrid oil palm empty fruit bunch (OPEFB) fiber glass composites exhibit an increase in stiffness, strength, and moisture resistance properties. The test result for the resistance of bamboo fiber glass composites under environmental aging has shown a good result compared with pure composites. Mechanical properties of composites such as tensile strength and compressive strength of natural fiber composite have been compared with the data of glass/epoxy composites. The results of research on jute composite laminates indicate lower strength compared with bamboo composite laminates that have higher tensile strength and high stiffness, while compressive test shows that compressive strength and modulus of jute composite is higher than bamboo composite [64]. The mechanical properties also depend upon natural fiber material property. Since glass fiber was designed and manufactured artificially in a special plant, natural fibers were available from nature and harvested by simple machines, which can lead to inconsistency during the manufacturing of product. In composite materials, the matrix function is to hold the reinforcement to form the desired shape, while the reinforcement function is to improve the overall mechanical properties of the matrix [65].

The reinforcing materials form the main load-carrying component in the composites, which provides high strength and stiffness and resistance to bending and breaking under the applied load. Based on this fact, even though the strength of natural fibers is not achieve to the level of traditional e-glass fiber, the natural fiber-reinforced composite still can be used, and economies of scale of natural fiber composite materials are more useful compared with e-glass fiber composites [66]. Fig. 14.6 showed that the pineapple leaf fiber-reinforced polymer composites are the result of mechanical properties of the polymer, which have significantly improved. The tensile strength and elastic modulus were increased around 22% and 60%, while flexural strength is increased to 19% and flexural modulus increased 50%, respectively [67].

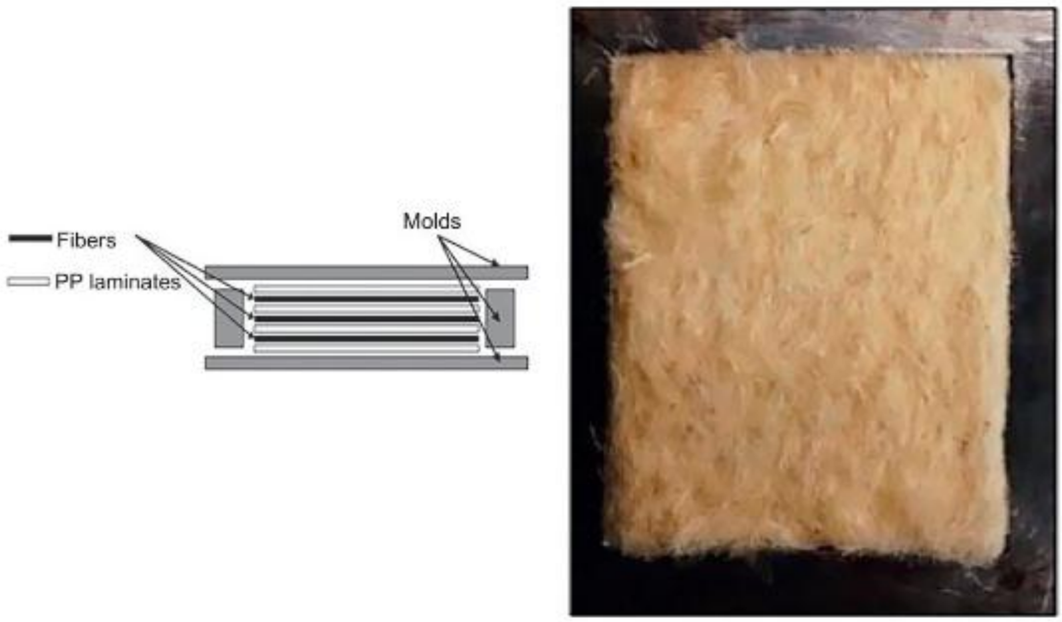

Fig. 14.6 Pineapple leaf fibers reinforced polymer composites [67].

14.4 Current applications of laminated composites from agricultural biomass

Composite's performance made from agricultural biomass encompasses the entire material knowledge of laminated composites regarding innovative and adapted strength under one roof. Natural fibers are now worldwide active in four sector industry—building and construction design, interior design and furnishings, furniture design, automotive design, and other industrial applications by its superior mechanical properties. All sections have a strong portfolio of products related to laminated composites combined with a deep understanding of solutions through physical and mechanical properties [66]. Key drivers of growth in design and technology are their close collaboration with research and a clear focus to enhance the quality of laminated composites. Strong capabilities in research and development (R&D) provide the basis to develop and to plan innovative products for users.

14.4.1 Furniture design

Agricultural biomass composites supported and proved by many researchers have high benefits as an alternative material for furniture production and components. Biomass materials are important to our environmental sustainability, suggesting the furniture designer to include design elements with environmental relationships in order to gain market attention [68,69]. Most countries have started to establish research- and development-based furniture such as in Malaysia where the agency established Forest Research Institute Malaysia (FRIM) and local public research university. A lot of amazing furniture designs in the market are made from biomass, and many furniture designers are competing to prove that biomass materials are not only stronger and resilient but also easier to design. For example, high success on the innovation in bamboo fiber and oil palm trunk (OPT) has improved the durability even in bending shapes. The research and development (R&D) in making advanced bio-based furniture products are able to continue the improvement in product innovation success. Initiatives to increase the use of biocomposite value are highly praised and encouraged to reduce environmental impact, improving innovation and advanced technology in the furniture manufacturing industry.

Agricultural biomass that possesses the characteristics of materials and textures is very useful for designers to create a unique and original design [10,70]. Fig. 14.7 showed the furniture design made from bamboo composites. As can be seen, Fig. 14.7A showed a multipurpose table named Sato. The designer, Suhaily, successfully designed a table using laminated composites made from agromaterials. The versatile materials with full high package improve in mechanical and physical compared with wood. Sato table has comparable design, high strength, and the ability and flexibility of laminated hybrid to create natural elements with natural finishing of biomass. Fig. 14.7B showed that a modern chair made from bamboo strips laminated has become a sustainable furniture and has unique identity compared with other furniture from other materials. The beauty of bamboo laminated composites as a furniture design is stunning, and it can be an activator of the rise of modern bamboo era in the furniture industry.

of 5%–10% of door weight. This is because the ability of plant fibers to absorb the humidity leads to an increased comfort, which cannot be reached with synthetic materials. Accurate modeling of straight and curved laminated composite beams is needed, and the proposed beam model for generally laminated composites from natural fibers including shear deformation and accurate curvature representation gives reasonably accurate results for vibration analyses [78,79,82]. This is important because composite beam structures are often used in complex environmental conditions and are exposed to various dynamic excitations and challenges [80].

14.4.4 Building and construction design

Now, years later, nonwood materials such as bamboo and rattan are used to build houses, with primary uses of traditional nonwood material construction found in Asia, Latin America, and East Africa. The material is round or elliptical in form, which makes joints and connections difficult. For example, rattan can produce special effects, and using rattan, joinery easily can be bent or straightened by heating and clamping to produce an attractive design. To overcome these limitations, development of engineered agricultural biomass is increasingly explored for construction purposes. Bamboo in its natural form is a light material that is comparable in strength with steel in tension and concrete in compression, yet acceptance is limited by the variance in cross section and mechanical properties. Therefore, past studies related with wood from OPT have explored the design of natural composites in relationship to efficiency and sustainability [10].

Growing interest in the research and design of engineered natural fibers is driven by the fact that the manufacturing process of composite maintains the longitudinal fibers in a section that can be laminated together to form a standard shape and size used in building and construction [83]. The process allows production of standard sections with more uniform properties. With interest in reducing their environmental impact, structural materials are scrutinized in terms of source, manufacturing, construction, operation, maintenance, and disposal. Additional consideration must be given to the performance of the material, not only in terms of structural capacity but also in terms of the environment [81]. Zea Escamilla and Habert [84] explored the environmental impact of different bamboo-based products. The study showed that engineered bamboo (glue laminated bamboo) has a higher environmental impact than lower industrialized products, which is attributed to the higher level of processing and contributions from other inputs into the products (Fig. 14.9).

Zhou and Xiao [81,85] investigated glued laminated bamboo (GluBam) beam and analyzed the environmental performance of the manufacturing process in comparison with other traditional construction materials, such as timber, plywood, cement, aluminum, and steel. Since bamboo is the next green building material, Vo Trong Nghia an architect for Kontum Indochine Cafe emphasizes on using natural ventilation and fresh water from the artificial lake as appreciation to the natural resources; this dome gives value-added features and uniqueness for the cafe. Marek Keppl and Toma Korec successfully incorporated bamboo trees to shape, using the parabolic curve and bamboo's natural flexibility to create a lightweight structure and light-filled environment, and it looks steady and stunning, and people will feel comfortable and safe (Fig. 14.10).

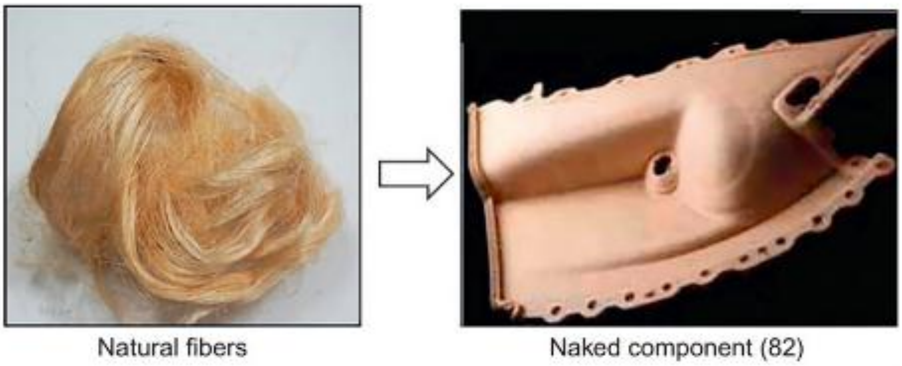

Fig. 14.9 Examples of vehicles components from natural fibers composites in the automotive fields.

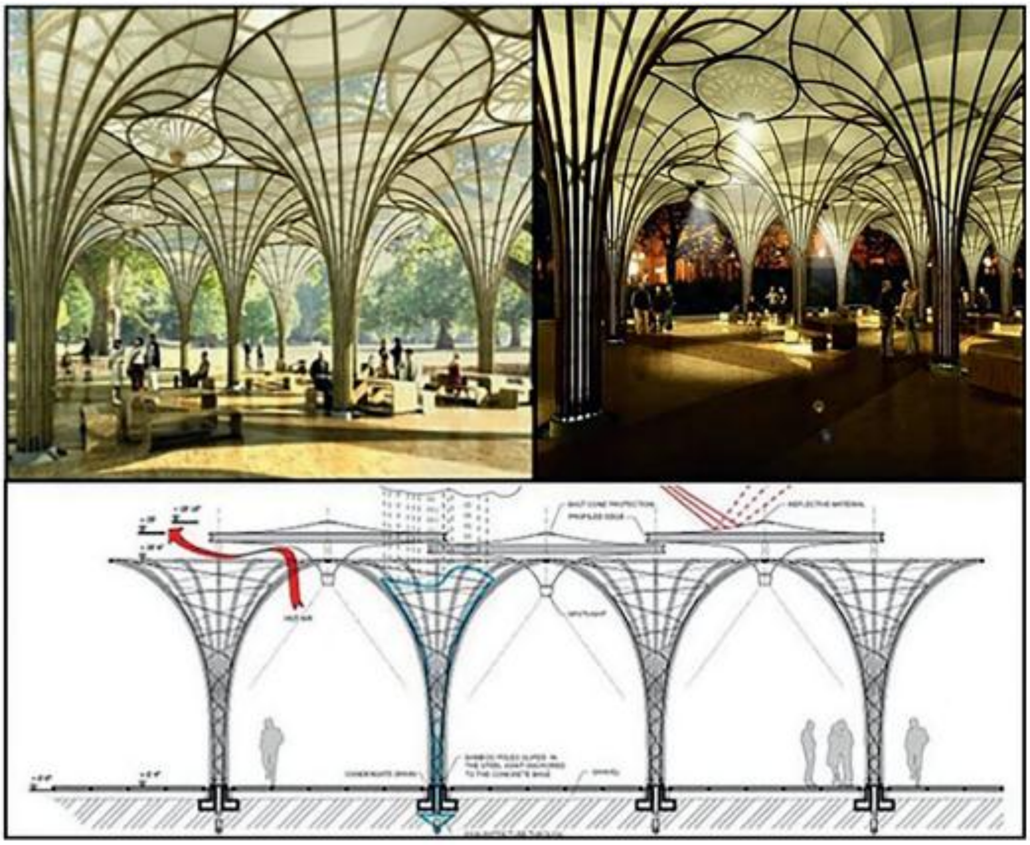

Fig. 14.10 Bamboo Pavilion, Hawai, USA by Marek Keppl and Toma Korec [86].

14.5 Laminated composites materials for sustainable applications

An aggressive agricultural biomass phenomenon, however, has been accompanied by substantial environmental costs. Therefore, it has attracted the attention from few research teams to investigate and observe the impacts of biodiversity on laminated composites. Researcher needs to create good relationship and build chemistry for a

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