Chapter 3

Bamboo, Its Chemical Modification and Products

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Additional information is available at the end of the chapter

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Abstract

Bamboo, a perennial woody grass belonging to Gramineae family and Bambuseae subfamily, is ubiquitous in many parts of the world. This biomass possesses high potential as a substitute for many lignocellulosic and non-lignocellulosic materials in various capacities of applications owing to its chemical composition as well as its physical properties. Its abundance, chemical composition and numerous applications are reviewed in this work. This chapter also examined some investigated chemical modifications through alkali hydrolysis, acid hydrolysis, coupling to enhance properties of bamboo fibre for specialised applications.

Keywords: bamboo, biomass, fibre, composition, modification, utilisation, resources

1. Introduction

The demand for a substitute to resources associated with environmental problems has brought about a strong interest in the use of raw materials and products that are renewable, sustainable and biocompatible. However, a great deal of research and technical work has been devoted to the use of natural plant fibre. Natural plant fibres have unequivocally contributed to economic prosperity and sustainability in our daily lives [1]. Bamboos, in particular, have attracted special attention owing to their awesome properties including and not limited to sustainability, renewability and biodegradability. They present versatile structure produced by physical and mechanical properties and low specific weight [2]. Properties such as appearance, strength and hardness combined with its rapid growth rate and capacity for sustainable harvesting have made bamboo an attractive substitute in different industrial sectors and these have successively created great opportunities for its development [3]. It has been reported that the density of bamboo varies from 500 to 800 kg/m^3 depending on anatomical structures such as quantity and distribution of fibres around vascular bundles [4], with its maximum density usually obtained from 3 years old culms [5, 6].

Bamboo is a perennial woody grass, which belongs to the family Gramineae and subfamily Bambuseae [7]. It is an evergreen, monocotyledonous (i.e. non-woody) plant, which produces primary shoot without any later secondary growth [8]. It is widely distributed in the world with China as the most extensive bamboo-producing country [9], having a global export volume of 57.3% in 2009 [10] as shown in **Table 1**. Bamboo is found in abundance in Asia and South America [11]. With over 1200 species and 70 genera, bamboo are found in natural forests, semi-exploited stands and vast plantations globally in an area of more than 14 million ha. [8, 12, 13]. Species of bamboo are found in all continents except in Europe [2]. The percentage of world bamboo resources by continent is shown in **Table 2** [14] and the countries with the most abundant bamboo resources are shown in **Table 3** [15]. The area covered by bamboo in Africa has been estimated at 1.5 million ha with about 43 species [10, 16]; that of Myanmar has been estimated at 2.2 million ha and that of India estimated between 3 and 20 million ha [17]. A total of 40 of the 43 species found in Africa are majorly distributed in Madagascar while the remaining 3 species are found in mainland Africa. Ethiopia has over 1 million ha of highland and lowland bamboo resources, which is about 86% of the African bamboo resource that serves as a subsistence material for rural communities [18, 19].

Bamboo is a lignocellulosic biomass from which some value-added products can be obtained. Although data on worldwide production of bamboo products are incredibly unreliable, they do not appear in significant commodity databases [8]. Its use varies from domestic household products to industrial applications, from medicine to nutrition and from toys to aircraft production.

It has 1500 recorded uses and a combined value of internal and commercial consumption of around US $10 billion in the world market [20]. In recent years, the development and utilisation

Country	Volume of global exports (%)
China	57.3
Indonesia	14.8
Vietnam	4.6
EU-27	3.0
USA	1.7
Philippines	1.6
Thailand	1.0
Singapore	1.0
Myanmar	0.8
Malaysia	0.8

Table 1. Top 10 exporter of bamboo globally in 2009 [10].

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Continent	Percentage of bamboo produced
Asia	65
South America	28
Africa	7

Table 2. Percentage of world bamboo resources by continent [14].

of bamboo have attracted particular attention, not only in paper, textile and food industry but also for construction and reinforcing fibres. In addition, with adequate technology, the stems can be used in the production of cellulose, bio-ethanol and starch [21]. Other bamboo products include bio-methane, flavonoids and functional xylo-oligosaccharides. Some studies have also shown that bamboo resource could be considered as a candidate feedstock of biomass energy for its high growth efficiency [2, 9, 22]. As a cheap lignocellulosic feedstock, bamboo has been adopted for bioenergy production. This adoption is due to its environmental benefits, fast growth and high annual biomass yield. The various uses of bamboo for humans are quite remarkable. Some minor applications include the use of its leaves for medical purposes, fresh edible shoots and culms for timber or as a raw material for pulping [8].

Bamboo is considered an alternative to wood owing to their excellent qualities in physical and mechanical attributes [23]. It attains maturity in 3 years as compared to wood, which takes almost more than 20 years. After maturity, the tensile strength of bamboo is comparable to that of mild steel [15]. It is one of the fastest growing plants [8]. It can grow in areas that are currently non-productive (e.g. on an eroded slope), and its root structure remains intact after harvest, thus, generating new shoots [24]. Bamboo grows in plains, hilly and high altitude mountainous regions, and in most kinds of soils, except alkaline soils, desert and marsh [25].

According to their morphology, bamboos are broadly divided into monopodial (or running) bamboos with 'leptomorph' rhizome system and sympodial (clumping) bamboos with 'pachymorph' rhizome system. These differences in rhizome systems can be because of their adaptations to climate conditions to which the bamboos belong. As a typical forest plant in the tropical and subtropical area, bamboo forest plays significant roles in its biological characteristics and

Country	Bamboo resources in percentage
India	30
China	14
Indonesia	5
Ecuador	4
Myanmar	2
Viet Nam	2
Others	43

Table 3. Countries with the largest bamboo resources in the world [15].

growth habits. Apart from its socio-economical utilisation, bamboo has many environmental benefits [7]. It has some ecological functions on soil erosion control, water conservation, land rehabilitation, carbon sequestration, etc. In China, bamboo forests are recognised as a massive carbon sink in the global cycles of carbon. They have high potentials in carbon fixation, and this is due to the prediction that the carbon stocks in bamboo stands based on previous data for 2050 may get to 1017.64 Tg C [26] or reach 1138.8 Tg C [27].

Some studies have revealed bamboo to produce higher biomass yield than other lignocelluloses crops with a growth rate ranging from 30 to 60 cm/day and height of about 36 m in growing season [28]. The aboveground biomass of bamboo in the Philippines was first reported as 146.8 Mg ha^{-1} $year^{-1}$ (Suzuki and Jacalne [119]). Nath et al. [29] reported that the total aboveground standing biomass of bamboo in northeast India was 42.98 Mg ha^{-1} $year^{-1}$. Hong et al. [30], when comparing the annual biomass yield between bamboo and *Miscanthus* species, reported that of bamboo to range from 5.9 to 49.5 Mg ha^{-1} $year^{-1}$.

2. Chemical composition of bamboo

Cellulose, hemicelluloses and lignin are the three major chemical compositions of bamboo, and they are closely associated in a complex structure [31]. They contribute about 90% of the total bamboo mass. The minor components are pigments, tannins, protein, fat, pectin and ash. Others include resins, waxes and inorganic salts. These constituents play an important role in physiological activity of bamboo, and they are found in cell cavity or special organelles [15]. The chemical composition of bamboo is known to be similar to that of wood, but bamboo has a higher content of minor components compared with wood [32].

Li et al. [33] in their studies reported the chemical composition of bamboo fibre as shown in **Table 4**. Usually, there is variation in the chemical composition of bamboo depending on their age. Notably, cellulose content decreases with increase in age of bamboo. Different authors have investigated different species and bamboo parts. They include bamboo (Kumamoto, Japan) with cellulose content of 47%, hemicelluloses 23% and lignin 28% [9]; bamboo with cellulose 43%, hemicelluloses 15% and lignin 26% [34]; bamboo (Dendrocalamus sp.) with cellulose 47%, hemicelluloses 16% and lignin 18% [35]; bamboo with cellulose 44%, hemicelluloses 30% and lignin 26% [36]; Moso bamboo (*Phyllostachys pubescens* Mazel), with cellulose 46%,

Chemical constituents	Percentage
Cellulose	73.83
Hemicellulose	12.49
Lignin	10.15
Aqueous Extract	3.16
Pectin	0.37

Table 4. Chemical composition of bamboo fibre [33].

hemicelluloses 23% and lignin 26% [37]; bamboo (*Dendrocalamus asper*) with cellulose 41%, hemicelluloses 27% and lignin 27% [38]; Moso bamboo (*Phyllostachys heterocycla*), with cellulose 42–47%, hemicelluloses 22–23% and lignin 23–31% [39]; bamboo, with cellulose 38.4%, hemicelluloses 20.5% and lignin 20.8% [40]; Moso bamboo (*Phyllostachys heterocycla*), with cellulose 37%, hemicelluloses 22% and lignin 24% [41]; bamboo shoots shell fibre (BSSF), with cellulose 23%, hemicelluloses 14% and lignin 11% and bamboo stem and leaf (BSL), with cellulose 21%, hemicelluloses 12% and lignin 12% [42].

3. Chemical modification of bamboo

Many research and technical works have been carried out on the chemical modification of bamboo fibres to improve their properties for specialised applications [43–46]. Chemical modification methods include alkali hydrolysis, acid hydrolysis, coupling, etc.

Alkali hydrolysis is a conventional technique. It is a chemical processing raw cellulose fibre to delignify and to remove the amorphous regions. It creates a rough fibre surface, activates hydroxyl groups and improves the fibre tensile strength. This process involves the initial use of an alkali solution (NaOH) to remove not only the cellulosic components but also the non-cellulosic components such as hemicellulose, lignin and pectin inside the plant fibre [1]. The alkali-treated fibres are then passed through multi-phase bleaching. Most of the manufacturers use this process as it requires not only a little time to yield the bamboo fibres but also less economic means mainly when compared with mechanical methods. Kumar et al. [47] in their study, soaked bamboo strips in 4% NaOH for 72 h to extract the fibre. This method removed 38–42% of the polysaccharides and lignin from the bamboo chips. The obtained pulp was cooled, filtered and washed, and then further treated with glacial acetic acid. Sodium chlorite was occasionally used to bleach the fibre to white. The treated pulp was called bleached bamboo fibre. The problem with this method was that fibre bundles with diameters of 100 ± 10.4 μm were also formed during the extraction; therefore, the parameters were chosen to optimise separation of bamboo fibre by using a minimum amount of NaOH [48].

In an exciting study, Kumar et al. [49] reported that the characteristic properties of mercerised bamboo fibres used for the preparation of bamboo fibre-reinforced epoxy composites made the bio composites cost useful for dielectric applications. In another interesting study reported by Kumar and Kumar [50], alkali treatment of bamboo fibre further increased the tensile and flexural strength of bamboo-epoxy nanocomposites by 60 and 42%, respectively, as compared to pure composites.

Many researchers have worked on the physical, mechanical and thermal behaviour (weathering behaviour, % water uptake, % thickness swelling and thermal stability), morphology properties and impact test of bamboo fibres reinforced novolac resin composites prepared using mercerised bamboo fibres. They reported that the modification improved various features such as fine structure, impact strength, wetting ability, interfacial strength, mechanical properties, weathering and thermal properties of the composites [51–53]. The effect of acrylic acid-grafted bamboo rayon on the antibacterial activity of acrylic acid-grafted bamboo rayon silver nanoparticles has been reported [54]. Bamboo rayon-copper nanoparticle composite fabric was also prepared using acrylic acid-grafted bamboo rayon revealed antibacterial activity against both Gram-positive and Gram-negative bacteria, which was durable until 50 washings [55].

In another study, the effects of alkaline and acetylating agents on the morphology of bamboo fibre-polypropylene were reported [56]. Their mechanical, thermal, rheological property, morphology and miscibility properties were extensively studied. The comparison of alkaline and acetylating treatments showed that the mechanical properties of bamboo fibre-polypropylene composites were improved and adhesion between bamboo fibre and polypropylene matrix was enhanced.

An HNO_3-$KClO_3$ method has also been used to extract fibre from bamboo samples. Before the addition of $KClO_3$, dry raw bamboo strands were immersed in a diluted nitric acid solution [57, 58]. After treating for 24 h at 50°C, the obtained bamboo fibre suspension was cooled then dialysed against distilled water to remove low molecular weight compounds. The slurry was then freeze-dried to obtain dry bamboo fibre.

He et al. [59] suggested a complicated method for obtaining bamboo fibre. Crude fibre bundles of bamboo, obtained by drawing bamboo chips roasted at 150°C for 30 min, were first immersed in water at 60°C for 24 h, and then air-dried before removing impurities further by repeated rolling. Subsequently, the fibre bundles were heated with 0.5% NaOH (w/v), 2% sodium sulphite, 2% sodium silicate and 2% sodium polyphosphate solutions for about 60 min at 100°C. The liquor-to-bamboo ratio was 20:1. After being washed with hot water, the fibres were treated with 0.04% xylanase and 0.5% DTPA (diethylene triamine pentaacetic acid) at 70°C for 60 min at a pH of 6.5. The fibres obtained were then heated for about 60 min at 100°C, except using 0.7% NaOH. In the bleaching step, the bamboo fibre was placed in a polyethylene bag with 4% H_2O_2, 0.2% NaOH and 0.5% sodium silicate for 50 min. The liquor ratio was 20, and the pH was maintained at 10.5. After treatment with 0.5% sulphuric acid solution for 10 min and then being emulsified for 5 days, refined bamboo fibre was obtained.

Maleic anhydride treatment has been reported to improve the mechanical (Modulus of elasticity and flexural modulus) as well as water-resistant properties (water uptake) of bamboo-epoxy composites [60]. The same trend in the properties of permanganate- and benzoylation-treated bamboo fibre polyester composites was observed [61]. In another study, the preparation of short bamboo fibre-reinforced polypropylene composites with various loadings percentages of chemically modified bamboo fibres was reported [62]. Maleic anhydride-grafted polypropylene was chosen, supported as a compatibiliser to improve adhesion between fibre and matrix.

Acrylonitrile treatment of bamboo fibre has been reported to improve the tensile, flexural and water absorption properties of acrylonitrile-treated bamboo fibre composites [49].

Anwar et al. [63] evaluated the effect of pressing time on physical and mechanical properties of phenolic-impregnated bamboo strips. The treatment of bamboo strips with low molecular weight phenol formaldehyde (LMwPF) resin followed by pressing at 140°C improved the dimensional stability and strength properties of the strips. The treatment improved water absorption, thickness swelling and linear expansion perpendicular to grain after 24 h of cold water soaking [63].

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Liu et al. [64] developed and reported an efficient and eco-friendly technology for the improvement of interfacial adhesion of bamboo fibre-Unsaturated polyester (UPE) composites. A soybean oil-based monomer, acrylated epoxidised soybean oil (AESO) monomer was grafted onto the surface of bamboo fibre using 1,6-diisocyanatohexane (DIH) as a linker, and the attached C=C bonds participated in the crosslinking of UPE resins, thus forming chemical connections between the bamboo fibres and the UPE matrix. This resulted in significant improvements in both the static and dynamic mechanical properties of the composites by the improved interfacial adhesion. In addition, it significantly prevented the penetration and movement of water in the composites and resulted in reduced water uptake rates and diffusion coefficients.

Bamboo fibres could also be modified by atom transfer radical polymerisation (ATRP) technique. ATRP is a technique, which could allow the incorporation of polymers with predetermined molecular weight onto the surfaces of particles, fibres or membranes. It has been extensively studied for graft copolymerization of vinyl monomers onto fibres in a living/controllable way [65]. This method has made the incorporation of poly(poly(ethylene glycol) methyl ether methacrylate) (PPEGMA) onto the surfaces of bamboo fibres to improve interfacial adhesion between bamboo fibre and poly-(butylene succinate) [66].

Lu et al. [67] carried out a comparative study on the effect of alkali soaking, silane coupling agent and maleic anhydride grafting on the mechanical properties of cellulose/poly(L-lactic acid) composites. They reported that the modifications improved the mechanical properties of the cellulose/poly(L-lactic acid) composites by improving the interfacial adhesion of the cellulose fibre and the matrix. NaOH solution pre-treatment of cellulose provided the composites with the highest stiffness, KH560 modification resulted in best ductility. Maleic anhydride grafting onto poly(L-lactic acid) balanced the improvements of stiffness and ductility, exhibiting best overall properties [67].

Silanes are recognised as efficient coupling agents that are used extensively in composites and adhesive formulations. Silane coupling agents have a hydrophilic structure with different groups attached to the silicon atoms that can act as a bridge; one end is interacting with the matrix and the other end reacting with the hydrophilic fibres [64]. The silane coupling treatment has been found to significantly improve the impact fatigue strength of the composites [66]. A functional silane was employed as a coupling agent to enhance the interfacial adhesion between bamboo fibre and polylactic acid [68]. The silane-treated bamboo fibre-reinforced polylactic acid composite showed excellent mechanical and thermal properties compared with the properties of polylactic acid composite containing delignified BF. It was thought that effective surface treatment from the silane coupling agent-improved adhesion between the polylactic acid matrix and the bamboo fibre. In another study, Kushwaha and Kumar [69] investigated the effect of silanes on the mechanical properties of bamboo fibre-epoxy composites. They prepared two sets of bamboo-epoxy composites, one with silane treatment bamboo mats and the other with silane treatment mercerised bamboo mats. The mechanical properties (tensile strength, elastic modulus, flexural strength and flexural modulus) observed that silane treatment improved the tensile and flexural strength, but the addition of silane treatment mercerised bamboo leads to significant reduction of the strength. Similarly, Kumar and Kumar [50] in their work confirmed that the alkali and silane treatments with nano-clay filler improved the dielectric and mechanical properties of bamboo-epoxy composites.

Lee and Wang [70] used lysine-based diisocyanate (LDI) as a coupling agent for polylactic acid/bamboo fibre and poly(butylenes succinate)/bamboo fibre composites which improved their tensile and water resistance properties. Two novel bifunctional monomers, namely isocyanatoethyl-methacrylate and N-methylol acrylamide, have been used as the coupling agents to strength the interface of bamboo fibre/unsaturated polyester composites [71, 72].

A recently reported work reported an improved interfacial strength between poly(vinyl chloride) (PVC) and bamboo flour in PVC/bamboo flour composites using novel coupling agents [73]. One pot synthesis generated the coupling agents. The increased content of the coupling agents used increased the morphological and mechanical properties of composites. The result revealed that coupling agent enhanced the affinity between fibre and polyvinyl matrix by lowering down the interfacial tension. SEM studies carried out showed a better dispersion of fibre into the PVC matrix due to an increased amount of coupling agents used. The enhancement in mechanical properties was also an indication of strong bonding between matrix and bamboo fibre [73].

Dilute acid pre-treatment of bamboo shoots shell fibre (BSSF) and bamboo stem and leaf (BSL) have been investigated for xylose and glucose yields [42]. Pre-treatment of bamboo (*Dendrocalamus asper*) with dilute sulphuric acid before enzymatic hydrolysis process to produce fermentable sugars has also been investigated [38]. Dilute phosphoric acid pre-treatment of bamboo was also studied for producing dissolving pulp for textile utilisation [74].

Recently in another study, a solvent (concentrated phosphoric acid) and organic solvent (95% ethanol)-based lignocellulose fractionation (COSLIF) methods have been developed to pretreat bamboo [34].

4. Utilisation of bamboo resources

Bamboo plays a significant role as a material for consumer products. With its high growth rate, a wide range of applications and renewability, bamboo resources occupy a noteworthy position in the twenty-first century as a versatile and vital raw material [20]. Besides, it is recognised as an industrial raw material globally and has tremendous potentials for economic development of nations [75]. The bamboo potential as an industrial raw material is linked to its agronomical and technological characteristics [2]. Given its proprieties, bamboo continues to be used for the production of new products. The multi-functional ranges of bamboo uses have shown that it may prove beneficial as a valuable and sustainable natural resource [76]. In China, it is the valuable raw material for the booming bamboo industry. Bamboo has been known to find large applications for both food and non-food industries. At present, there are about 3000 companies around the world that are engaged in the production of various bamboo-based products [77]. Bamboo provides food, shelter and medicine and serves as raw material for many industries. It has found application in different industrial sectors including civil construction, wood, paper and pulp, textile, electrical and electronics, agriculture and agro-allied, food, chemical and pharmaceutical, reinforcement, automobile and medicine. Some bamboo-based products include house construction materials, household items, biofuel, chemical and pharmaceutical products, pulp and paper, irrigation and drainage pipes and textiles materials, panels, flooring materials, charcoal, edible shoots and other daily-use articles [75, 77]. The use of bamboo fibres as reinforcement in composite materials has been immensely amplified with high-tech revolution in recent years. This is as a response to the increasing demand for developing materials that are biodegradable, sustainable and recyclable [15]. Apart from the above, several other applications exist, though on a relatively small scale. For instance, there are some situations where bamboo is used as poles for aerial antenna, electrification, rafters, fishing traps, yam stakes, etc. Ladapo et al. [75] further reported that the current uses of bamboo in Nigeria represent only a fraction of economic activities in the country.

Besides its role as a raw material for consumer products, bamboo has enormous prospects for industrial utilisation and as industrial raw material. Industrial application of bamboo is in the areas highlighted below:

4.1. Bamboo human food products

Bamboo is a good source of food particularly the shoot. It is a delicacy in Asia. In India, young and tender bamboo shoots are used as a seasonal vegetable in both rural and urban areas [78]. It has been reported to include natural products, such as potassium, carbohydrates, dietary fibres, vitamins and other active materials, which are used for traditional food in many countries [79] and further conversion of these carbohydrates, give rise to other products like xylitol. Figures of nutrient contents of *Bambusa vulgaris* show it to contain crude protein (10.1 g), crude fibre (21.7 g), ether extract (2.5 g), ash (21.3 g), phosphorous (86 mg), iron (13.4 mg), vitamin B1 (0.1 mg), vitamins B2 (2.54 mg) and carotene (12.3 mg)/100 g).

Tea made from the bamboo leaf is rich in silica, which is important in bone and other rigid tissue health. Silica improves bone health, strengthens hair and nails, improves dental health and make the skin more elastic and healthy [80]. Bamboo leaf tea is a low-calorie health food, which is rich in protein and fibre, but free of caffeine. As many cups as possible can be taken as bamboo tea stimulates metabolism without side effects [3]. The common species of bamboo for this purpose are given in **Table 5**.

4.2. Bamboo charcoal

Bamboo charcoal can be used in different industries including chemical, pharmaceutical and energy production industries (**Table 5**). Recent studies have shown that bamboo species are also a good source of quality activated carbon, which can find application in medicine, foods, chemical and metallurgical industries. Activated bamboo charcoal has found application in cleaning the environment, absorbing excess moisture and producing medicines [81]. Bamboo charcoal is generally used by goldsmith and in gardening to prevent moisture available to plants particularly in Japan [78].

Bamboo charcoals are multi-functional materials pyrolysed from bamboo under anaerobic conditions. During this pyrolytic process, bamboo is converted to stable charcoal. It serves as a substitute for wood charcoal or mineral coal and has been reported to possess absorption capacity which is six times that of wood charcoal of the same weight [3, 14]. Hence, it is a suitable absorbent. Studies have also revealed their uses as absorbent for dyes [82–85], heavy metal [86, 87], organic pollutants [88] and other substances [89, 90]. Other applications include for purification of waters, soils and sediments contaminated by PAHs; for environmental protection and architectural decorations [91] and as conductor and fuel [14].

Industry	Part of bamboo	Bamboo species	Bamboo products	References
Pulp and paper	Culm	*Bambusa vulgaris*	Pulp, paper, paper board	Okumura et al. [2], Ogunwusi and Onwualu [3]
Energy production	Stem, branch and rhizome	*Dendrocalamus sp., Bambusa vulgaris*	Bamboo charcoal, bamboo charcoal briquettes, bio-methane, Bio-ethanol	Ogunwusi and Onwualu [3], He et al. [7], Biopact [93], Kuttiraja et al. [35];Okumura et al. [2], Azzini et al. [96]
Wood	Culm	*Phyllostachys aurea, Guadua angustifolia, Melocanna baccifera*	Plywood, laminated bamboo board, mat ply bamboo, curtains ply bamboo, laminated wood strips, mat curtain plywood, door shutter, matchstick, bamboo clipboard, furniture and handicrafts, charcoal	Okumura et al. [2], Xuhe [77], Ogunwusi and Onwualu [3], Ogunwusi [105]
Chemicals and pharmaceuticals	Leaves, shoot, culm	*Bambusa vulgaris*	Cellulose, bio-ethanol, bio-methane, starch, charcoal, flavour and preservatives, bamboo leaf tea	Okumura et al. [2], He et al. [7], Costa et al. [43], Azzini and Gondim-Tomaz [106], Azzini et al. [96], Ogunwusi and Onwualu [3]
Reinforcement	Culm	*Guadua augustifolia, G. brang, G. levis, G. scortechini, G. wrayi*	Floor tiles, toys, bamboo composite decking, bamboo composite fencing, bamboo composite deck tiles, bamboo composite railings, bamboo composite dustbins, bamboo composite outdoor furniture, bamboo decking accessories	Khalil et al. [15], Lee and Wang [70], Ogunwusi [105]
Civil construction	Culm	*Bambusa balcooa, B. tulda, B. nutans, B. pallida, B, polymorpha, Dendrocalamus hamiltonii, Melocanna baccifera, D. giganteus, Gigantochloa apus, Guadua augustifolia*	Irrigation and drainage pipes, flooring & floor covering, lamination of strip (plywood), decking, bamboo scaffolding and cladding, engineered bamboo flooring products, high-density beams and panels, composite board, particle board, bamboo prefabricated house.	Ladapo et al. [75], Lobovikov et al. [14], Ogunwusi and Onwualu [3], Lipangile [102], Akinbile et al. [101]

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Industry	Part of bamboo	Bamboo species	Bamboo products	References
Food and cottage	Shoot, culm	*D. latiflorus, Dendrocalamus asper, D. hamiltonii, D. brandisii, D. strictus, D. latifloru, Bambusa blumenn,B. tulda, B. nutans, B. balcooa, B. polymorpha, B. pallida, Thyrsostachys oliveri, Gigantochloa albociliata, Melocanna baccifera*	Bamboo vegetable, bamboo edible shoots, bakery products, diary products, meat and aquatic products	Miura et al. [107], Okumura et al. [2], Xuhe [77], Parajó et al. [108], Nabarlatz et al. [109], Vazquez et al. [110], Aoyama and Seki [111], Aoyama and Seki [112], Chongtham et al. [113], Borah et al. [78]
Textile	Leaves, woody shoot	*Phyllostachys edulis and Bambusa emeiensis*	Bamboo cloth, bamboo rayon, bamboo linen	Teli and Sheikh [54], Ogunwusi and Onwualu [3], Waite and Platts [114]
Electrical and electronics	Culm	*Guadua augustifolia, G. brang, G. levis, G. scortechini, G. wrayi*	Hardware for electronics, wrist watches, chains, fan blades	Lee and Wang [70]
Agricultural and agro-allied	Leaves	*Yushania alpina* and *Oxytenanthera abyssinica*	Ornamental plants, bamboo livestock feeds	Mekuriaw et al. [115]
Automobile	Culm	*Guadua augustifolia*	Prototype of door trim	Khalil et al. [15]
Medicine	Leaves, culm, stem, sap	*Phyllostachys Sieb. et Zucc.* family (especially *P. nigra* var. *henonis*, *P. edulis* and *P. bambusoides, Bambusa bambos, Pleioblastus amarus, B. spinosa*	Antioxidants, flavonoids	Hu et al. [116], Jiao et al. [117], Xie et al. [118]

Table 5. Bamboo industries, parts, species and products.

However, bamboo is a green biofuel for fighting deforestation and climate change [92]. Because of its excellent characteristics, some countries are renewing their bioenergy strategies to include bamboo. It is worthy of note that a bamboo fuelled power station is being built in Mizoram state of India to help meet the energy need of India's northeast [93]. Bamboo may, therefore, serve as the key to combating energy problem, especially in developing nations if adopted. Common bamboo species that can be used for this purpose (see **Table 5**).

4.3. Bamboo cellulose and alcohol

Bamboos have agronomical and technological characteristics highly essential to obtain cellulose [2]. Their potential and utilisation for cellulose, bio-ethanol and other related products have been studied. It has been recognised as a useful resource for this purpose due to its higher growth rate, annual biomass yield and significant amount of sugars [2, 21]. He et al. [21] reported that bio-ethanol production from bamboo can also follow the general process for ethanol production from other lignocellulosic materials, which including pre-treatment, enzymatic hydrolysis and fermentation. The high contents of starch and cellulose, 70–85% of the stem, have given bamboo an advantage as an alternative source of alcohol production. The part transformed to alcohol represents the yield of 250–380 l ton^{-1} of bamboo [94] while that of sugar cane, when compared gave an average yield of 70 l of alcohol ton^{-1} [95]. In another study, Azzini et al. [96] developed a combined production process for cellulose fibres and ethanol from *B. vulgaris, which* gave good results to bamboo use. Other common species of bamboo used for this purpose are shown in **Table 5**.

4.4. Bamboo pulp and paper

Bamboo is endowed with a long fibre length, and this makes bamboo pulp suitable for paper-making. It has been found out that from 4 tons of bamboo nearly 1 ton of pulp is produced which is utilised in different furnishes for production of paper and board [78]. China and India use bamboo mainly for producing pulp and paper. Bamboo paper has the same quality with paper made from wood. Its brightness and optical properties remain stable while those papers make from wood may deteriorate over time. The morphological characteristics of bamboo fibres give paper made from bamboo a high tear index [97].

4.5. Bamboo medicinal products

Bamboo plant is considered medicinal. It has been found to have a high level of acetylcholine, which acts as a neurotransmitter in animals and humans [98]. Culms of many bamboo species secret siliceous materials, which can be used for medicine. This siliceous material is used as a cooling tonic and aphrodisiac, as a remedy for asthma and coughs [98] and other debilitating diseases. Medicine made from the leaves of *Pleioblastus amarus* is used for treating fever, fidgeting and lungs inflammation [98]. Stems and leaves of *Bambusa bambos* are used in traditional Indian medicine as a blood purifier, in the treatment of leucoderma and inflammatory conditions. It is also given internally for treatment of bronchitis, gonorrhoea and fever. The burnt roots of this species are used to treat ringworm, bleed gums and painful joints. The bark is a cure for eruptions [99]. The leaf bud of *B. spinosa* is used in leprosy, fever and haemoptysis. The sap of *B. vulgaris* is given as a remedy for phthisis in the Philippines [100]. Extractives from various parts of the bamboo plant have been used for hair and skin ointment, medicine for asthma, eyewash, potions for lovers and poison for rivals. Bamboo shoot is one vegetable that is free in pollution, low in fat and high in edible fibre and rich in mineral. It functions well in removing sputum, enhancing digestion, relieving toxicity, improving dieresis and it is frequently used for healing swollen tissues or oedema and abdominal disease in which watery fluids collect in cavities or body tissues [76]. The shoot also contains saccharine, which can resist little mouse tumour and has anti-ageing elements [20, 80].

4.6. Bamboo culm drainage pipes

Drainpipes made from bamboo serve as low-cost substitute to those made from assorted materials. The use of drainage pipes made of various assorted materials is very common in our markets [101]. These materials are very expensive, not readily available, require a high degree of maintenance and pollute water, which they convey due to the pipe's constituents. They include drainpipes made from wood boards or box drains, bricks, horseshoe-shaped ceramic tile, circular clay tile, concrete tile, bituminised fibre perforated pipe, perforated smooth plastic pipe to corrugated plastic pipe. Currently, corrugated pipes are frequently used, although clay and concrete pipes are still being used as well. In rural Tanzania, a bamboo pipe network is being used for providing safe and constant water supply to a large rural population [102]. In a study reported by Akinbile et al. [101] found that the use of bamboo (*B. vulgaris*) of predetermined lengths and diameters as a field drainage material was found effective. The result indicated that bamboo could be satisfactorily used as an alternative to the various assorted materials that are very common in markets to provide an advantage of cost, as well as easy transportation, handling and laying. Also, bamboo pipes do not contaminate the water being conveyed and do not react with the soil; unlike the other assorted materials, thus preventing the excessive cost of treating the water being conveyed for the various human and animal uses [101].

5. Bamboo building or civil construction materials

Bamboo is a principal construction material in many countries, particularly in rural areas. It can be used for almost all parts of houses, including posts, roofs, walls, floors, beams, trusses and fences [14]. At present, the bamboo utilisation in construction is of subjective form and based generally in traditional systems established in each country. In Asia, bamboo is quite common for bridges, scaffolding and housing, but it is usually a temporary exterior structural material. In many overpopulated regions of the tropics, certain bamboos supply the one suitable material that is sufficiently cheap and plentiful to meet the great need for economical housing [103]. However, bamboo offers an ecologically viable alternative to timber for construction due to its low-cost and fast growth rate [3]. Prior to bamboo utilisation in large scale as an economically viable engineering material, a study on properties and structures must be carried out. These studies can provide better cultivation, harvest and processing techniques, besides analysis of mechanical and physical properties of bamboo stems. Bamboo stems present excellent physical and mechanical properties that can be used as a substitute for other materials such as steel aiming fabrication of concrete structures. Several studies were conducted on physical and mechanical characteristics to test the bamboo as construction material. The mechanical properties of bamboo are strongly affected by the age, species and humidity. Bamboos do not break easily, and its original shape is regained when the load subjected to it is removed. It is suitable for reinforcing concrete [75]. Some bamboo products for building or construction purpose include ply bamboo, bamboo panels/composite boards of different types, particle boards, mat boards, bamboo parquet and bamboo fibre-reinforced plastic [5, 76, 104]. The common species of bamboo used for this purpose are given in **Table 5**.

6. Bamboo livestock feed and ornamental plant

The Japanese have used the leaves of bamboo as fodder for livestock for hundreds of years. It is also an essential food for the giant pandas in China because they survive only on bamboos. Many bamboos are popularly used as ornamental plants to beautify homes and gardens. Ogunwusi and Onwualu [3] reported that feeding chickens on organic diets containing fresh bamboo leaves lead to 70% weight gain more than those do fed on standard organic diets. This suggests that the fibre in the bamboo leaves enlarge the digestive tract and enable the chicken to consume more and grow faster.

7. Bamboo chemicals and pharmaceutical products

The ashes of bamboo are used to polish jewels and manufacture electrical batteries. Bamboo beverage and beer have been widely accepted mainly in Asian countries such as China, Korea and Japan. Bamboo has been reported to be valuable in health care delivery and processed into beverages, medicines, pesticides and other household items such as toothpaste, soaps, etc. The culm, shoot and leaf of bamboo have been reported to possess anti-oxidation, anti-ageing, antibacterial and antiviral properties. Some materials extracted from bamboo are used in fresh flavour and preservation of food. This is due to the nutritious and active minerals (such as vitamins, amino acids, flavine, phenolic acids, polysaccharide, trace elements and steroids) they contain [76]. Bamboo leaf contains 2–5% flavine and phenolic compound that have the power to remove active oxy-free radicals, stopping nitrification and abating blood fat. Of late, research has shown bamboo charcoal as one of the base materials for human health, from water treatment to its uses as a shield from electromagnetic radiation. Bamboo extracts contain valuable elements, which are used in pharmaceuticals, creams and beverages. Bamboo gas can be used as a substitute for petroleum. Activated charcoal is used as a deodorant, purifier, disinfectant, medicine, agricultural chemicals and an absorbent of pollution and excessive moisture. A number of researchers have also produced bamboo ethanol and butanol. Butanol is similar to ethanol being a form of alcohol. It has high-density; non-corrosive and can, therefore, be mixed with gasoline. Another significant product from bamboo is activated carbon. Activated carbon is a non-graphitic form of carbon, which is produced by activation of any carbonaceous material such as bamboo, wood chips, etc. Activated carbon is employed in the decolourisation of sugar and sweeteners, drinking water treatment, gold recovery, production of pharmaceuticals and fine chemicals, catalytic process, off-gas treatment of waste incinerators, automotive vapour filters, colour/odour correction in wines and fruit juices.

Some chemical and pharmaceutical products are cellulose, bio-ethanol, bio-methane, starch, charcoal, flavour and preservatives, bamboo leaf tea (see **Table 5**).

8. Bamboo handicraft products

Bamboo is known as one of the materials more versatile to the handicraft production because it is a raw material of easy acquisition, low-cost and demands simple tools in preparation. Besides, bamboo is also a material of high plasticity and easy to combine with other materials. Hence, it allows an artist to express his talent in several forms. Handicraft products with bamboo are exported mainly from Asian countries to other parts of the world. The excellent quality of these products is due to good qualification of the workforce and the availability of machines that assist the production process.

Bamboos are used for making skewers, chopsticks, boats, weapons, matchsticks, containers, poles, bows and arrows, rafts and fishing poles. Various craft products made of bamboo are baskets, tools, handles, hats, traditional toys, mat, flooring material, purses, bags, satchels, tea packaging, floor tiles, general household product, furniture, utensils, musical instruments, etc. Craft products are to be developed differently, marketed and promoted in innovative and various ways if they are to compete and survive in the international market. **Table 5** shows some typical bamboo species and parts used for this purpose [78].

9. Bamboo furniture

Bamboo serves as an excellent alternative to wood in the manufacture of furniture. It competes in market of wood without restrictions. In Asia, there is a significant production of furniture of bamboo. Artists of this continent have refined techniques that qualify these products to exigent markets. Various bamboo furniture products including bamboo panel, composite board and particleboard have been developed in China [76]. Bamboo mat board is being manufactured in China, India, Thailand and Vietnam [5]. Other bamboo furniture products are beds, cupboard, table, upholstery chairs [75], ply bamboo, laminated bamboo, mat ply bamboo, curtains ply bamboo, laminated bamboo strips, mat curtain plywood, bamboo chipboard, floor tiles and composites. Laminated bamboo furniture is on the rise rapidly in the world especially Asia. When bamboo is laminated and used to produce furniture, it is difficult to differentiate it from wood [75]. **Table 5** shows some typical bamboo species and parts used for this purpose.

10. Conclusion

The application of bamboo in many spheres of life as a suitable replacement for woody biomass in some instances provides arrays of opportunities in material industries. Bamboo being trees that grow and mature in a very short period of time can secure continuous supply of cheap tree and fibres compared to other woody biomasses. In addition, the excellent properties of bamboo enhanced via different chemical modification methods to improve their mechanical and thermal makes their fibre to be competitive with other materials used in the reinforcing of different polymers. With the application of correct treatment, suitable fibres can be extracted from bamboo for various purposes. And as such, several outstanding bamboo fibres can be obtained and incorporate other materials to produce excellent performance composites that can favourably compete with many conventional materials. The use of alkali hydrolysis has been majorly to remove the amorphous regions that are responsible for low resistance to fungus attack in the fibre. The interfacial adhesion between the fibre and other matrices can enhance the inclusion of coupling agents and fibre pre-treatment using acid hydrolysis. The use of bamboo fibres as a replacement for petroleum-derived fibres can breed the development of eco-friendly products that exert less pressure on the environment.

Bamboo fibres have great potential as an alternative to inorganic fillers and are raw material for fabricating a composite material, and their applicability is being widely investigated. Green composites, defined as biodegradable biopolymers reinforced by natural fibres, have very low impact on the environment, and thus they are one of the potential alternatives to replace conventional petroleum-based polymers and polymer composites. Bamboo has been used widely utilised in pulp and paper, energy production, chemicals and pharmaceuticals, reinforcement, civil construction, textile, electrical and electronics, agricultural and agro-allied, automobile and medicine. Although some of these applications are very limited in scope, continuous researches on bamboo can increase their potential and induce their aggressive interest in many more areas.

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