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REVIEW

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Prospect of bamboo as a renewable textile fiber, historical overview, labeling, controversies and regulation

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Abstract

Innovation in textile has brought alternative plant based fibers such as bamboo into the spotlight and as a replacement to petrochemical based synthetic fibers. Bamboo as a raw material is a remarkably sustainable and versatile resource but the manufacturing process is where the debate really gets heated and the sustainability and green image of bamboo is tarnished. Products made from bamboo are often labeled as 'eco-friendly', 'bio-degradable' and 'anti-microbial' irrespective of their method of manufacturing. The claims may not always portray the products authenticity and true environmental impact. By far, viscose process is predominantly used to create fibers from bamboo but the properties of natural bamboo fibers in such bamboo viscose products have been lost. However, bamboo textiles are not yet achieved their full potential and cleaner production processes are appearing. With abundant sources of raw material, relatively low cost; and unique performance of bamboo fiber it is only a matter of time to develop green and pure bamboo textiles. This paper analyses the prospects of bamboo fibers providing a view on bamboo as a plant and processed fiber, facts regarding the anti-microbial properties of bamboo fibers, its chemical properties, morphology, anatomy, historical overview, patents and modern bamboo textile industry.

Keywords: Natural bamboo fiber, Bamboo viscose, Litrax bamboo, Morphology, Anatomy, Patents, Bamboo fiber labeling, Regulation

Introduction

Although textile is one of the most ancient known, dating back to the very inception of culture there still remains room for innovation today. New ways have to be thought up of creating materials that will provide the best possible balance between properties sought, cost and quantities of material and energy used, so that these new materials may be created that are either biodegradable or can be easily recycled (CETI, http://www.ceti.com). What's more textile and apparel manufacturer are constantly exploring for natural renewable fibers having unique performances as their way of adding value to their products and to catch the attention of the consumers. These concerns drive research into ways to develop fiber derived from unconventional 'agro-resources' such as bamboo.

Bamboo plant as a resource is available in plenty and plays a great role in socio-economic development (Panda 2011; Yeasmin et al. 2015). It is fast growing (Devi et al.

2007; Rodie 2008; Nieder 2009; Hardin et al. 2009) and most of it is grown organically (though very little is certified organic), and it has been claimed that growing bamboo usually requires no pesticides and fertilizers (Devi et al. 2007; Rodie 2008; Nieder 2009; Hardin et al. 2009; Yueping et al. 2010) i.e. naturally organic. Bamboo textiles are fashionably chic, soft, cool, breathable and light (Textile Digest 2009; Hardin et al. 2009; About Mechanically Processed Bamboo http://www.getgloved.com).

Bamboo textile and apparel products are a recent development. Products made from bamboo are often labeled as 'green', 'bio-degradable', etc. irrespective of their method of manufacturing (Rodie 2008; Hardin et al. 2009). While 'agro-resources' by definition do not use petroleum as raw material, there are often hidden consequences and impact created by their uses. Besides, many apparel manufacturers often claimed that products made from bamboo have antimicrobial properties (Rodie 2008; Hardin et al. 2009 Textile Digest 2009; About Mechanically Processed Bamboo http://www.getgloved.com). The claims may not always portray the products authenticity and true environmental impact. However, more scientific investigations are needed to prove the claims and researches are still going on.

This paper analyses the prospects of bamboo fibers providing a view on bamboo as a plant and processed fiber, facts regarding the antimicrobial properties of bamboo fibers, its chemical properties, morphology, anatomy, historical overview, patents and modern bamboo textile industry.

Taxonomy and geographical distribution

Bamboo is the vernacular term for perennial, giant woody evergreen plants in the grass family Poaceae (syn. Gramineae); subfamily Bambusoideae (Scurlock et al. 2000; Sungkaew et al. 2009; Hodkinson et al. 2010; Panda 2011; Yeasmin et al. 2015). The most important characteristics that make majority of bamboo distinct from other grasses are their woody perennial habit and peculiar flowering and seeding behavior (Panda 2011). The taxonomy of bamboo is the most difficult domain and still not clearly understood partly because of the infrequent flowering of many species; some species even flower after a very long interval of vegetative growth (as long as 120 years) (Scurlock et al. 2000; Das et al. 2008; Panda 2011) and also partly due to extensive genome polyploidization (Das et al. 2008). In precise, the taxonomic demarcation of genera and species of woody bamboos at lower ranks are so far not well resolved. A number of species are known only vegetatively and new species are frequently been described (Triplett et al. 2006; Clark et al. 2007; Das et al. 2008). The earliest bamboo classification was attempted by Munro (1868) which described 170 species under 20 genera (Das et al. 2008; Clark et al. 2015). The most up-to-date comprehensive and phylogenetically based bamboo taxonomical system is derived from DNA sequence data in combination with various morphological and anatomical features (Clark et al. 2015). Currently bamboo encompass 1482 described species within 119 genera and are classified into three tribes: (1) Arundinarieae: the temperate woody bamboos, albeit some occur in the tropics at high elevations; 546 species, (2) Bambuseae: the tropical woody bamboos, even if some occur outside of the tropics; 812 species, (3) Olyreae: the herbaceous bamboos; 124 species (Clark et al. 2015) clearly supported by phylogenetic results (BPG 2012). However, 1575 bamboo species are reported (Goyal et al. 2013; Basumatary et al. 2015) and Waite (2009) accounted that although more than 1500 species of bamboo are found around the world, approximately 50 are involved commercially in trade. Almost half of these species are spread in Asia, mostly within the Indo-Burmese region which is also considered to be their place of origin (Grosser and Liese 1971).

Many DNA sequencing activities are being carried out in recent years for characterization of bamboo species for sustainable utilization of genetic diversity, its conservation and future studies (Yeasmin et al. 2015) facilitating easy availability of sequences in the public domain (Sungkaew et al. 2009; Yosodha 2011). Almost all the bamboos are polyploides (Gielis 1998; Kellog and Bennetzen 2004) and therefore the nuclear genomes of bamboo exhibit extensive variation in chromosome number, size and DNA content (Yosodha 2011). Bamboo phylogeny Group reported that approximation of total diversity vary from source to source. Discoveries of new species and genera in all of these tribes are still going on and phylogenetic analyses in a number of cases support generic recircumscriptions (BPG 2012).

Bamboo plants are found in almost all parts of world except those places having extreme cold climates like Europe though some species can be successfully introduced in mild temperate zones of Europe (IFAR/INBAR 1991; Tewari 1992; Panda 2011; Hakeem et al. 2015) (Fig. 1). The spreading of bamboo plants can be broadly assigned into three major divisions namely Asia–Pacific, America and Africa (Zhou 1998). Greatest diversity of bamboo is found in Southeast Asia and South America, where they occur in tropical, subtropical and temperate regions (Zhou 1998; Bystriakova and Kapos 2006; Hodkinson et al. 2010; Panda 2011; Goyal et al. 2013) while, fewer bamboo species are found in Africa in comparison to the other two regions (Zhou 1998; Bystriakova and Kapos 2006; Panda 2011) with the exception of Madagascar which is rich in endemic genera and species (Bystriakova and Kapos 2006; Panda 2011). They occur at latitudes from 51°N in Japan to 47°S in South Argentina and from sea level to 4000 m elevation though occurrence of herbaceous bamboo never exceeds an altitude of 1500 m (IFAR/INBAR 1991; Tewari 1992; Panda 2011). Qiu et al. (1992) reported that almost one thousand bamboo species are found in Asia, predominantly indigenous rather than plantation or introductions.

Bamboo morphology

Morphology (Morphe = form; logos = study) of bamboo refers to the external structure (form and features) of the bamboo plant's components. Bamboo does not have a central trunk like other woody plants and its major components include roots, rhizomes,

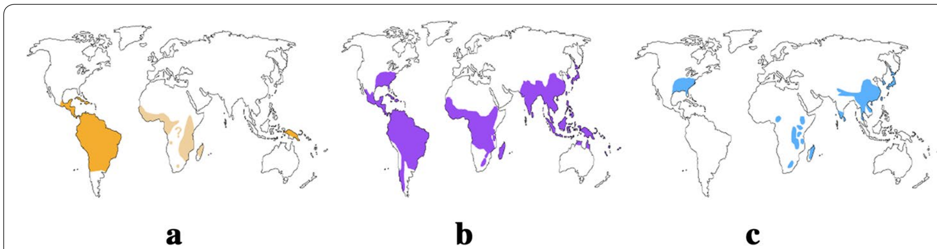

Fig. 1 Geographical distribution of bamboos: **a** herbaceous Bamboos, **b** all woody bamboos, **c** temperate woody bamboos [Source: http://www.eeob.iastate.edu/research/bamboo/bamboo.html, Map prepared by: Elizabeth Vogel and Anna Gardner; Courtesy: Dr. Lynn Clark, Iowa State University, USA]

culms, branches, leaves, and flowers (Seethalakshmi et al. 1998; Banik 2015; Liese and Tang 2015).

The rhizome is an essential parts of bamboo plants which bears roots. Stapleton (1997) reported that two major rhizome systems prevail but the terminology used to explain rhizomes has often been uncertain and indistinct. He reviewed the terminology and opined that the term pachymorph and leptomorph [prefered by McClure (1966)] were the most appropriate than the terms sympodial (clumping) and monopodial (non-clumping or running) which concern more with the branching patterns than actual morphological forms. The growth and branching pattern of bamboo is dependent upon the rhizome systems, as this determines whether the plant will be clump forming or non-clumping and will also determine the distances between individual culms (neck length). Bamboos are broadly classified into clumping types with pachymorph rhizome systems and running types with leptomorph rhizome systems (Janssen 2000; Das et al. 2008; Waite 2009; Banik 2015); in certain circumstances a mixed condition of both monopodial and sympodial types, known as amphipodial is witnessed (Das et al. 2008). However, according to Stapleton (1997) the term amphipodial or amphimorph though often used is possibly misleading.

The rhizome in a bamboo is well developed (Banik 2015) underground plant part (Das et al. 2008; Hardin et al. 2009) that spreads to produce an interconnected network and often send out shoots or new rhizome from its nodes (Das et al. 2008; Liese and Tang 2015). The young shoots are protected by sheaths that fall off as they grow up into mature culms ('Culm': Latin word *culmus* meaning stem) (Janssen 2000; Das et al. 2008). In pachymorph rhizome system the culms develop from the terminal buds whereas in leptomorph rhizome system these arise from the lateral buds of the rhizome (Janssen 2000; Banik 2015). After reviewing the terminology, Ding et al. (1997) suggested that only monopodial (running) bamboo possess a true rhizome (Liese and Tang 2015).

The culm is the most distinguishable upper ground part in the plant, may be arching or erect semiscandent or scandent (Seethalakshmi et al. 1998), characterized as a hollow cylindrical tube divided by nodes and internodes (Chaowana 2013; Liese and Tang 2015). The culm is complimented by the branching system which is more informative at mid position of the culm than the lower culm body (Das et al. 2008). The length of internodes appearing from the culm sheath towards the end of the growth period varies with the species and has a stable genetic basis (Banik 2015); longer in those species in which the growth periods begin earlier.

Two types of leaves—culm leaf and foliage leaf, which are functionally different, are observed in bamboo (Das et al. 2008; Banik 2015). The bamboo leaf develops from a sheath, which encircles the stems and is called a leaf-sheath. The leaf-sheath resembles a small culm-sheath but develops a large sheath blade that functions as a proper leaf (foliage leaf). The green foliage leaf essentially performs photo synthesis whereas the culm leaf protects the younger shoot. At the point of attachment of the blade of the sheath there are different combinations of features involving auricle, bristles and ligules which are as important as the colour of the culm sheath in the identification of individual species (Das et al. 2008; Banik 2015).

The Olyreae tribes are discerned by their rather weakly lignified culms, lack of both well differentiated culm leaves and outer ligules; restricted vegetative branching and unisextual spikelets on the contrary, Arundinarieae and Bambuseae tribes have a tree like habit with highly lignified, typically hollow culms, complex rhizome systems, clearly distinguished culm leaves, well developed aerial branching, and foliage leaf blades with outer ligules, and bisexual spikelets (BPG 2012; Clark et al. 2015).

The sequence of flowering in bamboos varies with species and accordingly these can be categorized into three major types namely annual, irregular (sporadic) and gregarious. However, the majority of bamboo species (for e.g. *Bambusa bambos*, *B. tulda*, *Dendrocalamus strictus*) exhibit gregarious flowering that occurs at long intervals with synchronized seed production. The entire clump at one location produces flowers and then dies back over the course of 2–3 years; the cycle repeats every 30–40 years even more than 60 years in certain cases (Scurlock et al. 2000; Das et al. 2008). Besides, almost all herbaceous bamboos exhibit seasonal flowering while the woody bamboos usually exhibits gregarious flowering pattern (Clark et al. 2015).

Anatomy of bamboo culm

The technological properties of a bamboo culm are determined by its anatomical features. A number of studies have been attempted to describe anatomical changes occurring in the culm tissues such as cell wall thickening and lignifications during culm maturation and their significance in change of technical properties (Liese 1987, 1998, 2004a, b; Alvin and Murphy 1998; Liese and Grosser 2000; Wahab et al. 2013; Liese and Tang 2015). Unlike wood, there are no such major differences found among genera and species of bamboo in their anatomical structure yet certain species are ideal for specific uses (Liese 1992; Liese and Tang 2015). Besides, growth conditions and aging have no significant effect on composition and structure of bamboo tissue. The thickness of culm wall shows significant difference between genera and species which has great impact on mechanical properties. The whole bamboo culm comprises of 50 % parenchyma, 40 % fibers and 10 % conducting tissue (vessels, sieve tubes with companion cells) with some variation according to species (Liese 1992, 1998; Chaowana 2013; Liese and Tang 2015).

Bamboo is an anisotropic and natural composite material due to the structure composed of mostly vascular bundles (which comprises of sclerenchyma, metaxylem vessels, sieve tubes with companion cells), embedded in a ligneous matrix (parenchyma) (Liese 1987; Smole et al. 2013; Dixon and Gibson 2014; Habibi and Lu 2014; Liese and Tang 2015). In other words, bamboo comprises of three fundamental tissues namely parenchyma, vascular bundles and epidermis (Habibi and Lu 2014).

Vascular bundles embedded in the parenchymatous ground tissue collectively play a role in the flexibility and stability of the culm. The parenchyma cells, which are smaller on the outer culm part and grow to be longer and larger towards the inner part, are of two types– one vertically longer and the other short, cube like fiber interspersed. The cell wall of the longer one has a polylamellate structure with alternating broad and narrow lamellae (Fig. 2) and become lignified in the early stages of shoot growth (Parameswaran and Liese 1980; Liese 1987; Liese and Tang 2015). The walls of shorter parenchyma cells remain mostly non-lignified even in mature culms and retain their cytoplasmic activity for a long time. Usually the maturation changes pertaining to lignifications and thickening of cell wall complete within 3–4 years (Liese 1998; Gritsch et al. 2004).

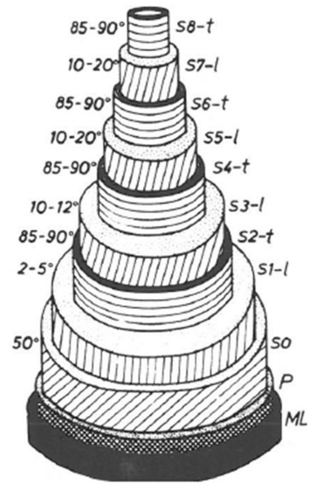

Fig. 2 Model of the polylamellate structure of a bamboo fiber wall (Liese 1985); [Reproduced from Liese and Tang 2015]. Figures on the left indicate fibril angles and letters on the right the terminology of wall lamellae. *ML* middle lamella, *P* primary wall, *S0* secondary wall, Transparent broad lamellae (S-l); (S1-l, S3-l, S5-l & S7-l), Denser narrow lamellae (S-t); (S2-t, S4-t, S6-t, & S8-t)

Fibers are present around vascular bundles as sclerenchyma sheaths (fiber sheaths; fiber cap) and in some species as additional fiber strands. In non-conventional fiber plant like bamboo sclerenchyma cells are organized in a similar manner than traditional fiber cells like flax and hemp. The bamboo fibers are slender, long, tapered and often forked at the ends and are aligned in the longitudinal direction of the culm. The fiber length shows significant variation between and within species (Liese and Grosser 2000; Chaowana 2013; Smole et al. 2013; Dixon and Gibson 2014; Liese and Tang 2015). The fibers add 40 percent mass and 60–70 percent of the weight of culm. The percentage of fiber is compact in the outer part (Fig. 3) while the parenchyma and conducting cells are plenteous in the inner part of the wall. Fiber length is not only significantly correlated

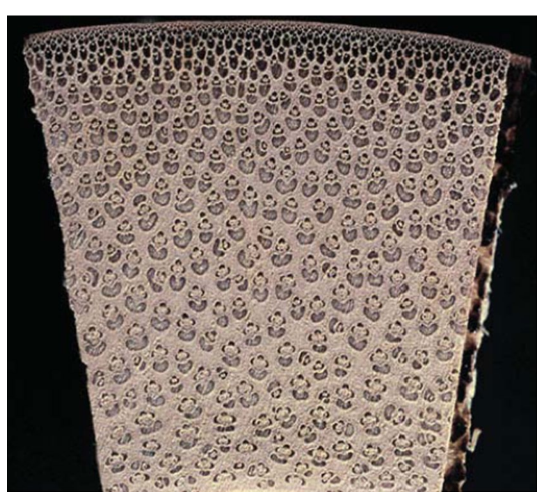

Fig. 3 Cross-section of a bamboo culm, vascular bundles within the parenchyma (Liese 1998); [Reproduced from Liese and Tang 2015]. The density of the fibers in the cross-section of a bamboo culm varies along its thickness. The fibers are concentrated in regions closer to the outer skin

with fiber diameter and cell wall thickness, but also with the modulus of elasticity and compression strength (Chaowana 2013; Liese and Tang 2015).

Both sides of the culm wall are covered by special tissue. The outer part, the cortex, consists of epidermal cells that are covered with waxy layer which prevent moisture loss in the bamboo culm. At the inner side, layer of parenchyma cells, form a special tissue (Chaowana 2013; Liese and Tang 2015).

Chemical composition of bamboo fiber

Bamboo is a natural ligno-cellulosic fiber obtained from bamboo culm. Its chemical composition is similar to bast fiber (Li et al. 2010) so, its structure and properties are often compared with other bast fibers such as flax and jute (Yueping et al. 2010). Besides, it belongs cellulose I crystalline structure, like that of cotton and ramie. Though bamboo fiber is *alike* a bast fiber, it is often misinterpreted as a bast fiber. Bamboo does not have a bark and the fiber occurs on the outer culm unlike a bast fiber which takes place in the phloem or bark of the plant. Therefore, bamboo could appropriately be called as a 'culm fiber' just as cotton is called—a 'seed fiber', or sisal—a 'leaf fiber'.

The major chemical constituents of bamboo are cellulose, hemi-cellulose and lignin accounting for over 90 % of the total mass and the minor constituents being soluble polysaccharides, waxes, resins, tannins, proteins and ashes (Seethalakshmi et al. 1998; Li et al. 2007; Chaowana 2013; Liese and Tang 2015). Tomalang et al. (1980) in their study found that bamboo culms consist of 60–70 % holocellulose (cellulose + hemicellulose = holocellulose), pentosans (20–25 %), hemicelluloses and lignin (each amounted to about 20–30 %). On the whole, bamboo contains 40–50 % α-cellulose, which is comparable with the reported α-cellulose contents of softwoods (40–52 %) and hardwoods (38–56 %). Cellulose contents in this range make bamboo a suitable raw material for the pulp and paper industry (Fengel and Wegener 1984; Dence 1992; Li et al. 2007). Table 1 presents approximate chemical analysis of some bamboo species.

Li et al. (2010) reported that bamboo fiber contains more than 70 % cellulose (Bamboo species: *Neosinocalamus affinis*, abundantly found in China). In general, the cellulose amounts as 'holocellulose' to more than 50 % of the chemical constituents (Liese 1987). However, the contents of hemicelluloses and particularly lignin are greater than that of flax and little less than that of jute fiber. Non-cellulose substances like pectin and hemicelluloses influence the fiber properties such as strength, flexibility, moisture and also density significantly (Li et al. 2010). Cellulose and hemicelluloses are carbohydrate polymer constituents of simple sugar monomers. Cellulose, like other plant cellulose, consists of linear chains of β-1-4-linked glucose anhydride units. Above 90 % of hemicelluloses in bamboo comprise of xylan (4-*O*-acetyl-4-*O*-methyl-D-glucuronoxylan, a relatively short polymer, degree of polymerization 200) (Liese 1987; Liese and Tang 2015). Lignin (a typical grass lignin) is a polymer of phenyl-propane units (*p*-hydroxyphenyl) (H), guaiacyl (G) and syringly (S) in a molar ratio of 10:68:22 (Wahab et al. 2013; Liese and Tang 2015).

The degree of polymerization (DP) for bamboo is higher than for dicotyledonous woods (a maximum of 15,000) (Liese and Tang 2015). However, the DP of bamboo fiber (species: *Neosinocalamus affinis* (at present known as *Bambusa emeiensis* '*Chrysotichus*'), single fiber length: 2 mm) is close to jute fiber and lesser than flax and ramie and

Table 1 The chemical composition of some bamboo species

Bamboo species	Holocellulose (%)	Alpha-cellulose (%)	Lignin (%)	Ash (%)	Sources
Bambusa blumeana	65.7–72.6	40.3–45.1	20.5–22.7	–	Latif and Liese (1995); Liese and Tang (2015)
Bambusa heterostachya	68.8–79.5	–	19.7–23.1	2.7–5.27	Latif et al. (1996)
Bambusa stenostachya	68.5–76.2	–	20.7–25.2	2.08–2.7	Chang et al. (2013)
Bambusa vulgaris	67.8–69.6	37.9–43.2	22.7–23.9	1.8–2.1	Latif and Liese (1995); Liese and Tang (2015)
Dendrocalamus asper	61.9–75.2	–	18.5–29.0	1.7–5.6	Prasetya (1996)
Gigantochloa brang	79.94	51.58	24.83	1.25	Wahab et al. (2013)
Gigantochloa levis	85.08	33.80	26.50	1.29	Wahab et al. (2013)
G. levis	63.5–67.2	36.2–42.5	23.3–26.6	1.4–1.9	Latif and Liese (1995); Liese and Tang (2015)
Gigantochloa scortechinni	74.62	46.87	32.55	2.83	Wahab et al. (2013)
G. scortechinni	66.8–68.1	40.5–41.4	24.9–27.9	1.1–1.4	Latif and Liese (1995); Liese and Tang (2015)
Gigantochloa wrayi	84.53	37.66	30.04	0.88	Wahab et al. (2013)
Phyllostachy pubescens	71.4	47.00	22.8	1.5	Li et al. (2007)
P. pubescens	68.6–73.8	46.08–47.9	21.26–23.95	1.26–1.95	Li (2004)
Schizostachyum zollingeri	68.8–74.3	48.7–52.6	22.1–22.9	–	Latif and Liese (1995); Liese and Tang (2015)

much lower than cotton fiber (Yueping et al. 2010; Li et al. 2010); the higher the lignin content the lower the degree of polymerization (Yueping et al. 2010). Yueping et al. (2010) also stated that the DP is strongly correlated to the length and width ratio of a single fiber. They deduced that bamboo fiber has lower DP than flax and ramie, consequently the single fiber length is very short i.e. 2 mm with a length and width ratio of about 120:1 as against more than 1000:1 in length and width ratio for flax and ramie. However, the length varies considerably between and within bamboo species and the range of length to width ratio lies between 150:1 and 250:1 (Liese 1987). Liese and Tang (2015) reported average single fiber lengths of some bamboo species which are more than 2 mm, especially *Dendrocalamus membraneus* (4.3 mm), *Gigantochola aspera* (3.8 mm), *Oxytenanthera nigrocilliata* and *Teinostachyum* sp. (3.6 mm), and *Bambusa textilis* and *B. tulda* (3.0 mm).

Besides, Liese (1987, 1992) reported that the chemical composition varies according to species, the growth condition, age and the part of the culm. As the culm tissue matures within a year when the soft and fragile sprout becomes hard and strong, the proportion of lignin and carbohydrates is changed during this phase. Yet, after the full maturation of the culm, the chemical composition tends to remain rather constant.

Manufacturing process of bamboo fiber

The manufacturing process of bamboo fiber is where the debate gets intense and the sustainability and green image of bamboo is tarnished. There are two main methods of producing bamboo fibers namely mechanical and chemical. The chemical process is of two kinds: one that follows the viscose process used to produce rayon where the fiber is broken down with harsh chemicals and extruded through mechanical spinnerets. The second one follows the closed solvent spinning loop which, is essentially the same process used to produce Lyocell fibers (DyStar Ecology Solutions 2010). There is another category of bamboo fiber known as bamboo charcoal nano fiber (Waite 2009) which is beyond the scope of this subject and not discussed in details.

Fiber extraction through mechanical process

The fiber extracted by mechanical process is often referred by the manufacturer as 'natural' or 'original' bamboo fiber and more or less the same manufacturing process used to produce ramie (Waite 2009).

1. The bamboo culms are split mechanically followed by rasping off the woody part.
2. The crushed bamboo strands are treated with enzymes to separate the fibrous materials from the remaining culm-parts.
3. Individual fibers are then combed out.
4. Fibers are then spun into yarns.

Natural bamboo fiber would be recognizable as bamboo under microscope (Fig. 4). Bamboo fiber produced by this process though considered eco-friendly is less used because it is time consuming, labor intensive, costly and serves a very specific niche of the textile market.

Fiber extraction through chemical process (Rayon Process)

The method essentially follows the same process as used to manufacture regenerated viscose rayon using hydrolysis alkalization with the multi-phase bleaching principle (Erdumlu and Ozipek 2008; Waite 2009; Ogunwusi 2013) and the process is as follows.

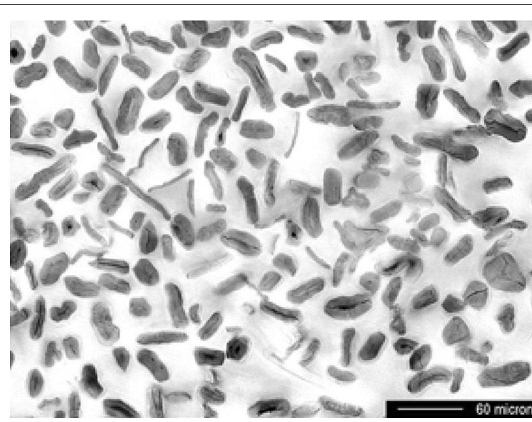

Fig. 4 Cross-section of a natural bamboo fiber

1. The bamboo culm is crushed into smaller fractions and soaked in a solution of 18 % NaOH at 20–25 °C for 1–3 h to form alkali cellulose.
2. The bamboo alkali cellulose is pressed to remove excess NaOH solution, crushed by a grinder and left to dry for 24 h.
3. In this stage, CS_2 is added to the bamboo alkali cellulose to sulfurise the compound, causing it to jell.
4. The remaining CS_2 is removed by evaporation due to decompression, resulting in sodium xanthogenate.
5. A diluted solution of NaOH is added to the cellulose sodium xanthogenate, which dissolve it into a viscose solution consisting of about 5 % NaOH and 7–15 % bamboo fiber cellulose.
6. The viscose solution is forced through spinneret nozzles into a larger container of diluted sulfuric acid (H_2SO_4) solution which, hardens the viscose and reconverts it to cellulose bamboo fiber which are spun into yarns (to be woven or knitted).

This process (Fig. 5) produce regenerated bamboo fiber which is essentially a rayon fiber which is silky, strong and elegant but just like any other rayon, involves toxic chemicals and harmful byproducts. Unless methods are used to capture and recycle the caustic chemicals, harmful byproducts can be released into air and water.

Fiber extraction by closed solvent spinning loop process

Prof. Peter Hauser of North Carolina State University had suggested at a workshop sponsored by the US Federal Trade Commission (FTC) in July 2008 that bamboo may also be processed into lyocell fibers (Textile Digest 2009). Closed loop process or lyocell process may be the solution to greener regenerated bamboo manufacturing.

1. Lyocell process uses *N*-methylmorpholine-*N*-oxide (NMNO) to dissolve the bamboo cellulose into viscose solution. NMNO are weak alkalines that act as surfactant and help break down the cellulose structure.
2. Hydrogen peroxide (H_2O_2) is added as a stabilizer and the solution is forced through spinnerets into a hardening bath (usually a solution of H_2O_2 and a alcohol like methanol or ethanol), which causes the thin streams of viscose solution to harden into bamboo cellulose fibers.
3. The regenerated bamboo fibers are spun into yarns.

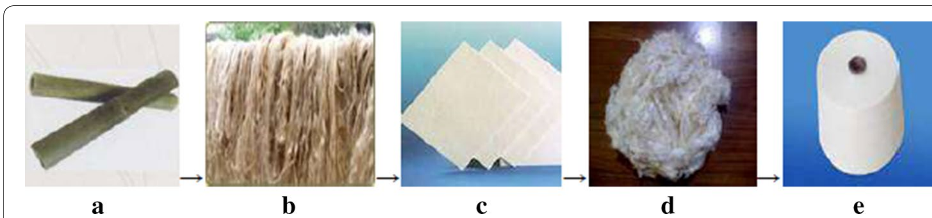

Fig. 5 Simplified bamboo viscose manufacturing steps (Lin 2008)[Reproduced from Waite 2009]. **a** Raw bamboo. **b** Bamboo processed into thick pulp. **c** Bamboo processed further into fine pulp sheet. **d** Bamboo rayon fiber. **e** Spun into yarn

While much more expensive, the lyocell process substantially reduces the environmental threats associated with the viscose process and thus, comparatively eco-friendly because the amine oxides are reported to be non-toxic to humans beings. The process being closed-loop, 99.5 % of the chemicals used during the processing are captured and recycled and virtually no waste is created and only trace amounts escape into the atmosphere. It is considered to be one of the leading methods of producing environmentally friendly regenerated fibers for textiles. Regenerated bamboo fiber made by lyocell process would be labeled as lyocell.

It should be noted that some manufacturing company such as Tanboocel bamboo fiber from Bambrotex claim they produce bamboo fiber with their proprietary closed loop system using the conventional chemicals (NaOH and CS_2) for producing rayon (Bamboo fabric store 2009).

Often, imprecise terminologies (for examples—'*soft, inner pith*' from bamboo and '*inner fibers*' are extracted from bamboo) have been used while describing the bamboo fiber manufacturing process. As seen in the Fig. 3 (Cross-section of bamboo culm), bamboo fiber is *denser on the outer part* of the culm than the *inner part*. Thus it is inappropriate to use the terms like the "*soft*", "*inner pith*", or "*inner fibers*." In fact, inner pith hardly contains any fiber and there is no such delineation as *hard and soft* bamboo fibers remarked Dr. Walter Liese (Wood Biologist, University of Hamburg, Germany) who has done numerous researches on bamboo structure and anatomy and is well recognized for his works worldwide.

Litrax (natural) bamboo fiber

Swiss brand LITRAX, new-founded under Litrax AG Limited, has moved its headquarters to Hong Kong in 2010. It has developed natural bamboo fiber that offers a green alternative for manufacturers looking for producing and marketing certifiable, sustainable bamboo-based apparel and home-fashion textiles (Rodie 2010; http://www.swicofil.com).

Litrax AG founded in 2005 creates sustainable recycled raw materials, functional polymer chips and dye solutions, and performance nano particles for a wide range of industries, from textiles, construction and cosmetics to medical, automotive and bioplastics, according to Felix Stutz, president of Litrax AG Limited. During its initial years, LITRAX promoted bamboo viscose products which were labeled as "viscose," in accordance with EU textile labeling laws. Later LITRAX has developed "greener" method of processing raw bamboo culms into natural bamboo fiber. Litrax's bamboo yarns have been tested by Austria's LENZING for harmful substances and comply with Oeko-Tex® Standard 100 class 1. The unique, biodegradable textile yarn engineered by Litrax is called LITRAX 1 (L1 NATURAL). It is made from bamboo using a high-tech process that includes opening up and refining the culm fiber cells through an enzyme process that separates longitudinal bamboo cells into textile fiber strands ready for further processing through carding and combing.

In order to turn bamboo into a fiber, the culm must first be crushed mechanically. The crushed bamboo strands are then treated with designed enzymes to separate the fibrous material from the glue-like lignin within the plant. This includes a series of precisely timed alternate steam-washing and enzyme treatment cycles, which also act on the vertical and horizontally aligned lignin of the resulting fiber bundles. The final step is to bleach the fibers with hydrogen peroxide. The resulting natural staple length varies between 70 and 150 mm, but can be cut to shorter lengths for processing, i.e. 50 or 38 mm staple (Table 2; Fig. 6). Litrax provides the LITRAX-1 (L1) natural bamboo fibers with a special DNA coding to protect its vertical supply chain and customers. The DNA coding will guarantee that customers are buying the original, authentic bamboo fiber from Litrax. The fiber is strong and durable. Litrax also team up with Lenzing Gruppe, a world leader in man-made cellulose fibers such as lyocell (tencel) and Lenzing modal, and introduce the blend of LITRAX-1 natural bamboo fiber and lyocell. The company develops natural bamboo blended fibers in part to keep the cost down and also to enhance the properties of fibers (Nieder 2009; Rodie 2010; http://www.swifcofil.com; http://www.litrax.com).

Bamboo charcoal fiber

With the development of new processing technologies, nanotechnology is introduced to manufacture bamboo charcoal fiber that improves the performance of textiles. Bamboo can be processed and turned into activated charcoal products that have applications in both traditional and high-tech industries (Tso 2009). Production of the charcoal has been documented as early as 1486 during China's Ming dynasty (1368–1644), when it was used mostly as a fuel source (Sheu 2007). Today, the technology of producing charcoal from bamboo is a highly specialized process where dried bamboo is carbonized in a kiln at very high temperature (800 °C or more, according to the performance desired), reducing it to charcoal (Fig. 7). The bamboo charcoal is sent for further processing to be turned into nano particles. This molecular nano charcoal/carbon powder is then embedded into natural or synthetic polymers to form fiber that are woven or knitted into fabric form (Sheu 2007; China Textile Magazine). It has been reported that the resulting fabric is enhanced with performance qualities such as odor absorption, launch of anions, electromagnetic shielding effectiveness, low surface resistivity, antibacterial and antifungal

Table 2 Technical data of LITRAX L1 bamboo fiber

L1 fiber characteristics	Dimensions
Fineness	5.7D
Fiber dimensions	38 mm from (natural 70–150 mm staple)
Fiber cross section	Kidney shape
Production process	Enzyme retting

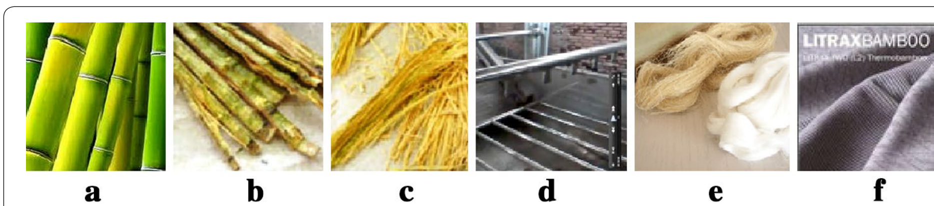

Fig. 6 Mechanical extraction of natural bamboo fiber [with permission from Litrax; trademark registered by Felix B. Stutz, Switzerland]. **a** Bamboo culms. **b** Mechanical splitting of bamboo culms. **c** Rasping of woody parts. **d** Enzyme bath. **e** Gray and bleached natural bamboo fibers. **f** Woven bamboo fabric

Fig. 7 Bamboo charcoal and activated carbon [Courtesy: GE Technology Inc., Taiwan]

property, far infrared ray emission, thermal regulation, prevention of static electricity buildup and so on (Dinsely 2010; Sheu 2007; China Textile Magazine; Kittinaovarat and Suthamnoi 2009; http://www.getek.com.tw; Lin et al. 2011a, b). Not all attributes are proved with sufficient scientific evidence. More scientific research is needed to prove these facts especially, the benefits of health related effect (Tso 2009).

According to the Leslie Jordan Apparel Design and Mfg Co. that produce functional apparel (Leslie Jordan Brand) for sports community the quantity of bamboo charcoal embedded into the textile fibers is usually 2 % or less which is not enough to make a product qualify for general environmental benefit claims besides, being insufficient to offer any antimicrobial properties. Moreover, it is often embedded into the synthetic polymers that are environmentally harmful, thus, negating any environmental benefits it may offer (http://www.lesliejordan.com).

The conception of bamboo fabric: history, patents and modern bamboo textile industry

Although bamboo is well appreciated and extensively used in life, the development of processed bamboo fiber, textile and apparel products are contemporary (Jiang 2011). The use of bamboo fiber for apparel is a 20th century development, initiated by several Chinese company (Smith 2011). According to the information obtained from the website '*ehow.com*,' Beijing University is accredited for developing the first modern bamboo textile process though it is likely that a number of manufacturers too discovered the method nearly the same time, in the early 2000s. The successful extraction of the bamboo fibers and use of modern bleaching chemicals to produce it white, lead to create commercially available bamboo fabrics and successfully market them in America. This statement is confirmed from the website of "Bamboo Clothing Limited, UK," which reported that Beijing University was first to discover the method of making fabric from bamboo in 2001 (Frequently Asked Question: Bamboo Clothing http://www.bambooclothing.co.uk/faqs.html). Subsequently, the techniques of manufacturing bamboo fabrics have been in progress, bringing new innovations in fiber mixing and other processes. The entire process is natural which, retain the organic heritage of the product.

In this context, Waite (2009) reported that the earliest record of US patents pertaining to bamboo textile was made by Philipp Lichtenstadt in 1864 (U.S. patent and Trademark office 2008). This patent described the process for disintegrating the fiber of bamboo, in order to use it in manufacturing cloth, cordage, mats or pulp for paper. The method described is something like as stated below.

1. The joints of bamboo are cut out and then split up into pieces of slivers of an inch in width.
2. The shredded bamboo is pickled in a solution of clear lime-water, nitrate of soda and oxalic acid.
3. The pickled bamboo is removed after 12–24 h in order to be boiled in a solution of soda ash.
4. The material is crushed and then combed, carded, or heckled. It is then spun into cordage, yarn or other forms of manufacturing.

The technique is quite similar to the process use today to manufacture regenerated bamboo cellulose, opined Waite (2009). Waite's statement is confirmed from the websites *greenearthbamboo.com* which informs that there is some interesting historical information on viscose from bamboo and one of the earlier history of patent is for "improvement in preparing fiber from the bamboo." It is a U.S. patent #41,627 and has a date of 16 February 1864 which deals with the process for "disintegrating the fiber of bamboo, so as to use it in manufacturing cordage, mats, cloth, or pulp for paper." There is another U.S. patent #87,295, dated 23 February 1869 which also discusses on the improvement of bamboo fiber preparation. A report from the website *ehow.com* remarked that neither of these patents that occurred in 1864 and 1869, made possible for commercialization of bamboo material, perhaps the demand for this materials were not so high in the locality where bamboo grew and the transportation costs were too expensive. One more patent was issued in 1881 for mixing bamboo fiber with wool and spinning into a yarn, the forerunner of modern bamboo yarn.

The existence documents which seem to be patents by Zhuzhou Cedar Ramie Industrial Co. Ltd, bring up an essentially mechanical process for turning bamboo into fiber to a great extent in the same manner that ramie is made into thread, and their website asserts they are "Natural bamboo fabric." The invention concerning a kind of yarn comprising bamboo fibers and its processing method is also described in the International publication number: WO 2004/076728 (10.09.2004 Gazette 2004/37) where it states that the basic bamboo fibers can be produced by the process disclosed in Chinese patent no. ZL0211138.7 or technical fibers made by reserving factitiously some lignin and pectin. The basic bamboo fibers are fed with emulsified oil and dried, then dewed and again fed with oil to facilitate the spinnability and fortify the dispersion and building property of the original bamboo fiber. After being stacked certain time, they are collected, tidied and drafted twice, made into slivers. Slivers are then combed, drawn, roved and spun into yarn. These bamboo fibers can either be drawn in pure form or mixed with other textile fibers to attain different characteristics. Clothes of different counts were produced from these fibers for spring and summer leisure and the yarn have a high wet permeability performance.

The above mentioned patent exist in the European Patent EP 1598458 A1 (Publication date: 23.11.2005 Bulletin 2005/47); and EP 1598458 B1 (Publication date: 31. Dec. 2008; also published as CN1483872A) and United States Patent 7313906 (Publication date: 01/01/2008) describe natural bamboo yarn (30–100 % by weight of natural bamboo fiber) and its method of production. The yarn is made by spinning either pure natural bamboo fiber or in combined with other textile fibers. In this patent the background information discloses the existence of Chinese patents for "Bamboo rayon" and "Natural bamboo fiber" which are briefly described as follows. The supposed "bamboo fibers" and bamboo textiles in the market at present are exactly products made from viscose fibers produced from bamboo pulp sheets (China Patent No. ZL02113106.6), in which, the characteristic of natural bamboo fibers in such bamboo viscose products has been damaged to a great extent. Hence, the authoritative organizations do not acknowledge those products as natural bamboo textiles. China Patent No. ZL02113180.7 gives an account of the process of manufacturing real natural bamboo fibers that effectively retains the excellent qualities of bamboo fibers. To differentiate it from the bamboo viscose, this fiber is labeled as natural bamboo fiber. The successful extraction of natural bamboo fiber leads to a stable establishment of bamboo textile industry (data.epa.org/publication-server; http://www.freepatentsonline.com). Table 3 present a few patents for manufacturing process of bamboo viscose and natural bamboo fibers.

Bamboo fabric labeling, controversies and regulation

Proponent claims that there are several benefits in the expansion of bamboo textile industry. Nieder (2009) remarked that bamboo's sustainability and marketability starts with the plant itself. It is a natural fiber which means it is renewable. Bamboo plant can be harvested sustainably in 3–5 years cycle unlike a tree forest that takes over 60 years to recover from deforestation. It is one of the fastest growing plant species and can grow and adapt to a wide variety of climatic conditions. As the bamboo root systems stay intact after harvesting, it improves soil quality and helps to rebuild eroded soil (Devi et al. 2007; About Mechanically Processed Bamboo http://www.getgloved.com; Panda 2011). Bamboo is inherently antimicrobial due to a bio-agent called bamboo chinone that the Japanese named "kun," which resists the growth of bacteria on the fiber, so it is hardly ever infected by pathogens or eaten by pests. Bamboo plant does not usually need the use of irrigation; pesticides and herbicides that often required to grow cotton and can grow in diverse climates; as a result, plantations can easily be maintained organic (Devi et al. 2007; Nieder 2009; Yueping et al. 2010; Kothari 2011; Rathod and Kolhatkar 2014).

Even though the above mentioned attributes make bamboo a sustainable and versatile raw material for various end-uses its farming must be properly managed so that the eco-system is not compromised (Waite 2009; Yiping and Henley 2010; Song et al. 2011). According to the assessment of Yiping and Henley (2010), intensive farming practices in China have had negative effects on bamboo biodiversity. Intensive management of bamboo species, increasing the density of bamboo culms per unit of land, effectively creates monoculture bamboo forests. This is accomplished by clearing other vegetative species, besides; performing topsoil tillage annually or twice a year and by applying various quantities of chemical fertilizers and pesticides. In the long-run it leads to a reduction in resilience to external threats such as pests, disease and adverse weather events and a

Table 3 Some patents for manufacturing regenerated bamboo fiber, natural bamboo fiber and its blends

S no.	Patent no.	Publication date/year	Invention	Source
1.	U.S. patent #41,627	16/02/1864	Process for disintegrating the fiber of bamboo	Waite (2009); greenearthbamboo.com; ehow.com
2.	U.S. patent, #87,295	23/02/1869	Improvement of preparing fiber from bamboo	greenearthbamboo.com; ehow.com
3.	International publication no. : WO 2004/076728	10/09/2004	Invention relates to a kind of yarn comprising bamboo fibers and its processing method	http://data.epa.org/publication-server http://www.freepatentsonline.com
4.	China patent no. ZL02113106.6	–	Viscose fibers produced from bamboo pulp sheets	https://www.google.com/patents/EP1598458B1?cl=en http://data.epa.org/publication-server http://www.freepatentsonline.com
5.	China patent no. ZL02111380.7	–	Discloses a process to produce real natural bamboo fibers that can efficiently keep the excellent merits of bamboo fibers. To differentiate the fiber from the rayon one, the fiber is called natural bamboo fiber	https://www.google.com/patents/CN101629322B?cl=en http://data.epa.org/publication-server www.freepatentsonline.com
6.	China patent numbers: ZL03128496.5, 004100464515 and 2005-G-13848	–	China Bambro Textile Co., Ltd use the combination patents to produce bamboo rayon in a process that trapped the chemicals. 73 % of CS2 and 26 % of H2SO4 are recycled. (Brand: Tanboocel bamboo fiber)	China Bambro Textile Co., Ltd—http://www.facebook.com.pages/Bamboo-FabricStore/
7.	European patent EP 1598 458 B1	31/12/2008	Yarn comprising bamboo fibers and its processing method Yarn made by spinning natural bamboo fibers alone or in combination with other fibers	http://www.google.kz/patents/EP1598458B1?cl=en
8.	United States Patent US 7313906 B2	01/01/2008	Method for preparing natural bamboo fiber and yarn prepared by spinning fiber alone or blending with other fibers in a ratio of natural bamboo fibers comprising 30–100 % by weight and other fibers comprising 70 to 0 % by weight	http://www.freepatentsonline.com/7313906.html https://www.google.com/patents/US7313906?dq
9.	CN1600907 B	8/12/2010	Preparation method for fabricating raw bamboo into spinnable bamboo fibers The method includes cutting bamboo into pieces, placing prepared bamboo pieces in pressure container for obtaining coarse fibre, using mildew aqueous solution; rolling and dividing the fibre, bleaching and rinsing; dewatering and adding reinforcer to enhance fibre strength; emulsifying and drying it for obtaining spinnable bamboo fibre	http://www.google.com/patents/CN1600907B?cl=en
10.	CN101629322 B	29/6/2011	Preparation method for processing bamboo into bamboo fiber with spinnability The method comprises of pulse electric shock treatment, high-temperature high-pressure cooking treatment and microorganism bacterial decomposing treatment; the microorganism bacterial comprises *Ceriporiopsis subvermispora* and *Trametes gallica*	https://www.google.com/patents/CN101629322B?cl=en

reduced capacity to erosion control and nutrient cycle, etc., most importantly leading to lower productivity of bamboo forests (Yiping and Henley 2010; Song et al. 2011).

Products made from bamboo are often labeled as "green," "biodegradable" and "100 % bamboo fiber", etc. irrespective of their methods of manufacturing. Besides, many apparel manufacturers often claim that their products made from bamboo have anti-microbial and moisture-transport performance properties. Natural bamboo fabric is soft and possesses high absorbency and antimicrobial properties but the chemical process bamboo rayon destroys this antimicrobial effect (Rodie 2008). However, the topic regarding the antimicrobial properties of natural bamboo fabric has been discussed in details separately.

In this context, Dystar Ecology Solutions reported that so long as bamboo fiber is produced by the viscose process, it will not be more sustainable than conventional rayon method. Both natural bamboo fabrics and bamboo rayon are sold by traders as bamboo fabric in order to cash in on bamboo's present green image. However, in mid-2009, the U.S. Federal Trade Commission (FTC) an autonomous government organization, formed exclusively for protecting consumers from unjust business practices, expressed concerns about the bamboo labeling, forcing companies to list "rayon made from bamboo" when products are not natural bamboo. FTC consequently charged four companies for deceiving their consumers by selling bamboo rayon inappropriately labeled as 100 % natural bamboo products (Rodie 2011).

Regarding FTC's apprehension about the labeling, claims and the environmentally unfriendly processing, China Bambro Textile Co., Ltd., a leading bamboo viscose manufacturing company issued a statement in their Facebook for their customers in 22nd Aug. 2009, about the brand "Tanboocel bamboo fiber" and the process they used, which states, "*it would be incorrect and naive to generalize that all bamboo fiber is processed exactly the same*." The company further remarked that though there are some similarities, there are also dissimilarities between brands and processing methods. Tanboocel bamboo fiber is a regenerated cellulose fiber manufactured by an environmentally friendly high tech process using natural organic bamboo. The process is a combination of their patent nos. ZL03128496.5, 004100464515 and 2005-G-13848. Though the companies use conventional chemicals such as NaOH and CS_2, they are recycled during the process of manufacturing. The bamboo is processed in an enclosed container where 100 % of the chemicals are trapped and held, not allowing to release into the atmosphere. 73 % of CS_2's are recycled, 26 % are recycled into H_2SO_4. Though the process is not completely green, the company makes every effort to make the process as eco-friendly as possible. Tanboocel bamboo fiber conforms to with Oeko-Tex® Standard 100. The company offers third party testing for all its customers to make certain that they are purchasing real bamboo rayon (Bamboo Fabric Store 2009).

By far, almost all available bamboo fabric in market is made using the viscose process. As per FTC guidelines this regenerated cellulose must be labeled as viscose or rayon but not as natural bamboo product. Janice Gerde (US Customs and Border Protection) reviewed research reports dating to early 1930s, using various instrumental approaches and observed that "*once the cellulose is simply cellulose, the source cannot be differentiated*." While testing samples that are labeled as "bamboo" by Fourier Transform Infrared

Spectroscopy (FTIR), the reference spectrum matched that of viscose rayon, with no identifiable variations (Textile Digest 2009).

The FTC Green Guides recommended further amendment in October 2010 to deal with the current changes in the market scenario. In the context of "*green*," "*eco-friendly*," "*renewable materials*" and "*degradable*" products the current Guides states that marketers can make unqualified general *environmental benefit claims* if they can validate all express and implied claims, or else, they should qualify the claim. Regarding *renewable* material, a marketer should be eligible for the claims with precise information about the material, its source and raison d'être for its renewability. Additionally, marketers should qualify renewable material claims if the item is not made entirely with renewable materials (excluding minor, incidental components). A marketer should qualify a *degradable* claim unless it can authenticate that the "entire product will completely decompose within a reasonably short period of time after its disposal." Marketers should not make unethical degradable claims for items destined for landfills, incinerators, or recycling facilities because decomposition will not occur within 1 year (Green Guides: http://www.eenews.net).

Facts regarding the antimicrobial performance of bamboo fiber

Often the debate pertaining to the antibacterial properties of bamboo textile creates a controversy. There are extreme opinions on this issue and only a few examples are mentioned here. Afrin et al. (2012) investigated the antibacterial activity of Australian grown bamboo plant (*Phyllostachys pubescens*). The bamboo extract made using water, dimethyl sulphoxide and dioxane, was compared against gram-negative bacteria, *Escherichia coli* and it was found that the extract made in 20 % dimethyl sulphoxide aqueous solution exhibited weak antibacterial activity while the extract made by 90 % dioxane aqueous solution showed strong antibacterial activity. It was also found that antibacterial agents are located in lignin and not in hemicelluloses or other water soluble chemical components.

Can the antibacterial performance claims be made for bamboo fibers whether natural or regenerated as for the unprocessed fiber from which it is derived? When processed into fiber mechanically it maintains its inherently anti-bacterial properties (Textile Digest 2009; About Mechanically Processed Bamboo http://www.getgloved.com). An eBay Guides "Natural fibers leading the way to textile innovations" published by 'jonano: bamboo and antimicrobial fashions'; on March 10, 2006 and written by Bonnie Siefers, owner/designer, jonano: a division of Sami designs, states that bamboo contains "bamboo kun" which imparts it's natural resistance to bacteria and is molecularly bonded into the cellulose fibers during fabric processing. Hence, bamboo fiber and therefore fabric has natural antimicrobial, anti-odor and resilience-added benefits. To prove his statement he further provided the quantitative antibacterial activity test conducted by 'The China Textile Industrial Testing Center (CTITC)' and 'Japan Textile Inspection Association (JTIA)'. Test performed by CTITC during July, 2003 on 100 % bamboo and cotton fabric against bacteria strain *Staphylococcus aureus* showed that the 100 % bamboo fabric had a 99.8 % antibacterial kill rate which exhibited bacterial growth. Again studies conducted by JTIA, revealed the long term antibacterial efficacy of the fabric. Quantitative test performed on 100 % bamboo fabric that has been industrially washed 50 times against bacteria strain type MRSA Staphylococcus IID 1677 showed that bamboo fabric exhibits greater than 70 % antibacterial efficacy (Results obtained from Shanghai Tenbro Bamboo Textile Ltd) (http://www.ebay.com/gds/). Hardin et al. (2009) examined several specimens of textiles and apparel that were labeled as "bamboo" by a number of online retailers in the years 2006–2007, to assess their characteristics and the authenticity of the claims being made for such fibers and materials. The researchers whose findings were published in "AATCC Review (2009)" reported that those fibers and materials were not made from natural bamboo fibers but were actually regenerated bamboo cellulose. Besides, these materials do not possess antimicrobial properties as claimed by the marketers.

Some studies done by researchers namely Xing and Liu (2004) reported that natural bamboo fibers have bactericidal property against some kinds of bacteria. Conversely, Zhou and Deng (2005) found that natural bamboo fiber does not possess any significant antibacterial effect and albeit it does, the bacteriostatic activity came from the crude and particular micro-structure of the natural bamboo fiber, not from the antibacterial constituents reported Zhou et al. (2008). Li and Dao (2012) investigated the antibacterial property of natural bamboo fiber and compared with the antibacterial property of other textile fibers namely flax, ramie, jute and bamboo viscose and found that natural bamboo fiber does not have natural antibacterial property. According to their findings which were presented on the 'proceeding of the 55th International Convention of Society of Wood Science and Technology, Beijing', the bacteriostatic rate of natural bamboo fiber against all the tested bacteria was zero. In contrast, the bacteriostatic rate of ramie against *Staphylococcus aureus* was over 90 %, and that of bamboo viscose fiber was 75.8 %. They concluded that the antibacterial performance of ramie has been attributed to the constituents of pyrimidine, purine or other antibacterial component and that of bamboo viscose may derive from the use of large amount of chemicals in the manufacturing process. In this regard, further scientific documentations are needed and researches are still going on.

Conclusion

The potential of bamboo plants as a resource for making textile fabrics is very high but it remains largely unrealized. A great deal of attention is focused on bamboo's sustainable attributes. The plant's high growth rate and carbon-absorbing properties makes it the most important plant fibers. Bamboo is a recurring and harvestable plant; it does not require replanting after harvest but will regenerate from its rhizome root structure. However, sustainable cultivation and management of bamboo resources should be top priority for the industries exploiting bamboo resources and importance should be given on practices employed for sustainable bamboo cultivation. Nevertheless, the economic benefits should not be achieved through environmental cost.

Natural bamboo fiber that has been processed mechanically is environmentally friendly but not yet commercially viable or affordable. Moreover, most bamboo fibers and fabrics in the market are produced by viscose process which uses chemical solvents that raise environmental concerns besides being quite different from the original bamboo fibers. While bamboo rayon is a good choice relative to other manmade fiber options, a naturally processed bamboo fiber would be far superior and preferable. Bamboo rayon would have a smooth, silky hand like other rayon. On the contrary, natural bamboo fiber being alike to bast fiber in chemical composition would produce linen like fabric but it might not possess any antibacterial properties as claimed by many. However, regarding moisture-transport performance properties researchers argue that bamboo fiber has a larger moisture regain capability than other natural fibers such as cotton because of its loose structure and existence of disordered non-cellulose substances (Li et al. 2010).

However, bamboo based textiles are not yet achieved their full potential and cleaner production processes are appearing. At present, there are only a small number of manufacturing plants in China that manufacture natural bamboo fiber. Ecologically pioneer textile manufacturing companies like Litrax and Lenzing have already introduced greener manufacturing processes into bamboo textiles. Researches are going on full swings for the development of eco-friendly, natural bamboo fabric. With abundant sources of raw materials, relatively low cost, and unique performance of bamboo fiber it is only a matter of time to develop green and pure bamboo textiles. Further, bamboo textile industry has the potential to provide livelihood for millions of people worldwide.

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