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Sustainable Textiles: the Role of Bamboo and a Comparison of Bamboo Textile Properties

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ABSTRACT

This paper delves into a subset of engineering for sustainable development—the engineering of sustainable textiles using bamboo. In particular, the document explores various questions relating to the subject, including: (1) what constitute sustainable textiles? and (2) what role can bamboo textiles play in sustainable development? The experiments performed attempt to answer two main questions: (1) what are the differences in textile properties between chemically-manufactured and mechanically-manufactured bamboo textiles? and (2) what are the differences in textile properties between two different species of bamboo (Phyllostachys edulis and Bambusa emeiensis)?

We can look at the textile industry through the lens of the triple bottom line of sustainability. At present, the industry has a poor track record for social and environmental concerns. The two most commonly used textile fibres—cotton and polyester—both cause serious environmental problems in their life cycle. This document focuses on one small aspect of the entire field of sustainable textiles—materials made from bio-based renewable resources in the form of bamboo species. The advantages of bamboo as a raw material include its fast renewability, its biodegradability, its efficient space consumption, its low water use, and its organic status. The advantages of bamboo fabric are its very soft feel (chemically-manufactured) or ramie-like feel (mechanically-manufactured), its antimicrobial properties, its moisture wicking capabilities and its anti-static nature. The main constraints of bamboo textiles are current costs and are those inherent in the textile industry: energy, water, and chemical requirements that are involved in manufacturing.

The textile properties examined relate to sustainability: wear and tear (and therefore durability) and moisture wicking (and therefore the need for machine washing and drying). The following are measured for fibre, yarn, and fabric: tear force, breaking force, breaking tenacity, moisture absorption and speed of drying, and surface morphology.

The work is divided into two parts. Part 1 addresses bamboo textiles in the context of sustainable development, providing a historical perspective, sustainable development framework, pertinent information about bamboo as a plant, and the various manufacturing processes, advantages, and constraints of the bamboo textile industry. Part 2 addresses the experimental component with a discussion of limitations, challenges, a system dynamics view of sustainable bamboo textiles, and final recommendations for sustainability within the textile industry.

Keywords: Bamboo, sustainable textiles, renewability, biodegradability

I. Introduction

A. Purpose

This paper deals with bamboo as one of the many possibilities for sustainable forms of textiles. Part 1 provides (1) a brief historical synopsis of bamboo textile engineering, (2) an overview of the sustainable textile industry, (3) an overview of bamboo as a raw product for textiles, and (4) the issues facing the bamboo textile industry. Part 2 provides (1) a description of experiments conducted on bamboo fiber, yarn, and fabric samples, (2) a discussion of results and implications for the bamboo textile industry, and (3) overall conclusions concerning sustainable textiles. The purpose is two-fold: to illustrate bamboo textiles' role in sustainable development and to explore manufacturing and species differences in bamboo textile sustainability-related properties.

B. Bamboo Textile Historical Overview

One of the earliest engineering practices involved the use of scientific principles to extract and manufacture textiles for practical applications. Between 1900 and 1950, total fiber production grew almost three times as fast as world population; from 1950 to 2006, it grew almost four times as fast (Coster 2007). Figure 1.1 shows the world consumption of principal apparel fibers in selected years from 1964 to 1982.

The cotton industry and the creation of bamboo fibre for textiles are historically interconnected. The earliest record of U.S. Patents concerning bamboo textiles was made by Philipp Lichtenstadt in 1864 (US Patent & Trademark Office 2008). This patent outlined the invention of a "new and useful Process for Disintegrating the Fiber of Bamboo, so that it may be used in manufacturing cordage, cloth, mats, or pulp for paper" (Lichtenstadt 1864). The process described is roughly as follows:

1. Take bamboo and cut out the joints.
2. Split up bamboo into pieces of slivers, of roughly half an inch in width.
3. Pickle bamboo in a solution of clear lime-water, nitrate of soda, and oxalic acid.
4. Remove pickled bamboo after twelve to twenty four hours in order to boil in a solution of soda-ash.
5. Crush and devil (comb, card, or heckle) the material.
6. Spin into cordage, yarn, or other forms for manufacturing.

This process is essentially the same one of 2009, in which one type of bamboo fabric is made from regenerated bamboo cellulose. In addition, the date of this discovery and patent is quite revealing—1864.

The English cotton textile industry began in the early 18th century. As the expansion of the industry reached the limits of the pre-existing English domestic market, stagnation ensued. This stagnation was resolved through the exploitation of export opportunities in the transatlantic slave trade from Africa and in the slave-based economy of the Atlantic system (Inikori 1989). After U.S. independence, large areas of the South were turned into cotton plantations, worked by slaves to supply British mills (Farnie and Jeremy 2004). The U.S. Civil War between the North and South lasted from 1861 to 1865. Beginning in 1862, then President Abraham Lincoln issued the Emancipation Proclamation, which called for the freedom of slaves. The freedom of slaves, however, depended on Northern military victory and thus influenced the goals of the Civil War. An end to the slave system would threaten the U.S. cotton industry in the South. It is thus fitting that during this civil war period (whose Northern victory could mean free slaves and thus a downturn in cotton production that benefited from slave labour), a U.S. patent was awarded for other forms of textile materials—namely bamboo.

C. Sustainability and Textiles

We can look at the textile industry through the lens of the triple bottom line of sustainability. That is, the businesses that make up the supply chain must address environmental and social objectives in addition to economic gains. At present, the industry has a poor track record for social and environmental concerns. The major social and environmental impacts are outlined in Figure 1.2 (Allwood, Laursen et al. 2006). These impacts include a contribution to climate change, the release of toxic chemicals, the addition of high waste volumes to landfill, water and space consumption, the use of non-renewable resources, low wages, low labour standards, low collective bargaining power, and a lack of fair trade. There are many wastewater pollution problems associated with the textile industry, including colour, dissolved solids, toxic metals, residual chlorine, and organic pollutants. Figure 1.3 shows a rough guide to the relative environmental impact of textile products throughout three stages in the product life cycle, as outlined in Sustainable Fashion and Textiles: Design Journeys. The figure shows that the 'use' stage for clothing is the most troublesome in terms of impact, while the 'production' stage for carpets is the most troublesome.

Figure 1.2: Unsustainable Impacts of Textile Industry (Allwood, Laursen et al. 2006)

Textile Environmental Impacts	**Textile Social Impacts**
Contribution to climate change -burning fossil fuels for (1) electricity needed in manufacturing, (2) agricultural machinery, (3) laundering (electricity and heating water)	*Low wages* -legal minimum wage sometimes lower than realistic minimum living wage -cycle of poverty
Toxic chemicals -fertilizers and pesticides in agriculture -manufacturing stages such as fibre extraction, pre-treatment, dyeing, printing	*Low labour standards* -poor working conditions (unsafe, long hours) -child labour
Waste volumes -non-biodegradable wastes to landfill -large quantities of wastes because of 'fast fashion'	*Low collective bargaining* -some countries do not grant the right to form unions
Water consumption -extensive water use (such as in cotton crop cultivation) -dramatic changes to local water resources (such as in Aral Sea region)	*Lack of fair trade* -subsidies and regulations prohibit fair trade of textiles
Non-renewable resources -fossil fuels (coal, oil, gas) used as main product in producing synthetic fibres and auxiliary chemicals	
Space consumption -large fields for harvest can take away space needed for food production	

Figure 1.3: A Rough Guide to Relative Impact of Textile Products throughout Life (Fletcher 2008)

	Production	Use	Disposal
Clothing	✔	✔✔✔	✔
Workwear	✔	✔✔✔	✔
Household textiles	✔	✔✔✔	✔
Furnishings	✔✔✔	✔	✔✔
Carpets	✔✔✔	✔	✔✔

The two most commonly used textile fibers—cotton and polyester—both cause serious environmental problems during production (Coster 2007). Cotton accounts for 11% of all pesticides and 25% of all insecticides used each year worldwide (WWF 2005). The growing of cotton consumes very large amounts of water, from 7 to 29 tons per kg of raw cotton fibers (Kalliala and Nousiainen 1999). The global water footprint due to the consumption of cotton products was estimated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as 256 Gm3/yr, roughly 43 m3/yr per capita on average; this means that the consumption of cotton products is roughly 2.6% of the total global water footprint (Chapagain, Hoekstra et al. 2005). Cotton cultivation causes local water shortages, as well as environmental catastrophes such as the shrinking of the Aral Sea in Uzbekistan (Anson and Brocklehurst 2007). It should be noted, however, that there is rain-fed cotton available as well as efficient irrigation techniques that can be employed to save water for irrigation; 99% of cotton in West Africa, for example, is rain-fed (Fletcher 2008). The world fiber demand for cotton increased by 74.4% from 1982 to 2006, with a demand of 14.74 million tons in 1982 and 25.71 million tons in 2006 (Simpson 2007). Cotton textile fibers account for one third of the total raw cotton yield; the by-products of cotton production include cotton seeds (to make oil or to be used as cattle feed), lints (to make viscose fibers), and waste (Kalliala and Nousiainen 1999).

Polyester is manufactured from a non-renewable resource—oil. The manufacturing process uses high levels of energy input, and it generates large amounts of harmful atmospheric emissions, including particulate matter, carbon dioxide, nitrogen oxides, hydrocarbons, sulphur oxides, and carbon monoxide (Anson and Brocklehurst 2007). From 1982 to 2006, the world fiber demand for synthetics increased by 243%, with a demand of 10.15 million tons in 1982 and 34.80 million tons in 2006 (Simpson 2007).

Organic textiles make up a part of sustainable textile criteria that revolve around the cultivation of the raw material under organic conditions. Organic production is based on a system of farming that maintains and replenishes soil fertility without the use of toxic and persistent pesticides and fertilizers and genetically modified seed (GreenBiz 2006). The soils of organic crops must have been kept free from toxic and persistent pesticides and fertilizers for at least three years (Coster 2007). Organic cotton is more costly to grow, since there are additional costs at each stage of processing (Coster 2007). Nevertheless, organic cotton has recently gained momentum as consumer pressure for eco-friendly products mounts. Global retail sales of organic cotton products increased by 85%, from US$583 million in 2005 to US$1.1 billion in 2006 (Marquardt 2007). The Organic Exchange expects global organic cotton product sales increase to $2.6 billion by the end of 2008 (GreenBiz 2006).

There is not a universally accepted definition of sustainable textiles. Many considerations and value judgments come into play when applying sustainability concepts to any industry. One central component of sustainable textiles is the idea of cradle to cradle processes. According to Michael Braungart, founder of the EPEA, there are three basic principles of Cradle to Cradle Design that model the principles of nature: waste equals food, use current solar income, and celebrate diversity (Braungart 2006). Cradle to Cradle Design provides a framework for creating products and industrial systems that turn materials into nutrients by (1) enabling the flow in the cyclical processes of nature and (2) enabling the circulation of valuable materials in closed loop production, use, recovery and reproduction (Braungart 2006).

Figure 1.4a expresses the concepts of sustainable textiles by listing five questions that should be answered when determining whether a textile is sustainable. Each category lists measurable impacts and/or key performance criteria. For simplicity, items on the list are only listed once under what is deemed as the most relevant category, though the impacts will be relevant across categories. Many of these criteria are used in third-party sustainable textile and organic textile certification bodies. The Institute for Market Transformation to Sustainability (MTS) has developed the Unified Sustainable Textile Standard. GreenBlue, a non-profit spin-off from McDonough Braungart Design Chemistry (MBDC), is developing a Sustainable Textile Standard (STS) (GreenBlue 2008). Figure 1.4b shows a list of sustainable and organic textile certification schemes.

D. Engineering for Sustainable Development and Textiles

The engineering of textiles is much like any engineering endeavour. **Figure 1.5** shows the three tradeoffs traditionally involved in the deliverability of engineering projects; it includes the implications for textile manufacturing. The primary concerns in the deliverability of engineering solutions are normally *quality, time, and costs*. Finding an appropriate balance is thus a challenge for many projects. Here, the three considerations occur at every stage in the life cycle of a textile product, and they are interlinked. The time to market includes all business-to-business markets that make up the textile chain (time from raw product to factory, time from factory to end-use design and assembly, time from end-use design and assembly to final customer). The quality concerns involve the quality of each input (such as raw cotton and weaving technique) to achieve the desired output (such as a cotton t-shirt). The quality considerations may involve the incorporation of standards such as ISO 9001, as well as subjective qualities such as fabric hand. Fabric hand is the assessment of a textile obtained from the sense of touch; it deals with fabric judgments such as roughness, smoothness, harshness, pliability, thickness, etc. (Behery 2005). Unlike some fields of engineering, there is room for both low quality (generally low costs, quick processing time) textiles, as well as high quality (generally high costs, long processing time) textiles.

Figure 1.4a: Criteria for Sustainable Textiles

	For materials, processes, inputs, outputs (each stage in product life cycle)...				
Measurable Impacts/ Performance Criteria	**Safe for human and ecological health?**	**Material (bio-based/recycled)?**	**Energy (renewable/efficient)?**	**Company/Facility (socially responsible)?**	**Cradle to Cradle (reclamation/reuse)?**
	Acidification	Fossil Fuel Depletion	Climate Change	Accountability	Landfill Quantity
	Air Pollution	✓**Renewable Source**	Energy Efficiency	Child Labour	Biodegradability
	Ecological Toxicity	Recycled Source	Renewable Energy	Equity	Reusability
	Eutrophication	✓**Space Consumption**		Fair Wages	Closed-loop Manufacturing
	Habitat Alteration			Full Cost Accounting	Recycled Content
	Human Toxicity			Transparency	
	Ozone Depletion				
	Photochemical Smog				
	Solid and Hazardous Waste				
	Water Quantity & Effluent Quality				

✓: Key component of bamboo textile advantages

Figure 1.4b: Selected Sustainable Textile Certifications

Governing Body	Name of Standard	Symbol(s)
GreenBlue	Sustainable Textile Standard (STS)	Work in progress
Institute for Market Transformation to Sustainability (MTS)	SMART© Sustainable Textile Standard	
EKO	EKO Sustainable Textile (GOTS), Control Union	
Institute for Marketecology (IMO)	OE, SA, IVN, OTA, Demeter, (GOTS)	Presents symbols of other certification bodies
Oregon Tilth	(GOTS)	
Soil Association (SA) Certification	Soil Association Organic Standard (GOTS), Control Union	
Ethical and Environmental Certification Institute (ICEA)	Organic Textiles Certification (GOTS)	
OneCert	(GOTS)	
KRAV	KRAV Certification (GOTS), Control Union	
Organic Exchange (OE)	OE Blended OE 100 Standards	
Demeter International	Demeter Certification Biodynamic Agriculture Certification	
Oeko-Tex Association	Oeko-Tex Standard 100 Oeko-Tex Standard 1000 Oeko-Tex Standard 100plus	

Figure 1.5: Traditional Tradeoffs in Textile Engineering

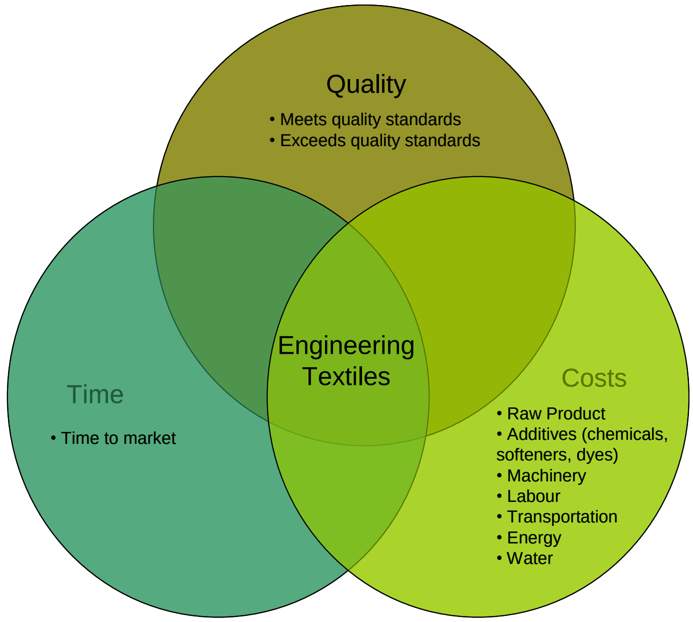
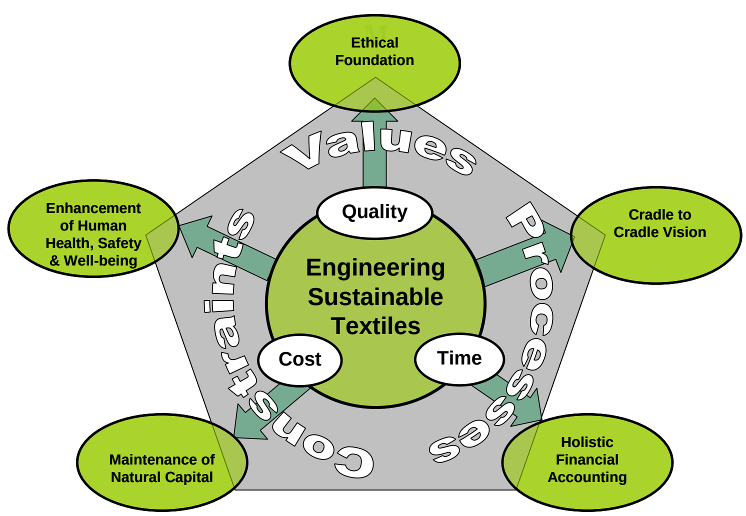


Figure 1.6, inspired by a figure connecting civil engineering and sustainable development by the Centre for Sustainable Development at Cambridge University (Fenner, Ainger et al. 2006), shows how the system of textiles must move beyond the usual quality, cost, and time considerations to incorporate five aspects that make it a sustainable entity. These considerations address the five questions delineated in **Figure 1.4**. An ethical foundation involves social and professional codes of ethics and value judgments. This should be the basis of sustainability considerations throughout the product's life cycle. Ensuring and enhancing human health, safety, and social well being, maintaining natural capital through materials choice and manufacturing processes, taking into account the environmental and social impacts of the textile when costing for the market, and using an entire life cycle, are all aspects that must be considered for sound sustainable textile engineering.

Figure 1.6: Five-point Pentagonal Sustainability Considerations in Textile Engineering

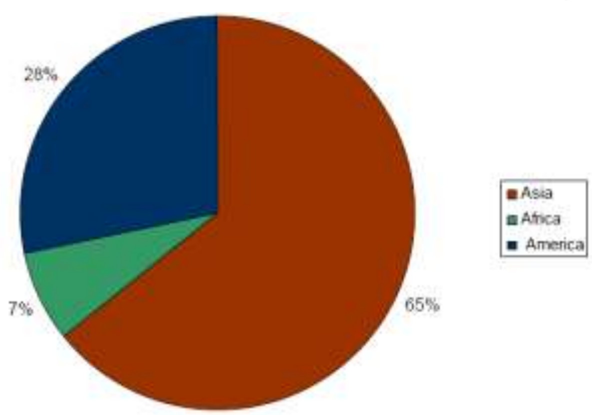


II. Bamboo the Plant

A. Bamboo Introduction

This section will detail bamboo properties, biodiversity, uses, and ownership. Bamboo has served as an important crop for centuries. It is known as “the friend of the people” in China, “the wood of the poor” in India, and “the brother” in Vietnam (Farrelly 1984). There are over 1500 species of bamboo worldwide, but only about 50 are commercially involved in trade (Hunter 2003). The bamboo plant supports an international trade worth over 2.5 billion USD (Hunter 2003); there are also over 2.5 billion people (38% of world population) involved in its trade or use (Bystriakova 2003). In 2003, the bamboo forest area was around 22 million ha, and it has been increasing at a speed of 3% per year; China hosts a bamboo forest area of 7.2 million ha (4.2 million ha of plantations and 3 million ha of natural stands in mountain regions) (Zehui 2003). **Figure 2.1** shows the contribution of world bamboo resources by continent.

Figure 2.1: Contribution of World Bamboo Resources by Continent (FAO

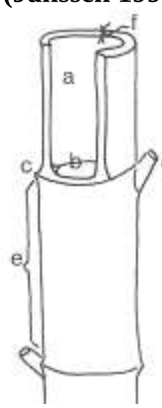


2007)

B. Bamboo Properties

Bamboos are tapered, cylindrically shaped grasses with mostly hollow forms (though some species are solid cylinders). Bamboos normally have a final height of 20-25 meters (Magel, Kruse et al. 2005). The biomass is produced within a growing season of about 3-5 months. Bamboo is 26-43% cellulose, 21-31% lignin, and 15-26% hemicelluloses (Mwaikambo 2006). Theoretically, the mechanical properties of bamboos mainly depend on the (1) species, (2) age, (3) moisture content, (4) position along the culm (top or bottom), and (5) positions of the nodes and the internodes (Janssen 1995). **Figure 2.2** shows a diagram of the parts of a bamboo culm. The culm is the main axis, or stem, of the bamboo. The macro-physical structure, as seen in **Figure 2.2**, can be divided into the (a) cavity, (b) diaphragm, (c) node, (d) branch, (e) internode, and (f) wall.

Figure 2.2: Structure of Bamboo Culm (Janssen 1995)



C. Ecology and Biodiversity of Bamboo

Bamboo is native to every continent except Antarctica and Europe (where it has been introduced); it endures both rich and poor soils, temperatures varying from -20°C to 47°C, as well as rainfall ranging from 76.2 cm to 635 cm per year (Farrelly 1984). **Figure 2.3** shows the natural global bamboo distribution.

Figure 2.3: Global Woody Bamboo Distribution (Bambuseae) (Vogel and Gardner 2005)

Bamboos grow in two main patterns: (1) clumps, or Pachymorph rhizomes (sympodial bamboos), and (2) running, or Leptomorph rhizomes (monopodial bamboos) (Janssen 1995). Harvesting for both patterns follows the simple techniques of clear cutting, in which large areas of bamboo forest are removed at determined intervals, or selective cutting, in which a few culms are removed while leaving the rest intact. From practice, a combination of both methods has proven best (Farrelly 1984).

Some bamboo species undergo simultaneous flowering followed by complete death of the entire population in cycles of 20-120 years (Bystriakova 2003). This “gregarious flowering” may occur over small or large areas. It is important to understand the phenomenon of gregarious flowering in order to sustainably manage the plant for end-uses. Despite past and current studies of bamboo behaviour, there is not yet a universally accepted cause of gregarious flowering.

Since bamboo is a grass and not a timber product, many places do not keep track of its biodiversity and quantity. Unfortunately, there is still poor knowledge of bamboo identification and distribution (Bystriakova 2003). The International Union for Conservation of Nature (IUCN) publishes a list of threatened and endangered plant species. This is important data for the sustainable management of bamboo forests. Even though the renewable and fast-growing properties of bamboo make it ideal as a sustainable material for various end-uses, its cultivation must be well managed so that the ecosystem is not compromised. If the ecosystem is not properly managed, the ability to use bamboos in the future could also be negatively impacted, as seen with unsustainable logging.

D. Bamboo uses and functions

There are over 1500 documented uses for bamboos (Bystriakova 2003), which include flooring, furniture, musical instruments, crafts, scaffolding, pulp and paper making, sports equipment such as skateboards, textiles, food in the form of young bamboo shoots, medicinal uses, and energy. Bamboo can address the global challenges of ecological and livelihood security. By generating employment through bamboo cultivation and manufacturing, and by providing fertility, stabilisation, water pollution treatment, and carbon sequestration to the environment, bamboo plays an important role in sustainable development (Lin, Reijenga et al. 2003). Bamboo’s potential contribution to poverty alleviation has not yet been realized in the Americas and Africa, where it is still seen by many as a weed (FAO 2007). **Figure 2.4** shows bamboo and rattan export and import statistics from the United Nations Commodity Trade Statistics Database (UN Comtrade) in 2007.

Figure 2.4: 2007 Bamboo and Rattan Export and Import COMTRADE Data

Commodities	HS Code	Exports	Imports
Bamboo shoots prepared/preserved otherwise than by vinegar/acetic acid, not frozen	200591	$194,567,362	$82,939,835
Basketwork, wickerwork & other articles, made directly to shape from bamboo	460211	$226,002,876	$177,302,954
Furniture of bamboo/rattan	940381	$131,994,283	$239,242,304
Mats, matting & screens of vegetable materials, of bamboo	460121	$213,096,580	$72,389,588
Plywood, veneered panels & similar laminated wood, of bamboo	441210	$162,569,847	$137,723,013
Pulps of fibres derived from recovered (waste & scrap) paper/paperboard/of other cellulosic material, of bamboo	470630	$320,029	$16,790,529
Seats of bamboo/rattan	940151	$52,742,846	$223,721,027
Trays, dishes, plates, cups & the like, of paper/paperboard, of bamboo	482361	$44,376,201	$69,210,664
Wood charcoal of bamboo (including shell/nut charcoal), whether/not agglomerated	440210	$11,059,173	$21,467,358
Plaits & similar products of plaiting materials whether/not assembled into strips; plaiting materials, plaits & similar products of plaiting materials, bound together in parallel strands/woven, in sheet form, whether/not being finished articles, of bamboo	460192	$18,760,086	$27,702,740

Data was assembled from the UN Comtrade Database

E. Bamboo Forest Ownership

There is a growing trend towards private and local ownership of bamboo resources. Bamboo forest ownership has traditionally been held by government, but many countries are shifting the model to privatisation. The Food and Agriculture Organisation (FAO) led a study on bamboo ownership (FAO 2007). In 2000, one-third of the bamboo forests were classified as private (land owned by individuals, families, private cooperatives, corporations, industries, religious and educational institutions, pension or investment funds, and other private institutions). This is in sharp contrast to the fact that no bamboo resources were classified as private in 1990.

E. Conclusion

Bamboo has much to offer in its raw form. Its geographical range is wide-spread, and its uses are numerous. As a grass, it has a diverse network of growth patterns and can flourish in harsh climates. Nevertheless, many animal and plant species depend on bamboo, and there are now bamboo species threatened by extinction. It will be important to develop a better understanding of bamboo biodiversity and inhibit the development of products from at-risk species. Bamboo forest area is increasing each year, and the trend for ownership is privatisation. Policy issues such as forest/farm management are critical to developing sustainable textiles and other products from bamboo.

III. Bamboo the Textile

A. Bamboo Textile Introduction

Textiles made from bamboo address the aim of sustainable development by utilizing a renewable resource to make clothes and other textile applications. Bamboo fabric is widely available in China, India, and Japan. Philadelphia-based *Footprint* provides socks made of 95% bamboo to offer “antibacterial and moisture-wicking properties and superior comfort” (TextileWorld 2008). London-based *Bamboo Clothing* supplies a range of bamboo clothes for men and women that stay naturally cooler in the summer and hotter in the winter, like Murino wool (Bamboo Clothing 2008). In 2006, roughly 10 million USD worth of bamboo textiles were sold in the U.S. and 50 million USD worth worldwide (Durst 2006). There are over 200 retail stores carrying bamboo textile products in the United States alone. The stores range from small, high-end designer clothing to mega-chains such as Wal-Mart and Bed, Bath & Beyond. This section covers details about bamboo textiles—the principal constituent, manufacturing processes, the advantages, and the disadvantages.

B. Bamboo—A Cellulose Bast Fibre

Cellulose is the most important component of the bamboo for textile purposes. Whether the cellulose is regenerated (chemical bamboo/viscose), or mechanically and biologically extracted from the stem (mechanical bamboo), bamboo textiles are made from bast fibres of cellulose. Bast fibre bundles are made of elongated thick-walled cells joined together both end to end and side by side and arranged in bundles along the length of the stem (Mwaikambo 2006). The bamboo culm is aligned with cellulose fibres along its length, carrying nutrients between the leaves and roots (Mwaikambo 2006).

Lignin is another important constituent of bamboo. There are two major schools of thought on the lignification of bamboo with respect to maturation. Some researchers have concluded that lignification *is completed in one growing season* (Lybeer and Koch 2005), while other researchers have found an increasing lignin content during maturation in later years (Lin, He et al. 2002). In either case, an increase in lignin translates to a decrease in cellulose content. Since cellulose is the primary component of bamboo textiles, younger culms may be better suited to textile applications, if lignification continues beyond the first growth season. Bamboo textiles are usually sourced from bamboo aged from three to five years.

C. Bamboo Textile Manufacturing Processes

There are two main manufacturing processes used to make textiles from bamboo—chemical processing and mechanical processing. Both methods engender negative impacts on the environment and human health, and there is room for improvement through closed-loop manufacturing strategies, more efficient equipment, and the use of more eco-friendly compounds to extract fibres.

The chemical process to make bamboo fibre and yarn essentially follows the rayon/viscose manufacturing process as follows:

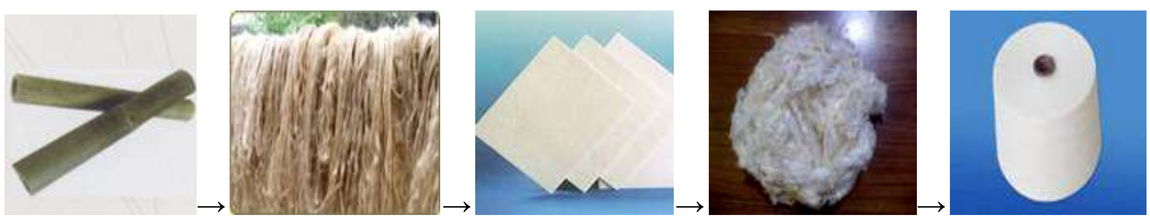
1. Leaves and inner fibres are removed from bamboo.
2. Leaves (in some cases) and inner fibres are crushed together to make bamboo cellulose.
3. Bamboo cellulose is soaked in a solution of 18% sodium hydroxide, NaOH, (also known as lye or caustic soda) at 20-25°C for 1-3 hours.
4. Bamboo cellulose and NaOH mixture is pressed to remove excess NaOH, crushed by a grinder, and left to dry for 24 hours.
5. Carbon disulfide, CS_2, is added to the mixture.

6. Bamboo cellulose, NaOH and CS_2 mixture is decompressed to remove CS_2, resulting in cellulose sodium xanthogenate.
7. A diluted solution of NaOH is added to the cellulose sodium xanthogenate, which dissolves it into a viscose solution.
8. The viscose is forced through spinneret nozzles into a large container of a diluted sulfuric acid solution, H_2SO_4 (that hardens the viscose and reconverts it to cellulose bamboo fibre).
9. The bamboo fibres are spun into yarns (to be woven or knitted).

For chemically-manufactured bamboo, the end-products of the main manufacturing steps used by Suzhou Shengzhu Household Co. are presented in **Figure 3.1**. In general, viscose fibre is made up of α cellulose (80%), hemicelluloses (15%), and pentosans (3.5%); other components include resin, soaps, sulphur, ash, and lignin-like substances (Sadov, Korchagin et al. 1979).

Figure 3.1: Simplified Bamboo Viscose Manufacturing Steps (Lin 2008)

From left to right: (1) raw bamboo is gathered, (2) bamboo is crushed and processed into thick pulp (raw chemical bamboo fibre) (Pure Fiber 2008), (3) bamboo is further processed into fine pulp sheets, (4) bamboo pulp is manufactured into fibre through wet spinning process, (5) bamboo fibres are spun into yarn



The mechanical process for making what some manufactures call “original,” “bio,” and “natural” bamboo fibre and yarn uses a ramie-like method as follows:

1. Bamboo culms are cut into strips.
2. Bamboo strips are boiled to loosen and remove inner fibres.
3. Natural enzymes are added to break the bamboo into a soft mass.
4. Individual fibres are combed out.
5. Fibres are spun into yarn.

For mechanically-manufactured bamboo fibre, the manufacturing steps and end-products of the main steps used by Suzhou Shengzhu Household Co. are presented in **Figure 3.2a** and **3.2b**. The mechanical bamboo fibre is similar to ramie (a flowering plant with the scientific name *Boehmeria nivea)*. The main chemical composition of the fibre is cellulose, hemicellulose, and lignin (90% of dry weight); other components are protein, fat, pectin, tannins, pigment, and ash (Lin 2008).

Figure 3.2a: Simplified Mechanically-Manufactured Bamboo Fibre Process (Lin 2008)

Left to right: (1) raw bamboo gathered, (2) bamboo braised into strips, (3) bamboo steamed and crushed, (4) biological enzymes added for degumming, and (5) bamboo fibre carded and spun into yarn

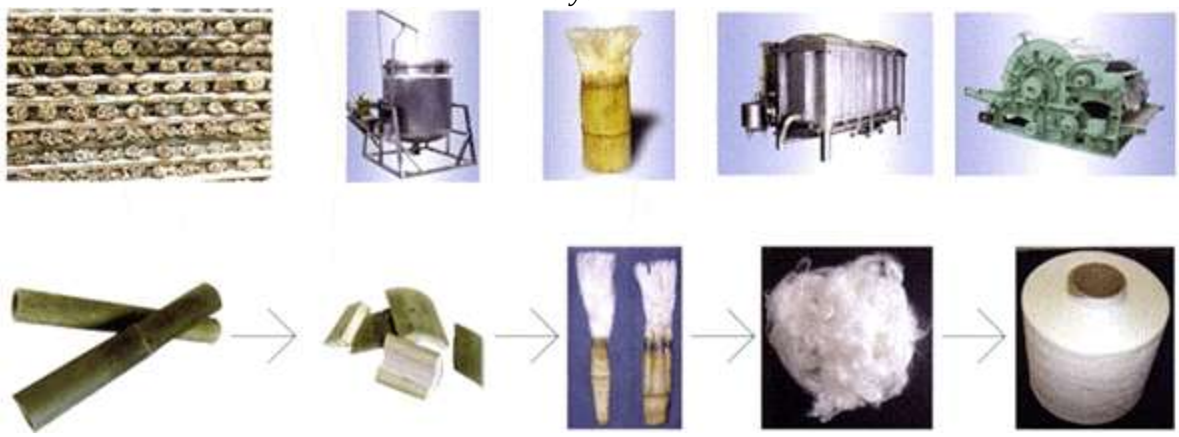


Figure 3.2b: Mechanical Bamboo Fibre Manufacturing (Lin 2008)

Left and centre photographs: cut bamboo culm boiled to remove inner fibres; Right photograph, from left to right: (1) post-boiled inner bamboo strips, (2) crushed bamboo fibres, (3) bamboo fiber after enzyme added, (4) combed/carded bamboo fibre

There is also a third category of bamboo fibre which falls under chemically-manufactured bamboo fibre—bamboo charcoal fibre. This fibre is made from nanoparticles of bamboo charcoal; the charcoal powder is blended into the liquid of viscose spinning (Lin 2008). However, the exploration and analysis of bamboo charcoal fibre is beyond the scope of this paper.

D. Bamboo Textile Advantages

The advantages of bamboo textiles can be divided into two main categories: (1) those derived from the use of the plant itself and (2) those derived from fabric properties given by the plant. The advantages of using bamboo as a raw material for textiles include its renewability, its biodegradability, its efficient space consumption, its low water use, its organic status, and its carbon sequestering abilities given a sustainably managed bamboo forest.

Bamboo is a grass and thus does not need replanting as other textile raw products (such as cotton or hemp). Bamboo replaces 30% of its biomass in a year, which is quite considerable compared to 3-5% biomass replacement by forest trees (Steinfeld 2001). Bamboo is the fastest growing plant in the world—it can grow a meter or more per day (Fu 2001). Moso bamboo can grow up to 1.19 m in 24 hours and 24 m high in 40-50 days (Fu 2001). This growth occurs naturally when sustained by rain water, obviating the need for irrigation or chemical pesticides and fertilizers. Bamboo sequesters more than five tons of carbon dioxide per acre (which is more than five times what an equivalent group of trees would absorb), while releasing thirty-five percent more oxygen to the atmosphere (Knight 2007). Bamboo yields 50 times as much fibre per acre as cotton (more than 20 times as much per hectare) (Durst 2006). Bamboo textiles provide quicker harvest readiness compared with 15-year old trees that are used to make lyocell, rayon, and other regenerated fibres (Rodie 2007).

Many properties of the bamboo plant are said to be appreciated in the processed textile. Since the bamboo is naturally hollow in the horizontal cross section, the fibre shows abundant gaps. These gaps can absorb and evaporate human skin moisture just as the bamboo plant absorbs and evaporates moisture in the ecosystem (INBAR 2004). The fact that bamboo does not require the use of pesticides is partly due to a natural antifungal and antibacterial agent, known as bamboo kun (or kunh). The same natural substance that protects bamboo growing in the field functions in the spun bamboo fibres (FAO 2007). The bamboo kun in bamboo stops odour-producing bacteria from growing and spreading in the textile. A quantitative antibacterial test was performed by the China Industrial Testing Centre in 2003 in which 100% bamboo fabric was tested with the bacterial strain type *Staphylococcus aureus*; after a 24 hour incubation period, the bamboo fabric showed a 99.8 % antibacterial destroy rate (FAO 2007).

There are several advantages of bamboo fabric such as its soft feel comparable to cashmere (chemically-manufactured) or ramie-like feel (mechanically-manufactured), its antimicrobial properties derived from the bamboo plant, its quick moisture absorption and drying capabilities, its ability to stay warm in cool weather and cool in warm weather, its ultraviolet protection, and its anti-static nature. The properties of bamboo fabric are those listed according to their manufacturers. There have been, however, disputes as to the reliability of manufacturing claims. In addition, some manufacturers claim that some bamboo properties are available in mechanically manufactured bamboo but not chemically manufactured bamboo viscose. For example, Litrax (headquartered in Switzerland with worldwide production facilities), has stated that antibacterial effects have only been found in mechanically manufactured bamboo using enzymes as opposed to bamboo viscose (Litrax 2008). At the 235th national meeting of the American Chemical Society, Appidi and Sarkar from Colorado State University stated that raw bamboo fabric "lets almost all damaging UV radiation pass through and reach the skin" (Dylewski 2008). Yet, BambroTex, a bamboo viscose manufacturer in China, found that 100% bamboo fabric did not let UV rays through when a UV textile test was completed using test method GB/T18830-2002 (BambroTex 2008).

The antimicrobial nature of bamboo textiles is indirectly explored in this paper. Clothing textiles are always in contact with microorganisms, such as bacteria, fungi, algae, and viruses, whether these microorganisms originate from the person wearing the textiles or from the external environment. Microorganisms can cause various problems such as health concerns (infection, disease, physical irritation, toxic responses) and general fabric discomforts (fabric rotting, staining, unpleasant odours) (Teufel and Redl 2006). The assessment of microbial communities in textiles involves various complexities and difficulties. One can group test procedures in five main categories as follows: agar diffusion tests, challenge tests, soil burial tests, humidity chamber tests, and fouling tests (Ramachandran, Rajendrakumar et al. 2003). Each test has its advantages and disadvantages, and researchers are exploring various amendments to established test procedures. It is important to highlight that the term antimicrobial is very broad, generally referring to a negative effect on the vitality of microorganisms

(Ramachandran, Rajendrakumar et al. 2004). Often, the debate as to whether bamboo textiles are antimicrobial actually covers only one type of antimicrobial property—bactericidal. The term "cidal" indicates significant destruction of microbes, while the term "static," as in bacteriostatic, indicates the inhibition of microbial growth (Ramachandran, Rajendrakumar et al. 2004). Regardless of this differentiation, it is clear that when ideal growth conditions are present, microbes will rapidly multiply and can then cause problems; most ideal growth conditions occur at high moisture, which is normally found under increased production of sweat (Teufel and Redl 2006). Thus, tests which analyse the moisture properties of textiles are pertinent to its microbial activity. In, Part 2 of this paper, the results of a moisture experiment for bamboo textiles will be presented.

E. Bamboo Textile Constraints and Market Analysis

The main constraints of bamboo textiles are those inherent in the textile industry: various energy, water, and chemical requirements that can be involved in its manufacturing. One constraint of bamboo, though not large, is the current cost/price. A bamboo t-shirt costs about $7 and is softer, easier to dye, and better at fighting odour than cotton (Durst 2006). According to Rich Delano who owns a bamboo textile company, bamboo fabric is "not as cheap as cotton yet, but it will be" (Durst 2006). **Figure 3.3** shows fibre prices of cotton, polyester, and wool from December 2007, as well as an organic cotton fibre price from June 2008. **Figure 3.4a** and **3.4b** show the price of chemical bamboo (viscose) and mechanical bamboo fibres. The cheapest fibre is polyester, followed by cotton. Organic cotton ranks third in terms of least cost; bamboo viscose fibre is at least 30% more expensive than the most pricey, highest quality organic cotton. Mechanical bamboo fibre is more expensive than wool.

Figure 3.3: Fibre Cost Trends from December 2007 for Cotton, Polyester and Wool (Simpson 2007)

Fibre	**Price (USD)**
Cotton[a]	$1.56/kg
Organic Cotton[b]	$1.76 - $3.00/kg
Polyester[c]	$1.41/kg
Wool[d]	$9.33/kg

a: 70.55 US cents per pound
b: Estimate from Organic Cotton Exchange (Ferrigno 2008)
c: On average, 1.41 USD per kg
d: 10.02 Australian Dollars per kg

Figure 3.4a: Chemical Bamboo (Viscose) Costs at Various Stages (Shuang 2008)

Fibre	**Price (USD)**
Raw chemical bamboo fibre (thick pulp)[a]	$5.71/kg
Chemical bamboo fibre (fine pulp, ready for spinning)[b]	$7.14/kg
Chemical bamboo fabric[c]	$7.14/m

a: 40 Yuan/kg
b: 50 Yuan/kg
c: 50 Yuan/m

Figure 3.4b: Chemical Bamboo Fibre and Mechanical Bamboo Fibre Costs (according to manufacturer) (Lin 2008)

Fibre	Price (USD)
Chemical bamboo fibre	$3.9 - $4.3/kg
Original/Bio/Natural/Mechanical bamboo fibre	$10.90/kg

Figure **3.5** summarises the advantages and drawbacks of bamboo textiles.

Figure 3.5: Summary of Advantages and Disadvantages of Bamboo Textiles

Advantages	Disadvantages
Based on raw plant	
No need for replanting	Manufacturing processes (energy, water, chemicals)
Growth sustained by rain-fed water	
No need for chemical fertilizers or pesticides	More costly than organic cotton
High yield for area (space consumption)	
Fast growth	
Biodegradable	
Extrapolated from raw plant functions	
Moisture wicking (absorption and evaporation)	
Antimicrobial	
Soft Feel (chemical bamboo)	
Breathability	
UV Protection	
Anti-Static	
Warm in Winter, Cool in Summer	

F. Conclusion

Bamboo textiles show clear advantages in the realm of sustainable development. There are a few mainstream manufacturing techniques that are currently used for the creation of bamboo textiles. These techniques are inspired by already-existing textile technology, as well as emerging nanotechnology. The drawbacks of bamboo textiles currently on the market are those inherent in the industry; these issues, such as energy, water, and chemical use, could be addressed through closed-loop manufacturing, eco-chemicals, water recycling, and economic tools (full pricing). Provided in this section was an overview of bamboo textiles and the two manufacturing methods concerned in the experimental analysis (covered in Part 2).

References

AATCC (2008). A Glossary of AATCC Standard Terminology. Research Triangle Park, American Association of Textile Chemists and Colorists.

Adams, W. (2007). "Smart Fabrics and Intelligent Textiles in the UK: Seven Companies at the Forefront of Innovation." Textile Outlook International **May-June**(129).

Ahmad, M. and F. A. Kamke (2005). "Analysis of Calcutta bamboo for structural composite materials: physical and mechanical properties." Journal of the International Academy of Wood Science **39**(6).

Allwood, J. M., S. E. Laursen, et al. (2006). Well Dressed? The present and future sustainability of clothing and textiles in the United Kingdom. Cambridge, University of Cambridge Institute for Manufacturing.

AmericanBambooSociety. (2007). Species Source List. http://americanbamboo.org/SpeciesSourceList.html. April 2007.

Anson, R. and G. Brocklehurst (2007). "Trends in World Textile and Clothing Trade." Textile Outlook International **November-December 2007**(132).

ASTM (2003). Annual Book of ASTM Standards Section 7: Textiles. West Conshohocken, American Society for Testing and Materials.

BambooClothing. (2008). Bam Bamboo Clothing Frequently Asked Questions. http://www.bambooclothing.co.uk/faqs.html. May 12, 2008.

BambroTex. (2008). Bamboo Nature Anti-U.V. http://www.bambrotex.com/second/anti_UV.htm. May 16, 2008.

Behery, H. (2005). Effect of Mechanical and Physical Properties on Fabric Hand. Boca Raton, Woodhead.

Bismarck, A., A. Baltazar-y-Jimenez, et al. (2006). "Green composites as panacea? Socio-economic aspects of green materials." Environment, Development and Sustainability **8**: 445–463.

Braungart, M. (2006). Cradle to Cradle. Textiles: The Quarterly Magazine of The Textile Institute. **1**.

Chapagain, A. K., A. Y. Hoekstra, et al. (2005). The Water Footprint of Cotton Consumption. Value of Water Research Report Series No. 18. Delft, UNESCO-IHE**:** 39.

Coster, J. D. (2007). "Green Textiles and Apparel: Environmental Impact and Strategies for Improvement." Textile Outlook International **November-December 2007**(132).

Durst, S. (2006). The Panda Food in Your Pants. Business 2.0. **7**.

Dylewski, A. (2008). A Boost for Bamboo-based Blouses and Blankets. http://www.newswise.com/articles/view/539088/. May 12, 2008.

EPEA. (2001). Eco-Intelligent Polyester Fabric: The First Technical Nutrient. www.epea.com/documents/EPEAProductCase_VictorInnovatex.pdf. April 20, 2008.

FAO. (2007). Extent and Characteristics of Bamboo Resources. ftp://ftp.fao.org/docrep/fao/010/a1243e/a1243e03.pdf. April 20, 2008.

FAO (2007). The Versatile Bamboo. Non-wood News 14. Rome, Food and Agriculture Organization.

Farnie, D. A. and D. J. Jeremy (2004). The fibre that changed the world: the cotton industry in international perspective, 1600-1900s. Oxford, Oxford University Press.

Farrelly, D. (1984). The Book of Bamboo: A comprehensive guide to this remarkable plant, its uses, and its history. London, Thames and Hudson.

Fenner, R. A., C. M. Ainger, et al. (2006). "Widening engineering horizons: addressing the complexity of sustainable development." Engineering Sustainability Journal **159 ES4**: 145–154.

Ferrigno, S. (2006). Organic Cotton Fiber Report. www.organicexchange.org/Documents/fiber_2006.pdf. April 29, 2008.

Ferrigno, S. (2008). Organic Cotton Fibre Price. Kent**:** Organic Exchange Farm Development Programme.

Fletcher, K. (2008). Sustainable Fashion & Textiles: Design Journeys. London, Earthscan.

Fu, J. (2000). "Moso Bamboo" in China. ABS Magazine. **21**.

Fu, J. (2001). Chinese Moso Bamboo: Its Importance. ABS Magazine. **22:** 5.

Goswami, B. C., J. G. Martindale, et al. (1978). Textile Yarns: Technology, Structure, and Applications. London, John Wiley & Sons.

GreenBiz. (2006). Global Market Booming for Organic Cotton Products, New Report Shows. http://www.greenbiz.com/news/news_third.cfm?NewsID=30957. April 14, 2008.

GreenBlue. (2008). Sustainable Textile Standard. http://www.greenblue.org/activities_stm.html. April 16, 2008.

Hunter, I. (2003). "Bamboo resources, uses and trade: the future?" International Network for Bamboo and Rattan **2**(4): 319-326.

Inikori, J. E. (1989). "Slavery and the Revolution in Cotton Textile Production in England." Social Science History **13**(4): 343-379.

ISO (2000). Textiles -- Tear properties of fabrics -- Part 2: Determination of tear force of trouser-shaped test specimens (Single tear method). International Organization for Standardization. **ISO 13937-2:2000**.

Jenkins, D. (2003). The Cambridge history of western textiles. Cambridge, Cambridge University Press.

Kalliala, E. M. and P. Nousiainen (1999). "Life Cycle Assessment Environmental Profile of Cotton and Polyester-Cotton Fabrics." AUTEX Research Journal **1**(1): 8-20.

Kanglin, W. (1998). Ecology and Habitats of Bamboos in Yunnan, China. Rome, Biodiversity International.

Knight, D. (2007). Going Green With Bamboo: Versatile Fiber Provides A Popular Alternative to Traditional Hardwood Floors. Environmental Design and Construction.

Lichtenstadt, P. (1864). Improvement in preparing fiber from the bamboo. U. S. P. Office. United States. **41,627:** 1.

Lin, G., T. Reijenga, et al. (2003). "Promotion of Sustainable Buildings in China: Integration of Bamboo and Renewable Energy Technologies." Chinese Forestry Science and Technology **2**(1): 40-45.

Lin, J., X. He, et al. (2002). "Lignification and lignin heterogeneity for various age classes of bamboo (Phyllostachys pubescens) stems." Physiologia Plantarum **114**: 296-302.

Lin, M. (2008). Bamboo Fibre Market Prices. M. Waite, SuZhou ShengZhhu Household Co. Ltd.

Lin, M. (2008). Suzhou Shengzhu Household Co Report. M. Waite. Suzhou**:** Personal Communication.

Litrax. (2008). Bamboo Fiber. http://www.litrax.com/index.html?lang=en-us&target=front.html. May 12, 2008.

Lybeer, B. and G. Koch (2005). "A Topochemical and semiquantitative study of the lignification during ageing of bamboo culms (Phyllostachys Viridiglaucescens)." IAWA Journal **26**(1): 99-109.

Lyle, D. S. (1977). Performance of Textiles. London, John Wiley & Sons.

Lymberis, A. and D. E. D. Rossi (2004). Wearable eHealth Systems For Personalised Health Management: State Of The Art and Future Challenges (Studies in Health Technology and Informatics). Lancaster, IOS Press.

Magel, E., S. Kruse, et al. (2005). "Soluble carbohydrates and acid invertases involved in the rapid growth of developing culms in Sasa Palmata (Bean) Camus." Journal of the American Bamboo Society **19**(1): 23-29.

Mankiw, N. G. (2004). Principles of Microeconomics. Mason, Thomson South-Western.

Marquardt, S. (2007). Global Organic Cotton Apparel and Home Products Market Tops One Billion Dollars in 2006, says New Organic Exchange Report. www.organicexchange.org/Documents/Oct31press.pdf. April 15, 2008.

Mwaikambo, L. Y. (2006). "Review of the history, properties and application of plant fibres." African Journal of Science and Technology **7**(2): 120 -133.

Patterson, P. (2008). Bamboo-zled? Ecotextile News**:** 18-20.

Pure Fiber. (2008). Bamboo Fiber Manufacturing Process. http://www.pure-fiber.com/about_bamboo.html#bamboo_fiber_manufacturing. May 2008.

Ramachandran, T., K. Rajendrakumar, et al. (2003). "Antimicrobial Textiles-An Overview." IE Journal **I**.

Ramachandran, T., K. Rajendrakumar, et al. (2004). "Antimicrobial Textiles-An Overview." IE Journal-TX **84**.

Rodie, J. B. (2007). Quality Fabric of the Month: Spotlight on Bamboo. Textile World. **March/April**.

Sadov, F., M. Korchagin, et al. (1979). Chemical Technology of Fibrous Materials. Moscow, Mir Publishers.

Schoeser, M. (2003). World textiles: a concise history. London, Thames & Hudson.

Shen, Q., D.-S. Liu, et al. (2004). "Surface properties of bamboo fiber and a comparison with cotton linter fibers." Colloids and Surfaces B: Biointerfaces **35**: 193-195.

Shuang, S. (2008). Bamboo Textile Prices. M. Waite. Beijing.

Simpson, P. (2007). "Global Trends in Fibre Prices, Production and Consumption." Textile Outlook International **September-October**(131).

Steinfeld, C. (2001). A Bamboo Future. Environmental Design and Construction.

Taylor, M. (1981). Technology of Textile Properties. London, Forbes Publications.

Tenbro. (2008). Tenbro. http://www.tenbro.com/. May 12, 2008.

Teufel, L. and B. Redl (2006). "Improved Methods for the Investigation of the Interaction between Textiles and Microorganisms." Lenzinger Berichte **85**: 54-60.

TextileWorld (2008). Footprint Introduces Bamboo Socks. Textile World. **March/April:** 1.

US Patent & Trademark Office (2008). Verification of Bamboo Fibre U.S. Patent. M. Waite. Washington, D.C.

Velez, S., J. Dethier, et al. (2000). Grow your own house Simon Velez and Bamboo Architecture. Weil am Rhein, Vitra Design Musuem.

Vogel, E. and A. Gardner. (2005). Bamboo Biodiversity Maps. http://www.eeob.iastate.edu/research/bamboo/maps.html. April 18, 2008.

WWF. (2005). Agriculture and Environment: Cotton, Environmental Impacts of Production: Use of Agrochemicals. http://www.panda.org/about_wwf/what_we_do/policy/agriculture_environment/commodities/cotton/environmental_impacts/agrochemicals_use/index.cfm. April 15, 2008.

Xu, X., Y. Wang, et al. (2006). "Effects on surface properties of natural bamboo fibers treated with atmospheric pressure argon plasma." Surface and Interface Analysis **38**: 1211-1217.

Xu, Y., Z. Lu, et al. (2007). "Structure and Thermal Properties of Bamboo Viscose, Tencel, and Conventional Viscose Fiber." Journal of Thermal Analysis and Calorimetry **89**(1).

YiChung, W. (2004). "Estimates of biomass and carbon sequestration in Dendrocalamus latiflorus culms." Chinese Forest Products Association **23**(1): 13-22.

Zehui, J. (2003). Preface. International Workshop on Bamboo Industrial Utilization, Xianning City, INBAR.