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Sustainable Textiles: the Role of Bamboo and a Comparison of Bamboo Textile properties (Part II)

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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.

IV. Experimental Exploration with Bamboo Textiles

A. Introduction

Bamboo textiles present a noteworthy opportunity for providing sustainable textiles. Nevertheless, the renewable properties of bamboo itself do not add much to sustainable development if the textiles cannot serve a practical purpose. Bamboo textiles must exhibit properties appropriate for its applications, thereby providing the end-user with a useful item. This section summarizes the materials used, methods employed, and results of experiments performed in order to assess some of the bamboo textile properties.

There are two main manufacturing methods currently being employed in the manufacture of sustainable textiles—chemically-based and mechanically-based processes. There are also over 1500 species of bamboo globally, of which only a few are being employed to create textiles. Some companies use only one species of bamboo for bamboo textile manufacturing, while other companies use many (such as 13 bamboo species) without distinguishing between species and textile properties. The experiments performed attempt to answer two questions regarding bamboo textiles: (1) what are the differences in textile properties between the chemically-manufactured and mechanically-manufactured bamboo textiles, and (2) what are the differences in textile properties between two different species of bamboo used to produce chemical bamboo (*Phyllostachys edulis* and *Bambusa emeiensis*)?

The textile properties measured here are as follows: tear force, breaking force, breaking tenacity, moisture absorption and speed of drying, and surface morphology. Tests are performed at various stages of the bamboo textile manufacturing process: fiber, yarn, and fabric. Comparative testing is necessary to develop and improve products (Lyle 1977), thereby making bamboo textiles more suitable for end-uses. The properties analyzed have special relevance to sustainable development. The ability to withstand forces is a key indicator of durability. The longer a textile lasts, the more one can prolong its eventual deposit in landfill, and perhaps the more one can refrain from replacing and wasting further resources. If a textile can absorb moisture quickly and dry moisture quickly, then the need for mechanical drying and perhaps washing (which are energy intensive) can be lessened.

B. Brief Literature Review

There are thousands of studies concerning various fiber, yarn, fabric, and general textile properties of various plant fibers. Topics covered include the sorption properties of flax fibers, the effects of cultivating methods on the mechanical properties of cotton fiber, the determination of porosity and cellulose content of plant fibers, the tensile properties of cocoon silk, the calculation of elastic properties of natural fibers, etc.

There are no current published academic works comparing bamboo textile properties between different bamboo species and between different bamboo textile manufacturing processes (chemical versus mechanical). Here, I provide a brief review of pertinent findings in the literature concerning bamboo textiles, ranging from studies that seek to improve bamboo fibers with surface modification, to comparisons of bamboo fibers with other textile fibers. Mwaikambo provides a review of the history, properties, and applications of various plant fibers, including bamboo. Mwaikambo presents the chemical composition, physical properties (such as diameter, length, bulk density), and mechanical properties (such as tensile strength, failure strain, and Young's modulus) of the fibers (Mwaikambo 2006).

Xu, Lu et al investigated the thermal and structural differences among chemical bamboo fiber, Tencel (regenerated cellulose made from the eucalyptus tree's wood pulp), and conventional viscose fibers. The pertinent findings are that: (1) chemical bamboo fibers suggest good water retention power due to the many voids in their cross-section and (2) chemical bamboo fibers and conventional viscose fibers possess better ability of absorbing and releasing water than Tencel (Xu, Lu et al. 2007). Xu, Wang et al analyzed the effects of atmospheric pressure argon plasma on the surface properties of bamboo fibers. They found that (1) cracks, pits, and small fragments appear on the fiber surfaces after plasma treatment, (2) surface roughness increases with longer treatment times and larger plasma powers, and (3) dyeability and hydrophilicity of fibers improves with surface modification using atmospheric pressure argon plasma treatment (Xu, Wang et al. 2006). Shen, Liu et al also explored the surface properties of chemical bamboo fibers using a column wicking technique. Their study was a comparison between bamboo fiber and cotton linter fiber (short fibers that cling to cottonseeds after long fibers are removed). The principal finding was that bamboo fiber has more than double the Lewis acid component compared to cotton linter fiber; the author suggests that this makes chemical bamboo fiber similar to the touch of water, since water is found to have the same Lewis acid component (Shen, Liu et al. 2004).

C. Materials

Bamboo fiber, yarn, and fabric samples were collected using two different species of bamboo—*Phyllostachys edulis* and *Bambusa emeiensis*. *Phyllostachys edulis* is known as “Mao zhu” in Chinese and “Moso” in Japanese; it was formerly known as Phyllostachys heterocycla pubescens (AmericanBambooSociety 2007). This is a popular bamboo for construction applications, as well as the textile industry. It was used to provide chemical bamboo samples and mechanical bamboo samples from Suzhou Shengzhu Household Co., based in Suzhou City China. *Phyllostachys edulis* has a monopodial and scattered rhizome system, and it is distributed throughout southwest China (Kanglin 1998).

Neosinocalamus affinis, now known as *Bambusa emeiensis 'Chrysotrichus,'* was used to provide chemical bamboo samples from a manufacturing company based in Shanghai and Sichuan China. *Neosinocalamus affinis* has a sympodial and tufted rhizome system, is large sized, is cultivated at less than 1900 m in altitude, and is widespread in the southwest of China (Kanglin 1998). The company (wishes to remain anonymous), uses bamboo fiber made from bamboo selected from the Sichuan Province in China.

Figure 4.1 indicates the samples collected including their specifications. The samples from Company A were received in April 2008 and stored at room temperature. The samples from Suzhou Shengzhu Household Company were received in May and June 2008 and stored at room temperature.

Figure 4.1: Bamboo Samples used in Experiments

Company	**Sample Type**	**Photograph**	**Specification**	**Amount**
Company A *(Bambusa emeiensis)*	100% Chemical Bamboo Raw Fibre (thick pulp)		Varied	0.5 kg
	100% Chemical Bamboo Fibre (fine Pulp)		1.56 dtex×38 mm (length)	0.5 kg

	100% Chemical Bamboo Yarn		32 Ne Ring spun	0.5 kg
	100% Chemical Bamboo Knit Fabric		32 Ne Dyed Pink	1 m
Suzhou Shengzhu Household Co. *(Phyllostachys edulis)*	100% Chemical Bamboo Fine Pulp Fibre		1.56 dtex×38 mm	0.2 kg
	100% Chemical Bamboo Yarn		32 Ne Ring spun	0.2 kg
	100% Chemical Bamboo Yarn		21 Ne Ring spun	0.2 kg
	100% Chemical Bamboo Woven Fabric		21 Ne Green and White Floral Pattern	0.2 kg
	100% Chemical Bamboo Knit Fabric		32 Ne Dyed Black	0.6 kg
	100% Mechanical Bamboo fibre		5-6 dtex×95 mm	0.2 kg
	100% Mechanical Bamboo Woven Fabric		21 Ne Blue and White Checkered Pattern	0.2 kg

To perform the scanning electron microscope (SEM) observations, the CamScan MX2600 was used. In order to conduct the moisture absorption and drying experiments, the following materials were used in addition to fabric: 17cm diameter embroidery hoop, deionised water, balance, pipettes and pipette tips, and a beaker. To perform the mechanical tests, a Hounsfield Low Load Electric Screw Machine was used.

D. Methods

SEM Images

Standard test procedures for live specimens were used to observe the differences in surface morphology among various bamboo fibers. The fibers were cut and gold-plated as preparation.

Moisture Wicking Tests

AATCC Test Method 79-2007 was employed to measure textile absorbency. The general procedure involves dropping water from a fixed height onto a taut surface (made taut through the use of an embroidery hoop). The time required for the specular reflection of a water drop to disappear is recorded as the wetting time. Five readings are taken, and the shorter the average time, the more absorbent the fabric. This AATCC method was slightly modified by using a pipette with 50 µL of deionised water instead of a burette. To measure the speed of drying of the different fabrics, 50 µL of deionised water was placed on a piece of fabric cut 4 cm wide and 5 cm long. The weight of the fabric was taken before and after the 50 µL of water was introduced, as well as at set time intervals until the weight of the fabric reached its initial recording.

Mechanical Tests

Mechanical tests were completed according to various internationally-recognized standards, including those from the American Society for Testing and Materials (ASTM), the International Organization for Standardization (ISO), the British Standards Institution (BSI), and the American Association of Textile Chemists and Colorists (AATCC).

Fibers

To measure the breaking force of the bamboo fibers, standard test methods had to be modified to conduct a comparison adequate for the short and fine chemical bamboo fibers. Bamboo fibers were measured at the following stages: thick pulp (earliest stage) chemical bamboo fiber, fine pulp chemical bamboo fiber, and mechanical bamboo fiber. Ten trials were completed for each sample type. The following method was employed:

1. A rectangular paper frame was constructed with a rectangular cut out.
2. Double-sided tape was then used to apply an adhesive surface to one side of the paper frame. The rectangular cut out was preserved by cutting through the double-sided tape.
3. Five individual fibers were carefully picked using fine tweezers and placed along the rectangular cut.
4. Masking tape was cut and placed along both ends of the fibers to hold them in place.
5. The paper frame and the attached fibers were then clamped using the Hounsfield tensile testing machine.
6. Slits were cut through two ends of the paper frame so that the only materials pulled during the test were the fibers (and not the fibers plus the paper frame).
7. A standard breaking force program was used with a load range of 5N, a speed of 100 mm/min, and an extension range of 10 mm.

Yarns

To measure the tensile properties of yarns, ASTM standard D 2256-02, Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, was employed. A single-stranded yarn is broken on a tension testing machine at a predetermined elongation rate (300 ± 10 mm/min) so that the breaking force is determined. A straight specimen configuration was used with a gage length of 250 ± 3 mm gage length. The breaking force of individual specimens is the maximum force to cause the specimen to rupture as read directly from the tension testing machine expressed in Newtons (ASTM 2003). A total of ten trials were performed for each yarn type. The breaking tenacity of an individual specimen is calculated using equation 1 as follows:

(1) B=F/T
where: B = breaking tenacity, CN per tex
F = breaking force, CN
T = linear density, tex

Fabric

To measure the tear properties of fabric, EN ISO 13937-2:2000, Tear properties of fabrics Part 2: Determination of tear force of trouser-shaped test specimens (Single tear method), was employed. The test method uses a test specimen cut to form trouser-shaped legs; the tear force measured is the force required to propagate a previously started single tear when the force is applied parallel to the cut and the fabric tears in the direction of applied force (ISO 2000). The tear force is calculated from the force peaks recorded on the tensile testing machine. A total of six trials were performed for each fabric type, three to calculate the tear force across warp and three to calculate the tear force across weft.

E. Results and Discussion

SEM Analysis

The SEM images show various similarities and differences among the four bamboo fiber types analyzed. Both species of chemical bamboo fiber displayed a tubular and ribbed (celery-like) longitudinal surface; the cross sections of both species were filled with voids (Figure 4.9 and Figure 4.10). The thick pulp of chemical bamboo fiber has a rough and very porous surface (Figure 4.11); this is to be expected as it is the closest to the actual bamboo plant among all of the fiber types. Mechanical bamboo fiber displayed a bamboo-like longitudinal section, tubular with nodes (Figure 4.12); the cross section displayed some voids, though much fewer than the chemical bamboo fibers. The mechanical bamboo fiber also has a higher linear density (5.88 dtex) than the chemical bamboo fibers (1.56 dtex).

Figure 4.9: ***Phyllostachys edulis*** **Chemical Bamboo Fibre**
Left: cross-sectional direction (SEM Mag7900X), Right: longitudinal direction, Diameter is 13.4 µm -15.6 µm (SEM Mag3346X)

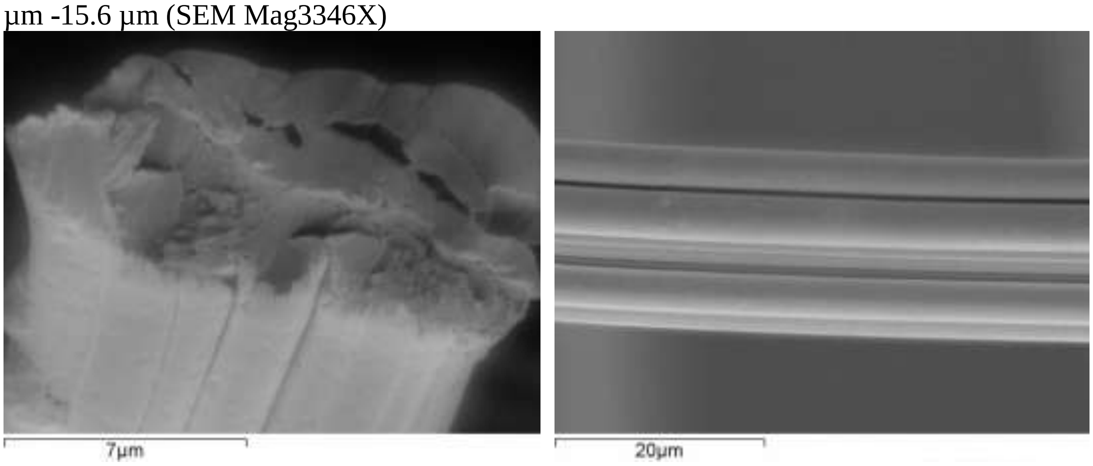


Figure 4.10: ***Bambusa emeiensis*** **Chemical Bamboo Fibre**

Left: cross-sectional direction (SEM Mag3346X), Right: longitudinal direction (SEM Mag2086X), Diameter is 12.3 μm -15.2 μm

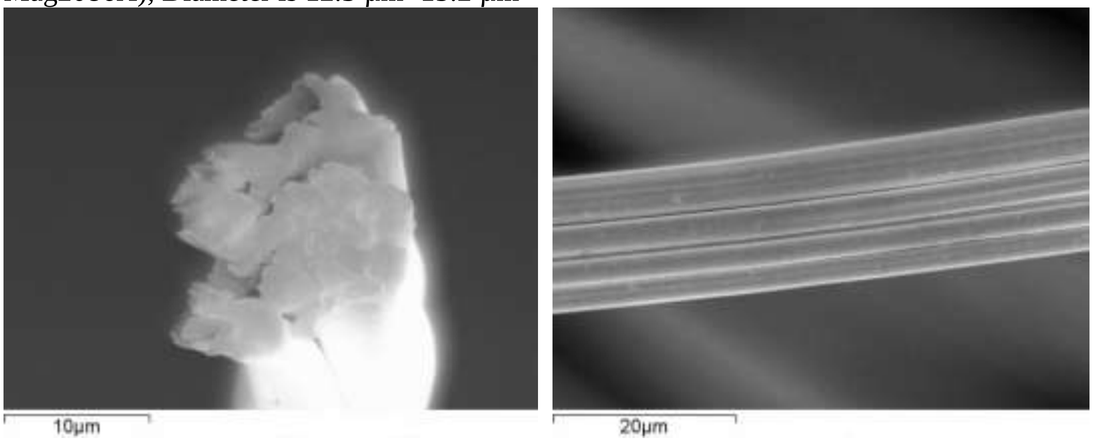


Figure 4.11: ***Bambusa emeiensis*** **Chemical Bamboo Fibre (Thick Pulp)**

Left: cross-sectional direction (SEM Mag1406X), Right: longitudinal direction (SEM Mag3152X), Diameter is ≈ 31.5 μm

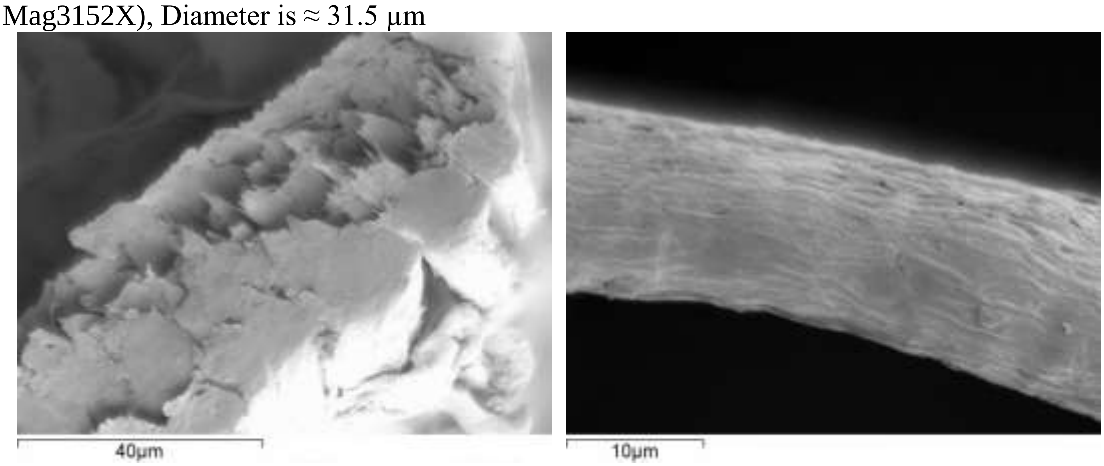
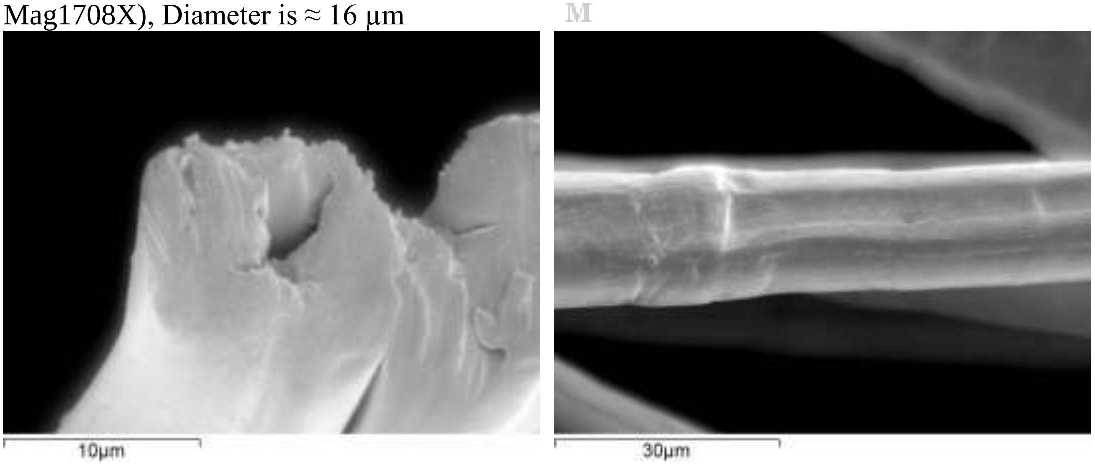


Figure 4.12: ***Phyllostachys edulis*** **Mechanical Bamboo Fibre**

Left: cross-sectional direction (SEM Mag4476X), Right: longitudinal direction (SEM Mag1708X), Diameter is ≈ 16 μm



Mechanical Tests

The following section provides summaries in table and graph form for the mechanical data gathered.

The results for fiber breaking force and breaking tenacity illustrate that mechanically-manufactured bamboo fiber is more than two times stronger than chemically-manufactured bamboo. There are no significant differences between species at the fiber level. The breaking tenacity of cotton, wool, viscose rayon, and polyester are all below that of the bamboo fibers tested (Figure 4.13 and Figure 4.14); therefore, bamboo fibers may be more resistant to wear and tear than conventional fibers. The raw chemical bamboo fiber was not used for comparative purposes (since only one sample was available at this stage in the manufacturing process); however, it is clear that the strength of the bamboo fibers is more present before continual processing. Graph 4.1 shows the mechanical testing results for bamboo fibers.

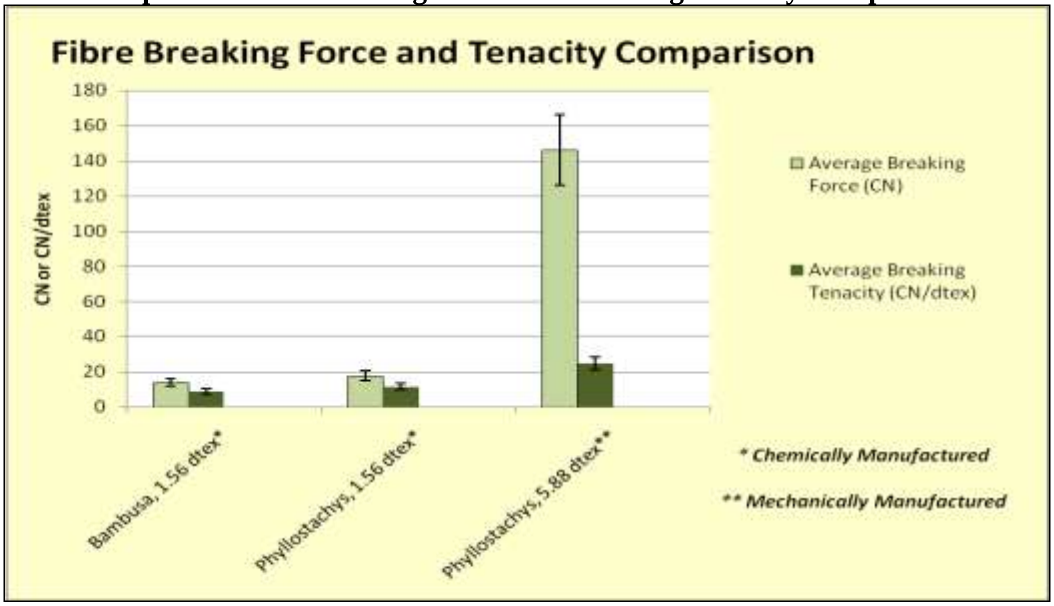
Figure 4.13: Fibre Breaking Force and Breaking Tenacity Comparison

Sample No.	**Bamboo Species**	**Manufacturing Method**	**Fibre Specification**	**Average [Breaking Force (CN)**	**Average Breaking Tenacity (CN/dtex)**
1	*Bambusa emeiensis*	Chemical (thick pulp)	Varied	406 ± 106	Varied
2	*Bambusa emeiensis*	Chemical	1.56 dtex	13.7 ± 2.1	8.75 ± 1.36
3	*Phyllostachys edulis*	Chemical	1.56 dtex	17.7 ± 2.8	11.4 ± 1.8
4	*Phyllostachys edulis*	Mechanical	5.88 dtex	146 ± 20	24.9 ± 3.64

Figure 4.14: Tenacity of Conventional Textile Fibres

Name	**Tenacity (gf/tex)**	**Tenacity (CN/dtex)**
cotton	35	3.5
wool	12	1.2
viscose rayon	20	2
polyester	39.5	3.95

Graph 4.1: Fibre Breaking Force and Breaking Tenacity Comparison

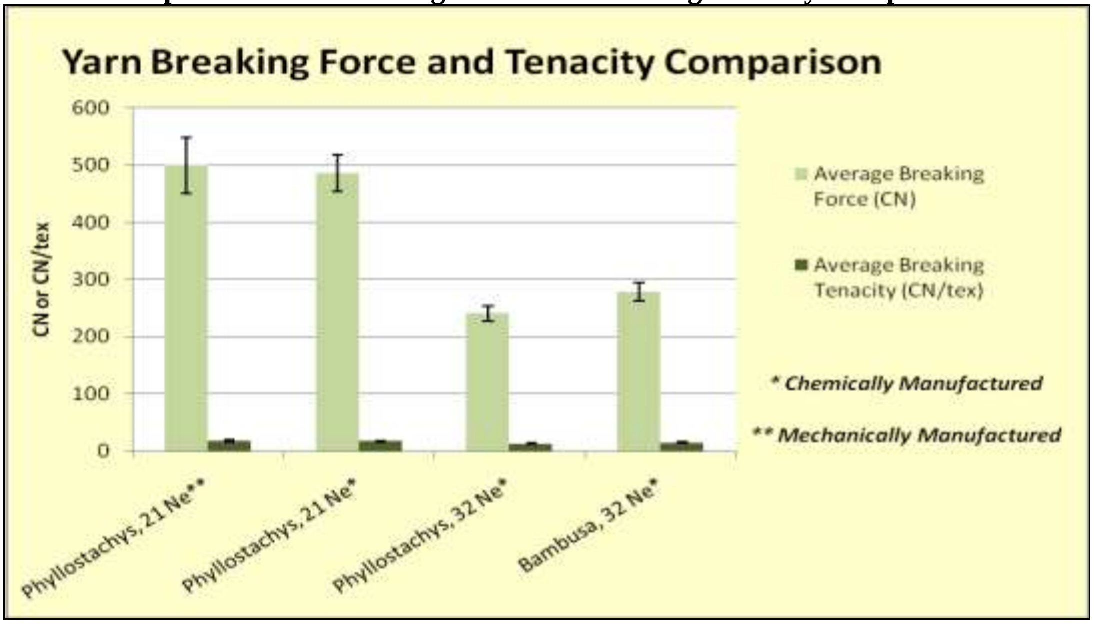


The breaking force and breaking tenacity of bamboo yarn reveal small differences between species and manufacturing method. It appears that the processing of fiber into yarn creates some level of strength degradation for mechanically-manufactured bamboo. As with bamboo textile fibers, there was no significant difference between the mechanical properties of different bamboo species in yarn form. Figure 4.15 and Graph 4.2 illustrate the mechanical testing results for bamboo yarn.

Figure 4.15: Yarn Breaking Force and Breaking Tenacity Comparison

Sample No.	**Bamboo Species**	**Manufacturing Method**	**Yarn Specification (Ne Count)**	**Average Breaking Force (CN)**	**Average Breaking Tenacity (CN/tex)**
1	*Bambusa emeiensis*	Chemical	32	278 ± 16	15.0 ± 0.87
2	*Phyllostachys edulis*	Chemical	32	240 ± 13	13.0 ± 0.72
3	*Phyllostachys edulis*	Chemical	21	485 ± 32	17.2 ± 1.1
4	*Phyllostachys edulis*	Mechanical	21	499 ± 49	17.7 ± 2.1

Graph 4.2: Yarn Breaking Force and Breaking Tenacity Comparison

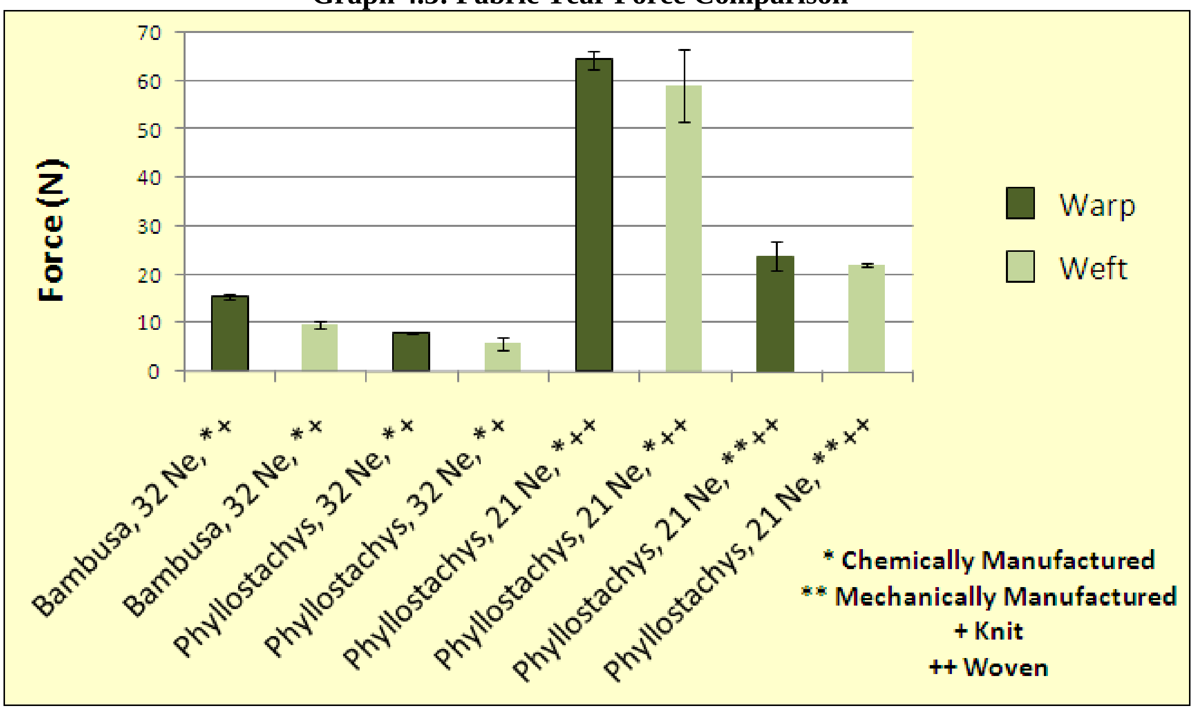


The fabric tear results show that the woven fabrics are more resistant to tear forces than the knit fabrics. Also, *Bambusa emeiensis* endured a higher tear force than *Phyllostachys edulis*. Ironically, mechanically-manufactured bamboo showed a much lower resistance to tear force than chemically-manufactured bamboo. However, the woven chemical bamboo fabric sample contained a floral pattern which almost created a double-layer; therefore, it is difficult to say with certainty that there is a difference in manufacturing method for these tests. Figure 4.16 and Graph 4.3 show the mechanical testing results for bamboo fabric.

Figure 4.17: Fabric Moisture Absorption Comparison

Sample Number	Bamboo Species	Manufacturing Method	Fabric Specification	Warp/Weft	Average Tear Force (N)
1	*Bambusa emeiensis*	Chemical	Knit, Ne=32	Warp	15.6 ± 0.59
	Bambusa emeiensis	Chemical	Knit, Ne=32	Weft	9.64 ± 0.70
2	*Phyllostachys edulis*	Chemical	Knit, Ne=32	Warp	7.99 ± 0.29
	Phyllostachys edulis	Chemical	Knit, Ne=32	Weft	5.86 ± 1.20
3	*Phyllostachys edulis*	Chemical	Woven, Ne=21	Warp	64.5 ± 1.9
	Phyllostachys edulis	Chemical	Woven, Ne=21	Weft	59.2 ± 7.4
4	*Phyllostachys edulis*	Mechanical	Woven, Ne=21	Warp	23.9 ± 2.88
	Phyllostachys edulis	Mechanical	Woven, Ne=21	Weft	22.1 ± 0.53

Graph 4.3: Fabric Tear Force Comparison



<u>Moisture Wicking Tests</u>

Figure 4.17 indicates the average absorption times for a drop of water to be absorbed by the corresponding fabric. *Phyllostachys edulis* has by far the quickest absorption time. When a drop of water was placed onto the green printed design on Sample 3 (*Phyllostachys edulis* chemical bamboo woven), the average absorption time was 2.45 s; when a drop of water was placed onto the cream-colored part of Sample 3 (flat design), the water absorbed instantly at 0.00 s.

Figure 4.17: Fabric Moisture Absorption Comparison

Sample Number	Bamboo Species	Manufacturing Method	Fabric Specification	Average Absorption Time (s)
1	*Bambusa emeiensis*	Chemical	Knit, Ne=32	5864.80
2	*Phyllostachys edulis*	Chemical	Knit, Ne=32	1376.60
3	*Phyllostachys edulis*	Chemical	Woven, Ne=21	0.00-2.45
4	*Phyllostachys edulis*	Mechanical	Woven, Ne=21	162.87

Figure 4.18 shows the total time that each fabric took to dry, once wet with one drop of water. The fastest drying fabric was the mechanical bamboo made from *Phyllostachys edulis*, while the slowest drying fabric was the chemical bamboo woven made from *Phyllostachys edulis.* It should be noted, however, that the design of the chemical bamboo woven fabric could have slowed the drying time because of the double-layer nature of the pattern.

Figure 4.18: Fabric Moisture Drying Comparison

Sample Number	Bamboo Species	Manufacturing Method	Fabric Specification	Total Time Needed to Dry (s)
1	*Bambusa emeiensis*	Chemical	Knit, Ne=32	6673
2	*Phyllostachys edulis*	Chemical	Knit, Ne=32	2853
3	*Phyllostachys edulis*	Chemical	Woven, Ne=21	8196
4	*Phyllostachys edulis*	Mechanical	Woven, Ne=21	452

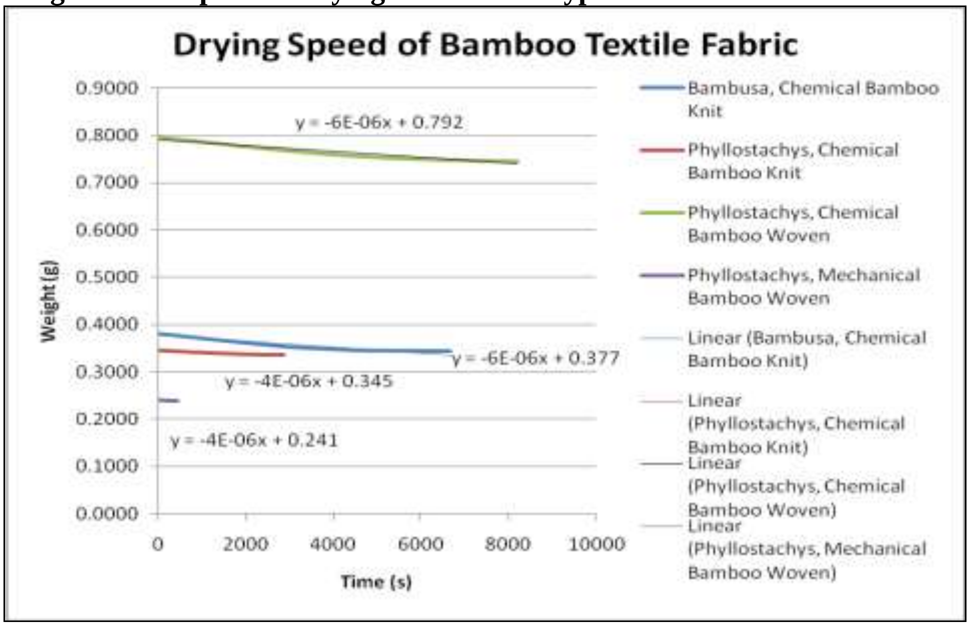
Figure 4.19 shows the moisture wicking capabilities of the fabrics in question. The last column provides the difference between the time of drying and absorbing normalised by the absorption time. Note that lower numbers indicate higher moisture wicking (fast absorption and fast drying).

Figure 4.19: Moisture Wicking Properties of Bamboo Fabric α: averaged time from range of 0s to 2.45s

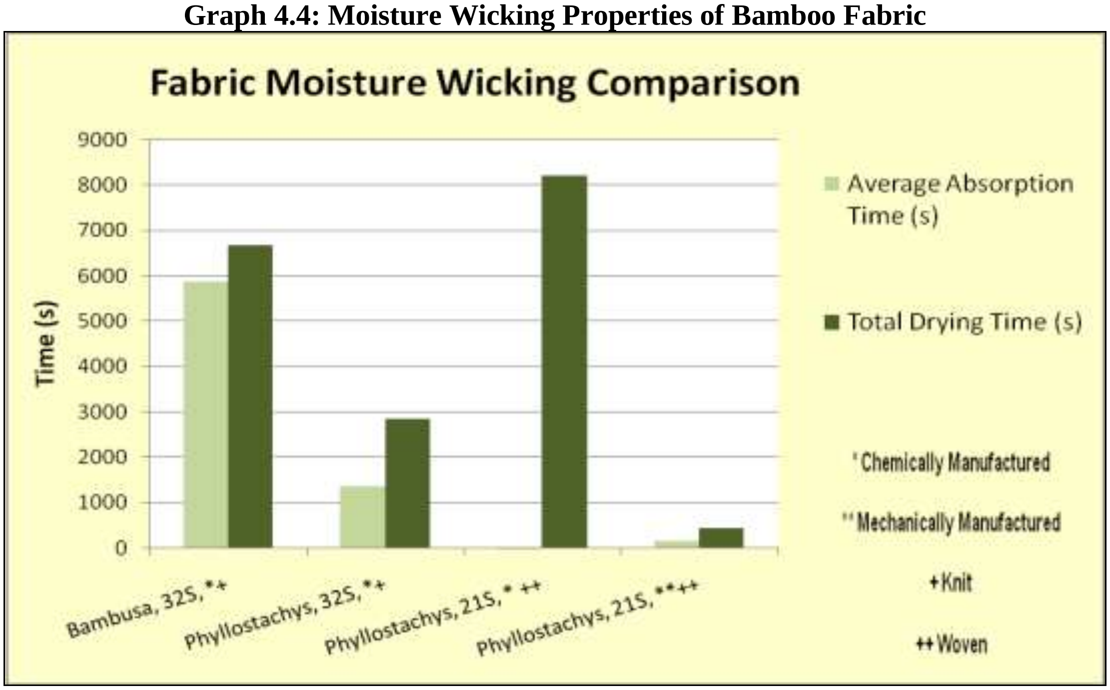
Bamboo Species	Manufacturing Method	Fabric Specification	Average Absorption Time (s)	Total Time Needed to Dry (s)	(Dry time-Absorb time)/Absorb time
Bambusa emeiensis	Chemical	Knit, Ne=32	5865	6673	6672
Phyllostachys edulis	Chemical	Knit, Ne=32	1377	2853	2852
Phyllostachys edulis	Chemical	Woven, Ne=21	1.2^{α}	8196	8195
Phyllostachys edulis	Mechanical	Woven, Ne=21	163	452	451

Figure 4.20 shows the graphs of weight plotted over time *after* the fabric had absorbed water. Note that the rates of change, or slopes of the graphs, are all small and close in value. **Graph 4.4** shows the moisture wicking results for bamboo fabric.

Figure 4.20: Speed of Drying for Various Types of Bamboo Textile Fabric



Graph 4.4: Moisture Wicking Properties of Bamboo Fabric



F. Conclusion

There are noticeable differences between textile strength in fiber, yarn, and fabric form, with some apparent degradation in processing. At the fiber level, mechanical bamboo's breaking tenacity is at least twice as big as chemical bamboo fiber. At the yarn level, there are small differences between species and manufacturing method for breaking tenacity. At the fabric level, *Bambusa emeiensis* has a bigger tear force and tearing tenacity than *Phyllostachys edulis*. Nevertheless, specie differences in fabric form are small. The tearing strength of mechanical bamboo fabric was much smaller than chemical bamboo fabric; however this could be due to the woven design in the chemical bamboo fabric.

The moisture absorption tests revealed well-defined differences between species, manufacturing method, and textile specification. In general, the woven bamboo fabric absorbed water much quicker than the knit bamboo fabric. In knit chemical bamboo textile form, *Bambusa emeiensis* took four times longer than *Phyllostachys edulis* to absorb water. In woven form (species kept constant with *Phyllostachys edulis*) the chemical bamboo absorbed water instantaneously, while the mechanical bamboo took 165 s on average to absorb. Based on these results, chemical bamboo woven fabric is better at water absorption than mechanical bamboo woven fabric, but chemical bamboo knit fabric takes a very long time to absorb. There also is a difference in absorption properties between bamboo species in textile form, and perhaps the same differences can be found in raw bamboo in nature.

The moisture drying tests revealed that some fabrics were better at absorbing than drying. *Phyllostachys edulis* chemical bamboo woven fabric was the quickest to absorb, but the longest to dry. This may have been due to the double layer of woven material to create the green floral pattern. When manufacturing method and specification were held constant, *Phyllostachys edulis* absorbed and dried faster than *Bambusa emeiensis*; this supports the SEM images since there are more visible voids in the chemical bamboo *Phyllostachys edulis* species. However, the fabric that has the best moisture wicking property is the mechanical bamboo made of *Phyllostachys edulis*. This sample absorbed water in a short time (163 s) and dried water in a short time (452 s); though it did not show many voids in the SEM cross-sectional image, the longitudinal section resembled a bamboo as a tubular shape with nodes. Perhaps there is some level of biomimicry in the fibers of bamboo that can be further explored.

There are two main conclusions that are drawn from the results: the species of bamboo is not trivial for bamboo textile applications and there are fundamental differences between the type and function of bamboo textiles that are manufactured chemically versus those that are manufactured mechanically with the aid of enzymes. Currently, many manufacturers who make chemical bamboo fabric add various species of bamboo into the mixture, without consideration of the differences. Although the research did not indicate a significant difference in mechanical properties such as breaking tenacity between species, moisture wicking properties varied significantly. There are also some blogs stating that mechanically manufactured bamboo is better than chemically manufactured bamboo; the study shows that the two textiles are not interchangeable, and that their appropriateness will depend on the goals of the application. Three specific conclusions can be made from the experimental tests: (1) mechanical bamboo fibers are much stronger than those chemically manufactured, but this strength at the fiber level does not remain consistent with further processing in yarn and fabric form, (2) *Phyllostachys edulis* exhibits better moisture wicking properties than *Bambusa emeiensis*, (3) mechanical bamboo displays better moisture wicking properties than chemical bamboo. Further work could explore more species of bamboo, as well as how small changes in the manufacturing process may change the quality of the textile at the fiber, yarn, and fabric levels. In summary, there is room for many different types of species and manufacturing methods for bamboo in the textile industry.

V. Bamboo Textiles: the Limits

A. Limitations

This paper shows how the properties of bamboo can be useful for textile applications in the realm of sustainable development.

However, there are many bamboo species and manufacturing steps not explored here that would nevertheless, add to the overall understanding of the subject. Also, since many bamboo textile operations are closed off to the public and researchers because of intellectual property issues, there is pertinent information regarding manufacturing that could not be included in this paper. It is important to emphasize that bamboo, or any single textile source, will not serve as a panacea to the sustainability issues of the textile sector. Over-reliance on one source, whether it is for energy or for textiles, is contrary to the underlying principles of sustainable development. In addition, different materials have different mechanical, physical, chemical, and technical properties that will serve for a diverse range of applications.

B. Challenges and Possible Mitigation Measures

There are many challenges facing the future of bamboo textiles, including:

1. The threat that bamboo farming communities become too dependent on textile industries and are left with little negotiating power with intermediaries or the global market (Bismarck, Baltazar-y-Jimenez et al. 2006)
2. The threat of over-exploitation in general and by an introduction of heavy machinery (that may damage the bamboo rhizome system), as well as with chemical pesticides and fertilizers.
3. The risk of consumer disinterest in "eco-textiles," or otherwise similarly labeled textiles that would support the growth in bamboo textiles. For example, world consumption of sisal and henequen in Mexico plummeted, and left many rural families desolate, mostly due to the development of cheaper synthetic polymer materials (Bismarck, Baltazar-y-Jimenez et al. 2006).

To mitigate some of these risks and address the challenges, the following is suggested:

1. To reduce the risk of overdependence on textile trade by local bamboo farmers, diversification and support from outside organizations are essential.

   • With the numerous documented and well-established end products from bamboo sources, farmers can diversify their product range so as to not become too susceptible to changes in any one market.

   • For bamboo farms that are owned by small farmers, fair/ethical trade schemes and fair/ethical trade support organizations, sustainable textile schemes, and connections to associations with bamboo bargaining power (such as INBAR) could be established. Organizations such as the Fairtrade Labeling Organizations (FLO), the Ethical Trading Initiative, and Sedex, are all working to promote fair trade globally. Organizations such as Social Accountability International, The Clean Clothes Campaign, the Fair Wear Foundation, and the International Fair Labor Association, work to promote ethical working conditions.

2. The risk of overexploitation is present with any crop; to keep this from occurring with bamboo, increased public pressure and sustainably managed "bamboo" forest certifications are suggested.

   • Public pressure to keep textiles organic can help to reduce the risk of introducing chemicals to bamboo farming. The high yield and renewable status of bamboo also make the use of chemical pesticides and fertilizers less attractive than for other textile raw crops.

   • Bamboo forests are currently poorly managed in comparison to their wood counterparts. Because bamboo is a non-timber resource, it is missing in many government classifications and third-party certification schemes. The introduction of such measures would ensure that bamboo forests are continually managed in a sustainable manner and would engender confidence in consumers.

3. There should be increased yet clarified public awareness in the subject of sustainable textiles to reduce the threat of consumer disinterest.

The issue of trade agreements in the international textile market is very important as it impacts the environment, workers, companies, end-users, and governments involved. The influence of government decisions on the sector, and therefore on the future of bamboo textiles, will not be treated here. It is a complex issue and beyond the scope of this paper, but it is also worth mentioning that agreements can have both positive and negative impacts on the communities involved, in both the short run and long run.

One aspect of the textile industry that undermines sustainable textile development is the advent of 'fast fashion.' That is, there are increasingly short leading times for new clothing textiles to reach the consumer markets and increasingly short shelf lives of the new clothing textiles. Figure 5.1 shows a simplified causal loop diagram concerning the sustainable bamboo textile industry. It shows how fast fashion undermines the entire system of a sustainable bamboo textile (SBT) industry, and a sustainable textile industry in general. The system boundary is set with two major conditions: (1) textiles are sourced from bamboo and (2) sustainability is a prerequisite for each stage of the life cycle. Therefore, the word sustainable in the diagram encompasses the relevant categories such as energy, water use, and chemicals.

The diagram assumes that the total amount of textiles in the worldwide textile stream remains constant (for example, people will buy x number of t-shirts regardless of the clothing material); a bamboo item would replace a polyester item, for instance. Two main items that were left out of the diagram but worth mentioning are the number of workers in industry and government/inter-governmental regulation. It is difficult to predict the effect that an increase or decrease in sustainable bamboo textiles would have on employment in the sector, mostly because machine automation continues to make jobs obsolete in the textile industry. Regulation (including treaties, quotas, tariffs, and taxes) is an important factor for a sustainable bamboo textile industry. However, it is not included here in an attempt to simplify the system boundaries. Also, regulation is likely to address the trade of textiles or the trade of bamboo, but it is not likely to address bamboo textiles specifically unless they became major world players in the textile market (such as cotton). The relationship between the number of people who buy SBT products and the price of SBTs is shown, assuming supply (more SBT manufacturers), remains constant in the long term. In general, a lower price indicates that more people will be able to buy SBT products.

There are two main loops. One is a positive, or reinforcing loop labeled "sustainable bamboo textile industry." This loop shows the positive relationships between public awareness, consumer education, consumer voice, retailer voice, the amount of SBT manufacturing and SBT quantity in the industry, and the number of people who purchase SBT products. This loop also leads to show how a sustainable bamboo textile industry leads to sustainable bamboo forest/farm certification schemes, as well as sustainable textile research and development. The second loop is negative, or balancing, and it is labeled "fast fashion in textile industry." This loop indicates how the relationships among quick lead times, consumer consumption of fast fashion, and the price of bamboo textiles leads to a less sustainable textile industry.

Low prices and fast fashion are interlinked. Assuming that one keeps the same budget, one can buy things more often if the items are sold at low prices. I will describe one possible scenario using the fast fashion loop. As the amount of SBTs increases, the overall size of the sustainable textile industry increases; this then leads to a decrease in the amount of fast fashion. As fast fashion decreases, consumer consumption of fast fashion decreases, and subsequently consumer consumption of SBTs within the fast fashion realm decreases. As the latter decreases, the price of SBT products must increase to make up for profit loss (all other things being equal), and this price change means that there will be less people who buy SBT products at this higher price. When the number of people who buy SBT products decreases, the amount of SBTs in the industry decreases, and therefore there is a decrease in the overall sustainable textile industry. Fast fashion is therefore creating an unpleasant barrier to the sustainable bamboo textile and overall sustainable textile industries.

The diagram shows that an increase in the number of SBTs is adding to a sustainable textile industry, all other things being equal. Yet, a truly sustainable textile industry would lead to a decrease in fast fashion, since unnecessary material waste is a key component of sustainability. What is a possible solution? One answer is the purchase of sustainable textiles that last longer and are more expensive; people would buy clothes less often (and therefore engender less textile waste and pollution), but retailers would make the same profits because goods would be sold at a higher price.

C. Final Recommendations

Finally, I propose a sustainable textile mix for the future, similar to the energy mixes in which society has a diverse portfolio of energy sources such as wind, solar, nuclear, coal with carbon capture and storage, oil and gas, etc. The current textile mix, with a clear majority belonging to petroleum-based synthetics and cotton fibers, is presented in Figure 5.2. Figure 5.3a and 5.3b show textile mix possibilities, randomly chosen, for the future.

C. Final Recommendations

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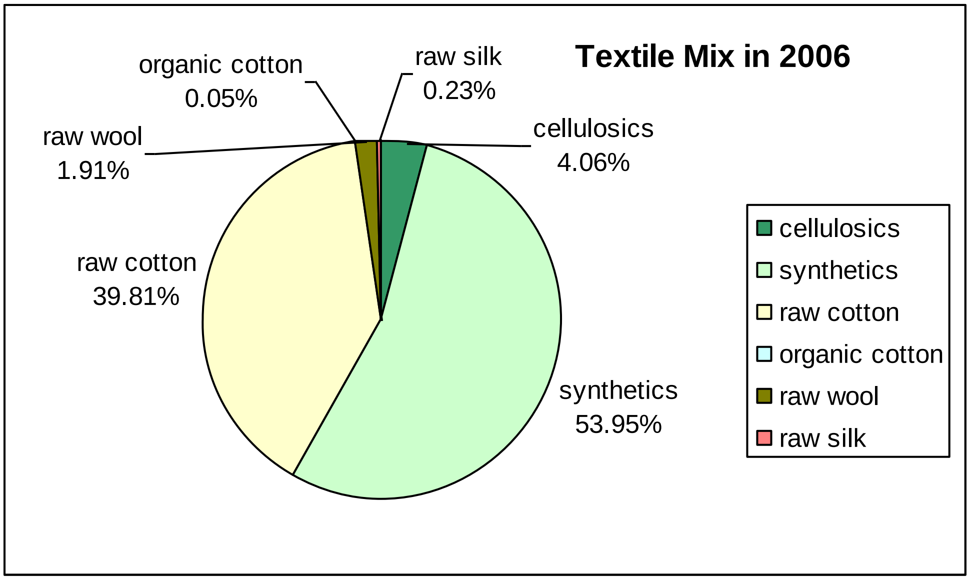
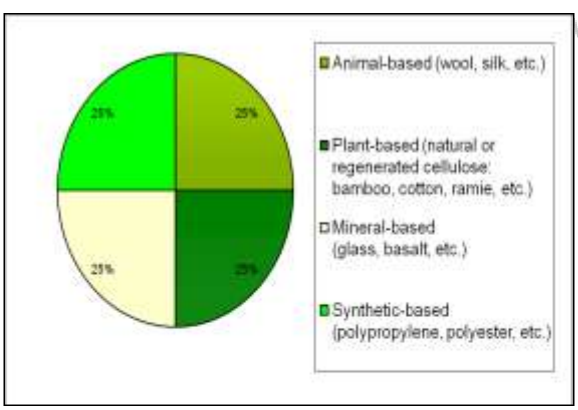
Figure 5.2: World Textile Mix (2006)

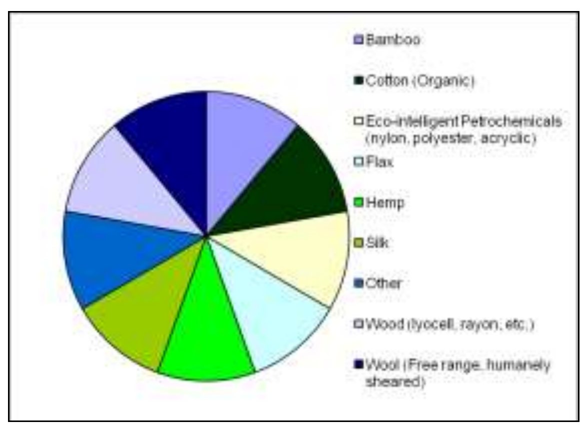


Note: Chart generated using data provided by Textile Outlook International (Simpson 2007). Organic cotton data taken from the Organic Cotton Fiber Report (Ferrigno 2006).

NB: man-made fibre demand figures are based on production data; natural fibre demand figures are based on consumption data to avoid inaccuracies arising from wide stock variations from year to year numbers may not sum precisely due to rounding

Figure 5.3a and 5.3b: Textile Mix Possibilities (5.3a, *left*, by fibre category, 5.3b, *right*, by fibre type)





The role of bamboo textiles in sustainable development was analysed through a thorough literature review, expert interviews and discussions, field visits in China, and experimental tests. Bamboo textiles present many solutions to the present unsustainable nature of textile engineering; however, energy, water, and chemical concerns in manufacturing still must be addressed. There are textile property variations among both species and manufacturing method for bamboo textiles. Thus, it is important to consider these two elements for the desired textile outcome. Further work in this field could analyse more bamboo species for textile applications, as well as treat small variations in manufacturing processes for the desired outcomes.

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