1. Introduction

Plant fibres have always been contributing explicitly to the economic prosperity and sustainability in our lives as they have application in almost every item used in our daily routine. Of late, there have been increasing demands for even more comfortable and eco-friendly products, and to satisfy them, researchers in the arena of textiles have been focussing on the renewable and biodegradable sources and environment-friendly processes. Among the natural fibre plants, bamboo is by far the most popular, owing to its versatile applications and for its significant contribution to the environment against negligible intake for its propagation.

Bamboos are the member of a group of woody perennials evergreen to deciduous plants of the true grass family Poaceae, which is a subfamily of Bambusoideae, from the tribe Bambuseae. The total population of bamboos in the world is represented by 80-90 genera and about 1,000-1,500 species. India occupies the largest area and is the second largest reserve of bamboos in the world. For textile applications, bamboo fibres are mostly produced from the tallest bamboo species Phyllostachys edulis which is more popularly known as 'Moso'. Also, bamboo being one of the high yielding sources of cellulose, regenerated bamboo viscose fibres too have conquered the market. This has happened mainly due to their claimed antibacterial nature, biodegradable properties, high moisture absorption capacity, soft smooth feel and UV protective capability. Currently, regenerated bamboo fibres are used in apparels (undergarments, sports textiles, t-shirts and socks), hygienic products (sanitary napkins, absorbing pads, masks, bandages and surgical gowns), ultraviolet protective clothing, home furnishing textiles, food packaging bags, etc. Due to such unique combination of outstanding and diverse functional properties, bamboo has been attracting much attention from the academia and the industry. Although, the manufacturers and marketers emphasize on the
demonstration of exquisite properties by the bamboo products, these claims are sometimes viewed with a bit of suspicion and require validation via research.

2. Extraction of Bamboo Fibre

The characteristics displayed by the bamboo products primarily rely on whether the bamboo fibre is of natural origin or a regenerated variety. Broadly speaking, there are two main modes of effective utilization of bamboos in the textile industry (Yueping et al., 2010):

a) Producing natural (bast) fibre via physical and chemical treatment
b) Spinning regenerated (pulp) fibre via retting bamboo plant into pulp

The former method gives bundles of original or pure bamboo fibres of 2 mm staple length, whereas the latter gives bamboo viscose filaments (also called regenerated bamboo cellulose) which could be further converted to staple fibres, if required. For the extraction of fibres from bamboo culm, both the processes commence with the splitting of bamboo strips picked directly from the bamboo clump, so as to remove the diaphragm and node. Further, the remaining hollow portions of the stalks are taken for either mechanical processing or chemical processing, depending upon the end applications (Phong et al., 2012).

2.1. Mechanical Route of Bamboo Fibre Production

The initially cut and crushed woody parts of the bamboo are treated with natural enzymes that break the bamboo into a soft, mushy and spongy mass. Subsequently, the natural fibres can be combed out mechanically to get individual fibres, followed by spinning yarn out of them. The fabric manufactured via this process is often termed as bamboo linen (Erdumlu and Ozipek, 2008; Kaur et al., 2013).

Mechanical extraction also involves procedures like steam explosion or heat steaming, high pressure refinery, crushing and super grinding, etc. (Kim et al., 2013). Zakikhani et al. (2014) have summarised the pros and cons associated with various methods of extraction of bamboo fibres. Apart from the difference in the technique adopted for extraction, the mechanical processes are classified on the basis of fibre quality as well. Yao and Zhang (2011) have reported that fibres obtained are rough in texture if the sequence of operations is cutting, separation, boiling and fermentation with enzymes. On the other hand, to obtain fine fibres, one should opt for the sequence: boiling, fermentation, washing and bleaching, oil-soaking and air-drying. In contradiction to chemical methods, the mechanical methods of bamboo fibre extraction are environment friendly and less time consuming as well (Khalil et al., 2012). On the other hand, mechanical methods, being more labour intensive and expensive, are less preferred by the clothing sector (Das, 2014).
2.2. Chemical Route of Bamboo Fibre Production

When it is required to have a regenerated bamboo viscose fibre for the end-use application, the moso bamboo stalks ought to be freed from lignin and hemicellulose. Several techniques like acid or alkaline pre-treatment, wet oxidation, steam pre-treatment, ammonia fibre explosion have been explored by various researchers (Hong et al., 2013). The basic idea is to cook the leaves and woody shoots of the bamboo plant in these strong chemical solvents and then perform alkaline hydrolysis combined with multi-phase bleaching. The process is like conventional viscose manufacturing process; and even the product obtained is similar to rayon or modal. This regenerated cellulosic form of bamboo was first introduced by Hebei Jigao Chemical Fibre Co. Ltd, China in 2002, though its origin dates back to 1864 when it was patented by Lichtenstadt (Waite, 2009). The details of the most common process sequence are depicted through a flow chart in Fig. 2.2.1.

To produce regenerated bamboo or bamboo viscose fibre, the leaves and inner pith of hard bamboo tree trunk are extracted, crushed and soaked in sodium hydroxide (NaOH) solution. The alkali cellulose which is generated in the process is pressed to squeeze out the excess solution, followed by shredding it so as to create more surface area for easy processing of cellulose. Thereafter, the shredded cellulose is kept in open to let it dry in the presence of ambient oxygen. Subsequently, carbon disulphide is added to the cellulose to cause gelling; and the excess of it is removed via evaporation. Later, it is ripened, filtered, degassed and finally, the bamboo viscose is wet-spun, i.e., forced through spinneret nozzles into dilute sulphuric acid solution, wherein the

![Fig. 2.2.1. Process sequence of alkaline hydrolysis-multiple phase bleaching mode of bamboo fibre extraction.](image-url)
cellulose sodium xanthate gets hardened and is reconverted to bamboo viscose filaments. In other words, sulphuric acid ($\text{H}_2\text{SO}_4$) behaves like a quenching solution allowing the strands to solidify into fibre and hence capable of being spun into a yarn (Erdumlu and Ozipek, 2008).

Researchers have conducted a number of studies to determine the best mode of retting, i.e., acid retting or alkali retting or chemical assisted natural (CAN) retting (Kaur et al., 2013), where the CAN retting route has been found to be most efficient for the pre-treatment of bamboo cellulose for its wet spinning. Studies on the optimisation of process parameters, so as to yield a fibre of desired characteristics, have also been documented (Hong et al., 2013; Zakikhani et al., 2014).

Often, concerns are raised on the eco-friendliness of the chemical route of bamboo viscose fibre production. Carbon disulphide is known to be toxic, consequently posing a threat to factory workers, as well as polluting the environment via air emissions and wastewater. Its recovery in most industries is about 50 per cent only. Also, sodium hydroxide and sulphuric acid too fall under the category of potentially hazardous chemicals (Copeland, 2010). One remedy is to opt for a process similar to lyocell process used for the manufacturing of Tencel. Here, N-methylmorpholine-N-oxide (NMMO) is used as a solvent and the hardening bath is generally water-methanol solution, both being non-toxic. Also, the process being closed-loop, 99.5 per cent of the chemicals used are recycled for re-usage, emitting only fractional traces into the environment (Das, 2014).

However, the outburst of bamboo fabric in the market has occurred on the basis of false eco-claims of bamboo being environment-friendly alternative to cotton, silk and polyester. Customers were wooed by spreading manipulated information about bamboo viscose fabric. Moreover, the soft touch and silk-like drape lured the customers who were unaware of the usage of toxic chemicals for processing of tough cellulose bamboo plant into soft fibres. Considering these facts, the US Federal Trade Commission (FTC) imposed stringent guidelines for the manufacturers: a product cannot be labelled as bamboo unless it is made from mechanically processed bamboo. It ought to be termed as 'bamboo viscose' or 'bamboo rayon' in case it is made out of cellulose regenerated from bamboo stalks (Federal Trade Commission, 2009).

2.3. Combination of Mechanical and Chemical Routes

This procedure is more common in paper and pulp industry in comparison to textile industry. Chemical treatment of bamboo strips is followed by either compression moulding or roller milling. The combination of both mechanical and chemical treatments results in better separation of fibres (Zakikhani et al., 2014).
2.4. Biological Approach to Bamboo Fibre Extraction

Generally, chemical method is most common one for the production of bamboo fibres. However, the processes involved are expensive and cause negative impacts on the environment and human health which calls for an improvement through closed-loop manufacturing strategies, better equipment, and usage of eco-friendly compounds to extract fibres. Hence, alternative green technologies for fibre recovery from bamboo have come into picture (Fu et al., 2011).

Various biological approaches for the production of macro-, micro- and nano-sized fibres from raw bamboo have been reported (Liu et al., 2012). Indigenous complex bacterial communities are used for the production of enzymes like hemicellulases, pectinases, oxidoreductases, etc. in order to extract fibres from the bast. They separate the cellulosic fibre bundles from the matrix (Fig. 2.4.1.) and affect the quality and the yield of the fibre. Fu et al. (2012) have verified that bio-retting of bamboo is a very gentle pre-treatment process and yet as effective as other conventional techniques.

![Fig. 2.4.1. Morphological changes of bamboo culms during the retting process. (a) Initial stage - bamboo is intact, (b) bamboo fibre loosening and de-pilling and (c) fibres separating from each other and falling into the lumen of the culm. Source: Fu et al., 2011.](image)

3. Properties of Bamboo Fibres and Their Products

The properties of the bamboo fibres are inconsistent with respect to time owing to the decrease in their cellulose content with aging (Khalil et al., 2012). Moreover, the method of extraction of fibre plays a significant role in defining the characteristics of the end-product. Since the manufacturing of bamboo pulp fibre follows a technique similar to that of viscose production, it is quite easy to predict the structure and properties of the same. Also, the chemical techniques involve cheap equipment, low energy consumption and an easy control over fibre properties when compared to steam explosion and mechanical methods of processing (Phong et al., 2012). Further, different methods have different potential to remove lignin which contributes to stiffness and yellowing of bamboo fibres. Simultaneously, the non-cellulosic components too affect fibre properties like strength, density, moisture absorbency,
flexibility, etc. (Li et al., 2010). The fabric woven out of mechanically extracted fibres have a rough and stiff feel, whereas, the one woven out of viscose-type chemical process possesses a very soft handle and good drape. Another difference is reflected in terms of strength and durability which is higher in case of mechanically processed fibres. These differences can be attributed to the alteration in physical form of the fibre during chemical processing which leads to the modification of molecular orientation within the fibre, and also its degree of polymerization. Hence, even though the bamboo viscose fibre is essentially same in chemical nature as its raw form, the yarns and fabrics manufactured out of both behave differently.

3.1. Studies Related to Pure/Virgin Bamboo Fibres

Natural bamboo fibres are similar to ramie fibres, but finer and shorter. The length of individual natural bamboo fibre varies between 1 mm to 5 mm (average 2.8 mm) and diameter 14 μm to 27 μm (average 20 μm); 10-20 individual fibres are packed into bundles. As evident from the low magnitude of fibre length, several problems are associated with their processing. Hence, these are mostly used as technical fibres for manufacturing nonwovens. They have a rough surface and a round cross-section with a small round lumen. The chemical structure of bamboo fibres comprises 57 to 63 per cent cellulose (36 to 41% α-cellulose), 22 to 26 per cent lignins and 16 to 21 per cent pentosans (Lipp-Symonowicz et al., 2011). Several researchers have tried to investigate the properties of pure bamboo fibres and the fabrics made out of them. Tao and Jiang (2011) analysed various features of bamboo fibres like fibre length and distribution, linear density, cross-section, degree of crystallisation, orientation, breaking strength, breaking elongation in dry and wet state, etc. Yang et al. (2006) investigated the change in strength, elongation and initial modulus with respect to temperature and time for natural bamboo fibres and bamboo pulp fibres.

Owing to its hollow cross section, bamboo fibre imparts breathability to the fabrics made out of it, making them cool and comfortable to wear. Also, such fabrics possess high hygroscopicity and are, hence, easy to dye and finish (Yao and Zhang, 2011). The fibre form of bamboo retains many of the properties it possessed in the plant form. One of the most important of such properties is hygroscopicity to the level of absorbing three times its weight of water. This is due to presence of micro-gaps and micro-holes in the fibre which, in turn, imparts excellent wicking ability to the fabric such that moisture is instantly pulled away from the skin and soon evaporated, giving a cooling sensation (Xu et al., 2007). Owing to the large amount of micro-cracks and grooves on the fibre surface, the fabrics have high breathability and thermo regulating properties, even higher than those made out of cotton and hemp. Also, they are believed to exhibit lower shrinkage, higher sorption of dyes, better colour
clarity, more wrinkle resistance and better lustre without mercerization in comparison to cotton fabrics (Sheikh, 2013).

Wang et al. (2009) evaluated the performance of a fabric manufactured out of a mechanically extracted bamboo fibre and concluded that the fabric possessed tremendous water and moisture absorbency, as well as better pilling and abrasion resistances under both dry and wet conditions, in comparison to flax and jute. However, the washing fastness was found to be unsatisfactory even under normal washing conditions, leave aside harsh conditions.

The fibre is devoid of any sharp spurs that could potentially cause any irritation to skin. Even, people who develop skin allergies to other natural fibres like wool and hemp do not show any such reaction on wearing bamboo next to their skin. Moreover, since the bamboo fibre is devoid of any free electrons, the fabric made out of it is antistatic, thus, fitting very well next to the skin, flowing lightly over the body without clinging to it (Das, 2014).

The most beneficial property that bamboo carries from its plant form to fibre form is its anti-bacterial activity. Bamboo plant contains a bacteriostasis bio-agent, 'bamboo-kun', i.e., 2,6-bimethoxy-p-benzoquinone, which imparts the plant natural resistance to microbes; and the protein dendrocin that has highly distinctive fungal resistance (Lipp-Symonowicz et al., 2011). These substances are bound very firmly to the bamboo cellulose molecule and are hence retained even after mechanical processing. Consequently, bacteria or mildew get killed on a bamboo fabric unlike on other cellulosic cousins of bamboo which facilitate their propagation leading to foul odour and even fibre degradation in worse cases. In fact, bamboo was used in ancient Chinese medicine owing to this property. A study conducted by the National Textile Inspection Association, China (NTIA), Shanghai, Microorganism Research Institute and Japan Textile Inspection Association showed that even after 50 washes, bamboo fabric possessed considerable anti-bacterial property. Moreover, being natural, it has no potential threat of causing skin allergy as in the case of chemical anti-microbial finishes (Das, 2014). Another justification for the inherent bacterial-resistance of bamboo is the presence of chlorophyll and sodium copper chlorophyllin which perform the function of antibiotics and deodorisation. This too has been verified by the Japan Textile Inspection Association. Also, some studies suggest the reflectivity of bamboo fabric to be lower than that of flax and cotton, implying that the bamboo fabric is a good absorbent of UV radiations. Moreover, the sodium copper chlorophyllin present in bamboo fibre has twenty times higher capacity to absorb UV radiations than cotton fibre (Yao and Zhang, 2011). The UPF of natural bamboo fibre is 22 which is considerably greater than that of ramie, i.e., 12 (Pavko-Čuden and Kupljenik, 2012).
Finally, the natural or 'virgin' bamboo fabric is completely biodegradable in soil and does not decompose into pollutants like methane. Hence, clothing made of pure bamboo has a negligible environmental footprint. So, it can be composted in an organic manner, unlike the synthetic fibres which do not deplete in the landfills for decades.

3.2. Studies Related to Bamboo Viscose Fibres

Of late, there has been extensive amount of research conducted on bamboo viscose fibres and their yarns and fabrics. Sarkar and Appidi (2009) reported that bamboo viscose is nothing but cellulose II with a low degree of crystallinity and high water retention and release ability. Consequently, the fibre exhibits desirable comfort, aesthetic and processing properties like good moisture absorption, permeability, soft handle, pleasing tactile sensation, excellent dye-ability, etc.

Fibres can possess a huge variety of cross-sectional shapes which determines yarn packing density and, in turn, strongly influences the low stress mechanical behaviour of corresponding fabrics. Also, the morphological parameters like free space inside the fibre, presence of crystalline and amorphous regions, degree of crystallinity, etc., too have affect on the mechanical behaviour of fibre and, hence, the fabric characteristics as well (Mishra et al., 2012).

Xu et al. (2007) found the cross-section of bamboo viscose fibre to be irregular and toothed (Fig. 3.2.1.), and confirmed that both longitudinal and cross sectional morphology of bamboo viscose fibre are fairly similar to these of regular viscose rayon fibre. They also spotted some striated cracks distributed over the length of bamboo viscose fibres and many voids in their cross-section, both of them being suggestive of good water retention capacity. The same was later validated by Erdumlu and Ozipek (2008) and Hardin et al. (2009) as well.

![Fig. 3.2.1. SEM micrographs of bamboo viscose fibre. (a) cross-sectional and (b) longitudinal.](source: Xu et al., 2007.)
Xu et al. (2007) also compared the properties of bamboo viscose fibre with those of viscose rayon, cotton and modal fibres. They noted that bamboo viscose and viscose rayon are similar in terms of dry tenacity, elongation at break and moisture absorption. However, the wet tenacity bamboo viscose was found to be slightly higher than that of viscose rayon. In comparison with cotton and modal, bamboo viscose was seen to possess lower tenacity, both in dry and wet states. Kaur et al. (2013) established that bamboo fibre is capable of being blended with various other fibres like cotton, hemp, modal, lyocell, etc. to achieve myriad combinations of properties.

Moving on from fibre level to yarn level, there is a scarcity of detailed analysis on the properties of 100 per cent bamboo viscose and bamboo fibre blended yarns. In an attempt to establish the usability of 100 per cent bamboo viscose fibre, Erdumlu and Ozipek (2008) manufactured yarns of six different counts and compared them with global level yarn quality of 100 per cent viscose rayon ring spun yarns, as well as, 100 per cent carded and combed cotton yarns of corresponding linear density as per Uster Statistics 2007. They found out that the breaking tenacity, elongation at break and yarn regularity decrease with increase in fineness of yarn which is the general trend observed for all kinds of spun yarns. The breaking elongation of bamboo yarn samples was observed to be within 5 per cent of the world level when compared with carded and combed ring spun yarns, and between 5-25 per cent of the world level when compared with 100 per cent viscose ring spun yarns. However, a threshold count is mandatory to achieve the commercial properties, below which blending with other fibres might be required to satisfy the requirements.

Majumdar et al. (2011) manufactured ring-spun yarns of different counts (20, 25 and 30 Ne) from 100 per cent bamboo viscose fibres, 100 per cent cotton fibres, and cotton/bamboo viscose (50:50) blended yarns and, thereafter, tested them for diameter, tensile, evenness and hairiness related properties. The study highlighted various interesting phenomena, supported with the reasons behind the same. Bamboo viscose blended yarns were found to exhibit lower diameter than the equivalent cotton yarns implying better packing of bamboo fibres in the yarn cross-section as compared to the cotton fibres. Besides, the bending rigidity of yarn was also found to reduce with an increase in the percentage of bamboo fibres owing to the reduction in diameter of the yarn and decrease in tensile modulus. The yarn tenacity was lowest for 50:50 cotton/bamboo viscose blended yarns as depicted in Fig. 3.2.2. It can be attributed to lower load sharing by the bamboo fibres at the point of rupture of their neighbouring cotton fibres which could have happened because of a wide difference in the breaking extension of these individual components.

The breaking elongation was found to increase continuously with the increase in the proportion of bamboo fibres, whereas the initial modulus was observed to follow an opposite trend. The mean hair length was seen to reduce continuously with
increasing percentage of bamboo viscose fibres (Fig. 3.2.3.). However, it was found to be independent of the yarn count for the same blend proportion. Scanning electron microscopic images (Fig. 3.2.4.) show that the fibres are more uniformly and compactly twisted in bamboo viscose yarn, whereas the packing is loose in cotton

Fig. 3.2.2. Stress-strain behaviour spun

Fig. 3.2.3. Effect of fibre proportion on mean hair length.
Source: Majumdar et al., 2010.
yarn. This can be attributed to lower bending and torsional rigidities of bamboo viscose fibres. Such a structure of bamboo viscose yarn is expected to show better air permeability and moisture vapour permeability in the fabric manufactured out of it.

Studies have also been performed for investigating the characteristics of fabrics made out of bamboo viscose fibres and their blends. Mishra et al. (2012) prepared plain woven fabrics from 100 per cent cotton, 100 per cent viscose rayon, 100 per cent regenerated bamboo viscose fibre and cotton/bamboo viscose blend (60:40) and then characterised them for hand values by analysing their tensile, bending, shear and compressive deformation at low stress. Bamboo viscose fabric showed better tensile extensibility than cotton and the cotton/bamboo viscose blended fabrics. Shear rigidity was higher for cotton and cotton/bamboo viscose blended fabrics than 100 per cent viscose rayon and 100 per cent bamboo viscose fabrics in both warp and weft direction, which is strongly suggestive of lower comfort, as well as, lower hand value in cotton and cotton blends. The overall bending rigidity was also higher in the case of cotton fabric due to its higher stiffness, higher diameter of constituent yarn than that of bamboo viscose and viscose rayon yarns. The total hand value was calculated to be higher for viscose rayon and bamboo viscose fabrics than cotton fabric.
Low stress mechanical properties of plain woven fabrics made from cotton, bamboo viscose and cotton/bamboo viscose blended yarns were investigated by Majumdar and Pol (2014). Three blends (100% cotton, 50:50 cotton/bamboo viscose and 100% bamboo viscose) were used to produce three yarn counts (20, 25 and 30 Ne) and each of these yarns was used to make fabrics with different pick densities. It was observed that the bending rigidity, bending hysteresis, shear rigidity, shear hysteresis and compressibility are lower for bamboo viscose fabrics as compared to those of 100 per cent cotton fabrics (Fig. 3.2.5.). On the contrary, extensibility, tensile energy and compressional resilience increase with the increase in the proportion of bamboo viscose fibres. The linearity of load-elongation curve was noted to decrease with the increase in the proportion of bamboo viscose fibres and with a decrease in the pick density. High proportion of bamboo viscose fibres, fine yarn count and low pick density showed lower shear and bending resistance in the fabrics. Higher proportion of bamboo viscose fibres and higher pick density yield higher compressional resilience. Such values were suggestive of bamboo fabrics giving a softer handle than the virgin cotton fabrics making the former suitable for apparel applications.

Apart from low-stress mechanical parameters, thermal properties, air permeability and water vapour permeability are also highly important in determining the comfort characteristics of a fabric. Considering this fact, Majumdar et al. (2010)
carried out an extensive study, wherein they chose three blends of fibres (100% cotton, 50:50 cotton/bamboo viscose and 100% bamboo viscose) to produce three yarn counts (20, 25 and 30 Ne) which were further knitted into three types of structures, viz., plain, rib and interlock, as depicted in Fig. 3.2.6.

Thermal conductivity of all types of knitted fabrics was found to decrease with an increase in the bamboo viscose component in the fabric owing to their lower inherent thermal conductivity value than that of natural cotton. Further, for the same blend composition, thermal conductivity was observed to decrease with increasing fineness of yarn owing to corresponding increase in the porosity of fabrics knitted from them. However, at constant blend proportion and yarn count, the thermal conductivity was found to be maximum for interlock fabrics and minimum for plain knitted fabrics. It is known that interlock structure is the tightest of all and, hence, has lowest porosity which vividly explains its highest thermal conductivity. Moreover, being the thickest of all the three structures, it also showed highest thermal resistance at same blend composition and yarn fineness. Thermal resistance value of plain knitted structures was seen to reduce with increase in the proportion of bamboo viscose fibres due to reduction in fabric thickness.

Majumdar et al. (2010) also found that air permeability increased with an increase in the proportion of bamboo viscose fibres in all knitted structures under investigation. This can be explained on the basis of lower diameter of bamboo viscose yarns than cotton yarns of equivalent count, causing tightness factor of viscose blended fabrics to be lower than cotton ones, allowing better passage of air through the fabric. The hairiness of bamboo viscose blended yarns was also seen to be lower than cotton ones
(as shown in Fig. 3.2.7.) which could be another contributing factor towards higher air permeability.

![SEM image of plain knitted fabric made from 24 tex yarn](image)

Fig. 3.2.7. SEM image (100 X) of plain knitted fabric made from 24 tex yarn. (a) One hundred per cent bamboo viscose, (b) one hundred per cent cotton and (c) 50:50 cotton/bamboo-viscose.


The diffusion induced water vapour transmission for the bamboo viscose fabrics was found to be higher than that of cotton fabrics due to higher moisture regain of the former fibre type. Among the three knitted fabrics, plain structure was found to have maximum water vapour permeability followed by rib and interlock structures. The reason could be attributed to the lower areal density and thickness of plain fabrics as compared to those of the other two structures.

Even Mishra *et al.* (2012) had investigated the thermal comfort characteristics of bamboo viscose fabrics while testing them for low stress mechanical properties. They concluded that the average water vapour permeability of bamboo viscose fabric was higher and water vapour resistance was lower than that of cotton fabric. This could be a consequence of the micro-channels running along the length of the bamboo viscose fibres, facilitating rapid absorption and transmission of moisture. In yet another work, fabrics knitted from bamboo viscose and its blends with various other fibres like organic cotton, elastane and polyester were analysed and reported to possess high moisture absorption, air permeability, porosity and pleasant hand (Pavko-Čudan and Kupljenik, 2012). Cimilli *et al.* (2009) studied comfort properties of socks made from different fibres like modal, micromodal, bamboo, soya bean, chitosan, etc. and further compared them with cotton and viscose. The socks from bamboo and soya bean fibres exhibited maximum thermal resistance and good water vapour permeability. Gun *et al.* (2008) analysed the dimensional and physical properties of fabrics knitted out of blends of modal, bamboo viscose and conventional viscose with cotton and reported the bamboo viscose-cotton blended fabric to be least prone to pilling.
3.3. Controversial Properties of Bamboo Viscose Fibres

There are quite a few ambiguities related to bamboo fibres which are misleading for users. In late 2006, a number of textile manufacturers, especially online retailers, started advertising bamboo fabrics possessing very soft touch, exhibiting deeper shades than cotton, having excellent UV protective and natural anti-microbial properties and grown in a very eco-friendly manner. This was instigated by the government authorities and the researchers across the globe to probe into such claims and unleash the truth behind the actual nature of bamboo being used in these unique garments (Lipp-Symonowicz et al., 2011). Hardin et al. (2009) bought such samples to investigate their morphology for identification of the fibre and also to test their anti-microbial activity. The fibres appeared very similar to conventional viscose rayon fibres, implying they were not 'pure' bamboo of the bast kind, but spun from regenerated cellulose of bamboo. Also, the samples did not show any anti-microbial activity, proving the fibre to be simply rayon type and not 'virgin' bamboo. Following this, the FTC charged fraud sellers of deceptive labelling and misleading advertising. Even the Competition Bureau of the Canadian Government established precise guidelines for the labelling of textile products directly or indirectly derived from bamboo (Competition Bureau, 2009).

It is already known that mechanically processed bamboo fibres can resist pest and fungi-infestation as they maintain the innate anti-microbial property of the bamboo plants due to the presence of bamboo-kun and dendrocin. However, the fibres obtained from regenerated cellulose of bamboo plant fail to retain them. Despite this fact, several researchers still state bamboo viscose fibres to exhibit anti-bacterial, anti-fungul and UV protection properties (Pavko-Čuden and Kupljenik, 2012). Chen and Guo (2007) compared the anti-bacterial properties of a bamboo viscose jersey with that of a common wood pulp jersey and declared the former to possess natural anti-bacterial effects. However, they attributed this effect to the hollow structure of the bamboo viscose fibres that facilitates absorption of humidity followed by its evaporation. Mishra et al. (2012) also observed the anti-bacterial property of bamboo viscose fabric to be superior to that of a cotton fabric. They had justified this behaviour due to the interaction of phenolic compounds still present in the bamboo viscose fibres with the bacterial membrane. Interestingly, attempts are being made for the antibacterial modification of bamboo viscose fibres using Ag, Cu or ZnO nanoparticles to ultimately obtain a grafted composite fabric out of it. Chitosan, a natural bio-polymer, has also been explored for the same with an intention to have a safe antibacterial agent for the apparel textile material (Sheikh, 2013).

In context of claims made for excellent UV protection property of bamboo viscose fabrics, several researchers have contradictory opinions. At the time, when the
FTC was taking rigorous actions to verify the validity of the tall claims made by bamboo fabric retailers, the Competition Bureau had also demanded evidences from the manufacturers, in support of UV-blocking claims (Competition Bureau, 2009). Sarkar and Appidi (2009) found untreated bamboo viscose to be incapable of providing protection against UV radiations, and rather suggested various treatments to impart both UV-protective and anti-microbial property to it. Observing that untreated bamboo exhibits optical reflectance, Afrin et al. (2012) tried to analyse its chemical structure to trace the roots of its UV absorption property. They reported lignin to be the origin of it, thereby, suggesting that bamboo viscose produced by conventional methods, would be incapable of providing UV protection since the lignin gets depleted during the degumming process. On the contrary, Mishra et al. (2012) demonstrated 100 per cent regenerated bamboo viscose fabric to have an excellent UPF rating. Also, Mahish et al. (2012) reported that UPF rating of bamboo/polyester blended fabrics increases with increase in the proportion of bamboo component. Considering the conflicts in the findings, Hatua et al. (2013) performed a comparative analysis on a set of eighteen fabrics made out of 100 per cent cotton and 100 per cent bamboo viscose yarns, using curve fitting technique. Yarns of three different counts (20, 25 and 30 Ne) were taken and fabrics with three pick densities (50, 60 and 70 PPI) for each count were woven for both cotton and bamboo viscose. Although the bamboo viscose fabrics demonstrated higher UPF in comparison to the cotton fabrics woven with same PPI and yarn count, it was not enough evidence to declare bamboo viscose to be inherently better than cotton in respect of UV protection. This is because the UPF values for cotton and bamboo viscose fabrics with comparable cover factor and areal density were found to be similar. For fabrics woven with same construction parameters, bamboo viscose fabrics performed better owing to higher areal density and cover factor than their cotton counterparts. Hence, it can be concluded that bamboo viscose is incapable of providing better protection than cotton against ultraviolet radiations.

4. Conclusion

As a consequence of the promotion of their unique properties, bamboo products have established a mark in the apparel textiles industry. The products manufactured from bamboo viscose dominate the market because of their considerably lower price and easy-to-maintain processing conditions. However, owing to faulty labelling, the products made from natural bamboo and from regenerated bamboo fibres are often confused with each other. Therefore, it is of prime importance to correctly distinguish between the virgin bamboo fibres from bamboo viscose fibres.

The foremost difference lies in the fact that pure bamboo fibre is obtained directly from the bamboo stalk, whereas the viscose form is obtained by regeneration of the raw
bamboo cellulose and, thereby, leaving minimal traces of original bamboo in it. The natural bamboo fibres resemble ramie, hemp and flax in terms of both molecular structure and performance attributes. For example, it maintains many of the inherent characteristics of bamboo like UV resistance, antibacterial and deodorant properties, being highly hygroscopic and yet exhibit breathability, low wrinkle resistance and launderable. On the other hand, bamboo viscose resembles silk in appearance (sheen, drape and feel) but not in respect of performance. Also, its morphology and degree of crystallisation are comparable with those of conventional viscose. An important point to be noted here is that the chemical processing of bamboo fibres is often questioned for its eco-friendliness. Though the conventional process is associated with emission of toxic chemicals in the ambience, but manufacturers have been exploring ways to minimise it.

In a nutshell, the user should be vigilant while selecting any bamboo product by first investigating its origin so as to determine its horizon of applications. Moreover, as both natural bamboo and bamboo viscose can be easily blended with other fibres, there is a wide scope to exploit the properties of both the fibres as per the requirements.

References


