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Polylactic acid/Lyocell fibre as an eco-friendly alternative to Polyethylene terephthalate/Cotton fibre blended yarns and knitted fabrics

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Abstract

Polylactic acid (PLA) and lyocell fibres blend can offer an eco-friendly alternative to commonly employed blend of polyethylene terephthalate (PET) and cotton fibres in textiles. PET fibre is non-biodegradable and depletes fossils fuels and adds to landfill sites whereas conventional cotton, dominant part of global cotton production, requires large quantity of water and pesticides during its production. In this study, 100 % PLA, 100 % lyocell and PLA-lyocell (PL) blended yarns, in varying ratios, were ring spun and subsequently weft knitted and compared with the PET/cotton blend (50/50). The yarns were evaluated for tensile properties while the fabrics were investigated for bursting strength, bending length, pilling propensity, water vapour resistance, thermal resistance and air permeability. The economic comparisons of the two blends were also included. The results indicated that

comparatively PL blends (in particular lyocell fibre rich blends) can offer environmental and performance advantages compared to PC blended knitted fabrics for casual summer clothing and active wear.

Keywords: Lyocell, polylactic acid, eco-friendly, cotton, spinning, blend

1 Introduction

The production of textile fibres has grown to nearly one hundred million metric tonnes with major categories being synthetics (63%), cotton (24%), regenerated cellulosics (7%), other natural fibres (5%) and wool fibres (1%) ("World Production of Cotton, Wool & Man-Made Fibres," 2016). Less than 1% of crude oil ends up as synthetic fibre ("Synthetic fibers," 2016) and polyester is the dominant synthetic fibre with a production of 55 million tonnes. The world fibre demand has a linear positive correlation with growth in GDP and the world fibre production is forecast to reach 130 million tonnes by 2025 (Qin, 2014). In addition, the recent substantial decrease in oil prices has further advantaged the price competitiveness of synthetic fibres. Textile industry has historically followed linear economy approach and the global trends of fast fashion have aggravated the environmental footprint of the industry. The choice of non-renewable resources can have hazardous impact on the environment as well as future supply chains. In line with the United Nations sustainable development goal to "ensure sustainable consumption and production patterns" ("Sustainable Consumption and Production," 2017), the choice of sustainable means to develop compostable, biodegradable and carbon neutral life cycle products is vital to reduce the environmental footprint of the textile industry (Tausif, Ahmad, Hussain, Basit, & Hussain, 2015). This can be achieved by but not limited to, the choice of sustainable materials, production processes and end-of-life recycling options. Polyethylene terephthalate (PET) fibre, cotton fibre and their blends are dominant raw materials, employed in the global textile industry as cotton and polyester staple fibres constitute for 58% and 28% of staple yarns , respectively (Chapman, 2010). Moreover, globally 40 % of textile clothing is comprised of cotton (Jacob, Francis, Thomas, & Varughese, 2006) and around 60 % contains polyester ("FAST FASHION, FATAL FIBRES," 2017). Textiles from blends of PET and cotton fibres offer advantages of strength, crease resistance, comfort and easy-care properties (Hagen, 2013; van der Velden, Patel, & Vogtländer, 2014) but PET–cotton production exerts the huge environmental impacts on marine aquatic ecotoxicity potential, global warming potential, and abiotic depletion (Zhang et al., 2018). Cotton is a natural fibre but to produce 1 kg of cotton fibres, require more than 20,000 litres of water (Hagen, 2013) and it accounts for 24% and 11% of the global sales of insecticide and pesticides respectively

(Allwood, Laursen, de Rodriguez, & Bocken, 2006). The use of high amount of fresh water is known to already have caused social and ecological issues in certain geographic areas (R. Blackburn, 2009). The use of organic cotton and genetically modified (GM) cotton is advantageous to some extent however, the problem of more fresh water usage and use of insecticides and pesticides still persists. Lyocell, a solvent spun fibre from wood pulp, is claimed to be a sustainable fibre because of replenished feedstock (sustainable managed forests), biodegradability and >99.5% organic solvent recycling efficiency during the fibre production. Lyocell is a biodegradable and absorbent with high dry and wet (contains 85% of dry) tensile strength. The mechanical action under wet states results in surface fibrillation of the lyocell fibre caused by highly oriented cellulose molecules. The fibrillation could be a disadvantage or can also be employed as an advantage in certain applications. The fibrillation can be controlled by the application of appropriate cross-linking agents usually before the dyeing operation (R. S. Blackburn, 2005). The hygroscopic nature of the lyocell fibre helps in temperature regulation of human body owing to high heat capacity of the water (Firgo et al., 2006). Lyocell fibre can be blended with a range of natural and man-made fibres such as polyester, wool, cotton and spandex to add performance and comfort in a clothing item (Gandhi, Burkinshaw, Taylor, & Collins, 2002; Kilic and Okur, 2011; Stanton et al., 2014).

Polyester (mainly polyethylene terephthalate, PET) is the most commonly employed textile fibre with over 50% share in total production of textile fibres. It has overall excellent performance characteristics however, it is a non-biodegradable fibre which depletes fossils fuels and adds to landfill sites (R. S. Blackburn, 2005). The recycled polyester fibers are being used as an alternative in different textile applications and are being researched for clothing applications although they have inferior mechanical properties (Yuksekkaya, Celep, Dogan, Tercan, & Urhan, 2016).

An alternative polyester can be bio-based polylactide (PLA) (Avinc and Khoddami, 2010). PLA is a thermoplastic aliphatic compostable polyester derived from renewable resources, such as corn starch (in the United States), tapioca roots, chips or starch (mostly in Asia) or sugarcane (in the rest of the world) (Drambei, Ciocoiu, Drambei, & Craus, 2009; Jeyaraj, Arumugam, & Kulandaiappan, 2015).

The world PLA market, by revenue, is valued at US $ 698 million in 2017 and it is expected to attain US $ 2,091 million by 2023 with packaging and fibres being the key areas of application ("Polylactic Acid (PLA) Market," 2018). In apparel, PLA fabrics offer good moisture management properties for sportswear, active wear, underwear and fashion wear due to its excellent wicking ability, fast moisture spreading and drying (Fletcher, 2013; Prakash, Ramakrishnan, & Koushik, 2012). PLA fibre has major application in packing industry and currently only around 2 % of PLA is used in the form of textile fibres ("Biodegradable plastics demand to grow 15% annually to 2015," 2013).

Owing to eco-friendly advantages of PLA and lyocell fibres, their blends can potentially be a sustainable alternative to PET and cotton fibres blend (Allwood, et al., 2006). PET/cotton (PC) blended apparels have many cost and performance advantages but with growing awareness around the world on water conservation and focus on biodegradable and sustainable resources, the fabrics produced from environment friendly fibres can offer an eco-friendly alternative (Hes, 2002). In a study (Sülar, Oner, Devrim, Aslan, & Eser, 2016), knitted fabrics were developed from PLA, Modal and Tencel fibres and their performance and biodegradability characteristics were compared with those of polyester fibre and its blends with viscose and cotton fibres. The results concluded that fabrics made from PLA, polyester and blends of polyester have shown better mechanical and moisture management performance. However, the current study aims to develop eco-friendly PLA and/or lyocell blended yarns and fabrics on an industrial scale, and therefore is commercially relevant, not only to compare the performance characteristics but also the financial viability, with yarns and knitted fabrics of a commonly employed blend (50/50) of PET and cotton fibres. The physical, mechanical and comfort properties of 100% PLA, 100% lyocell and their blends (25/75, 50/50 and 75/25) would be studied and compared with commonly employed PET and cotton blended yarns and knitted fabrics. In addition, an economic comparison of the two blends, PL and PC, would be carried out to highlight the financial viability of the PL blend in comparison to prevalent PC blend.

2 Materials and methods

2.1 Materials

Polylactic acid (PLA, Palmetto Synthetics LLC), lyocell (Tencel®, Lenzing AG), polyethylene terephthalate (PET) and cotton fibres were sourced. The properties of selected fibres are given in Table 1 and characteristic strength-elongation curves are plotted in Fig. 1.

2.2 Methods

2.2.1 Yarn production

100% PLA, 100% Lyocell and three different blend ratios of these two fibres (75:25, 50:50 and 25:75) were employed to prepare five different types of yarns. For comparison, a conventional PET/cotton blended (PC) yarn was also spun in 50/50 blend ratio only. The nominal linear density of all ring spun yarns was 19.7 Tex (N_e 30/1). The yarns were produced on an industrial ring spinning line (Nishat Textile Mills, Pakistan). The sliver blending of the fibres was carried on a drawing frame. The detail of machines, in the sequence of line, is given in Table 2. The spun yarns were tested for unevenness (U%), imperfection index (IPI) and hairiness. The results are presented in Table 3. Imperfection Index (IPI) was calculated by adding -50% thin, +50% thick and +200% neps of the average value. The microscopic images (Leica M205C) of prepared yarns are shown in Fig. 2.

2.2.2 Fabric production and processing

The spun yarns were employed to knit single jersey fabrics on a weft knitting machine (Fukuhara, Japan), at 0.26 and 0.30 stitch lengths. The knitted fabrics were treated in water at 100°C for 15 minutes to remove the water-soluble impurities and subsequently washed (27±3 °C, 645 rpm spin speed, washing time 12 min, final spin time 6 min and tumble dried) before any characterisation and testing. The physical properties of prepared knitted fabrics are given in Table 4.

2.2.3 Characterization and testing

The tensile properties of yarns were determined according to ASTM D2256-02. The bursting strength of fabric samples was tested using pneumatic bursting strength tester by SDL Atlas as per ASTM D 3787-07. The bending stiffness of the samples was measured using standard test method ASTM D1388-08. The pilling propensity of knitted samples was assessed according to ISO 12945-1:2000, pilling box method, for 5,000 revolutions. The fabric was rated on a scale of 1 to 5 (1─dense surface fuzzing and/or severe pilling and 5─no change). Thermal (Rct) and water vapour (Ret) resistance of knitted samples were evaluated according to ISO 11092:1993, with a sweating guarded hotplate (M259B, SDL Atlas). The air permeability of fabric samples was measured according to standard test method ASTM D737-96 (M021A, SDL Atlas).

3 Results and Discussion

3.1 Tensile properties of yarn

Fig. 3a shows the typical load-elongation curves of yarns under study and the results of tenacity and breaking elongation of yarns are plotted in Fig. 3b. The 100% PLA yarn exhibited lowest strength and highest breaking elongation, among the studied samples, and can be associated to the high breaking elongation of the constituent fibre. The strength was found to increase with the increase in proportion of lyocell fibre in the PL blends which can be explained by the fact that lyocell fibre is stronger than PLA fibre (Fig. 1). The other reason may be the finer lyocell fibre as compared to PLA (Table 1) as greater fibre fineness contributes to a greater number of fibres in the cross section of yarn of given fineness. In the PL blended yarns, the contribution of PLA fibres to overall tensile strength of the yarn is lower as the lyocell fibres fail earlier due to lower elongation at break (11%) as compared to elongation at break of PLA fibre (52%). Hence, the low tensile stress in the PLA fibres at the breaking elongation of lyocell fibre results in little contribution of PLA fibres in the overall strength of the PL blended yarns. This is evident in Fig. 3b, that all PL blended yarns have a breaking elongation comparable to that of the 100% lyocell yarn and the tenacity of the PL yarn increases with increasing component of the lyocell fibres. Compared to PC yarn, the strength of 25/75 PL and 100% lyocell yarns is higher whereas the strength of 50:50 PL is lower. The high strength of PC yarn, as compared to 100% PLA, 75:25 PL and 50:50 PL yarns, may be due to greater strength of PET in PC blend. As described earlier, the inherent properties of the fibres are a key factor affecting the strength of the subsequent yarn. The mean fibre length of PLA and lyocell fibres is similar to PET but greater than cotton fibre. However, cotton has low extension at break (5.6 %) and polyester is stronger (51.7 $cN.tex^{-1}$) than other three fibres in the current study. The yarns can be converted in to knitted and woven fabrics by interlooping and interlacing, respectively. The weaving operations include high tensions during the process and require high strength yarns with narrow tolerances. The process requirements of the knitting process are more forgiving and the use of this blend in knitted intimate apparel applications could be a potential area of application.

3.2 Bursting strength of knitted fabrics

Bursting strength is an important performance aspect of knitted fabrics. It is the force that must be exerted perpendicularly on the fabric surface in all directions until it ruptures. The results of bursting strength of prepared knitted fabrics are summarised in Fig. 4. The lower loop length (0.26 SL) results in a dense structure (courses × wales per unit area) and consequently higher mass area density which explains the higher bursting strength of the 0.26SL fabrics. (Chidambaram, Govindan, & Venkatraman, 2012; Gun, 2011). The bursting strength is likely to vary with the fibre type, strength (Gun, 2011) and breaking elongation (Wang, Liu, & Hurren, 2008) of respective yarns, and fabric structure. The low bursting strength of the 100% PLA fabric may be attributed to low strength of its constituent yarn (Fig. 3) whereas the fabric is expected to extend more and consequently more work is done before the fabric failure. The increase in proportion of higher strength lyocell fibre in PL blends results in the gradual increase of bursting strength of the respective knitted fabrics. In bursting testing, the fabric fails in the direction with the lowest extension; hence the contribution of PLA fibres in PL fabric burst strength is limited. However, PC blended fabric demonstrates higher bursting strength than PL blended fabrics. The bursting strength of PL blended fabrics especially with 50 to 100% proportion of lyocell fibres is comparable or even more than previous studies related to cotton and its blended fabrics (Coruh and Çelik, 2015; Hussain, Bin Younis, Usman, Hussain, & Ahmed, 2015; Tausif, et al., 2015).

3.3 Bending length of knitted fabrics

The bending rigidity is an important parameter regarding the aesthetics and drape of apparels. The bending rigidity of a fabric can be directly estimated from its bending length and mass per unit area of the fabric (Saville, 1999). The results of bending length of fabrics knitted with both stitch lengths are plotted in Fig. 5. It is apparent that 0.30 SL fabrics exhibit lower bending length compared to 0.26 SL fabrics, owing to lower mass areal density. The trend also shows that fabrics with high proportion of PLA fibres appear stiffer and the bending length decrease with increasing proportion of lyocell fibres. The inherent stiffness of PLA polymer is translated into fibre and in its subsequent products (Farrington, Lunt, Davies, & Blackburn, 2005). It is already known that bending stiffness of a circular textile material relates directly to its initial modulus and increases as a function of the fourth power of its diameter and is a function of an inverse power of the fibre length (Naebe, Yu, McGregor, Tester, & Wang, 2013). As PLA fibre has less fibre density (1.25 g cm^{-3}) than lyocell (1.3 g cm^{-3}) so PLA may result in larger yarn diameter for the same yarn fineness and hence increase in bending stiffness of subsequent fabric. Moreover, the greater fineness of lyocell fibre and the presence of superfine fibrils in the structure of lyocell fibre provide softer feel and low bending resistance of knitted fabrics with the increase in proportion of lyocell fibre in the PL blend (Badr, Hassanin, &

Moursey, 2016). Hence, the low bending rigidity of lyocell fibre helps in better packing of fibres in the yarn structure leading to lower yarn hairiness (Table 3 and Fig. 2) and smaller diameter of yarns with high proportion of lyocell fibre, which ultimately results in lower thickness of lyocell rich knitted fabrics (Table 4) due to easy compression of knitted loops. Thus, bending stiffness of fabrics decreases as the proportion of lyocell in the blends increases. However, in case of PC blended fabric, bending stiffness does not increase significantly for large loop length (0.30 SL) as compared to PLA, lyocell and their blended fabrics but dense structure (0.26 SL) of PC blend presents significant increase in stiffness. The low initial modulus of PLA and lyocell fibres than that of both cotton and polyester coupled with low flexural stiffness of lyocell fibre may be responsible for the low bending length of knitted fabrics especially with large proportion of lyocell fibres. As low stiffness is more appealing for apparel and home textile applications, so it is favourable to use PL blends especially rich in content of lyocell fibre in place of PC blended fabrics.

3.4 Pilling propensity of knitted fabrics

Pilling is a surface defect on the surface of fabric due to fibre movement or slippage out of yarns caused by abrasion and wear. Pilling occurs in four steps: fuzz formation, entanglement, growth, and wear off. The formation of fuzz and pills on the fabric surface can influence the fabric aesthetics and durability and its acceptance by consumers (Sülar, et al., 2016). The results of propensity to pilling of knitted fabrics are given in Fig. 6

. Among the PL blends, pilling propensity is low for fabrics with high proportion of PLA fibres. Furthermore, all types of PL blends show lower pilling propensity than PC blended fabric for both stitch lengths. Pilling phenomenon depends on many factors such as fibre type, inherent mechanical properties of the fibres, fibre dimensions, yarn structure and construction and thickness of the fabrics. The PC fabric results in lowest resistance to pilling. The cotton is weak fibre and pills can fall off. Whereas, PET is stronger, and pills fail to disengage from the surface and results in high fuzziness/pilling on the surface of fabric. In case of PL fabrics, PLA fibres with higher extension at break and work of rupture (Fig. 1) have greater ability to withstand repeated distortion and hence offer good resistance to pilling which can be associated to high pilling resistance of fabrics with high proportion of PLA fibres despite high hairiness of PLA yarns (Table 3). In contrast, the high strength and low elongation of lyocell blended yarns results in low resistance to pilling. Furthermore, the high strength of lyocell, compared to that of PLA, is likely to result in higher pilling (Saville, 1999).

3.5 Water vapour resistance

The water vapour resistance is a measure of the ability of a material to resist the water vapour transmission through it and under certain set of climatic conditions, low water vapour resistance of a textile assembly results in comparatively rapid transfer of water vapours through it thus giving a dry and comfortable feeling to the wearer skin (Badr, et al., 2016). The results of water vapour resistance of knitted fabrics are shown in Fig. 7. It is clear that 100% PLA, 100% lyocell and their blended fabrics have comparatively low water vapour resistance than PC blended fabric for both stitch lengths. This may be due to natural hydrophilicity of PLA fibres due to easy access of water molecules to the polar oxygen linkages in its polymer which improves the wettability of the fibre as well as the moisture vapour transmission of fabrics resulting in the improvement of breathability of the garment (Dugan, 2001). However, PLA fibre is not as wettable as cotton and has very low moisture absorption capacity thus improving only moisture transport phenomenon. Lyocell has a smooth surface with excellent moisture absorption ability. The low water vapour resistance of 100% lyocell yarn and its blends may be explained by the fact that lyocell fibre consists of hydrophilic crystalline nanofibrils arranged in a regular manner in its microstructure which help to absorb moisture in the capillaries between nanofibrils uniformly (Firgo, et al., 2006). This advantage contributes to more nanopores in the yarn and the subsequent fabric resulting in efficient vapour transport out of the structure and hence low water vapour resistance. The high-water vapour resistance of 75/25 PL blended fabric at both stitch lengths may be due to its higher areal weight (Table 4) and comparatively denser structure than other PL blends. The ability of cotton fibre not only to absorb and retain moisture but also its poor drying rate may lead to high water vapour resistance of PC blended fabric. Hence, considering the hot and humid climatic conditions, PLA, lyocell and their blended fabrics are more favourable to wear which may help to improve the comfort level of wearers.

3.6 Thermal resistance

Textile materials and structures could resist the flow of heat through them and could result in heat or cold stress, depending upon the climate. The low thermal resistance of a garment assists in loss of heat from the skin to the outer environment under a certain set of climatic conditions thus providing a cooler feeling to the wearer (Tausif, et al., 2015). The results of thermal resistance of knitted fabrics are summarized in Fig. 8. The fabrics with large loop length (0.30 SL) exhibit high thermal resistance irrespective of the types of fibres and their blends. The low mass areal density and high porosity of 0.30 SL fabrics result in more trapped air in the fabric structure. Air being a good insulator of heat (0.025 W m^{-1} K^{-1}) decreases the conduction of heat and results in high thermal resistance (Tyagi, Krishna, Bhattacharya, & Kumar, 2009). However, thermal resistance decreases in a slight gradual manner with the increase in proportion of lyocell fibres for both stitch lengths of PL blends. These results agree with the findings for bending length, as smaller diameter of yarns with high proportion of lyocell fibre, due to its low bending rigidity and better packing of fibres in the yarn, results in lower thickness (Table 4) and porosity of the corresponding fabrics. There is not much difference in thermal resistance of PLA rich and PC blended fabrics but there is slight decrease for samples with 50% or more proportion of lyocell fibres. The porosity and hence entrapped air due to inherent convolutions of cotton fibre in PC blend and high thermal absorptivity of lyocell fibre in PL blends (Firgo, et al., 2006) are likely to cause this small decrease. Hence, PL blends with high proportion of lyocell fibre (50% and above) can be more favourable in hot and humid environment of summer and offer an alternative to casual clothing as well as active wear.

3.7 Air permeability

Air permeability is the rate of air flow through the thickness of a fabric at a defined pressure difference. It is also an important parameter with respect to the comfort aspect of clothing. The results of air permeability of knitted samples under study are plotted in Fig. 9. As expected, the fabrics with 0.30 SL (and large loop length) show high air permeability. The increase in proportion of lyocell fibre in the blends increases the air permeability of fabrics. The yarns with high proportion of lyocell fibres are smaller in diameter, and the corresponding fabrics have lower thickness (Table 4), resulting in higher permeability of air through these fabrics. 100% PLA and PC blended yarns exhibited high level of hairiness, compared to PL blends and 100% lyocell yarns (Fig. 2 and Table 3) which is likely to offer higher resistance to flow of air. In PL blended fabrics, the decrease in yarn hairiness (Fig. 2 and Table 3) with the increasing content of lyocell fibre results in the expected increase in air permeability. Hence, PL blended fabrics can offer high air permeability and consequently better physiological comfort.

3.8 Economic Comparison

Despite the apparent eco-friendly advantages of PLA and lyocell fibres over PET and cotton, PET fibre is cheaper as compared to PLA, lyocell and cotton fibres. Table 5 includes the fibre prices (as of 2017/18) of fibres and yarns in Pakistan. It is pertinent to mention that prices are likely to vary overtime and geographical location. The demand of

PC blended fabrics is higher due to greater global market share of both PET and cotton fibres and certain performance advantages of this blend. Even though, the raw material cost of PC blended garment is lower, the yarn formation and fabric processing costs are higher according to the actual cost calculations taken from a local textile mill in Pakistan and presented in Fig. 10. This is mainly due to a greater number of machines required for cotton cleaning (incur 11% of overall cost) which contributes to lower cotton yield (almost 72% for carded, 88% for combed) due to removal of waste and increase in yarn conversion cost. The extra pre-treatment costs for cotton and PET as well as chemical and energy efficient treatments of PLA and lyocell over PET and cotton fibres during chemical wet processing also contribute to extra processing cost of PC blend. In line with principle of economies of scale, the price difference between PL and PC blended apparels could be reduced as the production demand increases for PL blended fabrics. For example, organic articles although cost higher than normal articles but are still preferred by certain consumers. There is a growing awareness in consumers to buy sustainable products and such consumers can be willing to pay the price premium due to environmental benefits as well as better/competitive performance properties.

4 Conclusions

In the present study, yarns and knitted fabrics of PLA fibre, lyocell fibre and their blends (in varying ratios) have been investigated as an eco-friendly alternative to those of traditional PET/cotton blend. The tensile strength of yarn and bursting strength of fabrics increased, with the increasing proportion of lyocell fibre in the blend, owing to higher strength of lyocell than PLA fibre. The PL blends, in particular with greater proportion of lyocell fibres, exhibited comparable tensile properties of yarns and busting strength of corresponding knitted fabrics (irrespective of stitch length) to that of PC blended fabric. The PL blended fabrics (mainly for lyocell fibre rich blends) showed lower bending length, water vapour resistance, thermal resistance and higher air permeability in comparison to that of PC blended fabrics. This can offer advantages in clothing performances, especially for summer clothing applications as the PL blends have the potential not only to reduce energy requirements to maintain temperature in hot climate but also to increase the comfort level of the wearer. The better results of pilling propensity also add to enhanced service life of PL blended clothing. Hence, PL blended fabrics can be an eco-friendly option to replace widely used PC blend with similar or in some instances improved properties for apparels and home textiles applications. This could help to reduce the depletion of fossil fuels, the dependence on freshwater resources as well as the consumption of pesticides thus can be an eco-friendly alternative for textile applications. The economic comparison shows the higher production cost of PL blended fabrics. However, the consumer may be willing to pay the price premium in exchange of environmental and performance advantages of PL fabrics compared to that of PC fabrics. In the long run, the economies of scale are likely to reduce the cost of the new blend.

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Tables

Table 1. Properties of fibres

Parameters	PLA	Lyocell	Cotton	PET
Fibre Length (mm)	38 (nominal)	38 (nominal)	26.8 (mean)	37.7 (mean)
Fineness (dtex)	1.66	1.60	1.81 (4.6 μg.inch^{-1})	1.40
Tenacity (cN.tex^{-1})	25.0	34.7	24.4	51.7
Elongation (%)	52.1	10.7	5.6	20.4
Moisture regain (%)	0.6	10	8.2	0.3
Uniformity Ratio (%)	-	-	49	-
Rd value	-	-	72	-
+b value	-	-	8	-
Trash content (%)	-	-	7	-

Table 2. Machinery for production of yarn samples

Machine type	Tencel/PLA blends Model and manufacturer	Polyester/cotton blend Model and manufacturer
Blow room line	Jingwei, China	Jingwei, China
Carding	TC-03 Trutzschler, Germany	MK-5 Crosrol, UK
Inter and breaker draw frame	DYH-500c Toyoda, Japan	DYH-500c, Toyoda, Japan
Finisher draw frame	RSB-D30 Rieter, Switzerland	RSBD-35 Rieter, Switzerland
Simplex	FL-16, Toyoda, Japan	FL-16 Toyoda, Japan
Ring frame	RY-4 Toyoda, Japan	FA-506 Jingwei, China

Table 3. Physical properties of yarns used in the study

Parameters	100% PLA	75/25 PL	50/50 PL	25/75 PL	100% Lyocell	50/50 PC
U%	14.32	12.45	10.79	10.13	9.34	12.45
Thin -50% /km	177.5	33.5	6.5	3.5	0.5	9.8
Thick +50% /km	195.5	63.5	23.5	10.5	6	235.5
Neps +200% /km	934	383	207	113	64	451.8
IPI	1307	480	237	127	70.5	697
Hairiness	8.1	6.8	5.86	5.8	5.23	8.38

Table 4. Physical properties of knitted fabrics

Stitch length	Yarn **t**ype	Areal Density (g.m^{-2})	Courses.cm^{-1}	Wales.cm^{-1}	Fabric thickness (mm)
0.26	100% PLA	184	24.02	9.45	0.74
	75/25 PL	188	27.95	9.84	0.68
	50/50 PL	169	29.13	9.45	0.60
	25/75 PL	158	26.38	9.45	0.54
	100% lyocell	169	26.38	9.84	0.48
	50/50 PC	140	26.77	9.84	0.58
0.30	100% PLA	174	17.72	9.45	0.83
	75/25 PL	166	19.29	11.02	0.77
	50/50 PL	133	18.50	10.63	0.63
	25/75 PL	138	18.90	10.24	0.54
	100% lyocell	123	18.50	10.24	0.48
	50/50 PC	132.5	17.72	9.84	0.64

Table 5. Local cost comparative chart of fibres and yarns

Fibre Type	Cost/Kg (US $)
PLA	2.50
Lyocell (Tencel)	2.55
Polyester	0.95
Pak Cotton	2.50
Yarn Type	**Cost/Kg (US $)**
30/1 PLA (100%)	5.50
30/1 Tencel (100%)	4.85
30/1 PLA/Tencel (75:25)	4.52
30/1 PLA/Tencel (50:50)	4.63
30/1 PLA/Tencel (25:75)	4.95
30/1 PC-Pak (52:48)	2.55

Figure Captions

Fig. 1. Typical strength-elongation curves of selected fibres

Fig. 2. Microscopic images of prepared yarns; (a) 100% PLA, (b) 75/25 PL, (c) 50/50 PL, (d) 25/75 PL, (e) 100% Lyocell, (f) 50/50 PC.

Fig. 3. (a) The tensile load-elongation curves and (b) tenacity and breaking elongation of yarns under study

Fig. 4. Bursting strength of knitted samples

Fig. 5. Bending length of knitted samples

Fig. 6. Pilling resistance of knitted samples

Fig. 7. Water vapour resistance of knitted samples

Fig. 8. Thermal resistance of knitted samples

Fig. 9. Air permeability of knitted samples

Fig. 10. Conversion cost comparison of PL and PC blended fabrics