

Comparative Analysis of the Effects of Time of Heat Setting and Wet Processing on Tensile Properties of Treated and Untreated Knitted PLA Fabric

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Abstract Poly (lactic acid) (PLA) is an aliphatic polyester and ecofriendly material of a natural origin with biodegradable properties. The monomer for PLA is lactic acid obtained from the fermentation of sugar and vegetables like corn and cassava. This study investigated the effect of heatsetting and wet processes on the tensile properties of treated and untreated Ingeo™ Poly (Lactic acid) PLA knitted fabrics. PLA samples of dimension 200mm x 200mm were subjected to heatsetting at a temperature of 130°C and increasing times of 15s, 30s, 45s, 60s, 90s, 120s and 240s respectively using the Werner Mathis infra-red heatsetting equipment and subsequently treated to wet processes including scouring, alkaline reduction clearing, dyeing and softening. Four tensile parameters were determined in warp and weft direction using the KES-FB system of fabric evaluation. These tensile parameters were tensile extension EM [%], linearity of load extension LT [-], tensile energy WT [g.cm/cm²] and tensile resilience RT [%]. The results showed (i) a consistent increase in tensile extension of treated PLA (unlike untreated PLA knitted fabric) with increasing time of heatsetting and wet finishing applications suggesting that treated PLA may tend to exhibit enhanced fabric hand or softness and increased formability (ii) Treated PLA to exhibit lower LT with increasing time of heatsetting and wet treatments implying a better formability and in-plane compressibility of treated PLA when compared to untreated PLA (iii) Treated PLA to display a greater tensile energy than untreated PLA, implying that treated PLA has greater flexibility, softness, gentleness and smoothness than the untreated PLA (iv) both PLAs exhibited low RT suggesting the general softness of PLA.

Keywords: Ingeo™ Poly (lactic acid), KES-FB system, linearity of load extension, tensile energy and tensile resilience

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1. Introduction

Ingeo Poly(lactic acid) is the only synthetic fiber available in large commercial quantities and wholly produced from an annually renewable raw material source that is not oil [1]. The fundamental raw material for the production of Ingeo PLA is corn [1,2]. Ingeo is Cargill Dow's brand name for the first man-made fiber derived from 100% annually renewable resources. The process starts with corn, an abundant raw material that can easily and efficiently converted into plane sugars which subsequently undergo fermentation [3]. The fermentation products are immediately transformed into high performance polymer called polylactide from which the branded Ingeo fibers and filaments are extruded [4]. Poly(lactic acid) is aliphatic polyester which is considered as a green material due to its natural based origin and biodegradable properties [5]. Lactic acid obtained from

the fermentation of sugar obtained from cassava or corn is used as a monomer for PLA polymerization [5,6]. Production of PLA is achieved through two major routes through direct condensation polymerization reaction of lactic acid and ring opening polymerization reaction of lactide, a cyclic dimer of lactic acid, yielding poly (lactic acid), poly (d-lactic acid) or poly(d,l-lactic) acid depending on lactic isomers used [6,7]. PLA can be melt spun into different types of fibers including monofilaments, multifilaments, bulked continuous filaments, staple fibers, short – cut fibers and spunbond fabrics by conventional melt spinning machines [6,7,8]. The fibers are then drawn and annealed to give desirable mechanical properties such as high tenacity, good toughness and good dimensional stability [9].

Ingeo PLA fibers are dyed using disperse dyes though not all disperse dyes are good for dyeing Ingeo fibers. Research to ascertain appropriate disperse dyes for dyeing Ingeo has been initiated by DyStar Co [10,45,46,47]. Though PLA fibers exhibit characteristics similar to

synthetic fibers, they are based on renewable natural sources and hence require re-engineered dyeing and finishing processes to obtain maximum benefits [38,39,40,41]. DyStar recommended some group of disperse for use in dyeing Ingeo PLA fibers. Three azoic dyes comprising of medium energy and heat fastness of trichromatic combination, two anthraquinone dyes and three benzodifuranone were recommended by DyStar [10,11,18]. An understanding of the dyeability of PLA knitted fabric is imperative in producing aesthetically appealing fabrics of commercial value and enduring durability to washing and fastness [42,43,44]. The dyeing properties of disperse dyes on PLA has been studied by many researchers in order to further the understanding of parameters that determine the dyeability of PLA [10,11,12,13].

Wet processes applied to PLA in this investigation are scouring, dyeing, alkaline reduction clearing, and softening processes. The essence of scouring is to remove impurities and surface contaminants. The scouring process is thought to have an impact on the fiber structure, properties and overall dyeing performance [14,22,37]. Generally, scouring is carried out using hot alkali which is a solution of caustic soda and detergent and usually occurring at significantly lower temperatures than those of heatsetting. Alkaline reduction clearing is a wet process of using caustic soda and sodium hydrosulphite ($\text{Na}_2\text{S}_2\text{O}_4$) to effectively remove unfixed dye at the surface of PLA fibers at 70°C and time duration of 10 to 15 minutes. This is because PLA fabrics may be contaminated with surface deposits of unfixed dyes after the dyeing process, especially at heavy depths of shade since there is tendencies for water insoluble disperse dyestuff to aggregate into relatively large particles as the dye bath cools down to below 100°C [15,38,39]. The softening process enhances the softening or handle of the fabric through the application of appropriate softening agents. The application of softeners produces a level of softness which may not be attained by mechanical finishing or modification of fabric construction [16].

PLA is a renewable synthetic fiber manufactured by extrusion through spinnerets to form filaments which in turn impact stress which are generated within the polymer structure and trapped in the material on cooling [19,20,21]. Dimensional stability is in turn impacted into the fiber when exposed to wet or heat treatments. Heatsetting of fibers introduces enhanced dimensional stability to the fiber thereby improving fiber morphology and orientation. Heatsetting temperature should be higher than the maximum temperature of the subsequent wet processes such as dyeing and ironing temperature so as to ensure the fabric attains dimensional stability [17].

The Kawabata Evaluation System is an industrial standard of determination of fabric handle through an objective mode of assessment. KES was used in this research to measure a series of fabric properties at low stresses comparable to those the fabric undergo during normal handling, tailoring, wearing and other end user application. The aim of this research is to determine the effect of time (of heat setting and wet processing) on the tensile properties of treated and untreated PLAs. Tensile properties evaluated using KES for this research are as shown in Table 1 below:

Table 1. PLA tensile properties evaluated using Kawabata Evaluation System

PROPERTY	DEFINITION
TENSILE	
Extensibility (EM)	% Extension at maximum applied load of 500g/cm
Tensile energy (WT)	Energy in extending fabric to 500g/cm
Linearity of load-extension curve (LT)	Linearity of load-extension curve
Tensile resilience (RT)	% Energy recovery from tensile deformation

2. Materials and Methods

Ingeo Poly (lactic acid) fabric- The Ingeo Poly (lactic acid) fabric used for this investigation was supplied by NatureWorks LLC, USA. Sixteen samples of pique knitted fabrics obtained from 150/144d Tex/ filament PLA were used for this study. The treated fabrics were subjected to wet treatments including scouring, dyeing, alkaline reduction clearing and softening processes after heatsetting treatments at 130°C at increasing time duration of 15s, 30s, 45s, 60s, 90s, 120s, and 240s respectively. The untreated 'pique' knitted fabric was used as control.

Dye - The dye used for this work is Dianix Yellow C-5G 200% having chemical name of 1-Ethyl-1, 2-dihydro-6-hydroxy-4-methyl -2-oxo-3-pyridinecarboxamide and molecular formula $\text{C}_9\text{H}_{12}\text{N}_2\text{O}_3$. The formular weight is 196.2 (Table 2) and the chemical structure is shown below, Figure 1.

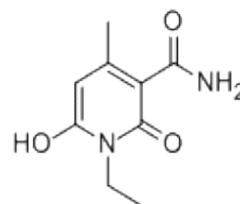


Figure 1. Chemical structure of Dianix Yellow C-5G 200%

Table 2. Characteristics of selected disperse dye

C.I.Number	Commercial name	Strength	Molecular Weight
Disperse Yellow C-5G	Dianix Yellow C-5G (DyStar)	200%	196.2

2.1. Experimental

2.1.1. Heat-setting Procedure

The heat-setting of knitted PLA fabrics were achieved using the Werner Mathis AG (Textilmaschinen Niederhashi/Zurich heatsetting equipment). The samples of dimension 200mm by 200mm were held on the sliding aluminum frame at a constant length and heated in dry air at a constant temperature of 130°C which is the maximum temperature for stabilizing PLA as recommended by Cargill Dow. The samples were pinned on the sliding aluminum frame pins and heat set for time durations of 15s, 30s, 45s, 60s, 90s, 120s and 240s respectively. The essence of prolonged heatsetting of PLA fabrics was to ascertain the behavior of PLA at high heatsetting time duration. After heatsetting, the fabric samples were allowed to cool down at room temperature for 24 hours.

2.1.2. Scouring Procedure

They heat-setted PLA samples of dimension 200mm by 200mm and total weight of 83g were scoured in 450mls of water using a Mathis LABOMAT Scouring equipment of rpm 55 revs/min for 20 minutes at 60°C in an aqueous solution containing 1.66g/l ERIOPON R, a non-ionic detergent and 0.83g/l sodium carbonate (soda ash). This process was carried out at a liquor ratio of 10:1 using a beaker at a continuous stirring. The essence of scouring all knitted fabrics is to extricate all knitting lubricants, oils, waxes, dirt and other forms of impurities before commencing subsequent wet processing operations like dyeing, alkaline clearing and softening. Scouring reduces any propensity for uneven dyeing, stains and dye fastness through the removal of oils, waxes and fats that may abide in the fabric. After scouring, they fabrics were rinsed with cold water and dried at room temperature.

2.1.3. Dyeing of knitted PLA Fabrics

Dyeing of PLA fabrics subsequently followed scouring, rinsing and drying. This took place at 110°C for 45 minutes using a laboratory scale Mathis LABOMAT Infra-red dyeing machine at a liquor ratio of 10:1 for each of the sample. The pH of the dye bath was maintained at 5±0.1 through the application of acetic acid. 2% of selected disperse dye Dianix Yellow C-5G 200% was used though the quantity applied to each sample was calculated from the percentage weight of the fabric sample numbered from 1 to 7 for easy recognition and assessment. The total dye bath of each sample was also calculated from the weight of the fabric and liquor ratio. Table 3 below shows the individual values as determined from the calculations;

Table 3. PLA dye values

PLA Samples	1	2	3	4	5	6	7
Weight of Samples (g)	11.40	12.00	11.67	11.60	11.50	12.35	8.92
Weight of Dye (g)	0.23	0.24	0.23	0.23	0.23	0.25	0.20
Liquor Ratio	10:1	10:1	10:1	10:1	10:1	10:1	10:1
Total bath (mls)	114	120	117	116	115	124	60

The Mathis LABOMAT Infra-red Uniprogrammer calibrations for the knitted PLA fabric initially read as follows, (Table 4).

Table 4. Mathis LABOMAT Uniprogrammer Calibrations for PLA

Uniprogrammer Calibrations PLA	Quantities
Rate of Temperature rise	30°C /min
Temperature	110°C
Time	45min
Gradient (Rate of cooling)	5°C /min
Revolution/mm	50 rpm

The Dyeing procedure for PLA as represented by Mathis LABOMAT Infra-red equipment is shown in Figure 2 below.

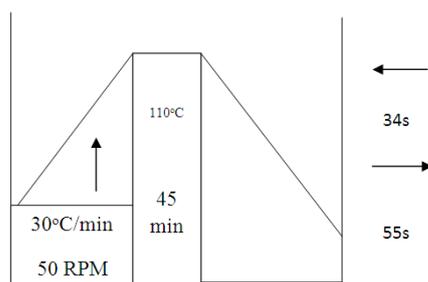


Figure 2. Mathis LABOMAT Uniprogrammer PLA dyeing procedure

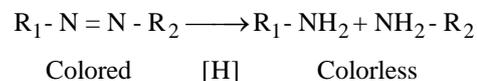
2.1.4. Alkaline Reduction Clearing Procedure

Alkaline reduction clearing is a process which occurs after dyeing and air drying in order to extricate surface disperse dye [23,24]. All the samples used for this study were subjected to the same alkaline reduction clearing procedure. The quantities of chemicals used were calculated from a combination of the total weight of PLA samples. The quantities are shown in Table 5 below:

Table 5. Alkaline reduction Clearing Parameters

PARAMETERS	QUANTITIES
Total weight of all samples	122.7g
Sodium Hydroxide	12g
Sodium dithionite	6g
Warm water	2 Liters
Temperature of plate	70°C -80°C
Time	10-20 minutes

From the above table, alkaline reduction clearing of both Knitted PLA samples occurred within 70°C to 80°C for duration of 10-20 minutes. 6g of Sodium dithionite and 12g of sodium hydroxide were used to create enabling alkaline conditions needed for clearing to take place and for accurate comparative analysis. The efficiency of alkaline reduction clearing is a function of the chemical structure of the disperse dye [27,28,29,30,31,32]. When disperse dyes are treated with reducing agents, due to their azo group content, they are sensitive to treatment with a reducing agent usually in form of alkaline solution of sodium dithionite (hydros). The reducing agent destroys the azo chromophore, resulting to a loss of its color through the splitting of the azo chromophore into two colorless amino compounds [33,34,35,36] as shown in the equation below:



Dye decolorization during alkaline reduction clearing process

The softening agents [25,26] used in softening the PLA fabrics were Ciba® Sapamine® HS and Siligen CSM which were applied on the samples through padding using the Werner Mathis AG padding equipment calibrated at a pressure of 2 bar and roller speed of 2.5m/min. The time of padding was 2 minutes at a temperature of 30 to 40°C. The two softeners were combined at 30g/l whereby 3mls of each were mixed with 200mls of water to affect the softening process. The liquor ratio was 10:1 at a Ph of within 5 – 6 sustained through the use of acetic acid. The liquor pick-up was about 90%. Ciba Sapamine is chemical composed of fatty acid ester, silicone, emulsion of fatty acid amide and polyalkylene. It is non – ionic/cationic in character with a pH of 4-5.5. Siligen® CSM is a hydrophilic silicone – based softener, a registered trademark of BASF, composed of wax, polysiloxanes and non-ionic surfactants.

After the padding process, the softened PLA fabrics were subjected to a drying procedure at a temperature of 110°C in 2 minutes using Werner Mathis AG equipment. The fabrics were then kept for storage for 7 days at room temperature and atmospheric pressure.

2.1.5. The Kawabata Evaluation System

The KES-FB system determines fabric properties at small loads equivalent to those the fabrics are subjected to at normal end use application. The tensile properties

determined were fabric extension [%], linearity of load extension, tensile energy [WT] g.cm/cm² and tensile resilience [%]. The specimen were clamped between two chucks each of 20cm long. A constant force of 200g was applied by attaching a weight to the front chuck of the specimen. When the test started, the back chuck constantly slid initially right to an angle of 8° then back to its original position.

3. Results and Discussion

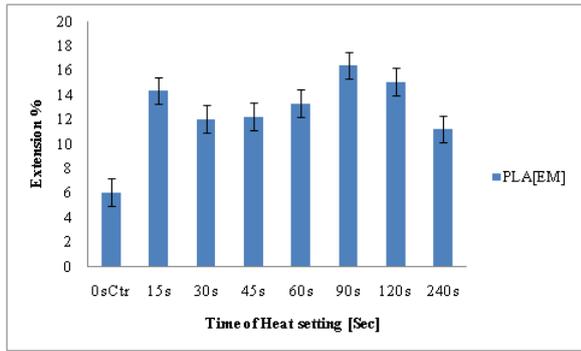


Figure 3. Comparative effect of heat-setting and wet processing on tensile extension (EMT) % of untreated control (0s Ctr) PLA and treated PLA fabrics

Figure 3 expatiates the effect of increasing time of heatsetting and various wet or finishing treatments on the extension of knitted PLA in comparison to the knitted loom fabrics or control. There is a remarkable change on the tensile extension [EMT] of PLA fabrics with increasing time of heatsetting and wet treatments especially at 90s. This implies that increasing heatsetting time of PLA beyond 90s may not necessarily improve tensile extension of knitted PLA. This is because finishing processes tends to alter the tensile extension of treated PLA knitted fabric properties. Treated PLA exhibited a consistent increase in tensile extension with increasing time of heatsetting and wet finishing applications unlike untreated PLA knitted fabric. This implies that treated PLA may tend to exhibit enhanced fabric hand or softness and increased formability with increasing time of heatsetting and finishing applications unlike untreated PLA.

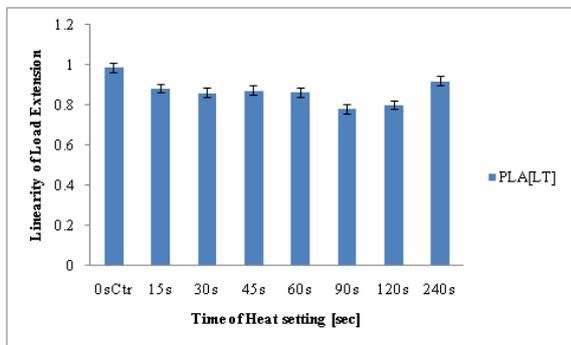


Figure 4. Comparative effect of increasing time of heat setting and wet processes on linearity of load extension LT of untreated (0s Ctr) control PLA and treated PLA fabrics

Figure 4 above shows no remarkable change in linearity of load extension of treated PLA with heatsetting and wet treatments though a slight decrease in this parameter was noticed. This result indicated a softer hand (larger

extension in the initial low load region of load extension curve of treated PLA unlike the untreated PLA. Subjectively PLA fabric stretch is linked closely to LT (initial resistance to tension). Treated PLA exhibition of lower LT with increasing time of heatsetting and wet treatments implies a better formability of treated PLA when compared to untreated PLA as extensibility under small loads represents in-plane compressibility which is equivalent to fabric formability. Hence treated PLA exhibits better formability and in-plane compressibility to untreated PLA.

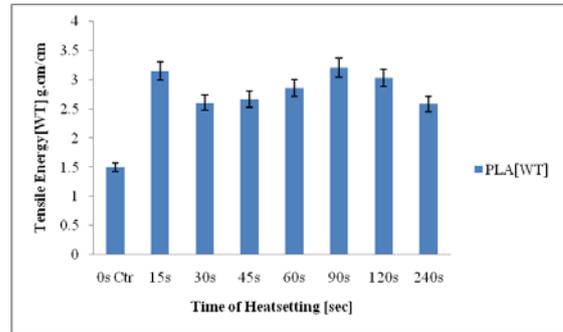


Figure 5. Comparative effects of heat setting and wet processes on Tensile Energy WT (g.cm/cm²) of untreated control and treated PLA fabric

In Figure 5, the effects of the time of heatsetting and wet processing on the tensile energy of both treated and untreated PLA were compared. The results show an increasing tensile energy of treated PLA fabric with increasing time of heatsetting and various applications of wet treatments when compared to untreated PLA. Tensile energy (WT) g.cm/cm² is the energy required to extend a fabric to the prefixed maximum load and closely related to fabric flexibility, softness, gentleness and smoothness. At heatsetting time of 90s, the highest level of increase in tensile energy of treated PLA was noticed. Hence, treated PLA exhibited a greater tensile energy when compared to untreated PLA. Beyond this timing no better value was added to the tensile energy of treated PLA. This implies that treated PLA exhibited greater flexibility, softness, gentleness and smoothness.

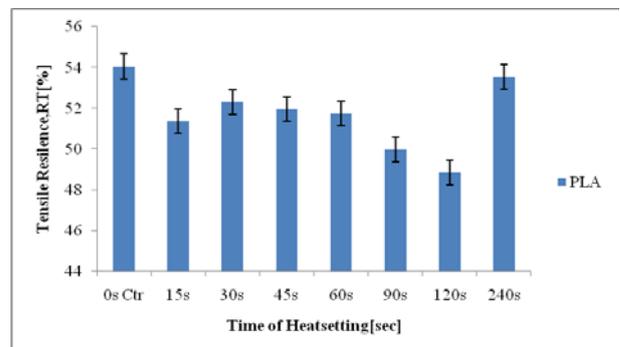


Figure 6. Comparative effect of heatsetting time and wet treatments on the tensile resilience of untreated control (0s Ctr) and treated PLA samples

Figure 6 represents the effect of heatsetting time and wet treatments on the tensile resilience of untreated control (0s Ctr) and treated PLA samples. The result shows no remarkable difference in tensile resilience between the treated and untreated PLA fabrics. Tensile resilience, RT % is a measure of the ability of a fabric to

recover after extension when applied force is removed. A lower RT as exhibited by PLA promotes softness.

4. Conclusions

This research comparatively analyzed the effect of time of heatsetting and wet processes on the tensile properties of treated and untreated PLA samples to enhance the understanding of the tensile properties of Poly (lactic acid) fabric using the Kawabata Evaluation System (KES-FB) for fabrics.

The best found time of heatsetting PLA yarns to minimize shrinkage during subsequent wet processing is within the range of 30 – 40s at 130°C.

Unlike untreated PLA knitted fabric, treated PLA exhibited a consistent increase in tensile extension with increasing time of heatsetting and wet finishing applications. This suggests that treated PLA have enhanced fabric hand or softness and increased formability with increasing time of heatsetting and finishing applications unlike untreated PLA.

Treated PLA decreased in linearity of load extension LT with increasing time of heat setting and wet processes than the untreated PLA. A smaller LT as exhibited generally by PLA indicates a smaller hand or a larger extension in the initial low load region of the load extension curve. Subjectively, PLA fabric stretch is closely linked to LT (initial resistance to tension) and RT (resilience). PLA exhibition of lower LT with increasing time of heatsetting and wet treatments implies a better formability as extensibility under small load represents in-plane compressibility which is equivalent to fabric formability. PLA tailorability improves with improved fabric formability.

An increasing tensile energy is noticed with increasing time of heat setting and wet treatments on treated PLA when compared to untreated PLA. Tensile energy (WT) g.cm/cm^2 is the energy required to extend a fabric to the prefixed maximum load and closely related to fabric flexibility, softness, gentleness and smoothness.

Treated PLA exhibited no much difference in tensile resilience to untreated PLA. Tensile resilience, RT % is a measure of the ability of a fabric to recover after extension when the applied force is removed. A lower RT promotes softness and RT increases in fabric finishing as the inter fiber force are reduced.

References

- [1] Auras, R. (2002) An Overview of Poly lactides as packaging materials. *Macromolecules Bioscience*.4; 835-64.
- [2] Bradbent, G. (2001) Basic principles of textile coloration. *Society of Dyers and colorists*, 2001.
- [3] Blackburn, R.S. (2005) Biodegradable and sustainable fibers, Woodhead Publishing Limited, North America.
- [4] Behery, H. (2005) Effect of Mechanical and Physical Properties on fabric hand, Woodhead Publishing Limited, 2005.
- [5] Cicero, J. (2001) Physical Properties and fiber morphology of Poly (lactic acid) obtained from continuous two step melt spinning. *J. Polymer Environ.*,9, 1-10.
- [6] Choi, J. (2010) Coloration of Poly (lactic acid) with Disperse Dyes 2: Dyeing Characteristics and color fastness, fibers and polymers, vol.8, No. 1, PP. 37-42.
- [7] DyStar, (2003) *Ingeo™ Fiber Coloration Pack*. Fibers Information, Ingeo™ fiber technical information.
- [8] Duncan J. (2000) Research Fiber Innovation Technology, Inc., <http://www.Fitfibers.com/publications.Htm>, INTC 2000, Dallas, Texas, USA, 2000.
- [9] Dartee M., Lunt J. and Shafer A. (2001) NatureWorks PLA: sustainable performance fiber. *Man-made Fiber Year Book*, pp.29-31.
- [10] DyStar (2004) Textilfarben GmbH and Co. Deutschland KG (2004) Ingeo™ Fiber Coloration pack, DyStar Plc .
- [11] Fambri ,L., Pegoretti, A., Incardona, S., Fenner, R.,Migliaresi,C. (1997) Biodegradable fibers of Poly (l-lactic acid) produced by melt spinning. *Polymer*, 38, 79-85.
- [12] Grupta, P. et al., (2007) Polylactic acid Fiber: An overview, *Progress in Polymer Science*, Vol. 32, pp 455-482, ISSN 0079-6700.
- [13] Gruber, P. (1992) Poly lactides NatureWorks™ PLA: Biopolymers in 10 volumes, volume 4, Polyester 3, Applications and commercial products, Wiley VCH; ISSN 3-527-30225-5.PP 235-49.
- [14] Gupta, B. (2007) Polylactic acid fiber: An overview. *Progress in Polymer Science*, vol. 32, pp. 445-482.
- [15] Gruber, P., O'Brien M. (2002) Poly lactides “NatureWorks™ PLA. In: Doi Y, SteinbuchelA, editors. Biopolymers in 10volumes, volume 4, polyesters III applications and commercial products. Weinheim: Wiley-VCH; p. 235-49.
- [16] Garlotta D. (2005) A literature Review of Poly (lactic acid). *J. Polymer Environ.*, 9(2); 63-84.
- [17] Gruber, P. (2002) Melt stable Amorphous lactide Polymer film and process for manufacturing thereof, US Patent 5, 484, 881. 1996
- [18] Gerber, H. (1978). Relations between the structure and properties of azo disperse dyes. *Journal of Society of dyers and colorists*, vol.94, pp.298-301.
- [19] Henton et al., (2005) Polylactic acid technology, In Mohanty AK, editor. Natural fibers, Biopolymers and Biocomposites, CRC Press, P 528-69.
- [20] Hartman, H. (1998) Biopolymers from renewable resources, Berlin; Springer; 1998.
- [21] Holten, C.H. (1971) Lactic Acid properties and chemistry of lactic acid and derivatives, Verlag Chemie, Germany.
- [22] Hyon, H. (1984) Effects of residual monomer on the degradation of DL- Lactide polymer, *Polymer international*, 46 (3); 196-202.
- [23] Hoogsteen, W., Postema, A.R., Pennings, A.J. and ten Brinke, G. (1990) Crystal Structure, Conformation, and Morphology of Solution-Spun Poly(L-lactide) Fibers. *Macromolecules*, 1990, 23, 634-642.
- [24] Holme, S. (2005) Lactic acid derivatives and properties, *Polymer*, vol. 29, pp.2229-2234.
- [25] Mooney, W.(2003) Chemical softening in textile finishing, Heywood, D (ed.) *society of dyers and colorists*, 251-307.
- [26] Haberer P. (2002) Silicon-Weichmacher: struktur-wirkungsbeziehungen. *Melliand Textilberichte*, 83, 336-338.
- [27] Hawkyard R. (2004) Synthetic fiber dyeing, *society of dyers and colorists*, pp.122-162.
- [28] Huda, M.S., Drzal, L.T., Mohanty, A.K. and Misra, M. (2005) Chopped glass and recycled newspapers as reinforcement fibers in injection molded PLA composite: A comparative study. *Composites Science and Technology*, 66, 1813-1824.
- [29] Jamshidi et al., (1998) Thermal characterization of Poly lactides, *polymer*, vol. 29, pp.2229-2234.
- [30] Kameoka T. (1997) USA Patent Number 5, 630, 849, May 20, 1997.
- [31] Kalb, B. and Pennings, A.J. (1980) General crystallization behavior of poly (Lactic acid). *Polymer*, 21, 607-12.
- [32] Kamel, M.M., Elshishtawy, R.M., Hanna, H.L. and Ahmed, N.S.E. (2003) Ultrasonic assisted dyeing: I. Nylon dyeability with reactive dyes, *Polymer International*, 52, 373-380.
- [33] Karst, D. and Yang, Y. (2005). Using the Solubility Parameter to Explain Disperse Dye Sorption on Polylactide, *Journal of Applied Polymer Science*, Vol. 96, pp. 416-422.
- [34] Kolstad, J.J. (1996) Crystallization kinetics of poly (L-lactide-co-meso-lactide). *Journal of Applied Polymer Science*, Vol. 62, Issue 7, pages 1079-1091.
- [35] Lunt, J. and Shafer, A.L. (2000) Polylactic acid polymers from corn. Applications in the textiles industry. *Journal of Industrial textiles*, Vol. 29, No. 3, January, p. 191-205.
- [36] Lipinsky, E.S. and Sinclair, R.G. (1986) Is lactic acid a commodity chemical? *Chem. Eng. Prog.* 82 (8):26-32.

- [37] Lunt, J., Shafer, A.; (2000) Polylactic Acid Polymers from Coin. Applications in the Textiles Industry. *Journal of Industrial Textiles*, 29, pp. 191-205.
- [38] Lunt, J. (2001) Properties and dyeability of fibers and fabrics produced from Poly lactide (PLA) Polymers, *AATCC Rev.*, I (September 2000), pp. 20-23.
- [39] Osman, A. (2007) Studies of the effects of Processing conditions and softeners on the physical characteristics and performance of Polylactic acid based fabrics, Ph.D Thesis, University of Manchester, UK.
- [40] Nakamura, T. (2001) An overview on Dyeing properties of Polylactic acid (PLA) fiber, *AATCC International Conference and Exhibition*.
- [41] Lunt, J. (1998) Large Scale Production, Properties and commercial applications of Polylactic acid polymers, *Polymer Degradation and Stability*, 59, 145-152.
- [42] Madigan, B. (1977) *Textile Dyes, Finishes and Auxiliaries*, Garland Publishing, Inc., New York and London, 1977.
- [43] Mochizuki, M. (2006) Properties and applications of aliphatic Polyester Products: *Biopolymers vol.4: Polyesters III*, Germany.
- [44] Matsuoka, M. (1986) Application of Disperse Dyes, Ahmedabad: *Ahmedad Textile Industry Research Association*, 1986.
- [45] NatureWorks (2011) [http:// www.natureworks llc. Com](http://www.natureworksllc.com)
- [46] NatureWorks (2003) PLA Polymer 2002D Data Sheet, NatureWorks LLC. Available from www.natureworks.com (assessed 4/5/12).
- [47] NatureWorks (2005) www.natureworks.com factsheet Apparel Dyeing Finishing.