

GENERAL

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Abstract

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Acknowledgments

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Dedication

With much love and gratitude, I dedicate this work to my family and many friends. First, to the soul of my mother **Kaouther**, my most beloved person, who taught me to trust Allah and taught me about dreams and patience, who had always believed in me. For her, my siblings and I were the universe center from day one and till the last moment. We are what we are only because of her unconditional love, her kindness and her support.

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Contents

GENERAL INTRODUCTION.....	2
Reception laboratory presentation	6
1. Textile Evaluation Department.....	6
1.1 Research and development.....	6
1.2 Laboratory equipment.....	7
2. Material Engineering department	7
2.1 Research and development.....	7
2.2 Laboratory Equipment.....	8
Chapter 1: Research Background	10
1 Polylactide fiber.....	11
1.1 PLA History and definition	11
1.2 Production of Polylactide	11
1.3 PLA properties and performance	16
1.3.1 PLA properties	16
1.3.2 Comparison of PLA with PET	18
1.3.3 Comparison between PLA and other synthetic fibers.....	20
1.3.4 Comparison of PLA with natural fibers.....	21
1.4 The environmental impact of PLA	21
1.5 PLA use and applications	23
1.6 Advantages and limitations of PLA.....	28
1.6.1 Advantages	28
1.6.2 Limitations of PLA.....	28
2. Biodegradability and Biodegradation of PLA	29
2.1 Biodegradable and sustainable fibers	29
2.1.1 Biodegradable fiber	29
2.1.2 Sustainable fibers	30
2.2 Factors influencing the biodegradation of PLA	32
2.3 Microbial degradation of PLA	33
2.4 Enzymatic degradation of PLA.....	34
2.5 PLA Biodegradability and biodegradation mechanism	35
2.6 Biodegradation behavior in soil and in compost.....	36
3. Recyclability in textiles	38
3.1 Recyclable fibers.....	38

3.2 Recyclability of PLA fiber	40
Chapter 2: Research Design	44
1. Materials and equipment used.....	45
1.2 Sample fabrics	45
1.3 Qualitative identification of the sample.....	45
1.4 Laboratory equipment used for data collection and analysis of results	46
2. Test methods.....	47
2.1 Determination of fabric structural and physical properties.....	47
2.1.1 Mass per unit area.....	47
2.1.2 Thickness test	48
2.1.3 Abrasion test	49
2.1.4 Friction test.....	49
2.1.5 Bursting strength	50
2.1.6 Tensile strength test.....	51
2.1.7 Optical microscope	52
2.2 Determination of thermophysiological comfort properties	53
2.2.1 Liquid moisture transport MMT	53
2.2.2 Thermal properties: the ALAMBETA instrument.....	55
2.2.3 Water Vapor permeability and resistance: the Permetest	58
2.2.4 Air permeability test.....	60
2.2.5 Thermal radiation insulation index: Infrared camera	60
2.2.6 Surface Roughness: The Talysurf CLI (chromatic, laser, inductive) 500	62
Chapter 3: Results and discussions.....	66
1. Structural and mechanical properties.....	67
1.1 Abrasion test Results for PLA	67
1.2 Friction test for PLA	68
1.3 Bursting strength test.....	69
1.4 Tensile strength test of PLA.....	71
2. Thermophysiological comfort properties	74
2.1 Liquid moisture transfer properties	74
2.2 ALAMBETA Thermal properties.....	78
2.2.1 Thermal conductivity and thermal resistance.....	78
2.2.2 Thermal absorptivity	81
2.3 Thermal insulation radiation index: Infrared camera	82
2.4 Air permeability	83
2.5 Water vapor permeability	84

2.6 Water vapor resistance	85
2.7 Surface Roughness	86
General conclusion	92
Bibliography.....	94

List of figures

Figure 1: Maslow hierarchy needs pyramid (1).....	2
Figure 2: Chemical structure of PLA. (7).....	12
Figure 3: Production of lactic acid from renewable resources such as corn. (14)	13
Figure 4: Two stereoisomers of Lactic acid. (14).....	13
Figure 5: Polymerization routes to PLA. (15).....	14
Figure 6: Examples of molecular configurations of PLA obtained through combining the two lactic acid isomers in varying proportions. (16).....	14
Figure 7: NatureWorks LLC's continuous production process of high molecular weight PLA. [(18), (19)]	16
Figure 8: Test results for water uptake and transport on PLA and PET fabrics (a) 1 minute and (b) 15 minutes after a drop of water was put on the fabric. (26)	19
Figure 9: Test results for flammability of fabrics of PLA and PET in accordance with the federal safety for vehicles FMVSS 302. (26)	20
Figure 10: Life cycle of PLA.....	22
Figure 11: Net CO ₂ emission of plastics from cradle to grave	23
Figure 12: PLA packaging use	24
Figure 13: PLA use in healthcare.	25
Figure 14: PLA in structural applications.....	26
Figure 15: PLA used for 3D printing.....	27
Figure 16: Life cycle of biodegradable and compostable fiber.	32
Figure 17: Schematic representation of the degradation behavior of the polymers (L-PLA, D-PLA, and PGA).....	35
Figure 18: Biodegradation of PLA in compost at 60°C.	36
Figure 19: Change in tenacity and the relative viscosity of PLA multifilament in soil burial. (54)	37
Figure 20: Aerobic composting test result of PLA fibers according to ISO 14855. (54)	37
Figure 21: Universal recycling symbol.....	38
Figure 22: SPI symbol indicating source material for possible recycling;.....	38
Figure 23: Composting association compostability mark.	39
Figure 24. PLA front side	45
Figure 25. PLA backside.....	45
Figure 26: The measuring balance.	48
Figure 27: Thickness tester.....	48
Figure 28: Nu-Martindale Abrasion & Pilling Tester.....	49
Figure 29. Friction tester.	50
Figure 30: Bursting strength tester.	51
Figure 31: The MMT apparatus design (60).	53
Figure 32: The ALAMBETA instrument. (61).....	56
Figure 33: The Permetest (Skin model) apparatus design and principle.	59
Figure 34 : TEXTEST Principle and Design.....	60
Figure 35: Infrared camera.....	61
Figure 36: The Talysurf conception.	63
Figure 37: Peak count Histogram taken from Talysurf measurements.....	63
Figure 38: Number of motifs taken Talysurf measurements.	64

Figure 39: PLA, ABS, PETG friction coefficient for $v=0,25$ m/s.	69
Figure 40: PLA, ABS, PETG friction coefficient for $v= 0.75$ m/s.	69
Figure 41: E-Modulus for PLA and other synthetic fibers.	71
Figure 42: Typical stress–strain curves for single PLA fibers with varying diameters. The inset figure shows the initial stage (up to 5% strain) of the stress–strain curves. (65)	72
Figure 43: (a) Tensile strength and modulus properties of the single PLA fibers with varying diameters and (b) relationship between the tensile properties and degree of crystallinity of PLA fibers (64).....	73
Figure 44. Finger print of Moisture Management properties for PLA.	75
Figure 45. Moisture Management different parameters (mean values).	75
Figure 46.Finger print of Moisture Management properties for a: PET, b: PVC, c: COOLMAX d: COTTON and e: WOOL (MERINOS).....	77
Figure 47.Influence of temperature drop across the textile layer on thermal conductivity and resistance of polymers.	80
Figure 48.Thermal insulation radiation index of PLA.	82
Figure 49.The heat loss forms of human body.....	83
Figure 50: Air permeability parameter for different fabrics.	84
Figure 51: PLA surface roughness appearances in 3D.....	88
Figure 52: ABS surface profile.	89
Figure 53: PLA surface profile.....	89
Figure 54: PETG surface profile.	89

List of Tables

Table 1. Fiber properties of PLA and PET	18
Table 2. Thermoplastics mechanical properties of different polymers (28).....	20
Table 3. Characteristics of natural fibers against PLA fiber.....	21
Table 4. Environmental impact and combustion characteristics of PLA and other conventional fibers. (27)	23
Table 5. Different forms of PLA fiber (33)	24
Table 6. Cost comparison of traditional and biodegradable polymers. (40).....	30
Table 7. Equipment and devices used.	46
Table 8. Greatness, properties and behavior of the material.	52
Table 9. MMT Grading table. (60)	55
Table 10. Thermal absorptivity intervals of textile fabrics. (61)	57
Table 11. Dry Abrasion test results for PLA.....	67
Table 12. Wet Abrasion test for PLA	67
Table 13. Bursting strength results.	70
Table 14. Comparison of Bursting Strength of PLA fabric with others. (67)	70
Table 15. MMT results for PLA fabric.	74
Table 16. ALAMBETA PLA test results	79
Table 17. ALAMBETA quantities ; symbols and units. (61).....	79
Table 18. Comparison of thermal properties between synthetic fibers.	80
Table 19. Thermal absorptivity results.....	81
Table 20. Thermal insulation of PLA.....	82
Table 21. RWVP (%) for PLA fiber.	85
Table 22. Ret comfort rating system. (61).....	86

General Introduction

GENERAL INTRODUCTION

At the beginning of the third millennium, the world population was approximately six billion, today it's about seven and a half billion, which expected to rise up to ten billion by the middle of the twenty first century. The exponential increase in population increases the demand on food, energy, water and other resources. Textiles is certainly one of those needs, and if we take a look at the Maslow Pyramid, we can easily find out that textiles and clothes is one of the very rare life elements that figures everywhere in the different parts of this pyramid (See Figure 1).

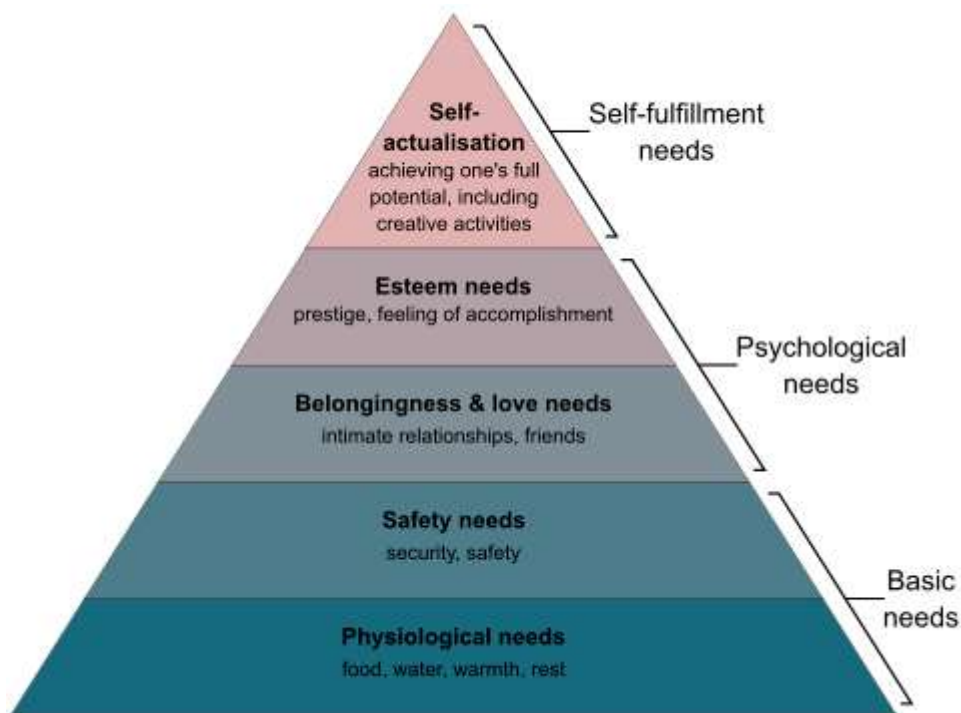


Figure 1: Maslow hierarchy needs pyramid (1).

First, we all need to cover our bodies, to feel warm, comfortable and to feel deniable; it's a fundamental need as important as food and water are. Then, it's a manner to express ourselves, express how we think and how we live, and especially what we want to be. It tells a lot about us. Finally the different aspect of textiles; garments, furniture, cars, luxury products are the main and the most notable aspect of wealth, good looking and self-fulfillment. Therefore, and since so long, people stopped being satisfied with what mother nature provides to us and started looking out for more resources and other solutions; artificial and synthetic fibers are the best compliment to the natural fibers.

Since the 1930s, research and development into synthetic chemical products has afforded a significant improvement in the quality of life and availability of products for consumption. Not least being synthetic polymers, specifically fibers, for apparel and furnishing applications. (2)

The main problems with synthetic polymers are that they are non-degradable and based on non-renewable resources. Since their invention, the use of these synthetic fibers has increased oil consumption significantly, and this continues today; arguably, Polyester, for example, is the most used of all fibers, taking over from cotton. Oil and petroleum are non-renewable resources and at the current rate of consumption, these fossil fuels are only expected to last for another 50–60 years; the current petroleum consumption rate is estimated to be 100,000 times the natural generation rate. (2)

Of even more concern is the ability of polymeric fibers to remain unchanged in the environment as such polymers do not degrade very readily, which has exacerbated the already existing ecological and environmental problems of waste building; the volume in waste disposal and landfill is very high. Landfills are decreasing in number, making less space available to discard waste. (3)

For this reason, producing recyclable polymers coming from green and renewable resources is no longer enough. We still need to make sustainable and biobased fibers so that we can help our planet to survive.

The work carried out aims to study the feasibility of replacing the petroleum-based polymers in general and Polyester in particular with Polylactic acid fiber '**PLA**'. It is divided into three main parts.

The first part is a **background research**, which introduces the studies in the literature review of the fundamentals of PLA properties, biodegradability and recyclability. **The second part** is an **experimental part** deals with the material, methods and processes used for the experimental work. **The third part** presents **results and discussions**. This work will be finished by a **general conclusion** meant to recapitulate the main results, in addition to the other ideas that can be studied and tested in further projects and presenting some perspectives to deepen the project.

***Reception Laboratory
Presentation***

Reception laboratory presentation

This end-of-studies project was carried out within the technical university of Liberec, in the faculty of textiles.

The faculty of textile engineering was established in the year 1960, as the second faculty of former university and provides, as the only one in Czech Republic, academic education through whole textile subject.

Faculty of textile engineering consists of six departments. There are department of Design, department of textile Evaluation, Department of clothing technology, Material engineering department, Nonwovens and Nano department and finally the department of textile technologies.

The research internship was carried out within two different departments; Material engineering department (4) and Textile Evaluation department (5). The laboratories research themes cover various fields ranging from materials to mechanics, thermal comfort and chemistry. Always at the service of textiles and clothing.

1. Textile Evaluation Department

1.1 Research and development

- Development of new methods and devices for comfort evaluation;
- Hand evaluation and prediction;
- Evaluation of textile utility properties (air permeability, surface roughness, drape, flexural rigidity, etc.);
- Development for the new methods for fabric surface analysis;
- Optimization of textile maintenance in terms of lifetime;
- Automatic quality monitoring of textile structures with the use of image analysis- defect detection, automatic evaluation of wearing density, homogeneity of the pores and other characteristics of fabric;
- Modeling of transport effects in the Nano porous materials using computer simulation;

- Development of new textile structure with higher comfort. (5)

1.2 Laboratory equipment

- The Moisture Management tester;
- Set of devices developed in the KHT for evaluation of heat (Alambeta) and humidity (Permetest) of textiles;
- Talysurf CLI 500-3D surface texture measurement system with the possibility to control the roughness in 3D;
- Climatic Test chamber Votsch Industrietechnik;
- Hydrostatic pressure or water column value measured by an SDL Atlas hydrostatic Head tester;
- Olympus BX51 microscope with the possibility to observe textile fibers, linear, and planar structure in passing and / or incident light and eventually studying their fluorescence;
- Miele professional complex maintenance system consisting of an industrial washing machine, drier, exhaust ironing table and mangle for complete servicing of household and industrial data maintenance. The washing machine is fully computer programmable as required. (5)

2. Material Engineering department

2.1 Research and development

- Characterization and study of different types of fibers like high performance fibers (Kevlar, Nomex, etc.) side emitting optical fibers special inorganic fibers (Basalt, Carbon), thermally adaptive PET, thermally adaptive fibers.
- Development of composites and nanocomposites; computer modeling of textile structures, textile composites based on the carbon fibers, Nano-reinforcement for composites, FEM modeling of composite properties and 3D fabrics preparation and properties for composites.
- Metrology and quality control:
 - Surface and hand evaluation of flat textiles;

- Thermal and mechanical properties of materials;
 - Electrical properties and EMI shielding;
 - Application of image analysis for special testing;
 - Complex evaluation of textiles quality.
- Calorimetry:
 - Evaluation of color and color differences;
 - Color changes based on sensors;
 - Measurement of UV protection.
- Functionalization of surfaces:
 - Applications of PLASMA microwaves, Laser and ozonization;
 - Chemical modifications of surfaces;
 - Analysis of foreign materials composition (dust, spots);
 - Special finishing techniques (felting, shear thickening).
- Nanoparticles:
 - Preparation of nanoparticles by milling or in situ deposition;
 - Nanoparticles for functionalization of textiles;
 - Characterization of nanoparticles effects. (4)

2.2 Laboratory Equipment

- Thermo-mechanical spectroscopy;
- Environmental microscopy and image analysis;
- Surface roughness;
- Dynamic mechanical analysis CX/04;
- Microspectro-colorimetry;
- Spectroscope (from UV to IR range);
- Infrared camera (FLIR camera);
- Thickness tester;
- Nu-Martindale abrasion and pilling tester;
- Tensile strength tester;
- Textile burst Tester –LH-13-62- (4).

Chapter 1:

Research Background

Chapter 1: Research Background

As usual, this background research is fundamental to clarify the work different parts and the main purpose of this graduation internship that helps to figure out the different sections.

In fact, in order to properly define the framework, this chapter begins by presenting a general overview allowing to define the PLA fiber, its production, its properties and especially the environmental impact; then we expose a summary in order to define this polymer

- Understand the structure and the origin of the fiber.
- Understand how it interacts with different factors.

This bridge between the previous knowledge, the basic information and the coming tests will allow us to know more about the sustainability of PLA fiber.

Is PLA a good alternative for petroleum based polymers such as PET?

1. Polylactide fiber

1.1 PLA History and definition

The Polylactide fiber has first appeared in 1988, the idea was about developing a new product with more value opportunities for starch processed by the company Cargill Inc. The Dr. Pat Gruber, who made this initiative and developed the first key processes to converse lactic acid into lactide; the processes and technologies were based on purification, polymerization and devolatilization of lactide. This fiber production had had been through different stages and it was finally commercialized under the trade name NatureWorks™. In November 1997, after it had been founded as a 50/50 joint venture Cargill Inc. and the Dow chemical company to pursue this final product in the market. (6)

Today, Cargill Dow, is building a global platform of sustainable polymers and chemicals completely made from renewable resources. To make this come true, the latest is using and further refining a combination of biological, agricultural processes and chemical technologies. The philosophy here is to get a “triple bottom line” of sustainability which means a new fiber from an economic, environmental and social perspective. (6)

In January 2020; and in many different countries like USA, Netherlands and Japan, a quantity of 140.000 metric tons of PLA were produced and commercialized worldwide. (6)

Polylactic acid or polylactide “PLA” is the first melt processable synthetic fiber, it’s fully biobased. We can get this fiber by using annually renewable resources such as corn starch, wheat and sugar beet, which makes this new fiber the only one combining ecological advantages with the high mechanical properties. This combination between natural and synthetic fibers finds a wide range of applications and uses from houseware, clothing to medical and construction.

1.2 Production of Polylactide

Polylactic acid $[(C_3H_4O_2)_n]$ is an aliphatic polymer derived from 100% renewable resources. The molecule chains with a helical structure form a synthetic polymer based on lactic acid $(C_3H_6O_3)$ (see Figure 2) (7), then passed by a fermentation of agricultural resources. This

polymer is compostable, easily degrades by simple hydrolysis under the appropriate conditions. [(8), (9), (10)]

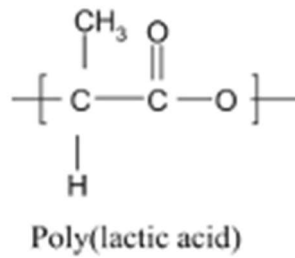


Figure 2: Chemical structure of PLA. (7)

The production of PLA starts with extracting starch from plants such as corn or sugar from sugar beet whey or molassas. This starch could also be extracted from rice, wheat, sweet potato, etc.

Many other low values by product wastes such as grass or even biomass could be used for PLA production in the next few years. (11)

First of all, the starches are converted to fermentable sugars (glucose, dextrose...) using enzymatic hydrolysis, microorganisms break the sugar into small species known as lactic acid.(Figure 3) (12)

Lactic acid has two different active stereoisomers; dextro (D-) and levo (L-). Natural fermentation will generally lead to a mixture in the approximate proportions 99.5% (L) and 0.5% (D) (13). Those two isomers have exactly the same physical properties, with one exception of the L-form rotates the plane polarized right in a clockwise sense while the D-form rotates it anti-clockwise. (14)

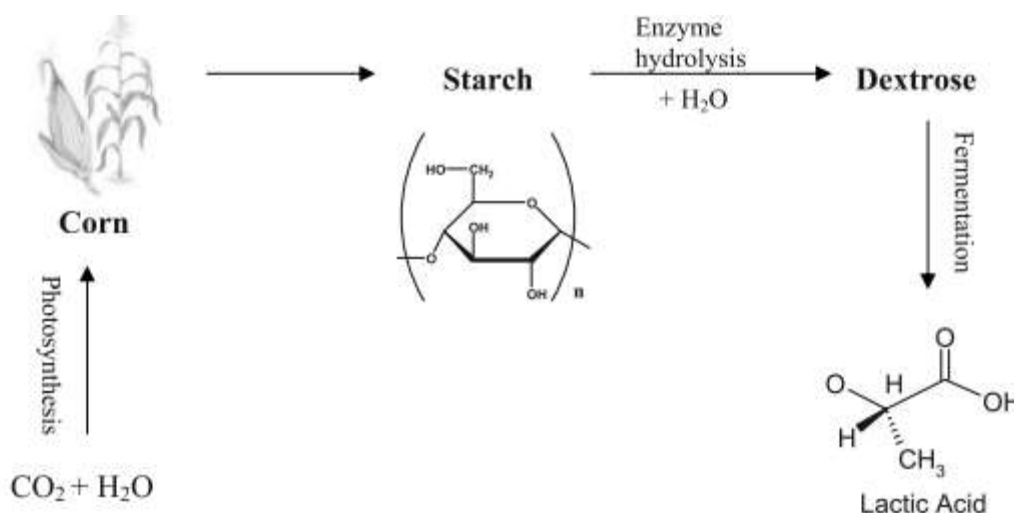


Figure 3: Production of lactic acid from renewable resources such as corn. (14)

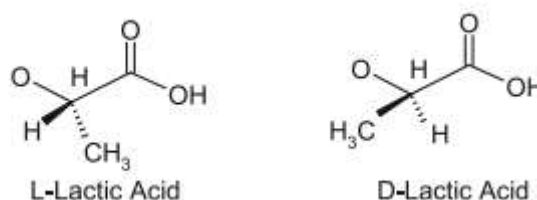


Figure 4: Two stereoisomers of Lactic acid. (14)

Lactic acid is the first monomer to get for the PLA production, then we have two major techniques to produce this fiber from the lactide. The conventional process is by polycondensation of lactic acid. This process should be carried under high temperature and high vacuum. A solvent is used to extract the water produced by the condensation reaction, the final product tends to have low to intermediate molecular weight ($M_w = 10.000 - 20.000$) due to difficulties of removing the water and impurities.

The second method is ring-opening polymerization of a cyclic dimer of the lactide. The final product of this method has a higher molecular weight polymer and uses milder conditions. (15)

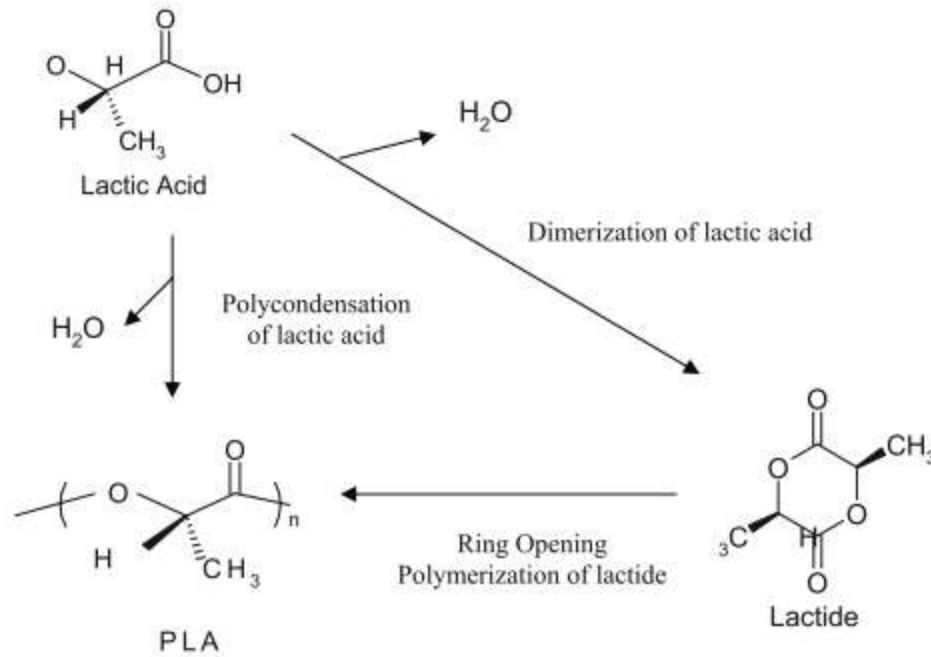


Figure 5: Polymerization routes to PLA. (15)

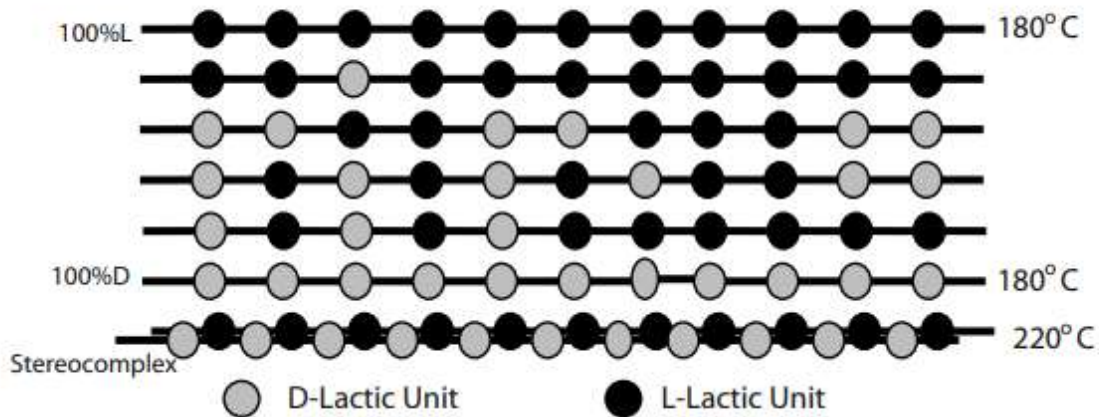


Figure 6: Examples of molecular configurations of PLA obtained through combining the two lactic acid isomers in varying proportions. (16)

Production of PLA Via the lactide route allows the possibility of modifying for superior control of the polymer properties by controlling the optical sequence of the polymer backbone.

Different characteristics of the polymer could be obtained through the controlled production of the optical isomers of the lactic acid via combining the two forms of lactic acid through the three lactide intermediates. A wide range of molecular weights of PLA could be produced by controlling the purity of the lactide. The ratio of D- and L-isomers and their distribution along the polymer backbone influence the molecular weight, crystallinity, and melting point of the

end product PLA. A high proportion of L-lactide can be used to produce crystalline polymers. Highly crystalline polymers can be achieved when the D-lactide content in the materials is less than 2%. The crystallinity of PLA decreases with increased D isomer level (20). Amorphous polymers can be produced using a relatively high D-lactide content (greater than 15%). The crystallinity and melting point of pure poly-L-lactide are about 37% and 175-178 °C, respectively. For example, PLA produced from meso-lactide is an amorphous polymer. On the other hand, Poly (L-lactic acid) (PLLA) is a part crystalline, relatively hard material with a regular molecular structure. The right balance of stiffness, toughness, melting temperature, and degree of crystallinity of PLLA can be controlled without disturbing the crystallinity with the insertion of D-lactide units. The D-form is normally thought of as an impurity in fermented lactic acid. Representations of PLA polymer chains having different ratios and distributions of the D- and L- isomers are shown in Figure 6, Different melting points of PLA, varying from 130°C to 220° C, can be obtained. PLA having only L-lactic units, has a melting temperature of 180°C and is shown in the upper row of Figure 6. A blend of poly (L-lactic acid) and poly (D-lactic acid) can lead to a polymeric stereocomplex with higher melting point than either L- or D-polymers alone (See the last row of Figure 6). However, the mixing ratio and the molecular weight of both polymers influence the stereocomplex formation. The melting temperature of the stereo-complex can be as high as 220°C. Nevertheless, the spin ability of the stereo-complex polymer still needs further research (14). NatureWorks LLC has developed a patented, low-cost continuous process for the manufacture of PLA polymer.

Synthesis of lactide and PLA from melt rather than in solution, possesses environmental and economic benefits (12). The continuous condensation of lactic acid is the first step in the production of low molecular weight PLA pre-polymer. Then, the pre-polymer is converted into a mixture of lactide stereoisomers. Finally, high molecular weight PLA is obtained via ring-opening polymerization.

This process completely eliminates the use of costly and environmentally unfriendly solvents. The remaining monomer is eliminated under vacuum and recycled back to the beginning of the process after the completion of the polymerization.

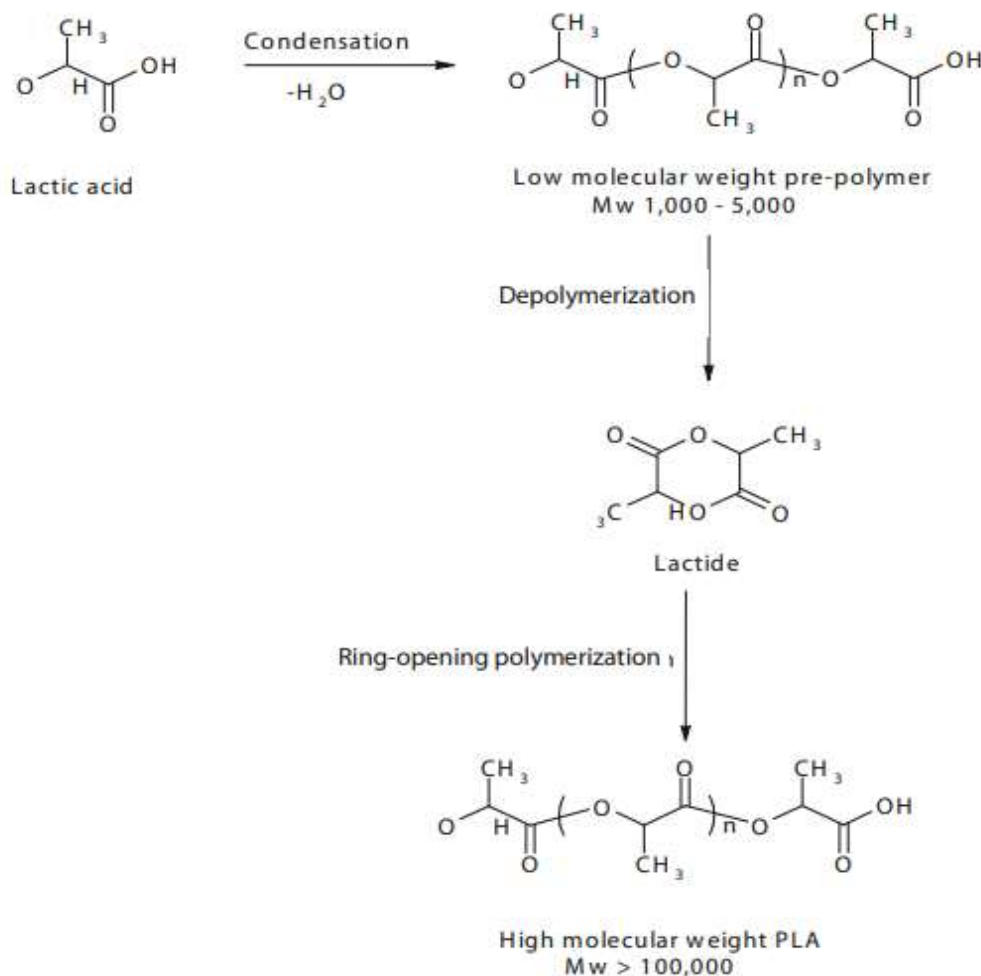


Figure 7: NatureWorks LLC's continuous production process of high molecular weight PLA. [(18), (19)]

1.3 PLA properties and performance

1.3.1 PLA properties

PLA combines ecological advantages with very good technical performance in textiles. PLA has high mechanical strength, compostability, and biocompatibility (21). As a melt-processable fiber from a vegetable source, PLA has many characteristics similar to many other synthetic fibers (7). The properties of PLA fibers are between those of Polyamide 6 and PET [(22), (23)]. On the other hand, the mechanical properties of PLA are considered to be broadly similar to those of conventional PET (8). Poly (lactic acid) is a relatively stiff polymer at room temperature but its glass transition temperature (T_g) is rather low, being in the range of 55°C

to 65°C. PLA polymer from meso-lactide can exhibit a glass transition temperature as low as 35 °C, The melting temperature (T_m) of PLA, having either the L- or D- isomeric form alone, is between 160-180 °C, whereas the melting temperature of stereocomplex PLA is 220°C.

The PLA polymer demonstrates a clear decrease in molecular weight on heat treatment above 190°C, at which the thermal degradation of PLA starts to take place.

Different mechanical properties of PLA, ranging from soft and elastic materials to stiff and high strength materials, can be achieved to a large extent. If higher mechanical properties of PLA are needed, semi-crystalline PLA is preferred to the amorphous polymer. The degree of crystallinity and molecular weight of the polymer extensively influence its mechanical properties. For example, if the molecular weight of PLA polymer increases, the tensile strength and Elasticity modulus increase.

Some typical properties of PLA are compared with those of conventional polyester (PET) in Table 1. The specific gravity of PLA is lower than that of PET. Varying the optical composition of PLA allows control of the melting point in the range from 130°C to 180°C, whereas that of PET is around 254-260°C, and typical melting point of PLA is around 170°C. However, its low melting point results allow domestic ironing temperature, leading to limitations for end users. Temperatures for ironing and garment processing should be lower than these of cotton and PET. (12)

PLA also has advantages with respect to smoke generation and flammability, having both higher limiting oxygen index (LOI) and lower smoke generation than PET. The deeper shades can be achieved because of the lower refractive index of PLA compared to PET using a given concentration of disperse dye on fibers of similar dimensions. PLA is highly resistant to degradation by ultraviolet radiation, with no loss in elongation after 100 hours in Xenon arc testing. PLA fibers do not provide a microbial food source and they do not support bacterial growth. Besides PLA fiber based fabrics exhibit lower odor retention than PET fiber based fabric It is unaffected by dry-cleaning solvents.

1.3.2 Comparison of PLA with PET

Table 1. Fiber properties of PLA and PET.

Fiber properties	PLA	PET
Specific gravity(g/cm ³)	1.25	1.39
Tm(°C)	130-175	254-260
Tenacity (g/d)	6.0	6.0
Elastic recovery(5% strain)	93	65
Water absorption (%)	0.4-0.6	0.2-0.4
Flammability	Continuous to burn for 2 min after flame removed	Continuous to burn for 6 min after flame removed
Smoke generation	63 m ² /kg	394 m ² /kg
Limiting oxygen index (%)	26	20-22
Heat of combustion (Kcal/kg)	4500	5500

PLA exhibits good moisture management and comfort properties. This is particularly important in respect of applications such as sportswear, underwear, and bed linen. Moisture management is the ability to transmit moisture away from the body with good wicking, faster moisture spreading, and drying. Breathability of fabrics is closely related to the transmittance water vapor through the fabric and by wicking of water. Hydrophilic fibers such as cotton and wool are usually considered to be comfortable and breathable whereas hydrophobic fibers such as polyester and polypropylene tend to be less so (24). The moisture regain and wicking property of PLA are superior to PET [(25), (20)]. PLA fibers wick moisture well without absorbing large amounts of water, which benefits sports and performance apparel. Its lower contact angle compared to PET that leads to improved wicking with water (25). PLA exhibits a quick removal of moisture from the body (14). It is stated that PLA fibers performed better than PET and cotton, either as 100% PLA fabric (alone) or when combined with cotton according to series of tests including breathability, water vapor transport, and thermal insulation measurements (12). Improved physiological comfort was experienced with PLA/cotton blend fabric compared to equivalent PET/cotton blend fabric (12).

The difference in moisture regain and water permeability between PLA and PET fabrics in wetting and drying has been tested under simulated studies, Figure 8 indicates the test results of wetting drying performance both after 1 min and 15 min from when a drop of water fell on the fabrics. It can be seen that PLA fabric absorbs water instantly and quickly diffuses it outwards and water has dried completely after 15 min. (26)

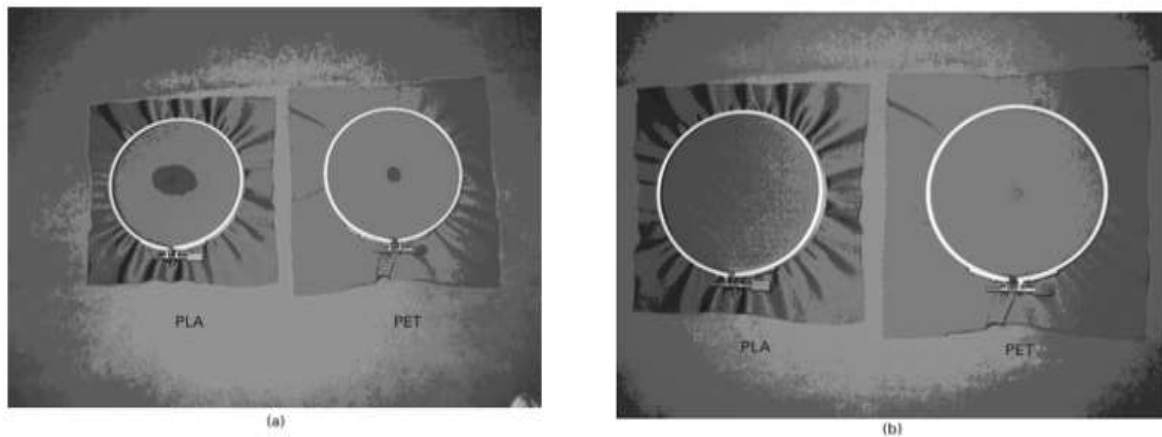


Figure 8: Test results for water uptake and transport on PLA and PET fabrics (a) 1 minute and (b) 15 minutes after a drop of water was put on the fabric. (26)

As far as self-extinguishing characteristics, PLA show very good flammability properties, although it is not a nonflammable polymer. It burns for only 2 minutes with low smoke generation ($63 \text{ m}^2/\text{kg}$) after the flame has been removed, while PET burns for 6 minutes with higher smoke generation ($394 \text{ m}^2/\text{kg}$). The calories produced from combustion of PLA fiber are relatively low 4500 Kcal/kg , nearly equal to that of cellulose fibers when compared to the 5500 Kcal/kg of PET fiber, as already shown in Table 1 [(26), (27)].

The LOI (limit oxygen Index) value of PLA fiber and spunbond fabric in accordance with JISK 7201 is higher as shown in table 1, i.e. 26 for PLA fiber, compared to 20-22 of PES and Nylon fiber. A higher value indicates that the PLA fiber has better flame retardant characteristics.

In terms of its flame-retardant property, under the standard conditions of the Federal Safety Specifications for Vehicles, the FMVSS 302 test demonstrated that PLA fabric performs better than PET fabric as shown in Figure 9. These advantages of low flammability and smoke generation for PLA fibers will lead to excellent fire safety in carpeting, home furnishings and sheeting fabrics for vehicles. (26)

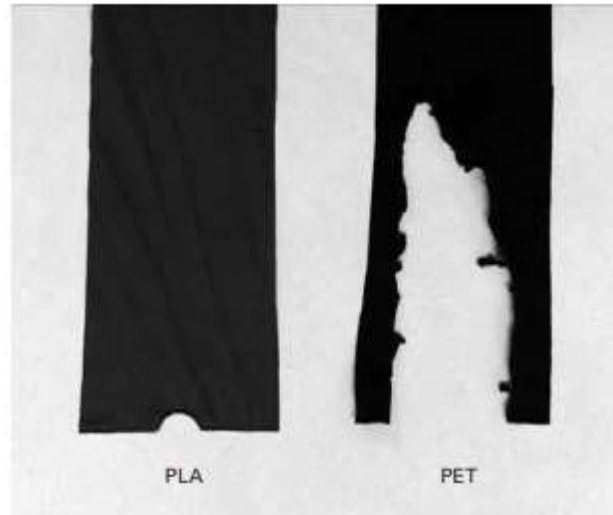


Figure 9: Test results for flammability of fabrics of PLA and PET in accordance with the federal safety for vehicles FMVSS 302. (26)

1.3.3 Comparison between PLA and other synthetic fibers

PLA is comparable to several polymers in term of crystallinity, rigidity and mechanical properties (See Table2). However, it lacks toughness. The latest can be improved by blending the PLA with other polymers by copolymerization or by structural modification.

For example, the stress at break and the elongation of pure PLA are respectively 50 MPa and 2%. However, the PLA-caprolactone combination reduces the tensile strength to 20 MPa and improves elongation giving very flexible films. The density of PLA (1.25 g/cm^3) which is lower than that of Polyethylene terephthalate PET (1.30 g/cm^3) but higher than that of Polystyrene (1.05 g/cm^3) and as high as that of most conventional polymers(between 0.8 and 1.1 g/cm^3).

Table 2. Thermoplastics mechanical properties of different polymers. (28)

Polymer	Tg(°C)	Tm(°C)	Density ρ (g/cm ³)	α_r (%)	E(GPa)
PLA	50-60	150	1.25	40-60	3-5
PP	5	165	0.92	30	1.2
HDPE	-100	134	0.95	20	1.1
PVC	75-105	160-220	1.39	58	2.9
PS	90-100	—	1.05	55	3.2
PET	70	255-265	1.34	47	2.6
ABS	90-120	—	1.05	50	2.5

1.3.4 Comparison of PLA with natural fibers

The huge difference between PLA fiber and the natural fibers in mechanical performance is clearly shown in the following table (Table 3).

Table 3. Characteristics of natural fibers against PLA fiber.

Fiber	Diameter(μm)	E (MPa)	α (%)
PLA	11-38	50	2
Cotton	12-25	10-26	6-8
Linen	12-30	50-70	1.3-3.3
Hemp	16-50	30-60	1.7-2.7
Jute	5-25	20-55	1.5-2
Sisal	100-400	9-22	3-14
Bananas	50-250	7-20	1.8-3.5
Abaca	50-280	-	2.1-2.4

1.4 The environmental impact of PLA

PLA is acknowledged to be a more environmentally-friendly polymer than PET (Table 1). The typical life cycle of PLA is shown in Figure 10 [(20), (21) (29)]. The monomer of PLA is sustainable. First of all, whose raw material (such as corn) is renewable and non-polluting, production of PLA fibers from corn will not result in a food crisis, since the amount of corn consumed in the production of PLA fibers is less than 0.02% of the total amount of world production (30). The latest is produced from plants and polymerized and processed into the desired products. Production of PLA requires 25-55% less fossil energy and 20-50% less fossil fuel resources than the production of petroleum-based polymers. So, the net result is a lower greenhouse gas emission and a significant energy savings. (30)

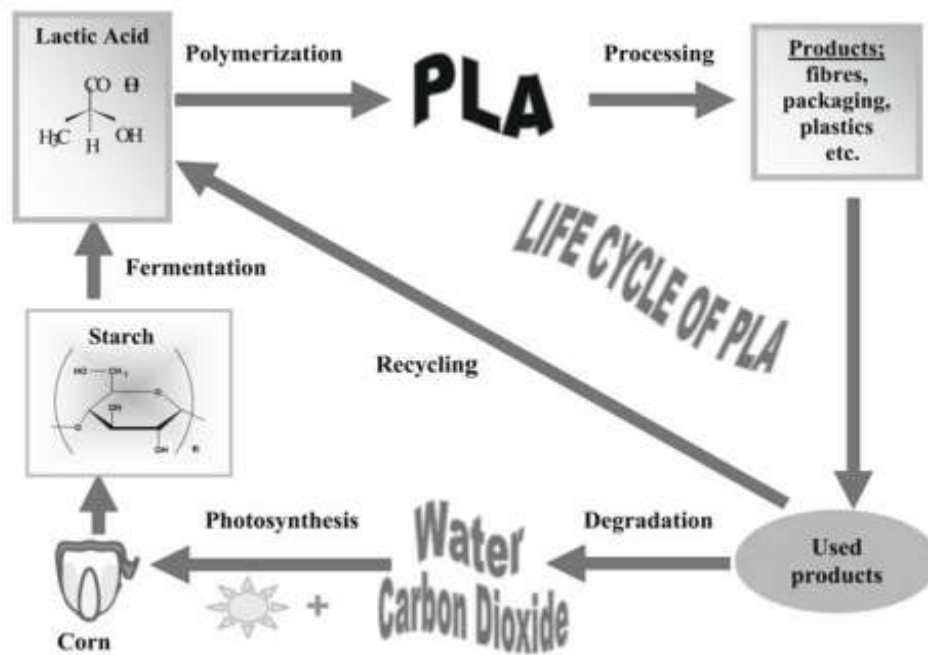


Figure 10: Life cycle of PLA.

With PLA, CO₂ is removed from the atmosphere when growing the feedstock crop, and returned to the Earth when PLA is degraded or incinerated. Since the process recycles the Earth's carbon, PLA has the potential for not increasing atmospheric CO₂ levels (31). However, as is the case for all polymers, fossil fuels are used in the processing of raw materials and resin production for PLA. Thus, the subtotal CO₂ emission (feedstock + processing) of PLA pellet production has been evaluated to be the lowest, compared with that of conventional petroleum-based plastics. (31) Furthermore, the CO₂ emission of PLA in the course of disposal, such as incineration or composting, is minimal, so that the total CO₂ emission of PLA from cradle to grave (feedstock + processing + disposal) is the lowest among existing plastics as indicated in Figure 11. (32)

Table 4. Compares the net CO₂ emission, calories from combustion and LOI (Limit of Oxygen Index) of PLA and conventional fibers, including both petroleum-based and regenerated cellulosic fibers (viscose rayon). It can be seen that PLA has the lowest level of CO₂ emission, the lowest heat of combustion, nearly equal to rayon, and the highest LOI value. In contrast, viscose rayon has the highest CO₂ emission due to the higher processing energy required, in spite of its origin from renewable resources.

Synthesis, properties and structure of polylactic acid fibres

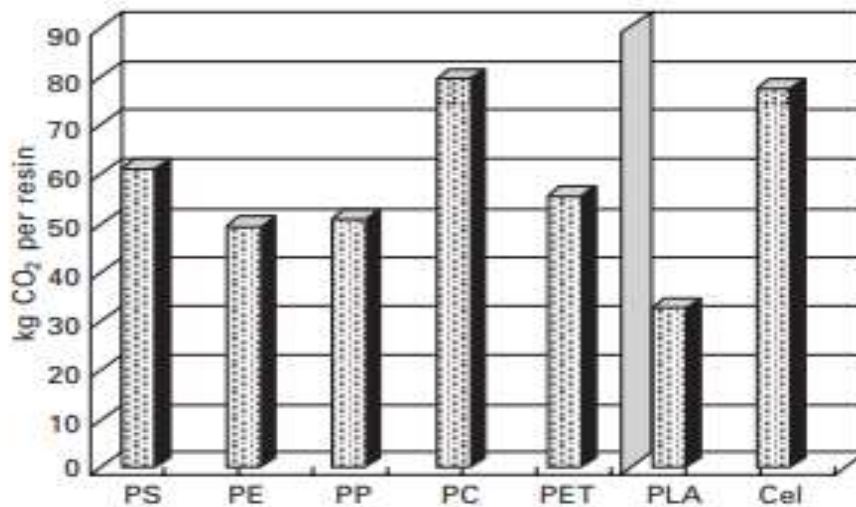


Figure 11: Net CO₂ emission of plastics from cradle to grave.

Table 4. Environmental impact and combustion characteristics of PLA and other conventional fibers. (27)

Material	Feedstock source	CO ₂ emission(Kg/ton)			Heat of comb.	
		Cradle → pellet	Inciner	Total	LOI (Kcal/kg)	
Polypropylene	Petroleum	1891	3200	5091	10500	21
Poly(ethylene terephthalate)	Petroleum	4143	2300	6443	5500	
Viscose rayon	Wood	13030	1650	14680	4500	18
Polylactic acid	Corn	1820	1830	3650	4500	24-29

1.5 PLA use and applications

PLA fiber finds a wide range of uses from medical and pharmaceutical applications to environmentally benign film and fibers for packaging, houseware and clothing. PLA is also used in composite materials. Primary applications could be with fibers, fiberfill (pillows, comforters,

mattresses, duvets); apparel (sport, underwear and fashion wear) also, it can be used as a nonwoven for agricultural and geotextiles, hygiene products, wipes, etc.

A wide spectrum of forms from staple fiber to composite materials can be produces from PLA (Table 5).

Table 5. Different forms of PLA fiber. (33)

Different forms of PLA
Staple fiber
Monofilament
Multifilament
Bicomponent fiber
Knitted structure
Spun bonded nonwoven
Needle punched nonwoven
Composite materials

Popular applications of Polylactic acid

- **Food contact approved Polymer for packaging**

PLA is a Food and Drug Administration (FDA) approved polymer for use as a food contact material. It can be used as a food package polymer for short life product such as fruits and vegetables. The common packaging applications of Polylactide include as containers, drinking cups, salad cans, overwrap and blister packages. (34)



Figure 12: PLA packaging use.

- **Biocompatible Plastic in healthcare**

Thanks to its biocompatibility and biodegradability; the health care and medical industry is making good use of PLA to make the tissue engineering scaffolds, delivery system materials or covering membranes and different bio absorbable medical implants.

Due to its versatility, PLA has been investigated for membrane applications (e.g. wound covers), implants and medical devices (fixation rods, plates, pins, screws, sutures, etc.), and dermatological treatments (e.g. facial lipoatrophy and scar rejuvenation). (34)

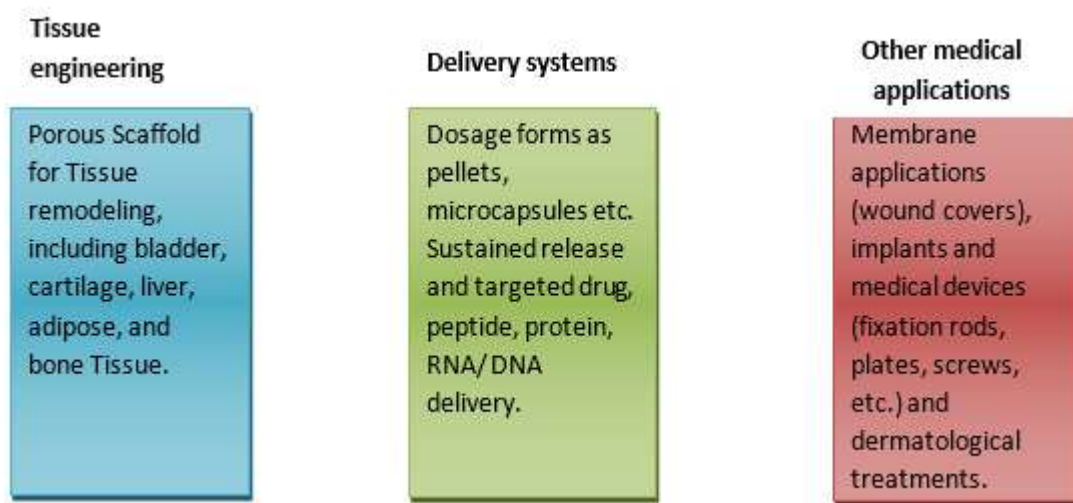


Figure 13: PLA use in healthcare.

- **Use of Polylactide in structural applications**

Biobased PLA and PLA-based composites are comparatively new for high-end automotive as well as electrical and electronics applications. These composites show better tensile strength and impact characteristics and hence could be used for interior parts of automobile or safety helmets.

Improved material properties enable this fiber to be used in floor mats, door trim, pillar cover, front panel and the ceiling material. Those biocomposites made from PLA are proposed for use in cover spare wheel or translucent roof, but only in hybrid concept vehicles. (34)



Figure 14: PLA in structural applications.

- **Fibers and fabrics made from PLA**



PLA is also suitable for textile fiber applications such as shirts, carpets, bedding, mattress, sportswear etc. due to its good moisture absorption, low smoke generation capability as well as good resistance to UV light. The polymer also has potential in mulch films and compostable garden waste bags, structural protective foams, insulation materials etc. (34)

- **Geotextiles**

Geotextiles and products for agricultural/horticultural applications are used in natural environments, and therefore they must disintegrate and degrade completely after their service life is over, in order to sustain the natural ecosystem. Service life is usually several years for geotextiles in applications such as soil erosion control, sandbags, vertical drain sheets and plant pots. PLA is a fully biodegradable material but it does not degrade too rapidly. This unique feature offers distinct benefits for geotextiles in agricultural/horticultural applications. (35)

- **Nonwovens and wipes**

The greatest potential uses for PLA nonwovens include baby wipes, and applications in the industrial, household and personal care markets. PLA can be directly processed into a

spunbond fabric with good mechanical properties under a high take-up speed of around 5000 cm/min. By using binder fibers, whose sheath component has a lower melting point of 130°C, nonwovens can be made by conventional thermal bonding lines. Spunlace nonwovens are manufactured by hydro-entanglement using a high-speed water jet. The superior wicking rate and faster absorbency of PLA make nonwovens of 100% PLA or blends of PLA with cotton and rayon highly suitable for a wide spectrum of wipe applications including nappies and baby wipes, floor and furniture wipes, clean room wipes, food service and vehicle cleaning.

- **PLA used for 3D printing**

Polylactic Acid, is one of the most popular materials used in desktop 3D printing. It is the default filament of choice for most extrusion-based 3D printers because it can be printed at a low temperature and does not require a heated bed. PLA is a great first material to use as you are learning about 3D printing because it is easy to print, very inexpensive, and creates parts that can be used for a wide variety of applications. Also, because it is one of the most environmentally friendly filaments on the market today. Derived from crops such as corn and sugarcane, PLA is renewable and most importantly biodegradable. As a bonus, this also allows the plastic to give off a sweet aroma during printing.

Pros

- Low Cost.
- Stiff and good strength.
- Good dimensional accuracy.
- Good shelf life.

Cons

- Low heat resistance.
- Can ooze and may need cooling fans.
- Filament can get brittle and break.
- Not suitable for outdoors (sunlight exposure).



Figure 15: PLA used for 3D printing.

1.6 Advantages and limitations of PLA

1.6.1 Advantages

PLA is a fully biobased fiber, biodegradable, and biocompatible polymer which has proved its efficiency showing so many advantages. (34)

- Its properties are on a par with currently widely used polymers like PES and PVC ;
- High performance grades that are an excellent replacement for PS (polystyrene), PP (Polypropylene) and ABS (acrylonitrile butadiene styrene) in more demanding applications;
- Today, by optimizing, the PLA production process and with increasing PLA demand, a reduction in its price can be achieved;
- PLA has some crystalline content which benefits the quality of the finished products;
- PLA has a high strength and high thermoplastic modulus with good appearance;
- It has high stiffness and strength, comparable to polystyrene (PS) at room temperature;
- Less energy is required in its production when compared to other plastics and has better thermal processing.

Further development of composites, nanocomposites and bio composites is expanding the properties and potential applications of PLA.

1.6.2 Limitations of PLA

However, there are still some disadvantages associated to this polymer (34);

- Its poor ductility, low impact strength and brittleness limits its use as compared to other thermoplastics such as ABS;
- Its glass transition temperature is low ($T_g \sim 55^\circ\text{C}$);

- As compared to PET (aromatic polyester), PLA is much more susceptible to chemical and biological hydrolysis;
- It has low crystallization rate and processing results mainly in amorphous products;
- It is thermally unstable and has poor gas barrier performance;
- It has low flexibility and requires long mold cycles;
- It has slow degradation rate.

2. Biodegradability and Biodegradation of PLA

2.1 Biodegradable and sustainable fibers

2.1.1 Biodegradable fiber

A material is defined as 'biodegradable' if it is able to be broken down into simpler substances (elements and compounds) by naturally occurring decomposers – essentially, anything that can be ingested by an organism without causing that organism harm. It is also defined that it must be non-toxic and able to be decomposed in a relatively short period even on a human time scale (36). Albertsson and Karlsson (37) defined the biodegradation of a polymeric material as 'an event which takes place through the action of enzymes and/or chemical decomposition associated with living organisms (bacteria, fungi, etc.) and their secretion products'. Biodegradable polymers can be classified into three main categories:

1. Natural polysaccharides and biopolymers; e.g. cellulose, alginates, wool, silk, chitin, soya bean protein; (38)
2. Synthetic polymers, particularly aliphatic polyesters; e.g. poly (lactic acid), poly (ε-caprolactone); (37)
3. Polyesters produced by microorganisms; e.g. poly (hydroxyalkanoate). (36)

Biodegradable polymers and the fibers which can be produced from them later are very attractive in offering a possible solution to waste-disposal problems, but these polymers tend to have a high price associated with them (Table 6) (40), the applications of these polymers need to be found and taken on by manufacturers in order to consume sufficiently large

quantities of these materials and drive the price down so that they can compete economically in the market. (39)

Table 6. Cost comparison of traditional and biodegradable polymers. (40)

	Material	Average cost \$/kg ⁻¹
Traditional polymers	Polypropylene	0.73
	High density polyethylene	0.82
	Polyethylene terephthalate	1.15
Biodegradable polymers	Polylactic acid	3.30-6.60
	Polyhydroxyalkanoates	8.80-13.9

One of the most important factors in developing new biodegradable fibers that can compete economically is the public perception of what a biodegradable polymer is (or should be); is the demand for such products which is driven by the public and the media. 'Biodegradable' chemistry is generally perceived by the public to be good for the environment (although that statement alone could be seen as a paradox, the term 'chemistry' often being associated with 'dirty' processes). Some industries use this to their advantage, but what is purported to be 'green' is often not so in reality. The paper industry claimed that paper packaging should be used as an alternative to plastic because paper was 'biodegradable' and plastic was not, without having any scientific evidence to support these claims; in actual fact, in a well-engineered landfill environment neither paper nor plastic is biodegradable. Polymer producers developed the first generation of 'degradable' polymers in the 1980s, which consisted of polyolefin polymers with starch additives that would cause fragmentation of the composite into polymer pieces in a biodegradable environment. However, in 1990 classification lawsuit forced producers to remove the degradable claim. The US Federal Trade Commission has, since created guidelines for environmental marketing claims, related to degradability, biodegradability, compostability and recyclability (39).

2.1.2 Sustainable fibers

Arguably more important than biodegradability is the concept of 'sustainability'. By definition, sustainable living is taking no more potentially renewable resources from the natural world

than can be replenished naturally and not overloading the capacity of the environment to cleanse and renew itself by natural processes. Resources are sustainable if they cannot be used up; for instance, oil resources are gradually decreasing whereas the wind can be harnessed to produce energy continuously. In terms of fibers, a sustainable fiber is one that ideally involves completely renewable chemicals in its production and non-fossil-fuel-derived energy in the production processes (36). Renewable sources of polymeric materials offer an answer to maintaining sustainable development of economically and ecologically attractive technology. Vink (41) set out a number of factors that the ideal sustainable material should meet; it should:

- Provide an equivalent function to the product it replaces, and perform as well as or better than the existing product;
- Be available at a competitive or lower price;
- Have a minimum environmental footprint for all the processes involved, including those up- and down-stream;
- Be manufactured from renewable resources;
- Use only ingredients that are safe to both humans and the environment;
- Not have any negative impact on food supply or water.

These criteria reflect a strong empathy with the need to address the environmental aspects, and demonstrated the positive benefits that poly (lactic acid) could achieve, both in terms of the manufacturing process, as well as the waste management disposal options at the end of a product's useful life. The most important concept in terms of a truly 'green' material (in terms of this project, a fiber) is the concept of a fully green life cycle of the product. This embraces innovations in the development of materials from biopolymers and other renewable resources; the preservation of fossil-based raw materials; the reduction of fossil fuels used in energy production for fiber processing; the reduction in the volume of waste; compostability in the natural cycle; complete biological degradability; protection of the climate through the reduction of carbon dioxide released; and the reduction and elimination of hazards and environmentally detrimental chemistry at any point in the life cycle (42). An idealized life cycle for a green fiber is given in Figure 16.

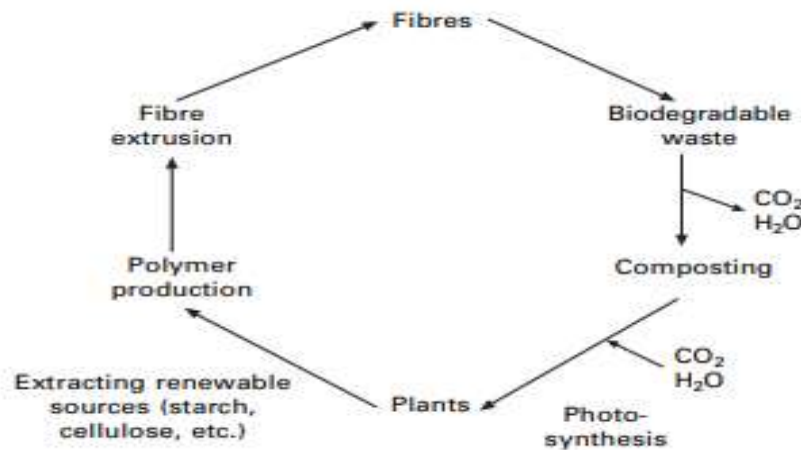


Figure 16: Life cycle of biodegradable and compostable fiber.

The key measurement tool to assess the environmental sustainability of a product is Life Cycle Assessment (LCA). Life cycle inventory analysis accounts for all inputs and outputs for a particular product and is typically practiced on a cradle-to-grave basis. A key benefit of LCA is the opportunity to benchmark performance against competitor products and processes in the marketplace, both to justify performance claims and to identify operations appropriate for performance improvement efforts. (39)

2.2 Factors influencing the biodegradation of PLA

In general, polymer degradation takes place through the scission of the main chains or side chains of polymers. Different degradation mechanisms whether chemical or biological can be involved in the degradation of biodegradable polyesters. A combination of these mechanisms can also happen at some stage of degradation. There are several important factors that affect the biodegradability of polymers (43). These are:

1. Factors associated with the first-order structure (chemical structure, molecular weight and molecular weight distribution).
2. Factors associated with the higher order structure [glass transition temperature (T_g), melting temperature (T_m), crystallinity, crystal structure and modulus of elasticity].
3. Factors related to surface conditions (surface area, hydrophilic, and hydrophobic properties).

Several reports said that the crystalline part of the PLA is more resistant to degradation than the amorphous part, and that the rate of degradation decreases with an increase in crystallinity (44). The degradation behavior of polymers also depends on their molecular weight (Mw). High molecular weight polyesters are degraded at a slower rate than those with low molecular weights (45). The melting temperature (T_m) of polyesters has a great effect on enzymatic degradability. In general, the higher the melting point the lower the degradability tends to be. The effects of the stereoisomeric content of PLA on the degradation rate of PLA films using proteinase K. They reported that the initial degradation occurred at the surface and that the degradation rate increased with high content of L-lactate unit. Likewise, the degradation of lactide oligomers and dimers and lactic acid monomers with different stereoforms has been investigated using *Fusarium moniliforme* and *Pseudomonas putida*. The low molecular weight oligomers were totally degraded regardless of enantiomeric composition. The L-dimer was consumed rapidly whereas the racemic oligomers were slowly assimilated. (45)

2.3 Microbial degradation of PLA

The ecological and taxonomic studies on the abundance and diversity of polymer-degrading microorganisms in the different environment are necessary because they are responsible for the degradation of plastic materials. Polymers are degraded in the soil by the action of a wide variety of microorganisms. The plate count and the clear zone methods using emulsified polyester agar plates are very efficient methods in the evaluation of the population of polymer-degrading microorganisms in the environment (46). By applying the clear zone method, it was confirmed that the population of aliphatic polyester-degrading microorganisms at 30 and 50 °C decreased in the order of PHB > PBS > PLA. (47)

The biodegradability of PLA depends on the environment to which it is exposed. In human or animal bodies, it is believed that PLA is initially degraded by hydrolysis and the soluble oligomers formed are metabolized by cells. Upon disposal in the environment, it is hydrolyzed into low molecular weight oligomers and then mineralized into CO_2 and H_2O by the microorganisms which are present in the environment. (48)

Soil burial tests show that the degradation of PLA in soil is slow and that it takes a long time for degradation to start. For instance, no degradation was observed on PLA sheets after 6 weeks in soil. The molecular weight of PLA films with different optical purity of the lactate units (100% L and 70% L) decreased by 20 and 75%, respectively, after 20 months in soil. On the other hand, PLA can be degraded in a composting environment where it is hydrolyzed into smaller molecules (oligomers, dimers, and monomers) after 45–60 days at 50–60 °C. These smaller molecules are then degraded into CO₂ and H₂O by microorganisms in the compost. (48)

2.4 Enzymatic degradation of PLA

Enzymes play a significant role in the degradation of polymers, although they are not solely responsible for the hydrolysis of polymers. The enzymatic degradation of aliphatic polyesters by hydrolysis is a two-step process. The first step is adsorption of the enzyme on the surface of the substrate through surface-binding domain and the second step is hydrolysis of the ester bond.

PHB depolymerases and lipases are the most extensively studied enzymes. Little information on L-PLA degrading enzymes has been reported so far (49). In 1981 the degradation of L-PLA was reported by proteinase. Since then, this enzyme has been used in studying the degradation mechanisms of L-PLA, copolymers of PLA and PLA blends. (50)

In 2000, the enzymatic degradation of PLA examined at 50 °C using 56 commercially available proteases. They found out that acid and neutral proteases had a little or no effect on L-PLA degrading activity but some alkaline proteases derived from *Bacillus* spp. showed appreciable L-PLA degrading activity.

Recently, we purified a commercially available α -chymotrypsin and compared its PLA-degrading activity with other serine proteases such as trypsin, elastase, subtilizing, and proteinase K. All tested serine proteases were able to hydrolyze L-PLA. Contrary to the report of 2000 report where it was proved that subtilisin could not degrade L-PLA, we found out that the L-PLA degrading activity of subtilisin was similar to the purified α -chymotrypsin (Lim et al. 2005). The difference in the results was probably due to the assay method used. It should be noted that in measuring the degrading activity of L-PLA, control experiment (reaction mixture

without enzyme or with inactivated enzyme) is necessary to confirm if the degradation is due to the enzyme or due to chemical hydrolysis. (51)

Figure 17 shows the degradation behavior of L-PLA, D-PLA, polyglycolide (PGA), and their copolymers by enzymes. It is well known that some serine proteases could hydrolyze L-PLA and DL-PLA but not D-PLA. It was reported that lipase could hydrolyze low molecular weight L-PLA and random copolymers of PLA such as: DL-PLA, poly(L-lactide-co-glycolide) and poly(D-lactide-co-glycolide) but not D-PLA, PGA, and high molecular weight L-PLA. [(51), (52), (53)]

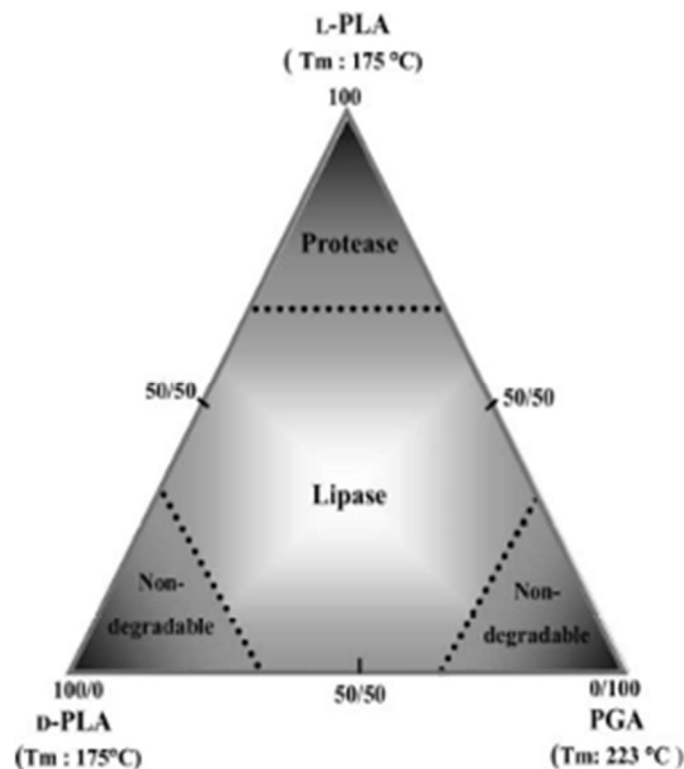


Figure 17: Schematic representation of the degradation behavior of the polymers (L-PLA, D-PLA, and PGA).

2.5 PLA Biodegradability and biodegradation mechanism

Under typical use and storage conditions such as at room temperature, PLA is stable. However, under very specific conditions of high temperature (> 60°C) and high humidity (> 80% RH), typified by the conditions for composting, PLA will disintegrate within one week to one month, followed by bacterial attack on the fragmented residues to give carbon dioxide and water. PLA is completely biodegradable when exposed in biologically active environments such as municipal compost facilities, along with other compostable organic materials. A typical

degradation curve of PLA under composting conditions is shown in figure 17 (27). In the primary degradation phase, PLA undergoes chemical hydrolysis, which is both temperature- and humidity-dependent and does not involve any microorganisms. As the M_n reaches approximately 10 000–20 000, microorganisms present in the soil begin to digest the lower molecular weight oligomer and lactic acid, producing carbon dioxide and water. This two-stage biodegradation mechanism differs distinctly from that of many other biodegradable polymers which degrade by a single-step surface erosion process, involving direct bacterial attack with enzymatic degradation on the polymer. Few reports exist on the microbial degradation of high molecular weight PLA. (48)

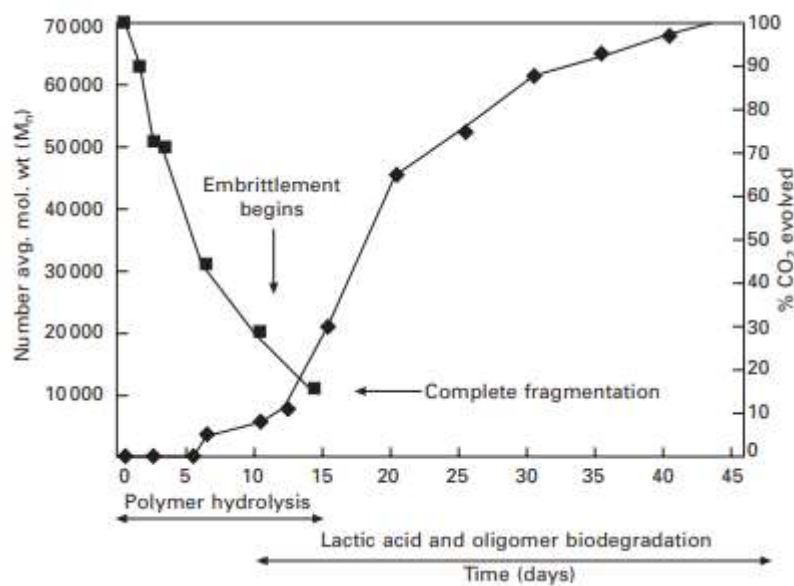


Figure 18: Biodegradation of PLA in compost at 60°C.

2.6 Biodegradation behavior in soil and in compost

In natural environments, such as in soil or in water, the degradation of PLA proceeds slowly, this being a convenient feature for agricultural/horticultural and geotextile applications. The percentage decreases in the tensile strength and relative viscosity of the PLA fibers following soil burial as a function of time are illustrated in Figure 19, these data indicating that degradation proceeds slowly, but steadily. (54) After two years, the fibers have lost 50% of their initial strength. A SEM photograph of PLA fibers subjected to 18 months of soil burial shows that a number of fine cracks appear perpendicular to the fiber axis. It is supposed that hydrolytic degradation occurs preferably in the amorphous regions between two crystalline zones. The compostability of PLA nonwovens (spunbond fabric, 25 g/m²) was evaluated under

simulated composting conditions. Evaluation of the ultimate aerobic biodegradation and disintegration was conducted by measurement of released biogas and disintegration at $60 \pm 2^\circ\text{C}$ after 45 days, according to ISO 14855. This test method is designed to yield a percentage and rate of conversion of carbon of the substance to released carbon dioxide. Figure 20 shows the cumulative biodegradation of PLA nonwovens compared with cellulose powder as a positive reference, the PLA showing near-equal biodegradability with cellulose after 45 days. (54)

Evaluation of the ultimate anaerobic biodegradability and disintegration under high solids, anaerobic digestion was based on carbon conversion of the test substance to methane and carbon dioxide and disintegration after 45 days, according to ISO 15985.

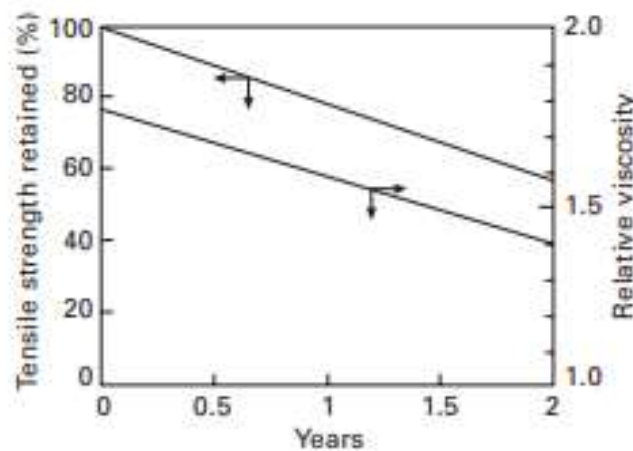


Figure 19: Change in tenacity and the relative viscosity of PLA multifilament in soil burial. (54)

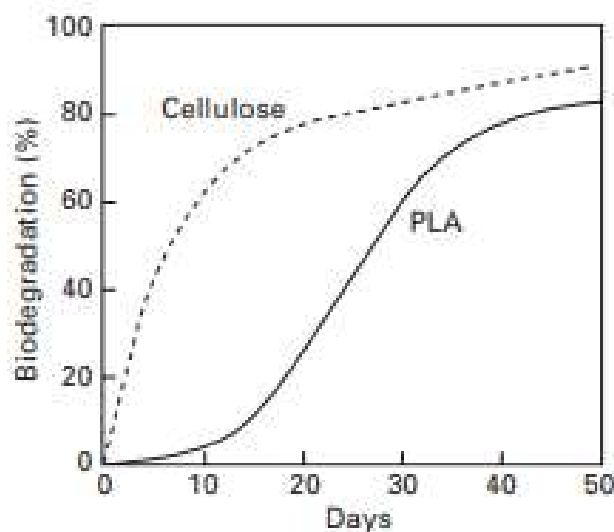


Figure 20: Aerobic composting test result of PLA fibers according to ISO 14855. (54)

3. Recyclability in textiles

3.1 Recyclable fibers

Recyclability is often confused by the public with biodegradability, the terms often being regarded as interchangeable. Obviously this is not the case, as recyclability refers to retrieving useful materials from waste via either mechanical or chemical breakdown. Recyclability of materials, however, is made publicly obvious through labelling techniques, in a way that biodegradability is not. The universal recycling symbol (Figure 21) means that the product is both recyclable and made of recycled materials. Manufacturers also use the symbol shown in Figure 22, developed by the Society of the Plastics Industry, to indicate the type of plastic used for the packaging; SPI code numbers range from 1 to 7.



Figure 21: Universal recycling symbol.



Figure 22: SPI symbol indicating source material for possible recycling;

(1) Poly (ethylene terephthalate); (2) high density poly (ethylene); (3) poly (vinyl chloride); (4) low density poly (ethylene); (5) poly (propylene); (6) poly (styrene); (7) other.

Recycling of polymers is on the increase and should be encouraged, but the process of both material and chemical recycling consumes a significant amount of energy, and, even if very efficient, could not cope with all polymers used. It is therefore very easy to understand the necessity for biodegradable polymeric fibers, which can be recycled by microorganisms. While in some ways biodegradable polymers and plastics recycling complement each other, there are concerns that widespread use of biodegradable polymers could be detrimental to

recycling. The main concern is that the contamination of recycled polymers with biodegradable polymers could adversely affect the properties of recycled polymers. This is becoming a common concern for many newly developed polymers, biodegradable or not.

Infrastructure, including collection systems and composting facilities, Germany has invested in compost infrastructure and more than 60% of all German households have been issued organic waste bins, whose contents are collected for composting. In 2001–2002 a successful pilot study was undertaken in Kassel, Germany to demonstrate the use of biodegradable packaging in connection with composting. The UK's first certification scheme for compostable packaging was launched by the Composting Association (55) in 2003. The scheme enables certification to the DIN V 54900, BS EN 13432 and ASTM D 6400 standards. In order to achieve certification materials, intermediates and additives are exhaustively tested in four different areas:

1. Chemical test (test for heavy metals);
2. Complete biodegradation;
3. Disintegration under compost conditions;
4. Ecological test (plant toxicity).

In addition to ensuring compostability, certification enables biologically degradable products to be identified by way of clear labelling. The compostability mark (Figure 23) serves to inform both waste consumers and disposers and the product must bear the inscription 'compostable' as well as the registration number assigned to it during the certification processes.



Figure 23: Composting association compostability mark.

Second-generation biodegradable polymers were commercially introduced around 1990 and are represented by the starch-based products offered by Novamont (Mater-Bi™) and by several families of polyesters. One of these polyesters, poly (ε-caprolactone), has been commercially available for more than twenty years; other biodegradable polyesters, which

have been commercialized very recently, include poly (lactic acid) and other aliphatic polyesters. As a result of plant investments made by Cargill-Dow LLC (now NatureWorks LLC) and others, biodegradable polyesters should become more affordable very soon, just as with most other polymers, processability is a very important factor in commercializing the biodegradable polymers. For example, some grades of starch-based polymers can be processed on standard low-density polyethylene extrusion equipment for making blown or cast film.

Other grades Introduction xix can be extruded on existing equipment with minor die modifications to make loose-fill foam. Polylactic acid can be processed in other ways similar to processing of polyolefins and also can be extruded with modifications. Performance properties are also important parameters to the commercial success. (55)

3.2 Recyclability of PLA fiber

PLA, is at least partially biodegradable. It's made from corn starch, so it breaks down easier than filaments that are made from synthetic materials like ABS.

Looking a little deeper, PLA is a thermoplastic polyester polymer, and you might recognize parts of this label. "Thermoplastic" means a type of plastic that becomes soft and can be molded once it is heated to a certain temperature, and "polyester" refers to more than a type of clothing; in this case, it's a polymer that includes naturally-occurring chemicals like the cutin of plant cuticles.

Basically, PLA uses the waxy parts of plants to form its shape, and that helps it break down into biodegradable parts instead of staying whole in a landfill forever or for a long period of time. **But the question is, can we recycle PLA fiber?**

The short answer is, we can definitely recycle PLA filament, but not in the same way you can recycle the milk jugs, food containers, and other types of everyday plastic. PLA has a lower melting point than other plastics, so it can't go into the same bundle with the rest.

However, this recycling process has diverse advantages, but also has its limitations.

- **Advantages**

- **Reduced waste;** even when everything goes perfectly, 3D printing can still produce a lot of waste. Recycling and reusing your PLA is a great way to start being kinder to the environment without giving up your hobby or business model. When you put your detached supports and failed prints back into your process or someone else's, that's a few pieces you're keeping out of landfills, which is beneficial to us all;
- **Saving money;** some companies and associations encourage sustainability and recyclable products and they even pay for such activities and for sure this recycling process is going to reduce the huge quantities of raw and expensive filaments;
- **Combined scraps;** when it comes to 3D printing use or packaging, we can simply keep all your discarded prints stored together, adding to them over time until you've got enough to turn them into material for a new project. It's a lot easier to see how much you have and map out the best use of it.

- **Limitations**

Recycling and reusing PLA filament isn't always smooth sailing. Here are some issues that we may have;

- **Complicated process:** Unfortunately, recycling PLA isn't as easy as rinsing it off and leaving it in your recycling bin with your normal pile. Its molecular composition gives it a lower melting point than other recyclable plastics, so if it gets mixed into those, it will stay solid while the rest is processed around it, causing issues for the recycling plant;
- **Significant investment:** filament recycling equipment isn't cheap;
- **Poor performance:** Again, unless done perfectly, there's a noticeable loss of performance in re-extruded filament. Its tensile strength is reduced from around 40 to 35 MPa.

Conclusion

Throughout this chapter, we have presented on one hand the new fiber “PLA”; its life cycle and its different properties ,On the other hand, we compared this fiber with PET, natural fibers and with other synthetic fibers as well. In the last part, we have presented the three notions; Biodegradability, sustainability and recyclability of textiles.

In the next chapter, we will introduce the methods and the materials we have used that we can figure out if we can really replace PET with PLA fiber and study the end-use properties of this material.

Chapter 2:

Research Design

Chapter 2: Research Design

The second chapter deals with the equipment and materials used in this study; this will also focus on the processes and methods of mechanical and comfort properties.

The performance of fibers made from natural and renewable resources and their suitability to become recyclable and environmentally friendly have been studied for several years. If the properties of this fiber (PLA) compete with those of certain synthetic fibers which are recyclable or even more sustainable, these characteristics should match.

It is within this framework that this part is articulated, the aim of which is to study and experimentally analyze the mechanical behavior as well as the comfort properties of a Polylactide 1 * 1 Jersey knitted fabric.

1. Materials and equipment used

Materials of the following specifications were used in the present study.

1.2 Sample fabrics

In this research project, one knitted PLA fabric (Figure 24, Figure 25) was used to determine the testing results, different samples with different dimensions, according to the standards, were exploited in order to evaluate the effect of investigated factors on the mechanical and physiological properties. The following pictures were given by an optical microscope.



Figure 24. PLA front side.

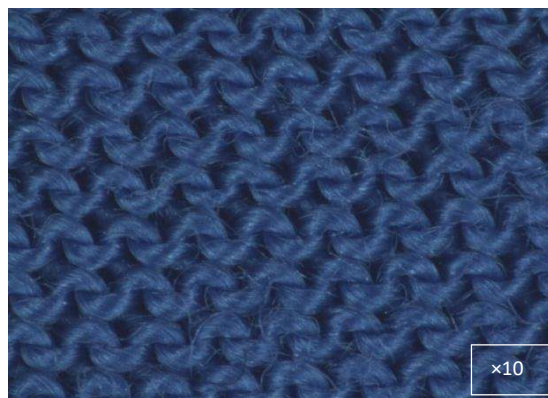


Figure 25. PLA backside.

1.3 Qualitative identification of the sample

The material is available in TUL labs. It has come in the form of a knitted T-shirt, crafted and dyed in blue. The latest was made in China while emphasizing that it is a fully biobased product.

1.4 Laboratory equipment used for data collection and analysis of results

All the devices used in this research study is mentioned in the following table (Table 7).

Table 7. Equipment and devices used.

Process	Equipment
Fabric production	The knitting circular machine
Structural and physical testing	
Mass per unit	Sartorius Measuring Balance
Thickness	Sodemat thickness Tester-AS 2001.2.15-198
Porosity	The optical microscope
Abrasion(dry/wet)	Nu-Martindale abrasion and pilling tester
Friction	Friction tester
Bursting strength	Textile burst Tester –LH-13-62-
Tensile strength	Dynamometer
Thermophysiological comfort testing	
Thermal conductivity	ALAMBETA instrument
Thermal absorptivity	ALAMBETA instrument
Thermal radiation	FLIR thermal camera
Moisture Management	Moisture Management Tester AATC-195-2009
Air permeability	TEXTTEST 3300 TESTER
Water vapor permeability	PERMETEST apparatus
Water vapor resistance	PERMETEST apparatus
Surface roughness	Talysurf CLI 500 device

2. Test methods

2.1 Determination of fabric structural and physical properties

We can't determine for how far this fiber is a good alternative for petroleum-based fibers without testing the structural and physical properties. This is literally our base to study the behavior of PLA after use. In this study, thickness, porosity, air permeability, abrasion, bursting strength and tensile strength are the physical and structural properties that were tested. (Fabric weight or mass per unit area was used with many tests).

The samples were at each time conditioned in the standard temperature and humidity ($T^{\circ}=20\pm 2^{\circ}\text{C}$ and humidity = $65\%\pm 5\%$).

2.1.1 Mass per unit area

The samples' dimensions and shape change from one test to another according to standards. However, at each time the weight of the latest should be mentioned generally before the test. But, sometimes, even after the manipulation is done we should measure it again. The fabrics were conditioned and tested in a standard atmosphere. Each of the specimens was weighted by a measuring balance (Figure 26). The mass per unit area was calculated as the mean mass per unit area of the 3 specimens using the following formula:

$$M = m/a \quad (1)$$

Where: -**M**: Mass per unit area (g/m^2);

-**m**: The mass of the specimen (g);

-**a**: The area of the specimen (m^2).



Figure 26: The measuring balance.

2.1.2 Thickness test

The thickness of this t-shirt was once measured before all of those tests were made. This test is about measuring the distance between the reference plate and the parallel pressed foot (AS 2001.2.15_198).

The sample was conditioned and tested in a standard atmosphere. After that, the thickness tested was done using the specific device (Figure 27), as the following process; after the presser foot was lifted, the fabric sample was positioned on the thickness tester reference plate, and then the presser foot was gently lowered to apply pressure to the fabric sample. The indicator reading was recorded.



Figure 27: Thickness tester.

2.1.3 Abrasion test

The pilling behavior of Polylactic acid fiber is investigated in both dry and wet conditions using a 'Nu-Martindale Abrasion & Pilling Tester' (Figure 28) according to the international standard ISO 12947-1.

The 5 different samples were subjected to predefined cycles of friction with a special disc having an abrasive surface and placed under a specified pressure (Figure 28).

In the case of Jersey knitted fabric, the test ends when a hole starts to be formed. The device records the number of the required cycles of the disc when this condition is reached.

In the second part of the work, PLA samples were wetted in distilled water at the lab conditions for 24 hours, followed by a drip dry for 5 minutes to avoid water excess on the samples.

For both tests; dry and wet abrasion test, the sample weight was measured at each time before and after the sample is damaged.



Figure 28: Nu-Martindale Abrasion & Pilling Tester.

2.1.4 Friction test

ASTM D1894 is a test method to determine the coefficients of friction of synthetic fibers. The PLA fabric under test is secured on a flat surface and a sled of known weight is wrapped in the same material. Using the crosshead's motion to drag the sled along the sample being tested, the force measured is used to determine this coefficient of friction.

The five samples of PLA were tested five times in the column direction and then, in the row direction. (Figure 29)



Figure 29. Friction tester.

2.1.5 Bursting strength

The bursting test was investigated to the PLA knitted fabric according to the standard ISO 13938-2019, after conditioning five specimens with the dimensions of 10 cm*10 cm and after determining the basis weight for each of them in g/m², we test those samples using the Textile Burst Tester –LH-13-62 (Figure 30).

The bursting device is designed to measure the resistance of fabric subjected to a hydrostatic pressure. This pressure is applied to a circular region of the specimen by an elastic diaphragm. The specimen is firmly held around the edge of this circular region by a pneumatic clamp. When the pressure is applied to a circular surface by a pneumatic clamp, the specimen deforms together with the diaphragm. The resistance corresponds to the maximum pressure sustained by the specimen before failure. This measurement is independent of the cutting direction to be made (column or row) because the failure occurs naturally in the slightest resistance direction. (58)



Figure 30: Bursting strength tester.

2.1.6 Tensile strength test

The tear strength test or experiment involves placing a small bar of the material to be studied between the jaws of a traction machine, which pulls on the bar until it breaks. The elongation and the applied force are recorded, which are then converted into strain and stress.

A modern variation of tensile strength testing is to use centrifugal force on an assembly to generate tensile stress. When the tensile strength limit value (expressed in MPa or N) of an assembly or a bond is equal to the applied centrifugal force, the rupture of these is generated and the rupture limit is recorded. The advantage consists in performing battery tests on several specimens subjected to a strictly identical stress during the test. (59)

The tensile test gives several important values:

- **E modulus or longitudinal modulus of elasticity** expressed in megapascals (MPa) or gigapascals (GPa);

- **The elastic limit** (when it exists), R_e , σ_e , σ_y , f_y (yield stress), which is used to characterize a conventional domain of reversibility ;
- **The tear strength** R_m , σ_m or f_u (ultimate limit) which defines the ultimate limit;
- The elongation at break $A\%$, which measures the ability of a material to elongate under load before it breaks, a property of interest in certain applications.
- **The Poisson ratio** ν , which corresponds to proportion between the transverse deformation (reduction in section) and the longitudinal deformation (relative elongation) of the part in the elastic range.

Table 8. Greatness, properties and behavior of the material.

greatness and international unit	Name	Properties	Behavior
E (GPa)	E modulus	Rigidity-Flexibility: rigid if E is high, flexible if E is low.	Elasticity
R_e (MPa) or σ_e	elasticity limit	Durability: important if R_e is high and soft if R_e is low.	Elasto-plasticity
R_m (MPa) or σ_m	tensile strength	Resistant if R_m is that important.	Elasto-plasticity
A (%)	Elongation at break	Ductility, malleability, fragility: brittle if $A\%$ is low.	Elasto-plasticity

2.1.7 Optical microscope

This microscope uses visible light and a system of lenses to magnify the images of textile materials. Those images can be captured by normal, photosensitive cameras to generate a micrograph.

It works on 2X to 20X magnification but we have used 10X magnification.

2.2 Determination of thermophysiological comfort properties

2.2.1 Liquid moisture transport MMT

The MMT (Figure 31) was used to test the liquid water transfer and distribution properties of fabrics. The principle is based on the fact that when the fabric transports moisture, the contact electrical resistance of fabric changes and the value of this change is influenced by two factors: the components of the liquid and the water content in the fabric. The liquid components are fixed so that the electrical resistance measured depends on the water content in the fabric. The specimen was held flat by top and bottom sensors with a certain pressure. A drop of water was pumped onto the upper surface of fabric to simulate a drop of sweat. The resistance of every couple of proximate metal rings decreased and the signal was logged into a computer and processed by the MMT software. The top surface is the surface close to human skin when worn and the bottom surface of fabric is the closest to the environment.

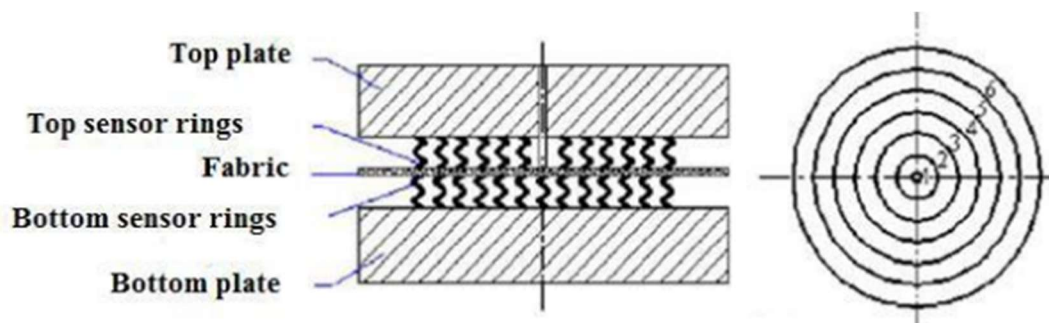


Figure 31: The MMT apparatus design (60).

The liquid management trend is in the form of “wetting time”, “absorption rate”, “one way transport capability”, “spreading/drying rate” and “overall moisture management capacity”.

Wetting time: is the time period in which the top and bottom surfaces of the fabric start to get wetted respectively after the test commences, which is defined as the time in seconds when the slope of total water content at the top and bottom surfaces becomes greater than (15°).

Absorption rate: is the speed at which the average quantity of generated sweat is absorbed during initial water content in textile material. Spreading speed: the accumulated rate of surface wetness to a maximum radius from the point at which the water droplet falls (from the center to the maximum wetted radius).

The maximum wetted radius: is the greatest water ring radius measured on the surface of fabric. Accumulative one-way transport capability: is the difference of the accumulative moisture content between the two surfaces of the fabric with respect to time.

Overall moisture management capability: presents the overall ability of the fabric to manage the transport of liquid moisture. It is calculated by using the following equation:

$$OMMC = C1 MARb + C2 OWTC + C3 SSb \quad (2)$$

Where:

- **C1, C2** and **C3** are the weights of the index of the absorption rate **MARb**, $C1=C3=0.25$ and $C2=0.5$;
- **SSb** is the spreading /drying rate (mm/sec);
- **OWTC** is the one-way transport capacity.

Those parameters are evaluated according to table 9. The moisture management test was performed according to the AATCC test method 195-2009.

The MMT is designed to measure, sense and record the liquid moisture transport characteristics of fabrics in multiple directions. An average of five readings was taken for each sample (3 samples taken from the same T-shirt but from different places).

The evaluation method of those results is mentioned in the Table 9.

Table 9. MMT Grading table. (60)

Index	Grade	1	2	3	4	5
Wetting time (sec)	Top	≥ 120	20-119	5-19	3-5	< 3
		No wetting	Slow	Medium	Fast	Very fast
	Bottom	≥ 120	20-119	5-19	3-5	< 3
		No wetting	Slow	Medium	Fast	Very fast
Absorption rate (%/sec)	Top	0-10	10-30	30-50	50-100	> 100
	Bottom	Very slow	Slow	Medium	Fast	Very fast
Max wetted radius (mm)	Top	0-7	7-12	12-17	17-22	> 22
	Bottom	No wetting	Small	Medium	Fast	Very large
Spreading speed (mm/sec)	Top	0-1	1-2	2-3	3-4	> 4
	Bottom	Very slow	Slow	Medium	Fast	Very fast
One-way transport capacity		< -50	-50-100	100-200	200-400	> 400
		Poor	Fair	Good	Very good	Excellent
OMMC		0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8
		Poor	Fair	Medium	Fast	Very Fast

2.2.2 Thermal properties: the ALAMBETA instrument

The principle of this instrument (Figure 32) depends on the application of an ultra-thin heat flow sensor (4) which is attached to a metal block (2) with constant temperature, which differs from the sample temperature. When the specimen is inserted, the measuring head (1) containing the mentioned heat flow sensor drops down and touches the planar measured sample (5), which is located on the instrument base (6) under the measuring head. Simultaneously, a photoelectric sensor measures the sample thickness. All the data are then processed in the computer according to an original program, which involves the mathematical model characterizing the transient temperature field in this slab subjected to different boundary conditions. To simulate the dry human skin and the real conditions of warm-cool

feeling evaluation, the instrument measuring head is heated to 32°C (the heater (3) and the thermometer (8)), which correspond to the average human skin temperature, while the fabric is kept at the room temperature 21°C. The measurement lasts for several minutes only, the evaluation of humid samples is reliable too since they don't turn dry during the measurement. (61)

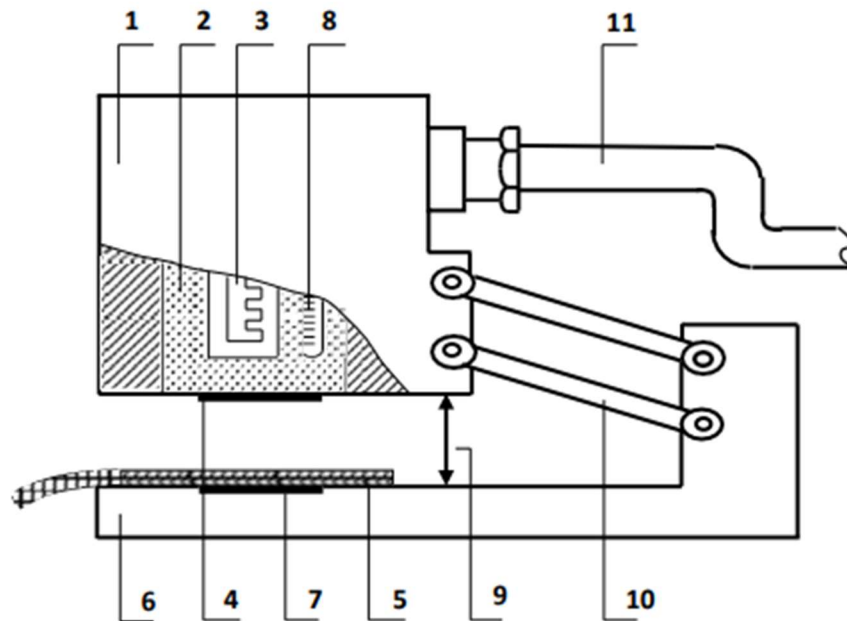


Figure 32: The ALAMBETA instrument. (61)

Alambeta measuring device was used for the measurement of the following properties: Thermal conductivity, thermal resistance and thermal absorptivity.

An average for five readings was taken for the dry PLA sample. Likewise for the wet sample.

To prepare the wet sample to test, we should

1. Use the COOLMAX stripes.
2. On the specific points already drawn on those stripes, using a syringe, we drop distilled water and wait 2 minutes until the spot becomes on the complete circular surface.
3. The stripe of COOLMAX is fixed on the PLA sample to test with the ALAMBETA. (In a different place at each time).

NB: The spot should be exactly in the middle of the circular plate.

The contact pressure was 200 Pa for all tests.

It was found that practical values of thermal absorptivity of dry fabrics have passed from 20 to 300 (See Table 10).

Table 10. Thermal absorptivity intervals of textile fabrics. (61)

ALAMBETA	Effect of fabric structure, composition and treatment of the level of thermal absorptive [$Ws^{1/2}/m^2K$], contact pressure 200 KPa
20-40	Microfiber or fine PES fiber non-woven insulation webs
30-50	Low density raised PES knits, needled and thermally bonded PES light webs
40-90	Light knits from synthetic fibers (PAN) or textured filaments, raised tufted carpets
70-120	Light or rib cotton RS knits, raised light wool/PES fabrics, brushed micro-fiber weaves
100-150	Light cotton or VS knits, rib cotton woven fabrics
130-180	Light finished cotton knits, raised light wool woven fabrics
150-200	Plain wool or PES/wool fabrics with rough surface
180-250	Permanent press treated cotton/VS fabrics with rough surface, dense micro-fiber knits
250-350	Dry cotton shirt fabrics with resin treatment, heavy smooth wool woven fabrics
300-400	Dry VS or Lyocell or silk weaves, smooth dry resin-free heavy cotton weaves (denims)
330-500	Close to the skin surface of wetted (0.5 ml of water) cotton/PP or cotton/spec. PES knits
450-650	Heavy cotton weaves (denims) or wetted knits from special PES Fibers (COOLMAX)
600-750	Rib knits from cotton or PES/cotton knits from micro-fibers, if superficially wetted
>750	Other woven and knitted fabrics in wet state
1600	Liquid water (evaporation effect not considered)

2.2.3 Water Vapor permeability and resistance: the Permetest

The Permetest is a measuring instrument (skin model) for the non-destructive determination of water-vapor and thermal resistance of textile fabrics (Figure 33). (61)

The porous sweating surface of the device simulates the skin and records the cooling heat flow caused by perspiration. The fabric sample to be measured is placed on a measuring head over a semi-permeable foil and exposed to parallel airflow at a velocity of 1m/s.

As with all the skin model systems, the measurements are carried out under isothermal conditions 20°C (± 2). This isothermal principle involves the temperature of the skin model surface, the air temperature and fabric temperature, when the fabric is kept in direct thermal contact with the skin model surface.

The computer connected to the apparatus determines the evaporative resistance (R_{et}) and the thermal resistance of textile fabrics in a similar way to that described in standard ISO 11092, as well as the RWVP (or relative negative heat flow responsible for the cooling of the body). These values serve to reflect the thermophysiological properties of textile fabrics and garments.

The higher the RWVP, the lower the R_{et} , and the better the thermal comfort of the garment. Due to the very short measuring time, which normally does not exceed 3 minutes, the fabric mass remains mostly unchanged during the measurements. Relative water vapor permeability of the textile sample RWVP (%) can be determined from the relation:

$$RWVP(\%) = \frac{q_v}{q_0} \times 100 \quad (3)$$

Where:

- q_0 : it means the instrument reading without a sample (heat losses of the free wet surface in W/m^2);
- q_v : it presents the heat losses of the wet measuring head (skin model) with a sample (W/m^2).

Water vapor resistance R_{et} when expressed in terms of the according to the ISO 11092 standard (Textiles-physiological effects-Measurement of the thermal and water vapor resistance) is as the following relationship:

$$Ret = (Pm - Pa) (qv^{-1} - q0^{-1}) \quad (4)$$

Where:

- **Ret**: presents the water vapor resistance ($m^2 \text{ Pa/W}$).
- **Pm**: is the saturation water vapor partial pressure at the surface of the measuring unit (Pa).
- **Pa**: is the water vapor partial pressure of the air in the test chamber (Pa).

All samples were put in the testing laboratory where relative humidity was between 60 and 62% and temperature was in the range of 20-22°C. Each sample was tested three times to calculate the mean values. (61)

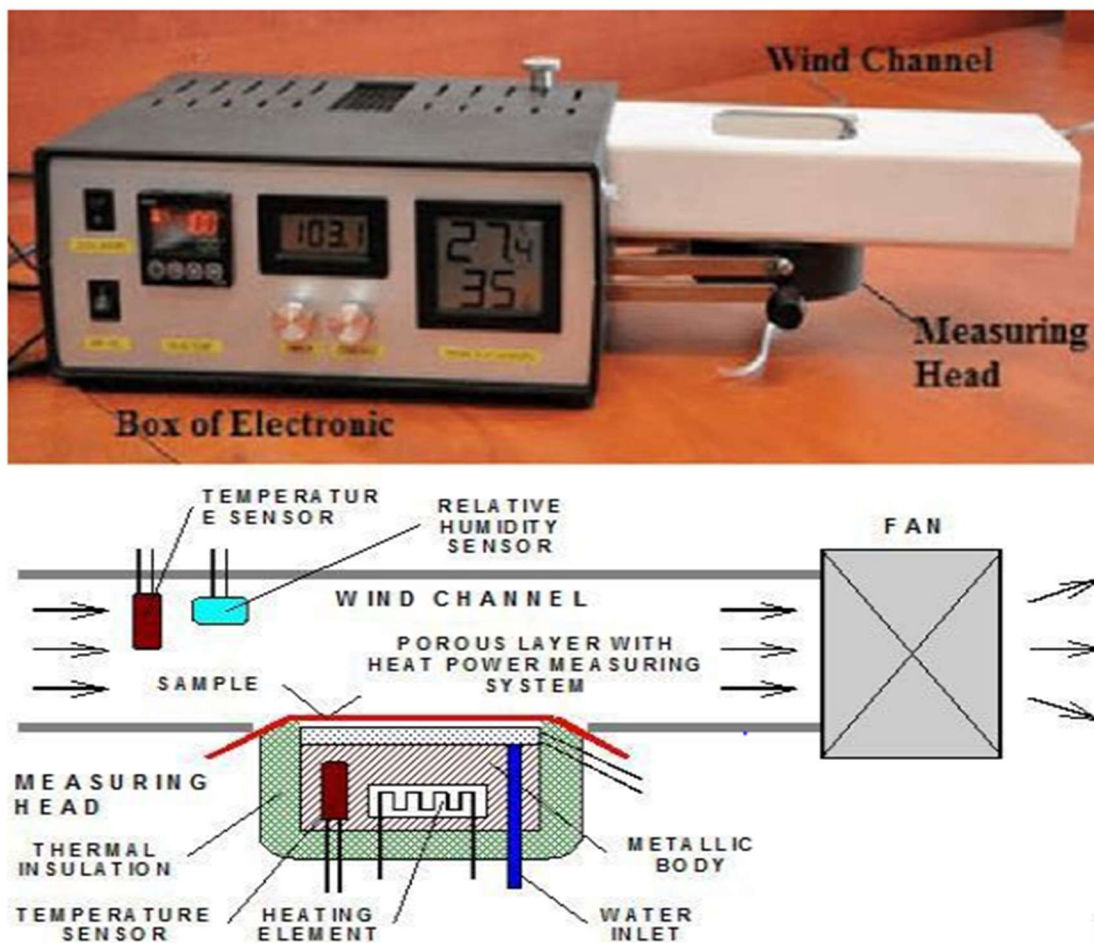


Figure 33: The Permetest (Skin model) apparatus design and principle.

2.2.4 Air permeability test

TEXTTEST Air permeability Tester (FX3300) was used to measure the air permeability according to the standard ISO 9237:1995 (F).

The device produces a constant flow of air that traverses the specimen vertically. The measured surface area is 20 cm and the differential applied between the two surfaces of the textile material was 100 Pa.

The airflow is changing slowly until the flow meter indicator is stabilized (see Figure 34). The displayed value is noted and the test repeated at least in different places of the fabric.

The main components of the air permeability tester are; Test head for positioning the test sample, clamping system for securing the test specimen to the test head without any distortion, air pump to draw a steady flow of the air perpendicularly through the test fabric and pressure gauge or manometer connected to the test head below the tested sample to measure sample drop across test sample in Pascal. (61)

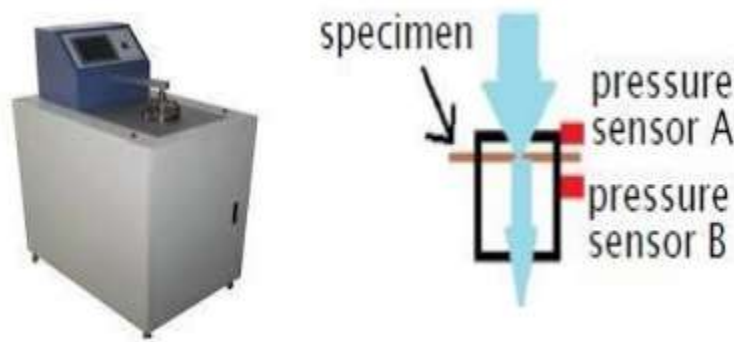


Figure 34 : TEXTTEST Principle and Design.

2.2.5 Thermal radiation insulation index: Infrared camera

The use of the infrared camera (Figure 35) was necessary to determine the thermal insulation radiation index of the PLA fabric; this parameter is given by the formula;

$$I = (T_s - T_R) / (T_h - T_R) \quad (5)$$

Where;

- T_s : Temperature of the sample.
- T_R : Temperature of the room.
- T_h : Temperature of the heater or the water bath.

The test was investigated through the following steps;

1. The heater is fixed on 40°C.
2. Keep a distance of 30 cm between the sample (5*5 cm) and the infrared camera.
3. Using this camera, testing 5 different specimen of PLA fabric, at each time we write down the values and take the photos from the camera for later illustration.

NB: We should check the room temperature with typical thermometer and at each test, we make sure that the camera is calibrated by checking the naked skin temperature (it should be $32\text{ }^{\circ}\text{C} \pm 1^{\circ}\text{C}$).



Figure 35: Infrared camera.

2.2.6 Surface Roughness: The Talysurf CLI (chromatic, laser, inductive) 500

Principle of the test method and apparatus design: (62)

This device (Figure 36) is the smallest of the series of general-purpose device CLI, which measures either inductive touch-way form Talysurf or non-contact using laser triangulation probeCLA control sensor. It is a device that allows measuring simultaneously the size, shape and surface roughness. In addition, this device is known as a 3D surface texture measurement system with the possibility to control the roughness in 2D.

Talysurf device is designed for non-contact extremely accurate measurement and analysis of surface structure, for the evaluation of the structure and shape of the surface. The principle of scanning the surface structure of the material is that the laser beam scans the points that consist of a set of discrete values X, Y, Z, during moving the element under stationary head. Non-contact scanning of the surface structure works on the principle of reflected laser beam.

During this measurement is the laser beam focused on the surface and the receiving optical system captures the reflected laser beam and then the beam is focused on the CCD sensing array.

CCD ensures appropriate distribution of the light beam in point. Surface texture deviations are then recorded as the changes of the reflected light. Precisely because of the non-contact laser technology Talysurf device was selected for scanning the surface of materials with lumps. During measuring of this material, there is no compression or any contact between the sensor and the lumps surface and therefore the change of their position either.

The recorded sample surface by the Talysurf device can be evaluated in a 3D model using Talysurf software, which allows better and more accurate evaluation of surface characteristics. The principle of imaging the surface shape of a material is shown in Figure 35. (62) This instrument was used in this study to give us an idea about the surface roughness of all used samples.

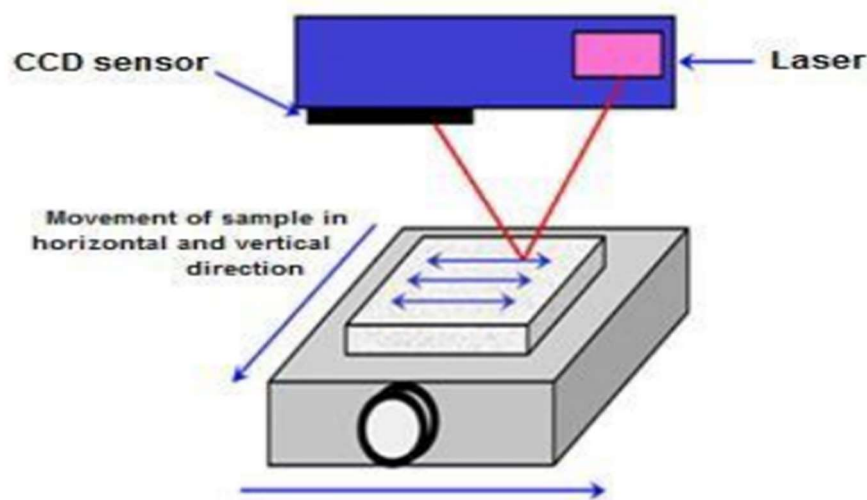


Figure 36: The Talysurf conception.

The device described below can offer many surface measurements; here we present some of them:

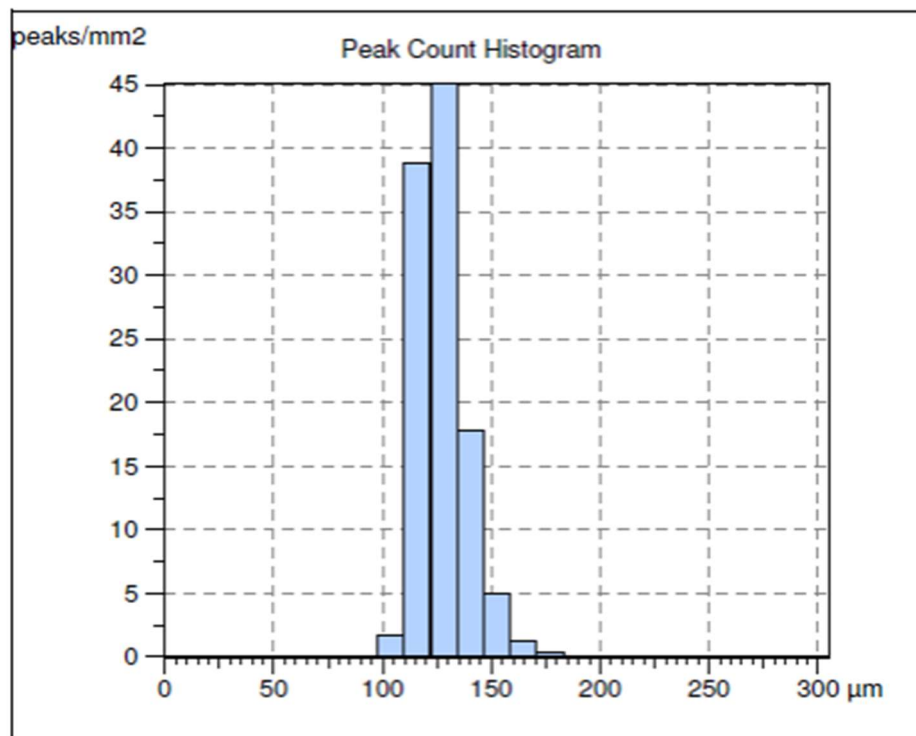
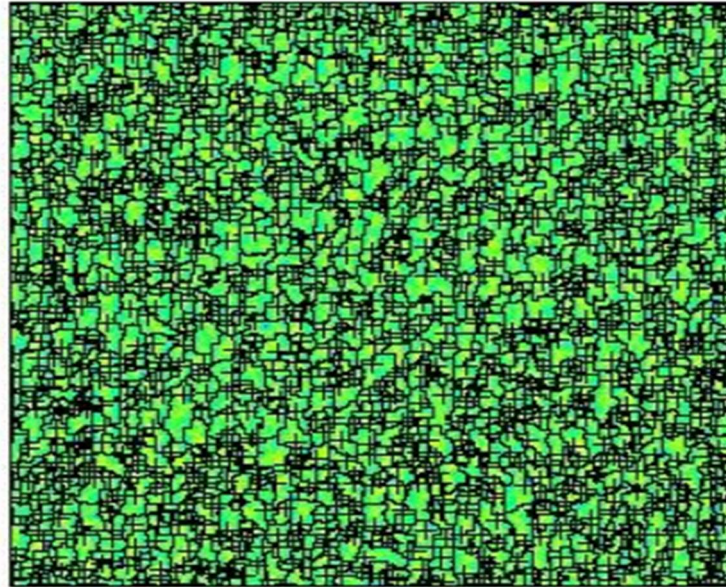


Figure 37: Peak count Histogram taken from Talysurf measurements.



Number of motifs	1192
Mean Height	13.2 μm
Mean Area	0.0842 mm ²

Figure 38: Number of motifs taken Talysurf measurements.

Conclusion

The second chapter has highlighted not only the equipment and the different devices used throughout this project, but also the standards, the operating mode and the process, which we have adapted as a basis for our next steps in this research. It only seems like a starting point to understand the behavior of PLA fiber and to clearly master its aptitude for reusing it in more than one application.

The next chapter is dealing and discussing the results of all the previous tests.

Chapter 3:

Results and discussions

Chapter 3:

Results and discussions

The third part of this graduation project is a global outcome according to the experiments carried out.

The goal from the beginning was to evaluate the existence of proven relations between the thermophysiological and technical properties of the fiber and its sustainability and its environmental impact. Also, to prove that this strong link has an important influence on the end use properties after all of this.

Comparing those results, which concern PLA fiber, to PET and other synthetic fibers is the key.

1. Structural and mechanical properties

1.1 Abrasion test Results for PLA

Table 11. Dry Abrasion test results for PLA

Dry Abrasion Test			
N° of the sample	weight before test (g)	weight after test(g)	Total number of cycles
1	0.183	0.151	7000
2	0.175	0.146	8000
3	0.177	0.177	8000
4	0.188	0.161	10000
5	0.197	0.171	10000
Mean Value	0.18	0.161	8600
St.dev	0.007	0.01	1095.44

Table 12. Wet Abrasion test for PLA

Wet Abrasion Test			
N° of the sample	weight before test (g)	weight after test(g)	Total number of cycles
1	0.551	0.181	5000
2	0.792	0.187	5000
3	0.711	0.169	6000
4	0.622	0.177	6000
5	0.563	0.181	7000
Mean Value	0.648	0.179	5800
St.dev	0.084	0.005	683.13

As shown in Table 11, Polylactide knitted fabric gets damaged in the dry state after 8000 to 9000 cycles which is a little bit lower than polyester knitted fabric that gets damaged after

10.000 cycles. This makes PLA comparable to polyester, one of the polymers who exhibit the highest abrasion resistance.

Fabrics intended for military and police uniforms are exposed to a number of physical and chemical agents in the course of regular use, rain and moisture being most frequently encountered. This means, that apart from testing dry abrasion resistance, we should test wet abrasion test.

The damaged PLA wet samples, after the second test (Table 12) have shown more pronounced reduction in abrasion resistance in the wet state (after 5000 cycles) which is not the case for polyester.

Abrasion resistance parameter is very important for high performance fabrics used by mountain climbers, soldiers, policemen, firemen etc. Therefore, we can affirm that PLA can't replace PET or at least perform on the same level for such applications.

1.7 Friction test for PLA

Recently, rapid prototyping technologies, or 3D printing also called additive manufacturing, have been widely used for design and manufacturing of various parts of systems and mechanisms.

A wide range of research has been carried out in the field of 3D printing in order to investigate mechanical properties of the parts manufactured with the use of such technologies; friction, tensile strength, stiffness, and other properties that depend on other various conditions of 3D printing, such as layers' thickness, density etc.

The most commonly used materials for rapid prototyping technologies are PLA and ABS. That's why, it was required and fundamental to study the friction property of our specimen and to compare it later with ABS and with PET as they are the main PLA competitors. (63)

In the following chart we can find out the difference in the friction coefficient between those three polymers.

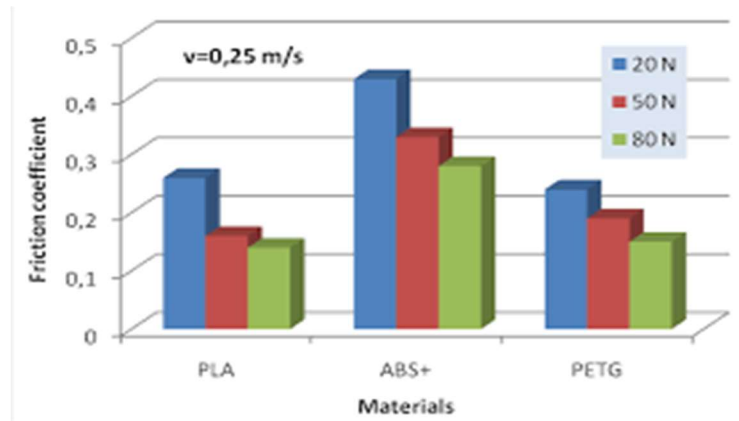


Figure 39: PLA, ABS, PETG friction coefficient for $v=0,25$ m/s.

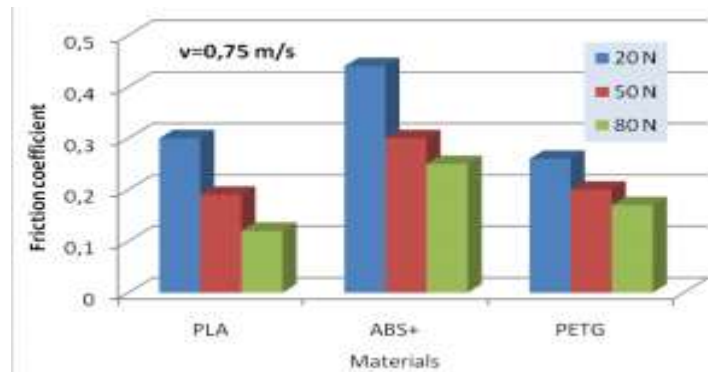


Figure 40: PLA, ABS, PETG friction coefficient for $v=0,75$ m/s.

As shown in Figure 39 and Figure 40, the values of friction coefficient depending on the type of material and the normal load, it can be concluded that with increasing normal load with all the previous materials, there is a significant reduction in the coefficient of friction. It is clear that this coefficient does not depend on the slip speed, we got nearly the same values with 0,25 m/s and 0,75 m/s.

The highest coefficient of friction is for ABS fabric, while PETG is slightly higher than PLA.

Globally an average of 2.0 of friction coefficient for PLA can be considered as a good behavior against friction.

1.3 Bursting strength test

Bursting refers to the force required to break the fabric. When force or pressure is vertically applied on a fabric, it's called bursting. The force needed to rupture the fabric (when applied perpendicularly) is called bursting strength.

The aim of this test is to analyze the bursting strength of Polylactide acid. Five different samples of our knitted fabrics were tested, where the surface mass was 149.5 g/cm^2 .

The results of this test are illustrated in the following table (see Table 13).

Table 13. Bursting strength results.

	Bursting strength (KPa)	INDEX	BENDING (mm)
Average	467	3.116	28.64
Highest	489	3.258	44.59
Lowest	448	2.987	11.7
ST, DEV	45.4	0.103	16.059
VAR COEFF	3.3	3.293	56.065

An average of 467 KPa of strength to break the PLA knitted fabric is giving evidence once more that PLA has a very interesting mechanical properties. This is explaining the use of Polylactide in the structural applications, composite materials and health care equipment as well.

For this parameter, the bursting strength we can highlight the use of PLA in health and medical care field where the knitted fabrics, used in the prostheses, are wanted to be highly resistant against bursting and other mechanical constraints. For such applications, many other knitted fabrics made from synthetic fibers were investigated previously. Therefore, it makes sense to compare PLA to other fabrics. (See Table 14)

Table 14. Comparison of Bursting Strength of PLA fabric with others. (67)

Fabric code	PLA	PLA/PHBV	PET	PA 6
Bursting strength (KPa) [CV%]	468 [3.3]	503 [0.53]	>827.3	504.8 [2.25]
Bursting height (mm) [CV%]	28.64 [56]	12.0 [0.82]	Not broken	10.2 [0.82]

As shown in Table 14; the bursting strength of the blend of PLA and PHBV (50 %/ 50%) knitted fabric (i.e. 503 KPa) meets the requirement of textiles industrial productive which is higher than that of degradable PLA fabric, but lower than PET and PA 6.

The PET fabric sample was not broken by the bursting strength tester, this indicates that the PET fabric possesses a high bursting resistance, which exceeds the measurement range of the device. This means that once again PET has overperformed the PLA concerning the physical properties.

1.4 Tensile strength test of PLA

Tensile strength is measured for knitted Jersey fabrics made from PLA and other polymeric fibers as well, the results are presented graphically in this chart.

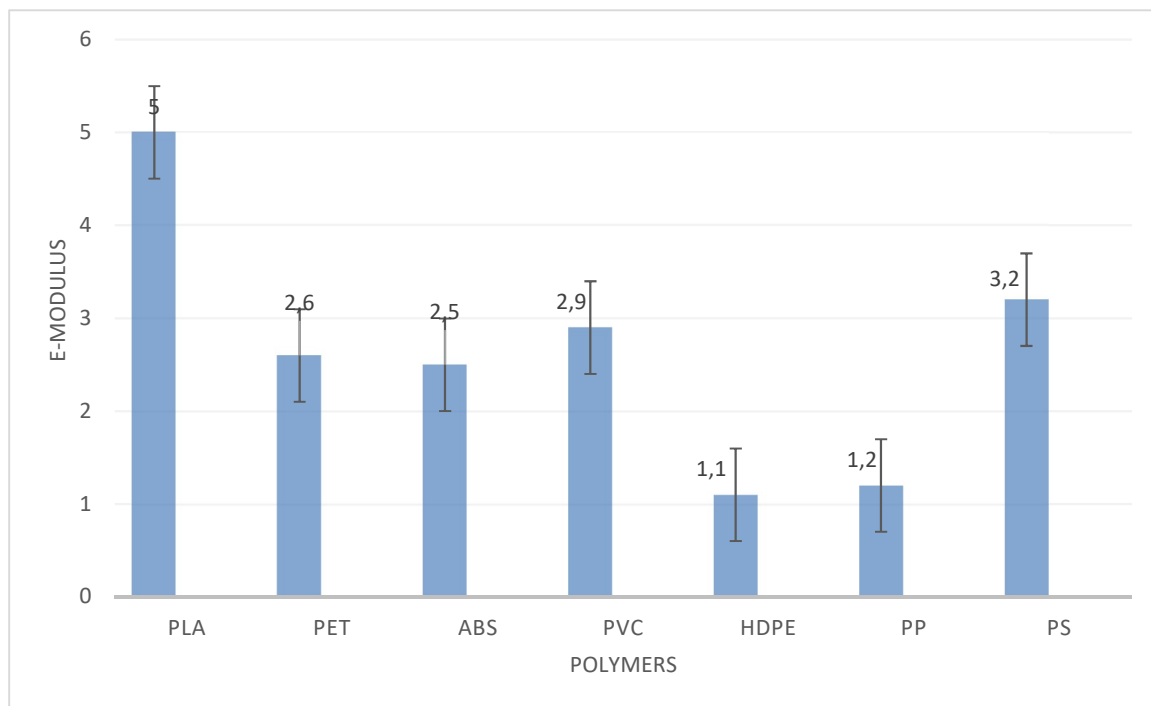


Figure 41: E-Modulus for PLA and other synthetic fibers.

This chart (Figure 41) confirms again what was mentioned previously, in the research background chapter, the PLA has the advantage of high mechanical performance since it has the highest E-modulus among all the synthetic fibers mentioned above (PP, HDPE, PVC, PET and ABS), However this study of mechanical behavior shouldn't stop at this point. To be able to find out the end-use properties of this fiber. Where it can be required and where it is useless and we should rely on other synthetic fibers.

PLA, itself, has many subcategories and other derivations, depending on the diameter, the crystallinity, the structure (L-PLA or D-PLA). So, this variety should be significant and confers more benefits for other applications.

The diameter of the PLA varies between 11 and 38. This interval gives a wide range of tests. The stress-strain curves of the PLA fibers as a function of diameter are all presented in Figure 42, where the inset figure shows the strain region up to 5% and an increase in stress is seen with decreasing fiber diameter. The tensile strength, modulus and elongation at break properties can be readily obtained from the stress-strain curves that the PLA 11 and the PLA 20 fibers revealed ductile characteristics with sufficient flexibility compared to the larger diameter fibers, which displayed a more brittle failure mechanism.

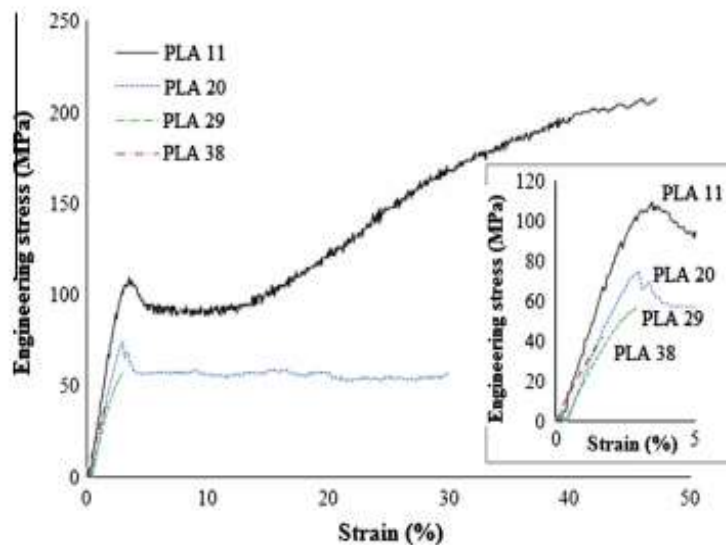


Figure 42: Typical stress–strain curves for single PLA fibers with varying diameters. The inset figure shows the initial stage (up to 5% strain) of the stress–strain curves. (65)

The tensile properties of PLA fibers were seen to decrease with increasing fiber diameter as presented in Figure 43.a, the tensile strength and modulus properties for PLA 11 were 213 MPa and 4.8 GPa respectively. However, comparatively higher tensile strength properties have been reported in the literature for PLLA fibers. For example, the tensile strength and modulus of PLLA fiber with diameter ranges from 11 to 14 μm were reported to be 320 MPa and 5.5 GPa, respectively. PLLA is made of pure L-lactide which possesses a higher degree of crystallinity, which could explain the higher mechanical properties obtained for PLLA fibers compared to the PLA investigated in this study. As expected, PLA 11 fibers displayed a statistically significant increase in tensile strength and modulus properties when compared to larger diameter PLA fibers (20–38 μm), since tensile properties are a function of crystallinity and molecular chain orientation of the matrix relative to the fiber axis. To support this statement, the tensile properties of the PLA fibers were plotted as a function of crystallinity

(see Figure 43b) where a sharp increase in tensile strength and a steady rise in modulus properties with increasing crystallinity of the PLA fibers were observed. For instance, 34% crystallinity in PLA 11 fibers exhibited around 41,9% and 55% increase in tensile strength and E-modulus properties compared to the thicker PLA 38 fiber (16% crystalline).

As a conclusion, PLA fiber confers one of the highest mechanical resistance, but we are still able to improve this behavior by choosing the appropriate diameter, crystallinity rate and the molecular configuration.

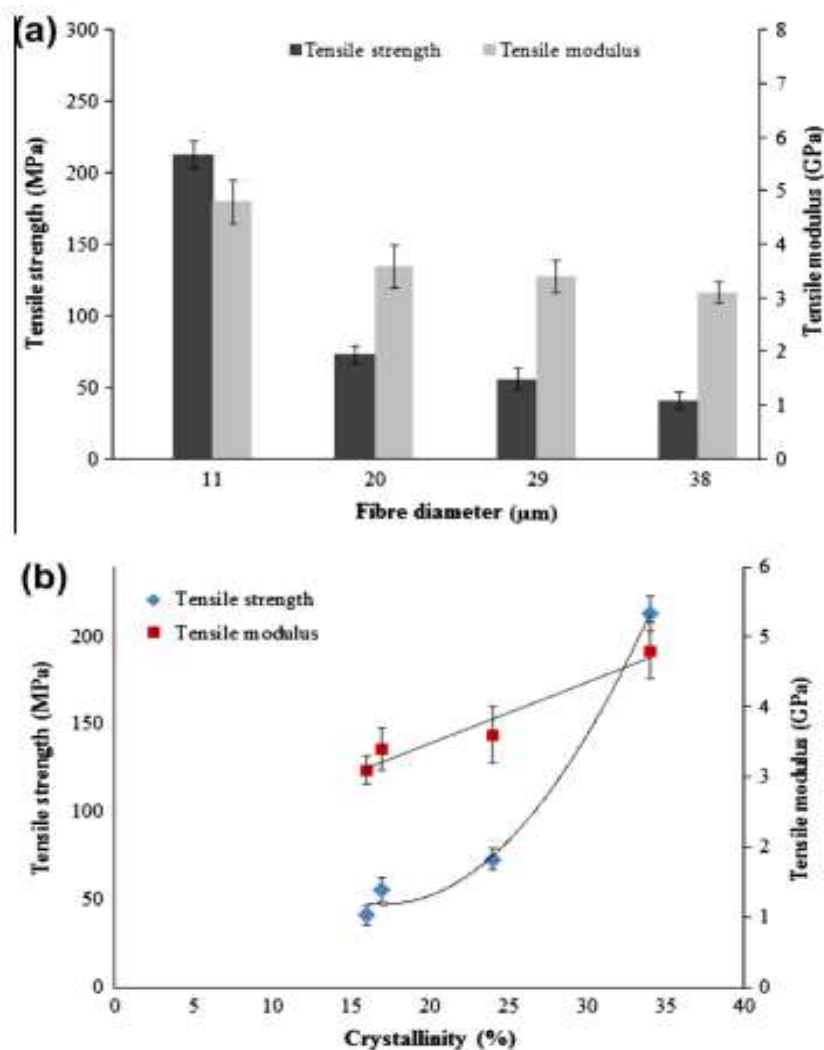


Figure 43: (a) Tensile strength and modulus properties of the single PLA fibers with varying diameters and (b) relationship between the tensile properties and degree of crystallinity of PLA fibers (64).

2. Thermophysiological comfort properties

The properties of experimental samples were measured for the following comfort properties; Liquid moisture management, water-vapor permeability, water-vapor resistance, air permeability, thermal conductivity, thermal resistance, thermal absorptivity, thermal radiation insulation index and surface roughness.

2.1 Liquid moisture transfer properties

The main liquid moisture transfer properties investigated in this work are: the wetting time, the spreading speed, the maximum wetted radius, the OMMC, the absorption rate and the one-way transport capacity.

The results of these different measurements are illustrated in Table 15.

Table 15. MMT results for PLA fabric.

	Wetting Time Top(sec)	Wetting Time Bottom(sec)	Top Absorption Rate(%/sec)	Bottom Absorption Rate(%/sec)	Top Max Wetted Radius (mm)	Bottom Max Wetted Radius (mm)	Top Spreading Speed (mm/sec)	Bottom Spreading Speed (mm/sec)	Accumulative One-way Transport Index (%)	OMMC
F1	6.178	6.084	30.72	52.728	25	30	2.372	2.504	220.116	0.669
F2	6.008	6.031	30.06	51.719	25	30	2.301	2.611	235.166	0.61
F3	7.207	7.02	36.927	57.936	25	30	3.298	3.468	242.699	0.723
F4	7.582	7.956	49.072	74.920	20	25	2.433	2.583	162.619	0.77
F5	7.201	7.03	37.918	57.941	25	30	2.008	2.991	200.861	0.629
Mean	6.835	6.824	36.939	59.049	24	29	2.483	2.832	212.292	0.681
St.dev	0.624	0.713	6.844	8.343	2	2	0.433	0.359	28.661	0.059

The previous table is translated into a finger print of moisture management according to the grading scale which is a 5-point-scale and to the AATCC test methods 195(1-5) (See Table 9).

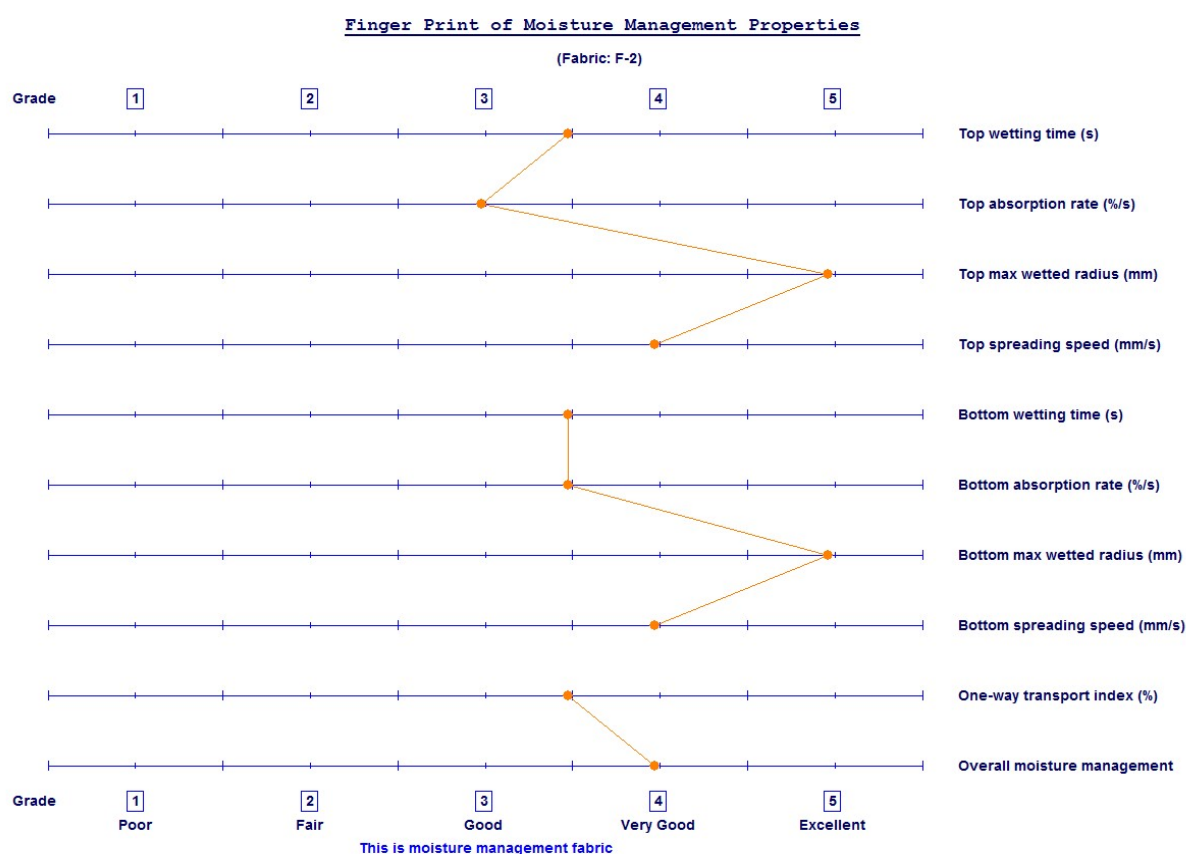


Figure 44. Finger print of Moisture Management properties for PLA.

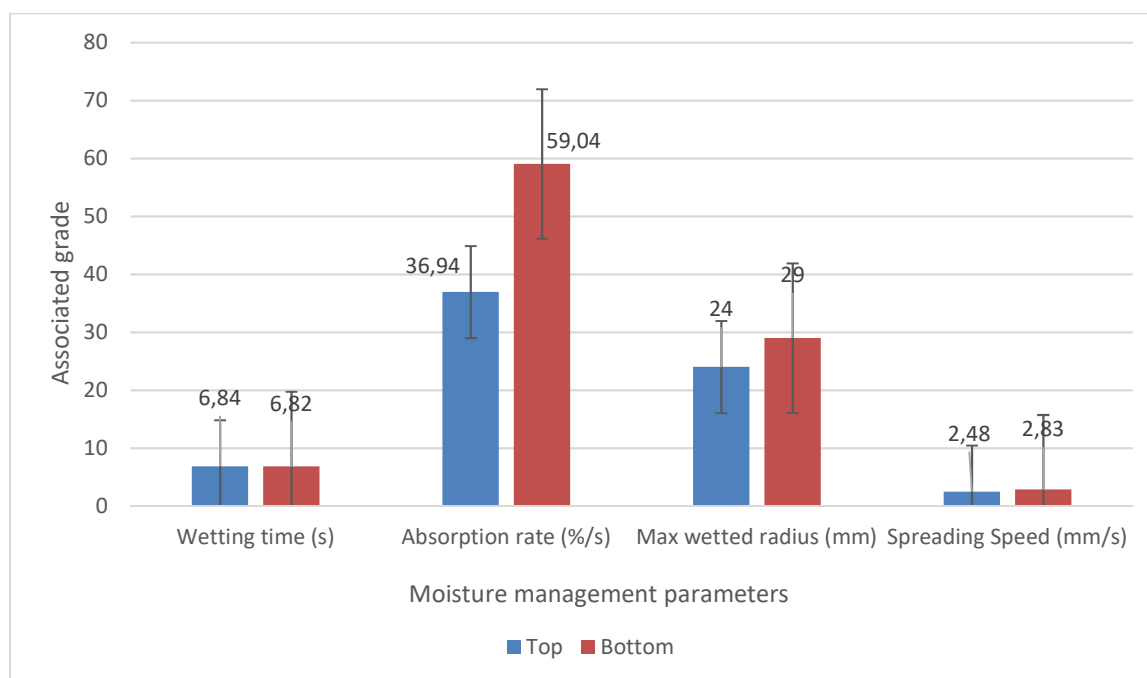


Figure 45. Moisture Management different parameters (mean values).

Generally, and according to the finger print in Figure 44, the chart in Figure 45 and the grading table (Table 9), the PLA fiber represents an extraordinary moisture management properties; they all range between GOOD (grade of 3) and excellent (grade of 5).

First, for Wetting time, on both sides; bottom and top, this parameter has an average of 6.8 while the grades of the indexes of the latest are: 1(≥ 120) = No wetting, 2(20-119) = slow, 3(5-19) = Medium, 4(3-5) = Fast and 5(< 3) = Very Fast.

PLA has a fast reaction to get wet (3 to 5 seconds only). This means that the wetting time here is medium or maybe closer to fast behavior.

Concerning, the Absorption rate, the range values were compared using the grade scale. The grades of the indexes are: 1(0-10) = Very Slow, 2(10-30) = Slow, 3(30-50) = Medium, 4(50-100) = Fast and 5 (> 100) = Very Fast.

The previous results of the PLA fabric absorption rate (%) have an average of 36.94 and 59.04 on the top and the bottom respectively, which means that the PLA absorption of humidity is considered as "Fast".

The Max wetted radius is 24 and 29(mm) on the top side and the bottom side respectively, while the grades of the indexes for this parameter are: 1(0-7) = No wetting, 2(7-12) = small, 3(12-17) = medium, 4(17-22) = large and 5(> 22) = very large. Therefore the polylactide fiber shows a very large wetted radius, with the grade of "excellent" for this parameter.

The speed at which the average quantity of generated sweat is absorbed, range values are always compared using the grading scale where the grades are: 1(1-10) = very slow, 2(1-2) = slow, 3(2-3) = Medium, 4(3-4) = Fast and 5(> 4) = very fast. So, the PLA spreading speed is almost the same on both sides and it's around 2.5 mm/s: medium speed.

For the rest of the parameters mentioned previously (One-way transport index and the overall moisture management), they have nearly the same values on both sides of the Polyactide fabric with a good to excellent grade.

Same moisture management properties test was investigated for other synthetic fibers; Polyester, PVC, CoolMax and some other natural fibers like Cotton, Merinos .After measuring the six different parameters and evaluating them according to the grading scale, we end up to resume the results in the following MMT finger prints.

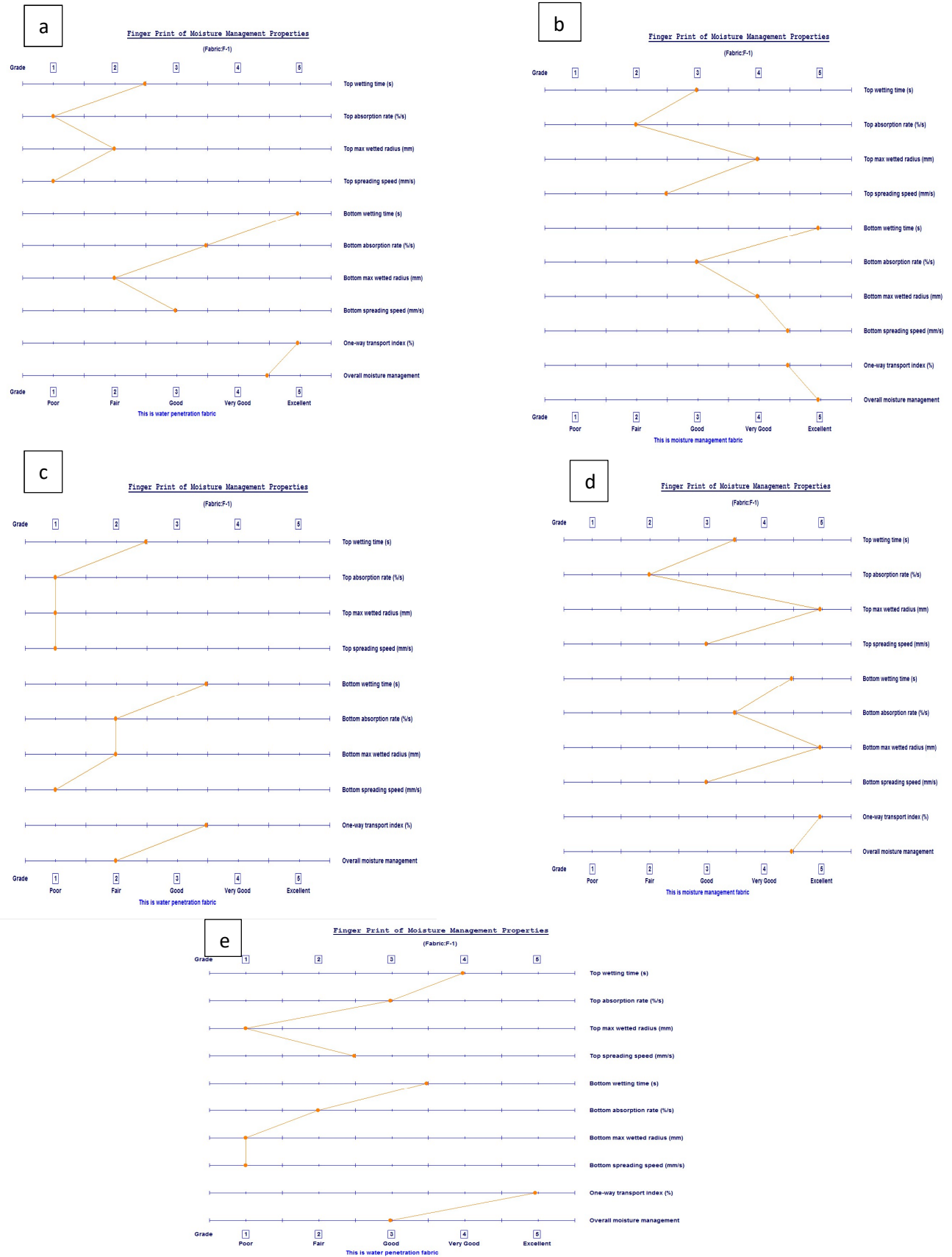


Figure 46. Finger print of Moisture Management properties for a: PET, b: PVC, c: COOLMAX d: COTTON and e: WOOL (MERINOS).

Those three different synthetic fibers PES, PVC and COOLMAX present dissimilar behavior face to the moisture effects. PES and COOLMAX are more comparable to each other, but PVC has represented a better properties which are a little bit higher than PLA → Good overall moisture management in global.

For natural fibers, they bring a lot of similarity to PLA, especially cotton that gives the closest finger print to PLA indeed. That reminds us to what was mentioned above in the research background, where we cited that although PLA fiber is a hydrophobic synthetic polymer, it exhibits good moisture management and comfort properties in close proximity to these hydrophilic cotton and Merinos fibers.

This was just expected since PLA is an aliphatic polyester having no aromatic structure .PLA is primarily hydrophobic but more hydrophilic than PET. The moisture absorbency and wicking properties are superior to those of PET and many other polymers. These is a considerable interest in PLA either as an inner wicking layer or as an intimate blend with other natural fibers like cotton and Merinos. Garments made from PLA are expected to feel more comfortable and it is being considered for use in sportswear as well as shirt applications. Wearers of PLA fabric will experience physiological comfort even under active wear conditions.

2.2 ALAMBETA Thermal properties

2.2.1 Thermal conductivity and thermal resistance

High thermal resistance and conductivity of thermal insulting fabrics is a major factor in the decision to use them in protective apparel applications and other functional textiles, therefore we measured the different thermal comfort properties that the ALAMBETA can provide (Table 16).

Table 16. ALAMBETA PLA test results

n° of test	H	P	Q	λ	A	B	R
1	0.5	1.29	0.39	41.6	0.11	127	12.1
2	0.51	1.33	0.41	41.9	0.11	132	12.2
3	0.49	1.3	0.41	40.9	0.09	136	12
4	0.47	1.34	0.42	40	0.1	128	11.8
5	0.44	1.24	0.4	39.3	0.1	123	11.1
Mean value	0.48	1.3	0.41	40.74	0.1	129.2	11.84
St.dev	0.02	0.032	0.01	0.82	0.01	4.06	0.36

Where, the different parameters above are illustrated with their units, symbols and their corresponding indications (See Table 17).

Table 17. ALAMBETA quantities ; symbols and units. (61)

Quantity	Symbol	Multiplier	Unit
Thermal conductivity (coefficient)	λ	10^{-3}	$\text{W.m}^{-1}.\text{K}^{-1}$
Thermal diffusivity (coefficient)	a	10^{-6}	$\text{m}^2.\text{s}^{-1}$
Thermal absorptivity, thermal activity coefficient	b	1	$\text{W.m}^{-2}.\text{s}^{1/2}.\text{K}^{-1}$
Thermal resistivity	r	10^{-3}	$\text{K.m}^2.\text{W}^{-1}$
Sample thickness	h	1	mm
Peak heat flow density ratio (q_{fmax}/q_s)	ρ	1	1
Peak heat flow density (q_{fmax})	q	10^3	W.m^{-2}
Number of measurements in statistics ⁽¹⁾	n	1	1

Under the same standardized conditions ($T^\circ=20\pm 2^\circ\text{C}$ and $H=65\%\pm 5\%$), originally 5 knitted fabrics we used, made from PAN,PES,PP,PVC and Viscose fibers.The mass per square meter of fabric varied from 0.25 to 0.3 Kg/m^2 . We get the following results (Table 18).

Table 18. Comparison of thermal properties between synthetic fibers.

N° of the fabric	Fabric	Thermal conductivity λ ($10^{-3} \text{ W.m}^{-1}.\text{K}^{-1}$)	Thermal resistivity r ($\text{K.m}^2.\text{W}^{-1}$)	Thickness (mm)
1	Viscose	50.9	10.3	0.53
2	PLA	40.74	11.84	0.48
3	PES	54.9	17.3	0.97
4	PAN	51.4	17.5	0.89
5	PP	52.8	17.8	0.94
6	PVC	44.8	19.2	0.86

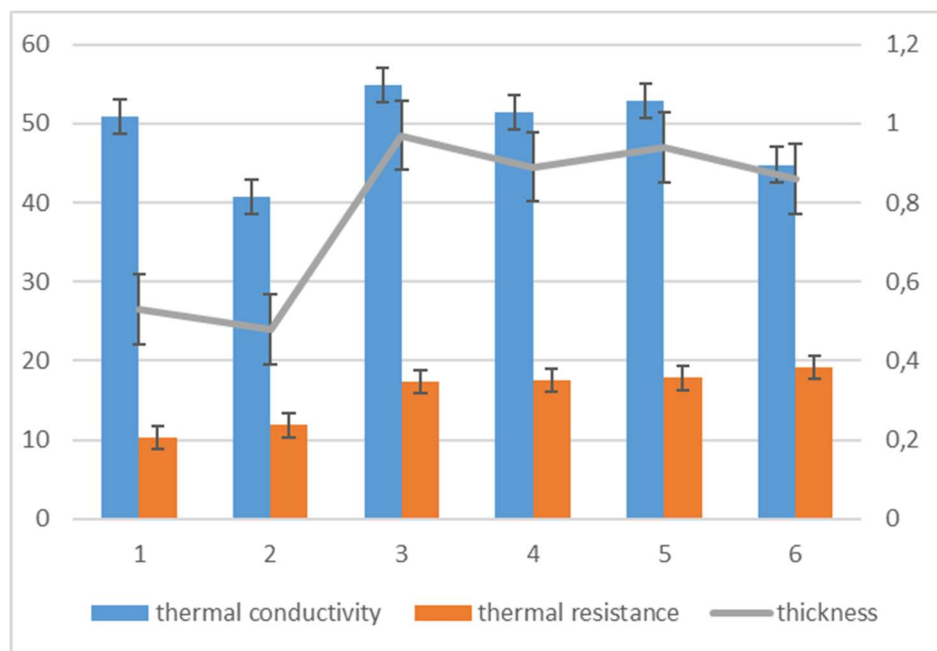


Figure 47. Influence of temperature drop across the textile layer on thermal conductivity and resistance of polymers.

It may be observed from Figure 47 that the lowest thermal resistance and thermal conductivity values are obtained for fabrics made of 100% PLA, whereas the PES, PAN and Viscose exhibited the highest effects. This result may be attributed to the fact that fibers have lower thickness. However, Viscose presents relatively a low thickness (0.53 mm). This makes us reconsider the factors that influence the thermal behavior of a fabric. Certainly, it has a strong link with the structure (thickness, air gaps, woven or knitted structure, etc.), but also, the latest clearly

depends on the origin of a fiber. As it is known, Viscose is coming from a very famous thermal insulator “The Wood”.

2.2.2 Thermal absorptivity

The warm-cool feeling of textile is another important aspect for clothing comfort and its sensation is a transient heat conduction phenomenon. When fabric is placed on the skin, heat flows away from the skin because skin temperature is higher than the cloth.

Loss of heat causes the skin temperature to fall and the faster the heat transfer occurs between the fabric and the body, the more intense the feeling of coolness.

It demonstrates the capacity of a material to give warm-cool feeling when a material is touched for a short time approximately for two seconds. The higher is the thermal absorptivity of a fabric, the cooler is its feeling.

While testing the PLA wet samples using the COOLMAX wet stripes .We obtained the results presented in the following table and chart. (Table 19)

Table 19. Thermal absorptivity results.

N° of the sample	Thermal Absorptivity (dry sample) ($\text{W.m}^{-1}.\text{s}^{1/2}.\text{K}^{-1}$)	Thermal Absorptivity (wet sample) ($\text{W.m}^{-1}.\text{s}^{1/2}.\text{K}^{-1}$)
1	127	477
2	132	429
3	126	466
4	136	497
5	128	442
Mean	129.8	462.2
St.dev	3.71	24.31

The thermal absorptivity average of these PLA samples determined using an ALAMBETA instrument, with a standard deviation around 24, are illustrating the poor performance of this material in front of warm-cool feeling of a garment. Therefore, it harms the comfort sensation of textile fabrics.

Taking into consideration this result, we can not recommend the PLA to use in the production of winter clothes nor in other similar items.

2.3 Thermal insulation radiation index: Infrared camera

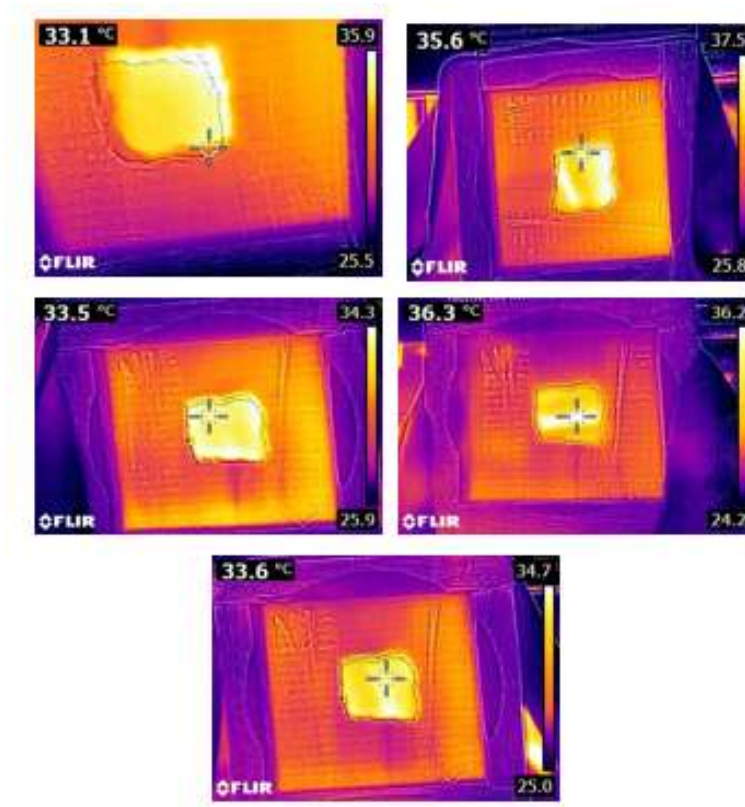


Figure 48. Thermal insulation radiation index of PLA.

The temperature values given by the thermal camera and indicated on the photos above allow us to determine the thermal insulation radiation index of PLA fabric ; After calculating the mean values I_{mean} .

Table 20. Thermal insulation of PLA.

N° of sample	T_s	T_R	T_h	I
1	33.1	24.4	40.5	0.54
2	35.6	24.4	40.5	0.69
3	33.5	24	40	0.59
4	36.3	24	40.6	0.74
5	33.6	24	40.3	0.59
Mean thermal Insulation for PLA	34.42	24.16	40.38	0.63
St.dev	1.28	1.28	1.28	1.28

An average of 0.63 of thermal insulation radiation index can be considered as an acceptable index. Since, such value can show that PLA knitted fabric will only allow 60 % of the heat to pass from a heating body or from the sun to the human body which shows that Polylactide is

not the best fiber to use for winter clothes. This reminds us to the Polyester and CoolMax materials which are not recommended for warm articles for the same reason.

The following figure (Figure 49) shows the different forms of losing heat from the human body where we can see that the radiation is taking the biggest part with nearly 45 %. This means that our bodies need to cover such loss by warmer materials who have better thermal radiation insulation index.

This result has just confirmed what was said previously about the thermal absorptivity parameter of PLA concerning its performance face to the warm-cool feeling.

The heat loss form human body ;

- Conduction $\simeq 5\%$
- Respiration $\simeq 10\%$,
- Perspiration /Evaporation $\simeq 20\%$,
- Convection $\simeq 25\%$,
- Radiation (with electromagnetic waves) $\simeq 45\%$,

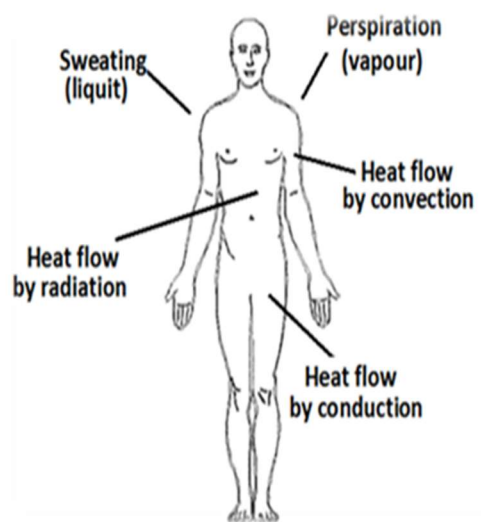


Figure 49. The heat loss forms of human body.

2.4 Air permeability

The air permeability of a fabric is closely related to the construction characteristics of the yarns and fabrics in which large volumes are occupied by air. The air permeability of a fabric is a measure of how well it allows the passage of air through it and is defined as the volume of air passed in one second through 100 sq.mm of the fabric at a pressure difference between the two surfaces of the textile material was 100 Pa. (66)

It is often used in evaluating the breathability characteristic and the porosity of the fabric.

The results of air permeability mean values for PLA fabric and other knitted fabrics (polyester, acrylic, cotton, wool) are illustrated in the following chart (Figure 50).

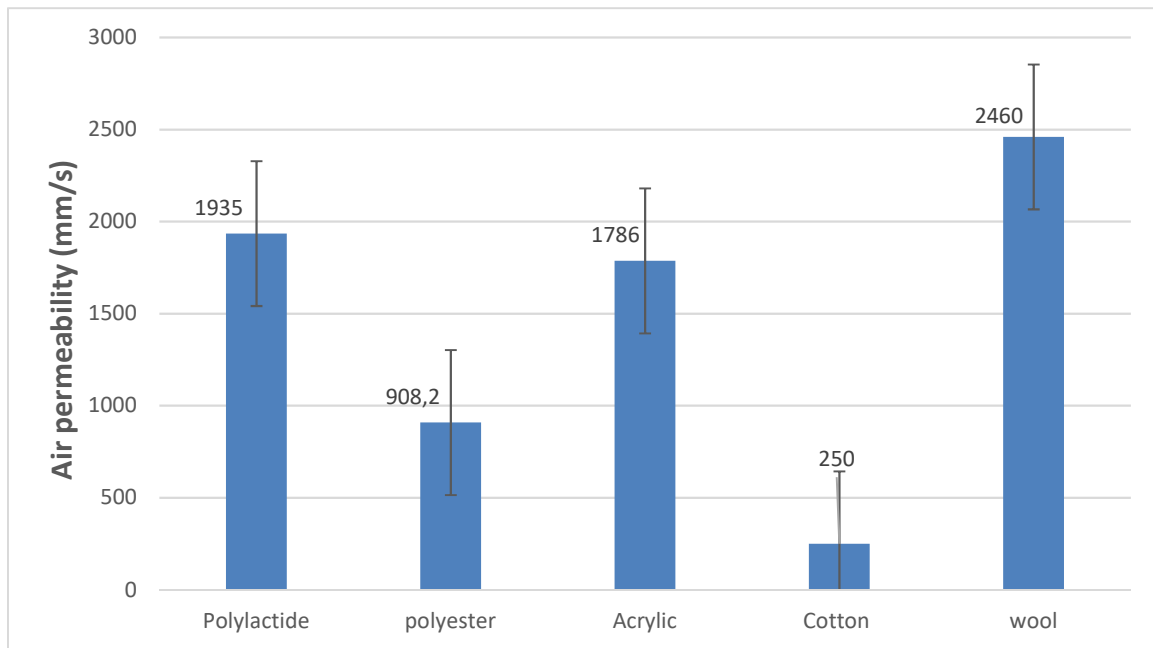


Figure 50: Air permeability parameter for different fabrics.

As shown in Figure 50, there is a significant difference between the five fabrics. The PLA exhibits the highest air permeability values among all the synthetic fabrics, and coming in the second place just after the wool which exhibits a very important air permeability (almost 2500 mm/s).

The difference observed between air permeability values of knitted fabrics due to the difference in their characteristics covering properties, thickness, density, weight, etc.

2.5 Water vapor permeability

Water vapor permeability gives the ability to transmit vapor out of the body. Higher moisture resistance with high thermal resistance of the textile layers produce more heat storage on body skin causing uncomfortable sensation.

We tested the PLA fabric 5 times in different bases in both directions, and we arrived to the results in the following table (Table 21).

Table 21. RWVP (%) for PLA fiber.

N° of sample	RWVP%- columns direction	%RWVP-rows direction
1	81.9	77.6
2	84.9	81.9
3	78.3	76.6
4	79.7	77.4
5	79.8	68.8
Mean Value	80.92	76.46
St, Dev	2.29	4.25
VAR COEF	5 .28	18.1

Many water vapor permeability tests were investigated for 100% PES fabric and for other samples made of 50:50 cotton/polyester fabric in different structures (knitted /woven), with different weave design and different directions. We end up to the result that PES has a water vapor permeability of 74% to 76% and 70% for blends cotton/polyester when PLA has a water vapor permeability up to 81% which is a considerable difference.

Similar to PET, PLA is basically hydrophobic, but more hydrophilic than PET. The water regain of PLA is 0.5% higher than that of PET 0.3%, which can be strongly behind that difference in the water vapor permeability of those fibers.

2.6 Water vapor resistance

Water vapor resistance (R_{et}) indicates how much a textile can allow the passage of water vapor through it.

In both directions, columns and rows, PLA jersey knitted fabric has an average of water vapor resistance of 2 m² Pa/W which is slightly lower value when compared to samples made of 100% PES who have an average of 2.5 m²Pa/W of resistance.

PLA has a lower density (1.25g/cm³) than that of PET (1.34 g/cm³). PLA is inherently a moderately polar material due to the basic repeat units of ester bonds. This leads to a number of unique attributes such as resistance to both water and vapor.

According to the classification of the Hohenstein Institute presented in Table (22). All the experimental samples used in our work are extremely breathable and comfortable at a higher level of activity (their R_{et} are under $6 \text{ m}^2\text{Pa/W}$). (61)

Table 22. R_{et} comfort rating system. (61)

Rating	Ret Value	Description
Very good	0-6	Extremely breathable and comfortable at a higher level of activity.
Good	7-13	Very breathable and comfortable at a moderate rate of activity.
Satisfactory	14-20	Breathable, but uncomfortable at a higher rate of activity.
Unsatisfactory	21-30	Not breathable, giving a moderate comfort at a low rate of activity.
Very unsatisfactory	+31	Not breathable, uncomfortable with a short tolerance time.

2.7 Surface Roughness

Modern manufacturing processes provide for careful control of parts at each stage of their production cycle. Surface roughness is among the main controlled parameters. Microgeometry of the surface layer of parts has a significant impact on their performance. The study of surface roughness parameters in this perspective is a very urgent task, since it allows predicting the performance and durability of both individual parts and components and mechanisms in general. In this case, the development of methods for assessing roughness based on the use of modern software for processing images of controlled surfaces can be an efficient approach.

Roughness measurements are done in the middle of surface (with four repeated measurements). Figure 51 shows the 3D pictures of each tested sample, the appearance of the obtained surface, roughness parameter and the surface profile. (68)

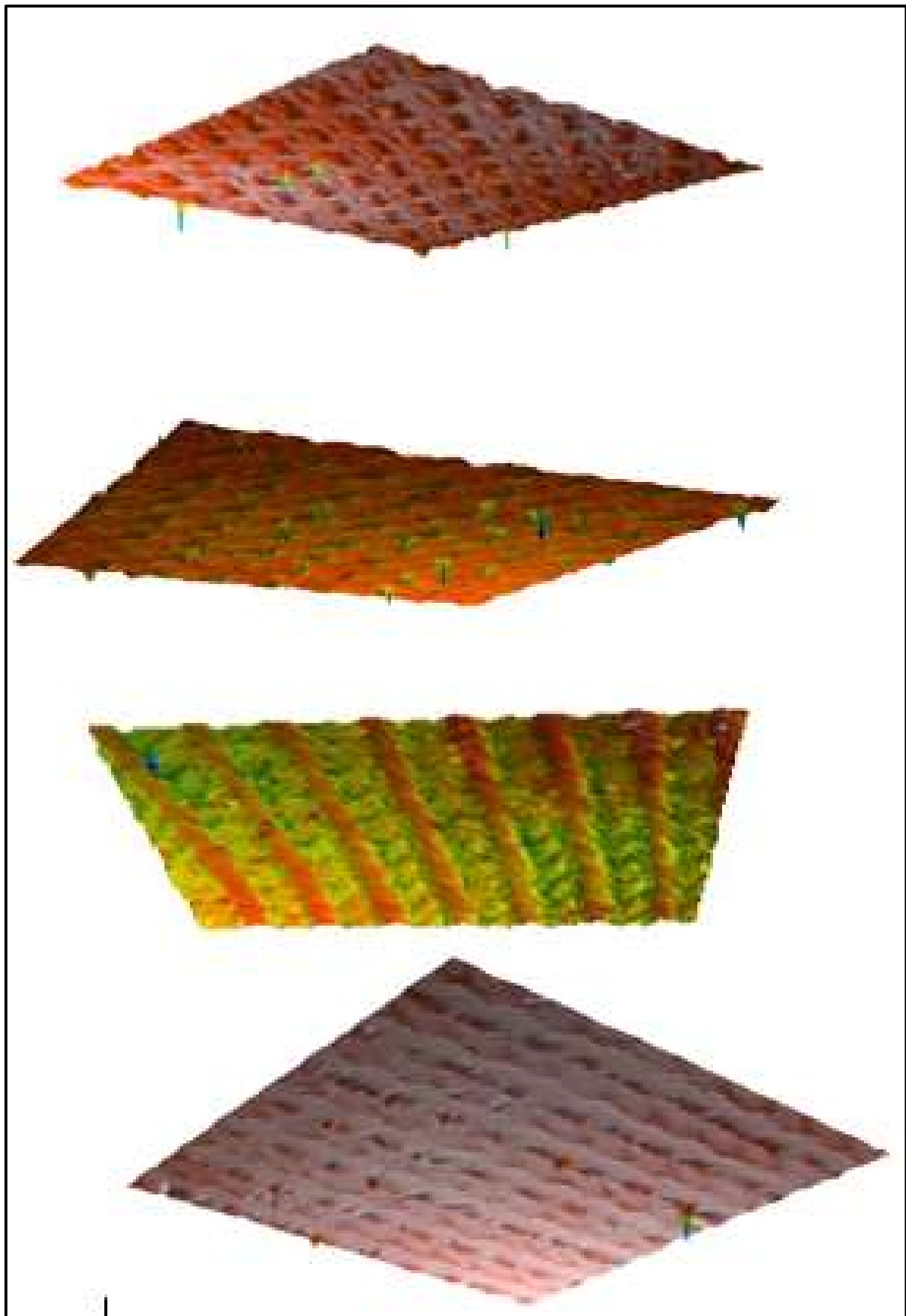


Figure 51: PLA surface roughness appearances in 3D.

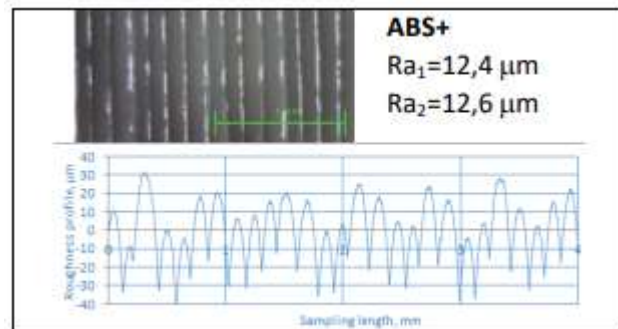


Figure 52: ABS surface profile.

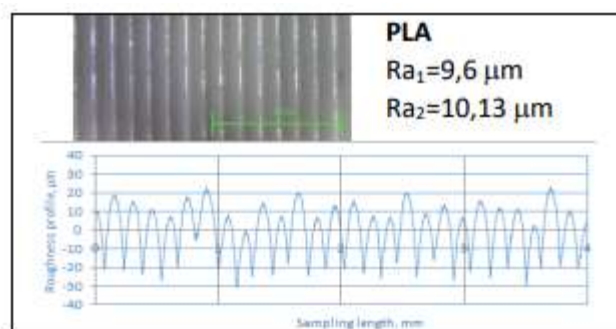


Figure 53: PLA surface profile.

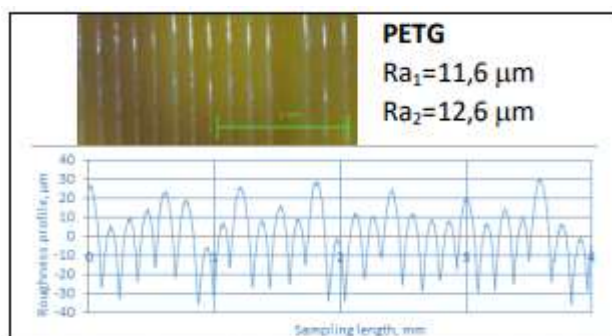


Figure 54: PETG surface profile.

By analyzing the shape of the surfaces obtained, the unevenness of the different profiles and values of R_a , it can be concluded that there are differences between the samples and the smallest roughness has samples of PLA material. Furthermore, it can be noticed that in samples of ABS and PETG material, there is an equal distribution of the material with the occurrence of local increase and decrease in the height of an evenness.

Conclusion

In this third chapter, we have presented the main obtained results:

We have found that the mechanical behavior of Polylactic acid fiber is relatively high and could be considered as a good competitor to PET concerning the tensile strength, friction test and the bursting strength. However, it has its limitations; the wet samples of PLA fabric didn't show the same mechanical performance.

For thermophysiological comfort properties, starting with the liquid moisture transfer properties; the PLA has overperformed itself and has shown better results than other synthetic fabrics like PET, CoolMax and PVC. In addition, the PLA gives the closest finger print to Cotton among all the tested materials.

For the thermal conductivity and the thermal resistance, it was illustrated that those two parameters are very linked to the thickness of the fabric as well as its origin. However, the PLA has, relatively, a good thermal conductivity and an acceptable thermal resistance which can allow it to be used as a thermal conductor fabric.

Concerning the thermal absorptivity and the thermal radiation insulation, we have found that the PLA has an acceptable performance which can't really protect the human body from the cold weather nor to cover the loss of heat from the body via radiation, convection, etc.

For air permeability the comparison between Polylactide, Polyester, Acrylic, Cotton and wool had showed that PLA has an excellent air permeability and comes in the second place just after the wool.

For water vapor permeability and the water vapor resistance determined using the Permetest and according to the comfort rating system, we found that the PLA is considered as an extremely breathable and comfort at a higher level of activity which allows the use of this fiber for sportswear, army wear, etc.

Finally, the surface profile of PLA shows the evenness and the distribution of the material which was slightly higher to the ABS and PET.

General Conclusion

General conclusion

Our end of studies project entitled “Study of end-use properties of Poly lactic acid fiber” aimed to study the analogy between the Polylactic acid fiber (PLA) and the polyester fiber, to what extent the PLA can replace the PET and other petroleum-based polymers and for how far this new fiber can be efficient in various end use applications.

We can affirm that for such a characterization and such a study of a new fiber, it is essential to detail the part of mechanical properties and thermophysiological properties as well.

To characterize the mechanical behavior of PLA, we determined some technical properties. First, we simulated the abrasion resistance of this fiber in both status dry and wet, where wet abrasion resistance is significantly reduced, we have mentioned a decline of approximately 32% of the fabric abrasion resistance (from 8600 cycles to get the fabric damaged in the dry state to 5800 in the wet state) .That result confirm that PLA can't replace PET or perform that efficiently when it comes to personal protection clothes (for people working in rainy days, in the seas, in fires etc.) .Then using the bursting strength tester and the dynamometer had proved that PLA has a strong mechanical behavior against such constraints (Load, extension, stress..), which can be further improved while choosing the appropriate parameters. It can even reach a Tensile strength and an E-Modulus of 320 MPa and 5.5 GPa respectively for PLA 11-14 ($\varnothing = 11 \mu\text{m}$ or $\varnothing = 14 \mu\text{m}$).

The same thing for friction test that highlighted the important friction coefficient of this fiber which can be a privilege for many use fields.

In fact, thermophysiological properties have the same importance as much as the mechanical properties do .Using the “Permetest “to simulate the water, vapor permeability and the resistance to water-vapor as well. According to The classification of Hohenstein institute, PLA is one of the most breathable and comfortable fabrics at a very high level of activity. The R_{et} doesn't pass an average of $2.5 \text{ m}^2\text{Pa/w}$ that makes PLA an excellent fabric choice for sportswear. “Alambeta” was used to evaluate the thermal properties; thermal conductivity, thermal resistance and thermal absorptivity. To characterize the water transport, the moisture management tester “MMT” was used and some tests were carried out to determine

The wetting time, spreading speed, the maximum wetting radius and the absorbance rate. All those parameters were regrouped in only one parameter OMMC: overall moisture management capability.

It was found that the moisture absorbency, the whole comfort properties of PLA fibers; being better than those of PET fibers, make them more attractive for use in various kinds of garments like T-shirts, underwear, sportswear etc. One interesting application is that disposable garments made from PLA nonwovens, because they are fully biodegradable in composting and environmentally friendly with reduce of CO₂ emission in combustion.

Since the development of PLA fiber is clearly in its early stages compared with conventional synthetic fibers, its commercial viability has been limited in replacing petroleum-based synthetic fibers other than for biomedical applications such as sutures. However, technological improvements that both reduce production costs and widen its material performance are already under way at a variety of companies and institutes. PLA will provide the first example in the polymer industry where environmentally friendly bioprocessing and chemical processing technologies are brought together with biomass feedstocks to create a major commercial opportunity.

Finally, we recommended, to extend the study for other derivations, from the used basic structures to study all the characteristics of a PLA fiber which is already recycled. We can compare the row material with recycled fiber. Is the latest going to perform just the same way or is it going to lose its privileges and its high performance once recycled?

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