Polylactic Acid

Synthesis, Properties and Applications

Vincenzo Piemonte
Editor

Chemistry Research and Applications

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POLYLACTIC ACID: SYNTHESIS, PROPERTIES AND APPLICATIONS

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PREFACE

This book describes the synthesis, properties and applications of PLA through fourteen original chapters that will guide the reader through a fascinating journey into the world of PLA, providing interesting insights for those who intend to use this polymer for innovative applications, or simply those who want learn more about this very important biodegradable and bio-based plastic. PLA biodegradability introduces this polymer in a world of eco-friendly and human-friendly applications in several technological fields. In short, this book will appeal to all the readers who not only want to have a reference book of consolidated notions on PLA, but also, and especially, to those who want to discover new potentials and new application fields of this unique biodegradable polymer.

Chapter 1 - In the last decade, research was concentrated on polylactic acid (PLA) as thermoplastic matrix to produce plastics and composites. Generally, PLA based plastics and composites are prepared by compression molding and injection molding methods. Prior to the production of the materials, blending of PLA with additives is an important step to overcome the brittleness in the materials and to reduce the overall cost. Recently, few companies have come up with PLA incorporated with fillers so as to reduce the cost of PLA. Among them, Cereplast Ltd is one of them which sell PLA with starch as a filler in it. But most of the work relating to PLA based plastics and composites have been reported for PLA procured from NatureWorks Inc, Biomers and several other companies. They have several grades of PLA. So it is important to analyze the properties of plastics and composites prepared from different grades of pure and impure PLA and to justify the use of additives for various applications. Mechanical, thermal, morphological, water uptake and other properties of plastic and composites with PLA as raw material, procured from different sources, are different. Hence, the source and the type of PLA as raw material must be taken into consideration in order to optimize the conversion of PLA to molded parts and films. In short, it is stated here that samples from NatureWorks PLA or Biomer PLA showed high mechanical properties while PLA samples from Cereplast Ltd. i.e., filler added PLA showed low mechanical properties. However, elongation at break is almost same for NatureWorks PLA or Biomer PLA or Cereplast PLA. Thermal stability of PLA procured from Cereplast Ltd was lower with higher char yield in comparison to PLA procured from NatureWorks. In addition, the properties of the PLA based composites depend on the nature and type of PLA used. In this chapter we have tried to evaluate the properties of PLA based plastics and composites prepared from different sources/grades.

Chapter 2 - Poly(lactic acid) (PLA) is a well-known aliphatic polyesters derived from corn and sugar beets, and it degrades to non-toxic compounds in landfill. Until the last decade, the main uses of PLA have been limited to biomedical and pharmaceutical applications such as implant devices, tissue scaffolds, and internal sutures, because of its high cost and low molecular weight. The new method to synthesis PLA (ring-opening polymerization), which allows economical production of high molecular weight PLA polymer, has broadened its applications. Because PLA is biodegradable and derived from renewable source, it has considered as one of the important solutions to the plastics wastes problem. However, PLA falls short of the required properties for potential applications because of its inherent brittleness, low toughness and high cost comparing with the traditional polymers (PE, PP, PS...). In general, polymer blending is the common method to modify such these drawbacks; the aim of this review is to discuss the recent developments in PLA polymer blends.

Chapter 3 - Processing of poly(lactic acid) (injection and extrusion/injection) as well as annealing of processed materials were studied in order to analyze the variation of its chemical structure, mechanical properties and thermal stability. Processing of PLA was responsible for a decrease in molecular weight, as determined by GPC, due to chain scission. The degree of crystallinity was evaluated by means of differential scanning calorimetry and X-ray diffraction. It was found that mechanical processing led to the quasi disappearance of crystal structure whereas it was recovered after annealing. These findings were qualitatively corroborated by means of FTIR. By analyzing ^{1}H NMR and ^{13}C NMR chemical shifts and peak areas, it was possible to affirm that the chemical composition of PLA did not change after processing, but the CH_3/CH area ratio increased, which can be attributed to a different molecular environment, caused by an increase of the degree of crystallinity or/and by the presence of smaller molecules. The mechanical behavior was determined by means of tensile testing (Young modulus, yield strength and elongation at break). The thermal stability of the various materials was established by calculating various characteristic temperatures from thermograms as well as conversion and conversion derivative curves. An integral method (based on the general analytical solution), differential methods (based on the 1st conversion derivative and on the 2nd derivative) and special methods have been used to assess the kinetic triplet of the thermal decomposition. A new equation was developed to calculate the reaction order.

Chapter 4 - The annual supply of poly(lactic acid) PLA is expected to increase rapidly in near future owing to various attractive properties such as high rigidity, biodegradability, and biocompatibility. However, considerable efforts will be required to overcome the following defects; (1) poor heat resistance due to low degree of crystallinity, (2) mechanical brittleness, and (3) poor processability. Recently, we proposed new technologies to solve the problems by mixing various types of polyesters with precise morphology control. This chapter is composed of three parts; (1) Enhancement of crystallization of PLA by poly(butylene succinate) (PBS), (2) Material design of soft and ductile PLA by miscible blends with polyester-diol (PED), and (3) Improvement of melt elasticity and thus processability of PLA by addition of flexible nanofibers of poly(butylene terephthalate) (PBT). Although PBS is known to be immiscible with PLA, it is found that molten PBS acts as a nucleating agent for PLA. As a result, the degree of crystallization of PLA is enhanced by addition of a small amount of PBS. Furthermore, the nucleating ability is pronounced under flow condition, which is presumably attributed to the enlargement of PBS droplets. Consequently, the blend quenched during uniaxial stretching shows high stress at tensile deformation even beyond the glass transition temperature (Tg) of PLA. PED composed of adipic acid and ethylene glycol or diethylene glycol is found to be miscible with PLA in a molecular level. Because PED shows low Tg as compared with PLA, Tg of the blends decreases with increasing the blend ratio of PED. Owing to high molecular weight, PED is not diffused out on the surface, which avoids surface tackiness. Moreover, some blends exhibit shape-memory function. Finally, a new method to enhance the melt elasticity of PLA is proposed in order to improve the processability at various processing operations, in which free surface deforms in a molten state. It is demonstrated that fibrous PBT is generated in PLA by melt-stretching process with prompt cooling. The diameter of the fibrous PBT dispersion is found to be approximately 600 nm and the aspect ratio is larger than 400. A small amount of PBT nanofibers, which exist in a solid state at processing temperature of PLA, can enhance the strain-hardening behavior in elongational viscosity.

Chapter 5 - Polylactic acid (PLA) as a biodegradable hydrolysable aliphatic semi-crystalline polyester is produced directly through polycondensation from lactic acid monomers; or alternatively by ring opening polymerization of the cyclic lactide dimmer. The idea of replacing non-biodegradable plastics through biodegradable polymers is far from being superior as material performances are still at the developing stage, beside productions cost being too high compared to the routinely applied polyolefins. In addition, material performance needs to be tailored for the particular application to meet end-user expectations. The use of inorganic fillers as well as plant-derived organic fillers is seen as an approach to adjust material performance of composites, and maintain renewability and biodegradability at even reduced costs at the same time. The arising problem is the often observed low compatibility between filler types and the hydrophobic polylactic acid matrix, with the consequence of inferior physico-mechanical properties. Incorporation of hydrophilic fillers of organic and inorganic origin, respectively, results in poor dispersion, high viscosity, and lowered thermal, mechanical and viscoelastic properties. In the presented research, different approaches are shown to enhance interfacial compatibility between a hydrophobic poly(lactic acid) matrix and hydrophilic inorganic and/or organic filler. Effects of surface modification of ligno-cellulosic filler on the resulting filler-polymer interactions were determined. The influence of PLA matrix induced crystallization on the compatibility with hydrophilic filler was investigated. Finally, the effectiveness of combined modifications, i.e. the filler and the polymer matrix, respectively, was examined. Higher interfacial adhesion and reinforcement as a consequence of the applied modification types were recorded through thermal analysis, morphological indicators, mechanical characterization, and in particular through dynamic-mechanical analysis. The presented results illustrate that dynamic-mechanical analyses, as through the determined relaxation phenomena, in particularly suited to reveal the effectiveness of the used modifications in terms of improved interfacial compatibility between natural organic/inorganic filler types and the polylactic acid matrix.

Chapter 6 - This chapter studies the effect of different nanoparticles on properties and degradation trend in compost of Polylactic acid -PLA-. Here, it is also presented the effect of medium temperature on the degradation trend of PLA, and how similar nanoparticles can differently affect the degradation mechanism of PLA depending on the conditions of degradation. In general, it was found that the above nanocomposites based on montmorillonites, fumed silica and unmodified sepiolite showed considerable improvements in the PLA matrix properties, due to the achievement of a good level of polymer/filler dispersion as well as to a high filler chemical compatibility with PLA, presenting these materials several potential final industrial applications. For montmorillonites and fumed silica systems, the highest improvements were found by the presence of nanoparticles with better distribution, dispersion and compatibility with the polymer, especially in the case of montmorillonites given their higher contact surface with the polymer matrix associated to their platelets like morphology. Unmodified sepiolite particles showed similar thermo-mechanical improvements in PLA than those presented by the addition of montmorillonites, even higher in some cases because of their good dispersion and high polymer/filler interactions, without the need of organic modifiers, and regarding these sepiolite particles as potentially interesting materials for the enhancement of PLA properties. Concerning to the biodegradation of PLA and nanocomposites, a predominant bulk degradation mechanism of degradation was confirmed for neat PLA in compost and a different effect of nanoparticles was observed to influence this mechanism depending on the compost temperature: if this temperature is around 40°C the addition of nanoclays was found to increase the PLA degradation rate because of the presence of hydroxyl groups belonging to the silicate layers, this phenomenon was particularly evident for the highest dispersed clay in the polymer; however, if this degradation temperature is around58°C the presence of nanoparticles seemed to slightly delay polymer degradation due to a reduced polymer chain mobility in the bulk material at this temperature, which results in a lower water absorption in the polymer matrix and/or a lower enzymes/polymer miscibility as compared to neat PLA.

Chapter 7 - Polylatic acid (PLA) is use in many products with short life cycle. Important applications of these are found in the biomedical field, where PLA and blends of it are used to produce scaffolds that temporarily replace the biomechanical functions of a biologic tissue, while it progressively regenerates its capacities. In the case of commodity products, PLA claim clear environmental advantages in several brief use applications, mainly in their final stage of life (waste disposal), which can clearly be evident through life cycle assessment. For a biodegradable product, performance will decrease along its degradation. From the final user point of view, performance should be enough for the predicted use, during all its life cycle. PLA can present short term performances similar to conventional plastics. Hydrolytic and/or enzymatic chain cleavage of PLA leads to α-hydroxyacids, which are ultimately assimilated in human body or in a composting environment. However, the mechanical behavior of PLA along its degradation time, which is an important aspect of the project, is still an unexplored subject. The failure criteria for maximum strength as a function of degradation time have traditionally been modeled according to a first order kinetics. In addition to this, in chapter, also hyper elastic constitutive models, such as the Neo-Hokean, the Mooney-Rivlin modified and the second reduced order will be discussed. These can be used to predict the mechanical behavior of a generic device made of PLA. A numerical approach using ABAQUS is presented, where the material properties of the model proposal are automatically updated in correspondence to the degradation time, by means of a User Material subroutine (UMAT). The parameterization of the material model proposal for different degradation times can be achieved by fitting the theoretical curves with the experimental data from tensile tests. When loading conditions are simple and the desired life cycle is known, a "trial and error" approach may be sufficient to design reasonable reliable devices. In more complex situations, device designers can use numerical approaches to define the material formulation and geometry that will satisfy the initial requirements, without the occurrence of any degradation, using conventional dimensioning. However, the lack of design tools to predict long term behavior has limited the application of biodegradable materials. The considerations and the dimensioning methods presented here, may overcome this limitation. The material model proposal presented here can be used as a design toll for generic biodegradable devices.

Chapter 8 - The use of synthetic polymers is nowadays a common practice in the conservation of historical artefacts. Commercial products don't fully satisfy the necessary requirements for application in Cultural Heritage. Therefore scientific community takes interest in the development of new compounds with specific features. In the last years, polymers from renewable resources have attracted increasing interest as potential substitutes to petrochemical-based material in many applications. Among these, Polylactic Acid (PLA) has risen particular attention. Beside other major use (e.g., packaging, biomedical devices) actually PLA may represent an attractive alternative to conventional synthetic polymers used in conservation of Cultural Heritage. In this chapter a comprehensive survey of conservation materials and the most relevant achievements related to the application of PLA in this field is reported and discussed. Furthermore perspectives and opportunities for the future are given.

Chapter 9 - Besides a reduction in volume of biomass and bioplastic waste, different synergetic interactions occur during co-pyrolysis of willow and polylactic acid (PLA). The flash co-pyrolysis of willow and PLA at 723 K results in an enhanced pyrolytic oil yield with a lower water content and a higher calorific value. In this chapter, the influence of flash co-pyrolysis of willow and PLA on the condensable and noncondensable pyrolytic gases is investigated in further detail with the aid of Py-GC/MS combined with statistical data analysis and pattern recognition. Here, the occurrence of synergetic interactions for willow/PLA blends is confirmed. Additionally, some specific features of the respective pyrolytic oil, obtained from a semi-continuous pyrolysis reactor, are analysed with a multitude of complementary analytical techniques. Based on the obtained results, a confrontation with willow/PHB (polyhydroxybutyrate – previous research) blends is performed and an explanation of the observed synergy is proposed accordingly.

Chapter 10 - Interest in bio-polymers from natural resources such as plants, stems largely from increasing regulation and public concern on ecological issues and the need for sustainable alternatives to finite petrochemical products. Performance of bio-polymers can be obtained as good as synthetic polymers but with several environmental advantages: they create almost no toxic emissions; their raw materials are sustainable, renewable and widely grown. Over the last decade polylactic acid (PLA) has been one of the most promising biopolymers and better manufacturing practices have improved the economics of producing lactic acid monomer through fermentation of renewable resources like corn, sugar beet and sugarcane. In addition to being thermoplastic, biodegradable, biocompatible and compostable, PLA shows good mechanical and barrier behavior and it has the ability to reinforce fillers. This chapter gives a review of available literatures on the production sources of PLA, provides information on its synthesis routes and deals its interesting applications in biomedical, food packaging and structural fields.

Chapter 11 - Synthetic materials capable of sensing and responding to external stimuli emulate the dynamic and adaptive nature of living matters, and have been pursued for biomedical applications in the past decade. Thermal-responsive shape memory effect is a phenomenon where a material changes its intrinsic physical/chemical properties and manifests such a change, on a macroscopic scale, as reversible shape and mechanical property alterations in response to thermal stimulations. In polymers, the shape memory effect is determined by the polymer network structure, which also dictates the mechanical and degradation properties of the material. Polylactic acid (PLA), a class of clinically used biodegradable synthetic polyesters, has been one of the top choices in the design of resorbable thermal-responsive biomedical devices and tissue scaffolds. The intrinsic hydrophobicity, brittleness and high glass transition temperatures of traditional PLA, however, has made it difficult to engineer good shape memory performance (e.g. stable shape fixing, rapid shape recovery rate) within a narrow physiological temperature range while achieving suitable mechanical properties and degradation profiles for *in vivo* applications. Innovative macromolecular / network design strategies need to be developed to meet such a challenge. This chapter reviews recent progress in engineering polylactic acid-based thermal-responsive shape memory polymers and discusses their limitations and promises for biomedical applications.

Chapter 12 - Bio-degradable poly (lactide) (PLA) and poly (lactide-glycolide) (PLGA) microspheres and microcapsules have important applications in Drug Delivery Systems (DDS) of protein/peptide drugs. By encapsulating protein/peptide drugs in the microsphere or microcapsules, their circulation time in blood can be prolonged. However, in the preparation and applications of PLA/PLGA microspheres or microcapsules containing protein/peptide drugs, the problems of broad size distribution and poor reproducibility of microcapsules, and deactivation of protein/peptides during the preparation, storage and release, are still big challenges. In this chapter, the techniques for control of the diameter of microspheres and microcapsules will be introduced at the first, then the strategies about how to maintain the bioactivity of protein drugs during preparation and drug release will be described. The membrane emulsification technique including Direct Membrane Emulsification and Rapid Membrane Emulsification Process were developed to prepare uniform-sized PLA, PLGA microspheres and microcapsules, the diameter of microspheres and microcapsules can be controlled from submicron to several ten microns by these two processes, and the reproducibility of products can be guaranteed. Furthermore, compared with conventional stirring method, the big advantages of membrane emulsification process were that the uniform microcapsules with much higher encapsulation efficiency can be obtained, and the release behavior can be adjusted by selecting microcapsule size. Mild membrane emulsification condition also can prevent the deactivation of proteins, which frequently occurred under high shear force in mechanical stirring, sonication, homogenization methods. The strategies for maintaining the bio-activity of protein drug were developed such as adding additives into protein solution, modifying protein before encapsulation, employing hydrophilic PELA as wall material, and so on. It was found that PELA microcapsule can maintain protein drug efficiently compared with PLA and PLGA, because PEG sequence can prevent the contact between protein drugs and hydrophobic PLA or PLGA. The PELA microcapsule containing recombinant human growth hormone (rhGH) was evaluated, less aggregation and hydrolysis of rhGH occurred during its release of 45 days.

Chapter 13 - Drug delivery systems (DDS) have shown their potential in improving the bioavailability of drugs at the site of action in the human system. Among polymers used in the designed of DDS, poly(D,L-lactic acid) and poly(D,L-lactide-co-glycolide) have been the center focus for developing nano/microparticles encapsulating therapeutic drugs in controlled release applications due to their bioerosionable and biocompatible characteristics. Preparation of microparticles of PLA and PLGA by spray-drying technology is the aim of this chapter. This technique allows obtaining drug-loaded microparticles in a unique step, with reproducible results, and a significant efficiency of encapsulation of a drug. Microparticles with an average size between 0.9±0.4 μm and 1.93±0.74 μm can be obtaining as a function of the selected variables, and encapsulation efficiency around 97% for hydrophobic drug, for example tamoxifen, and close to 74% for hydrophilic drugs, for instance 5-fluorouracil, can be obtained. Kinetic release of a drug from PLA or PLGA can be modulated as a function of the polymer composition of the particle and size particle, since hydrolytic cleavage of the backbone linkage can modulate drug release, especially in the case of hydrophobic drugs. Degradation of microparticles depends on the molecular weight of the polymer, the percentage of lactide and glycolide units, and also the preparation method. Subcutaneous injection of microspheres of PLA and PLGA in rats has showed up a correlation between length of in vitro and in vivo degradation as a function of microparticle composition. Pharmacokinetic studies have indicated a significant increase in the mean residence time of a drug when it is administered by microparticles of PLA or PLGA instead of in solution. Furthermore, histological studies have shown that drug-loaded PLA and PLGA prepared by spray-drying do not trigger rejection symptoms. Therefore, spray-drying technology can be considered useful in preparing drug delivery microparticulated systems based on PLA and PLGA.

Chapter 14 - Poly(lactic acid) (PLA) ultra-thin films (nanofilms) came up in the last years as novel materials for therapeutic and surgical applications, as well as conceptually new tools in the fields of tissue engineering and regenerative medicine. The present chapter describes the preparation methods to obtain PLA structures with a nanometric thickness and a large surface area, reporting the main features of such devices and the possibilities of functionalizing them by means of the inclusion in the polymeric matrix of nanoparticles with targeted physical properties. *In vitro* evidences regarding the interactions of mammalian cells with PLA nanofilms are described, based on studies carried out with fibroblasts, skeletal and cardiac muscle cells, osteoblasts, and rat and human mesenchymal stem cells. The application of PLA ultra-thin films for *in vitro* tissue regeneration and *in vivo* applications are also described, highlighting the novel contribution that such structures could bring in comparison with traditional biomaterials and bioengineering approaches.

CONTENTS

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Chapter 1

PROPERTIES OF PLASTICS AND COMPOSITES PREPARED FROM DIFFERENT SOURCES/ GRADES OF PLA

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ABSTRACT

In the last decade, research was concentrated on polylactic acid (PLA) as thermoplastic matrix to produce plastics and composites. Generally, PLA based plastics and composites are prepared by compression molding and injection molding methods. Prior to the production of the materials, blending of PLA with additives is an important step to overcome the brittleness in the materials and to reduce the overall cost. Recently, few companies have come up with PLA incorporated with fillers so as to reduce the cost of PLA. Among them, Cereplast Ltd is one of them which sell PLA with starch as a filler in it. But most of the work relating to PLA based plastics and composites have been reported for PLA procured from NatureWorks Inc, Biomers and several other companies. They have several grades of PLA. So it is important to analyze the properties of plastics and composites prepared from different grades of pure and impure PLA and to justify the use of additives for various applications. Mechanical, thermal, morphological, water uptake and other properties of plastic and composites with PLA as raw material, procured from different sources, are different. Hence, the source and the type of PLA as raw material must be taken into consideration in order to optimize the conversion of PLA to molded parts and films. In short, it is stated here that samples from NatureWorks PLA or Biomer PLA showed high mechanical properties while PLA samples from Cereplast Ltd. i.e., filler added PLA showed low mechanical properties. However, elongation at break is almost same for NatureWorks PLA or Biomer PLA or Cereplast PLA. Thermal stability of PLA procured from Cereplast Ltd was lower with higher char yield in comparison to PLA procured from NatureWorks. In addition, the properties of the PLA based composites depend on the nature and type of PLA used. In this chapter we have tried to

evaluate the properties of PLA based plastics and composites prepared from different sources/grades.

1. INTRODUCTION

Poly lactic acid (PLA) is a thermoplastic resin derived from annually renewable resources such as corn or sugarcane and is designed for extrusion/thermoforming applications. Importantly, they have good biocompatibility and are biodegradable in nature [1]. There are various grades of PLA which falls in the category of pure and impure PLA polymers. Pure PLA with different molecular weights can be obtained from NatureWorks, Inc, USA; Mitsui Chemicals Inc.; Japan, Miyoshi Oil & Fat Co. Ltd; Biomer, Krailling, Germany; East Link Degradable Materials, Ltd, Hong Kong; Galastic, Galactic s.a; Jamplast Inc. Ellisville, USA; PURAC, Groningen, The Netherlands. Pure PLA polymer is transparent and clear in appearance while impure polymer is an opaque in appearance. Impure PLA without exact molecular mass with starch added in it can be obtained from Cereplast, Inc, USA.

Permanent crude oil price stagflation as well as the ecological aspects of both production and disposal of standard oil-based plastics are presently two of the main concerns worldwide and that is the reason there are so many companies involved in the production of PLA. However due to high price level, which is not yet competitive - current turnover in this field is not really profitable due to high synthesis costs, unsatisfactory production capacity, poor and less transparent regulations.

PLA is a relatively brittle material, and difficult for film-blowing or extrusion. The processability of the PLA resins can be improved by copolymerization [2-7] or blending PLA with other polymers poly (ethylene oxide) (PEO) [8], poly (ε-caprolactone) (PCL) [9-11], poly (vinyl acetate) (PVA) [12], poly (hydroxyl butyrate) (PHB) [13,14] and poly (butylenes succinate) (PBS) [15,16]. The incorporation of other polymers may be by melt blending, reactive compatibilization process. Sometimes peroxides such as dicumyl peroxide are also added as a crosslinking agent. Plasticizers such as poly (ethylene glycol) (PEG), [17-22] triacetine (TAc) [23] and low molecular weight citrates [24-29] can be added to reduce the brittleness in the PLA materials.

PLA can be used as a matrix to produce composites/ biocomposites/ nanocomposites depending on the types of reinforcement. By using natural fibers, a full ‘‘biocomposites” can be produced [30]. PLA biocomposites have been studied by numerous research groups. The most described processing methods for preparing biocomposites/ nanocomposites or composites are compression molding, mixing, injection molding or other, non-common techniques for thermoplastic polymers. However, the injection molding is in common use for thermoplastics such as PLA. Furthermore, nanocomposites can be very easily processed by using nanofillers.

PLA has found market acceptance in the packaging and medicine sector [31]. But it has still not found any meaningful market acceptance as an engineering resin, because of its non-satisfying impact resistance and low heat distortion temperature. Therefore, manufacturing of PLA light-weight parts with a high impact resistance would lead to new application fields, e.g., automotive or electrical industry.

In this chapter, we will discuss about the properties of PLA based materials in native/ blends/ composites as per their source.

2. TYPES/GRADES OF PLA

Table 1 discusses about the types and the grades of PLA used in the research / product development world wide.

Table 1. Different grades of PLA

Name of the Company	Grade	Melt Flow Index (MFI)
NatureWorks, Inc, USA	2002D	5-7 g/10min at 210°C
	3001D	10-30 g/10min at 190°C
	4042D	5.7 g/10min at 190°C
	2100D	5-15 g/10min
	3051D	7.75 g/10min at 210°C
	4031D	Not mentioned
	4032D	Not mentioned
	4060D	Not mentioned
	6200D	Not mentioned
Cereplast, Inc, Hawthorne, USA	CP-INJ-1001EZC	10–12 g/min at 190°C
Mitsui Chemicals, Inc., Japan	LACEA H-280 LACEA H-100	8–10 g/min at 190°C
Miyoshi Oil & Fat Co., Ltd	PL-1000	Not mentioned
Biomer, Krailling, Germany	Biomer L 9000	Not mentioned
East Link Degradable Materials Ltd., Hong Kong	Poly(lactic acid) (PLA)	Not mentioned
Fortum, Finland	Poly(lactic acid) (PLA)	Not mentioned
Galactic s.a.	Galastic	6.6 g/min at 190°C
Jamplast Inc., Ellisville, USA	PLA	Not mentioned
Polymer Source Inc., Montreal, Canada	P6463B PLA	Not mentioned
Purasorb PL, Purac, America	PLA	Not mentioned
Shenzhen Guanghua, China	PLA:ESUNMP1001	Not mentioned
Shimadzu Corp., Japan	LACTY 2012	Not mentioned
Wei Mon Industry Co., LTD, Taipei, Taiwan	PLA	Not mentioned
Unitika Co. Ltd, Japan	PLA	Not mentioned

From the Table, it is clear that NatureWorks provides several grades of PLA. The size exclusion chromatographic (SEC) analysis of commercial 2002D PLA showed a number average molecular weight (Mn) of 117000. Density of 2002D and 3001D has been reported as 1.24 g/cm^3. 4042D grade PLA consists of 92% L-lactide and 8% D-lactide units, with polydispersity index of 2 and a density of 1.25 g/cm^3. PLA resin (CP-INJ-1001EZC) obtained from Cereplast, Inc, Hawthorne, USA is one fifth of the price when compared with NatureWorks PLA. To improve the biodegradability of this PLA resin, supplier has incorporated cereal starch (wheat, potato and tapioca) in this grade of resin. Biomer L 9000