

Poly (Lactic Acid): An Eco-Friendly Biodegradable Polymer

Satya Lakshmi S., Vineela N.*, Srinivasa Rao Y., Kamala Kumari P.V.

Department of Pharmaceutics, Vignan Institute of Pharmaceutical Technology, Duvvada, Visakhapatnam-530049, India.

*Corresponding Author: Vineela N.

Abstract

Poly (lactic acid) or poly (lactide) (PLA) is bio-based, renewable and biodegradable aliphatic thermoplastic polyester. Lactic acid is synthesized industrially either by biological or chemical route. For the production of lactic acid biological method is mostly preferred as it gives optically pure lactic acid. PLA could be a technical and economical alternative to the problem of eventual disposal of very large amount of plastic packaging worldwide. A summarized description is given regarding the physical, thermal, mechanical properties, technologies for PLA production, synthesis of poly (lactic acid) (PLA) from its monomer, poly blends and finally the biomedical applications discussed here.

Keywords: PLA (lactic acid), Poly blends, Polycondensation, Fermentation, Lactide, Oligomers.

Introduction

Poly (lactic acid) or poly (lactide) (PLA) is bio-based, renewable and biodegradable aliphatic thermoplastic polyester. It is derived from the renewable resources, such as cornstarch and sugarcane. These polymers are considered as biodegradable and compostable. PLA is a thermoplastic, high-modulus, high-strength polymer that can be made from annually renewable sources to

yield articles for use in the industrial packaging field. Bacterial fermentation is used to make lactic acid. It is then converted to the lactide dimer to remove the water molecule that would otherwise limit the ability to make high molecular weight polymer. After the water is removed, the lactide dimer can be polymerized without the production of the water [1].

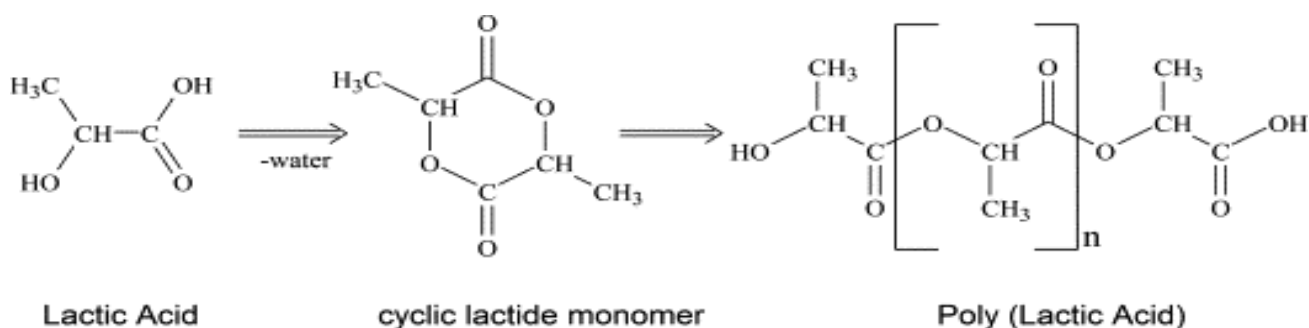


Figure 1: Polymerization of Lactic acid

PLA is also one of the most investigated sustainable polymers because of its numerous advantages, such as biodegradability, biocompatibility, compostability; good mechanical properties. PLA is a leading biomaterial for numerous applications in medicine [2]. As a bioabsorbable polymer, PLA is one of the most promising biopolymers [3]. This is due

to the fact that the monomers may be produced from non-toxic renewable feedstock as well as due to being a naturally occurring organic acid. PLA synthesis requires rigorous control of conditions like temperature, pressure and pH the use of catalysts and long polymerization times [4]. It can be prepared by different polymerization processes from lactic acid including: poly-condensation, ring

opening polymerization and by direct methods like azeotropic dehydration and enzymatic polymerization. Production of lactic acid biological method is mostly preferred as it is optically pure [5]. Simple hydrolysis of the ester bond is used to degrade PLA. Presences of enzyme are not required to catalyze this hydrolysis. The rate of degradation depends on the isomer ratio, and the temperature of hydrolysis, size and shape. PLA undergoes thermal degradation at temperature above 200°C.

PLA degradation depends upon impurities, temperature, time, low molecular weight and catalyst concentration [6]. Typically it can only degrade promptly in months at a high temperature (around 58°C) under the industrial composting conditions. Moreover, it has a low heat distortion temperature and poor water barrier properties compared with conventional thermoplastics [7].

While biodegradation of PLA is advanced in the ground, where moisture and microorganisms exist, still a period longer than 2 months is needed for decomposition; however biodegradation does not advance in air. As a solution, by adding photo degradability to a biodegradable polymer, degradability can be efficiently promoted under any conditions [8]. They degrade easily in physiological conditions. Their degradation products are excreted through kidneys and eliminated through carbon-dioxide. It can also be recycled to its monomer by thermal depolymerized or by hydrolysis [9]. PLA homopolymers have a narrow processing window.

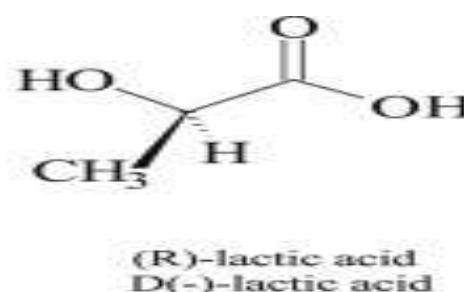
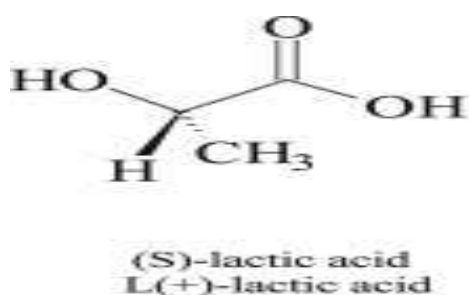


Figure 2: Racemic mixture of lactic acid

Lactic acid can be manufactured by chemical synthesis or microbial fermentation processes. The Chemical Synthesis process uses petroleum-based chemicals which may subject to the potential supply problem of crude oil and its dramatic price variation. A disadvantage of the Chemical Synthesis process is that it produces only the racemic (50:50) mixture [10].

The amorphous PLA is soluble in most organic solvents. Crystalline PLA is soluble in chlorinated solvents at elevated temperatures. It can be crystallized by slow cooling. When disposed properly, will hydrolyze to harmless, natural products. PLA has degradation time in the environment on the order of six months to two years which compares 500 to 1000 years for conventional plastics [6].

Four categories of biopolymers are recognized and they are:

- Extracted directly from natural raw materials.
- Produced from chemical synthesis from bio-derived monomers.
- Produced from micro-organism or genetically modified bacteria.
- Produced from crude oil.

Production of Lactic Acid:

The Swedish chemist Scheele first discovered it in the year 1780. Existence takes place in two different isomers the *dextrorotatory* form called L (+) or S lactic acid, vs. the *levorotatory* form called D (-) or R lactic acid. The sign of (+) and (-) indicates the direction of rotation of plane-polarized light by a chemical. These are produced by different enzymes (lactate dehydrogenases) present in living organisms.

In Microbial fermentation process the particular microbe and the specificity of its LDH(Lactate dehydrogenase), and the lactic acid fermentation process can produce rather pure D-LA or L-LA with high optical purity, or a mixture of them with low optical purity (many microbes can produce lactic acid. But a competitive commercial process requires a robust, fast-growing, low-pH, and high-yield

strain with low-cost nutrient requirements. During fermentation, alkalis such as lime (calcium hydroxide solution) must be added to neutralize the lactic acid produced by microbes. And this controls the pH of fermentation broth at an optimal level for the microbes [11]. After fermentation, lactic acid must be collected from the broth and purified to meet its final specifications. Depending on the raw materials, microbes, and media used, the recovering steps and conditions may need to be adjusted.

Typical downstream process includes:

- Removal of production microbes .
- Sulphuric treatment.
- Removal of gypsum to recover crude lactic acid .
- Purification of lactic acid by ion exchange chromatographic resins.

The important building block for PLA is Lactic acid. During PLA production the optical purity of lactic acid is used. Many factors like pH, less crystallinity and composition of co-polymers can influence the biodegradability of the product [12].

Physical Properties

Polymers may be either semi crystalline or amorphous. Semi crystalline polymers have regular repeating units. They allow the chains to fold into dense regions called crystallites. They act as cross linkers giving the polymer higher tensile strengths and higher modulus (stiffness) compared to an amorphous analog. No polymer can organize into fully crystalline material results amorphous areas in semi crystalline polymers. Characteristic temperatures of a polymer can be determined by DSC (differential scanning calorimetry) is used most when compared to several ways. There is a drastic reduction in flexibility of amorphous polymers when they are cooled below a characteristic transition temperature called the T_g. These temperatures for PLA are ranging from 190 to 250°C [13]. In the solid state, PLA can be any of the semi-crystalline or amorphous, depending on thermal history and stereochemistry.

For amorphous PLAs, the T_g defines the upper use temperature for most commercial applications.

PLA works as a glass with the ability to creep until cooled to its β-transition temperature of approximately -45°C. Below this temperature PLA will act as a brittle polymer [14].

Thermal Properties:

PLA is a semi-crystalline or amorphous polymer with a melting temperature (T_m) and a glass transition temperature (T_g) of approximately 55°C and 180°C, respectively. Due to different structural parameters, the thermal properties of PLA could be affected, such as molecular weights and composition and was described by Flory-Fox equation

$$T_g = T \sim - K/M$$

To the stereo-chemistry of PLA polymers, during the production of PLA sheets, stretch blow molding of bottles, and fiber spinning, the crystallization behavior could be affected by processing parameters. The effect of multi extrusion process the tensile properties, impact strength, melt flow index, and permeability of water vapor and oxygen of PLA was reported and the results showed that the tensile strength and impact strength of PLA reduced marginally after the multi-extrusion process, whereas the melt flow index and permeability of water vapor and oxygen were increased by the multi-extrusion cycles [15].

Mechanical Properties

The mechanical properties of lactic acid-based polymers can be varied. To a large extent ranging from soft and elastic plastics to stiff and high strength materials are varied. PLA has an tensile modulus of 3 GPa, tensile strength of 50-70 MPa, flexural modulus of 5 GPa, flexural strength of 100 MPa, and an elongation at break of about 4%. Superior mechanical properties have been achieved by stereo-complexation of enantiomeric PLAs, which was credited to the formation of stereo complex crystallites giving intermolecular cross links. The mechanical properties of PLA that are the intensively studied in association to a series of biopolymers include tensile properties. Dividing the original mechanical properties by the polymer density, specific tensile strength (σ*, in Nm/g) and specific tensile modulus (E*, in kNm/g) are obtained [14].

Barrier Properties

PLA was used in packaging applications

there has been a basic for a clear understanding of the barrier properties of PLA. The barrier properties of the polymer, is strongly affected by the crystallinity of PLA, where the decrease in crystallinity was a negative aspect in terms of the mechanical and barrier properties.

Many studies have reported betterment of the barrier properties of PLA. The effects of a synthetic phenolic antioxidant (SPA) structure on the mechanical, thermal, and barrier properties of PLA were reported [14, 15].

Generally, there are three methods/routes for high molecular weight PLA production. They are:

- Direct Polycondensation Polymerisation.
- Azeotropic condensation Polymerisation.
- Ring open Polymerization.

Direct Polycondensation Polymerization

Here, it is possible to polymerize lactic acid in the presence of a catalyst at reduced pressure. It is the least expensive route. However it is tough to obtain high molecular weights polymers of above 1, 00,000 Da. As it is hard to remove water completely from the highly viscous reaction mixture. The polymer obtained has a low molecular weight (1000-5000Da). Thus through this route the polymer produced holds inferior mechanical properties like young modulus, which is among the major requirements for packaging plastics.

Since a high molecular weight polymer can be obtained by making use of coupling agents or adjuvant e.g. bis (tri-chloromethyl) carbonate and carbonyl diimidazole is required. Low PLA quality and reaction by-products (water & alcohols) are produced. They must be either neutralized or detached completely from high viscous reaction mixture, adding cost and complexity therefore this route is not preferred [12].

Azeotropic Condensation Polymerization

In azeotropic condensation polymerization, lactic acid is converted directly to high molecular weight PLA through an organic solvent-based (toluene, xylene or diphenyl ether) process with the azeotropic removal of water by distillation.

It is possible to manipulate the equilibrium between polymer and its monomer to overcome the problem of water removal in an organic solvent. Therefore lactic acid is polycondensed directly into a polymer of high molar mass. This method yields high molecular weight polymers which can cause unwanted degradation, uncontrolled or irreproducible hydrolysis rates, catalyst toxicity and differing slow release properties but with considerable catalyst impurities.

High activity catalyst (such as boric or sulphuric acid) and low boiling organic solvent is used; and water as a by-product need to be removed azeotropically. Catalyst dried and recycled to the reaction system. Organic solvents which results in impurities, water removal and regenerating of catalyst increases process cost are used hence not feasible to this research [12].

Ring Open Polymerization

This is a form of chain-growth polymerization, where the terminal end of a polymer chain acts as a reactive centre in which further cyclic monomers can react. A longer polymer chain is formed by opening its ring system [17]. Here lactic acid is first polymerized to low molecular weight polymer. Following the stereoisomer form of lactic acid used lactide is always formed through internal trans-esterification to lactide, in the "back-biting" reaction. Different impurities like water, lactic acid and oligomers contained in the crude oligomers, which is catalytically depolymerised.

In the presence of catalyst lactide (3, 6 dimethyl 1, 4-dioxane 2, 5,-Dione) is a six member cyclic dimmer is prepared by thermal cracking of low molecular weight PLA oligomers at high temperature and low pressure. The ring of lactide then opens to form high molecular weight. PLA lactide can affect polymerization reaction leading to the development of a low molecular weight polymer with high degree of racemization [12].

Synthesis of Poly lactic acid

Using a poly-condensation reaction starting from lactic acid, poly lactic acid is synthesized. The major limitation of this poly-condensation reaction results in low molecular weight of polymers. During the

polymerization process water generated should be removed, and rapidly equilibrium occurs between polymerization and the depolymerization reaction. This polymerization requires long reaction times with high temperatures in combination. To overcome the limitation, and to produce cyclic lactide monomer, initially lactic acid is oligomerized and catalytically dimerized. The high molecular weight polylactide is made by ring opening polymerization (ROP) from lactide monomer.

Tin alkoxides and aluminum are commonly used catalysts for lactides polymerization [18]. A major difference between the tin and the aluminum is tin catalysts are good transesterification catalysts, whereas aluminum catalysts are not. They have the advantage of being more hydrolytically stable than those of

aluminum and can be easier to handle and use in polymerizations. The stereo chemical composition of the lactide monomer stream can determine the stereo chemical composition of the resulting polymer. The bonds to the chiral carbons are not broken in the polymerizations. PLA can be produced with varying fractions of L and D lactide. The unreacted monomer has to be removed by washing with ethanol after polymerization process [6].

Ring open polymerization compared with direct condensation polymerization has few manufacturing steps, low cost, and easy to manipulate. Lactide can be prepared by a decompression method. Here the water is separated from the system then some catalysts are added into reactor. Lactide is obtained after reacting for several hours [11].

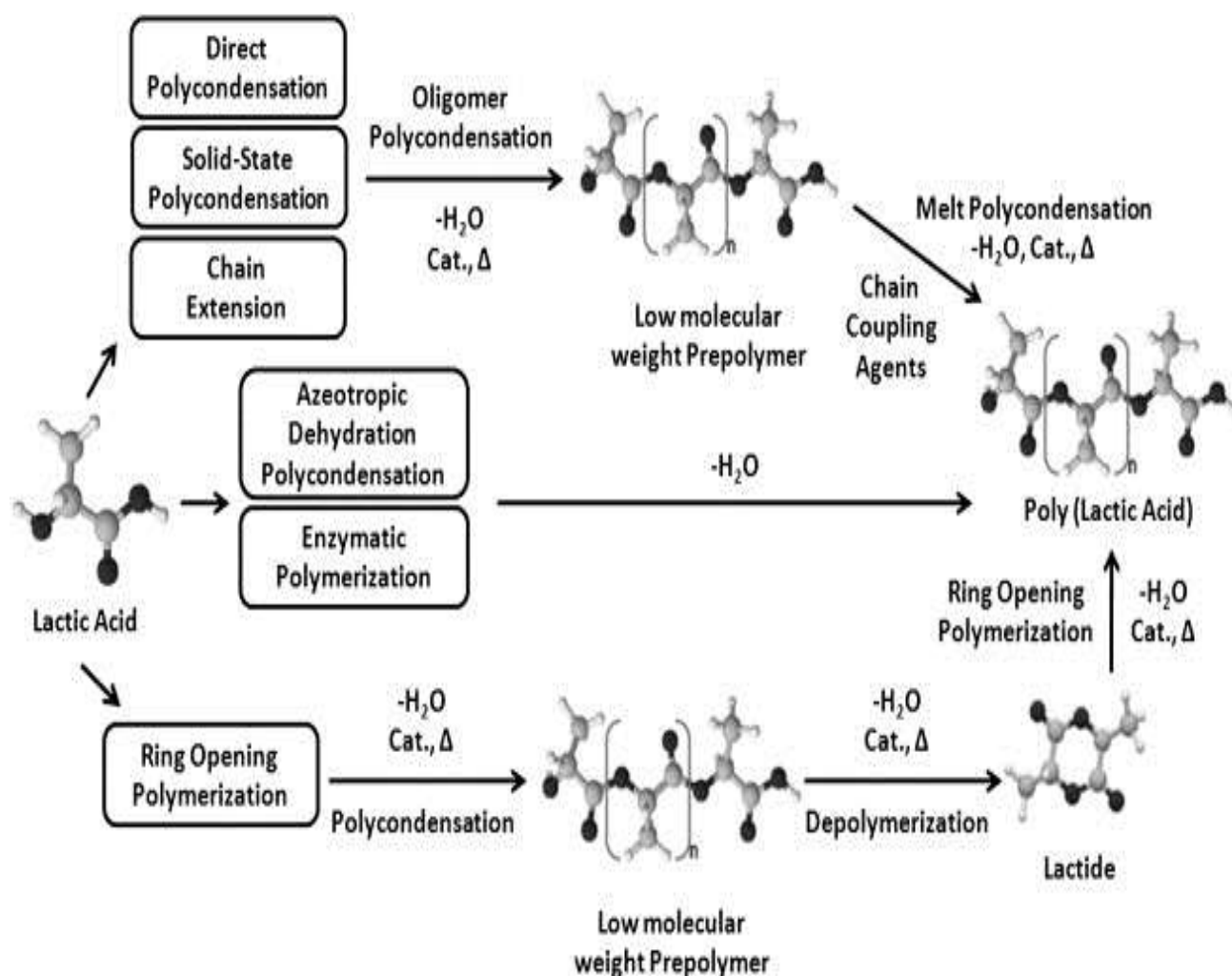


Figure 3: Polymerization of Lactic acid

Polyblends

Polymer blending is a cheap and convenient strategy for developing new polymeric materials, combining the benefits of various existing polymers. The properties of the resulting polymer blends also are tunable by

changing components and compositions of blend. Therefore, many flexible or elastic polymers are blended with PLA to reinforce its toughness. Some bio-based materials of natural rubber, bio-elastomers obtained from some plant oils and their derivatives,

polyamide 11 (PA11), and biodegradable materials, like poly (butylene adipate-co-terephthalate) (PBAT), poly (butylene succinate) (PBS), starch, and cellulose, are extensively used to modify PLA without losing its sustainability. PLA-based polymer

blends, especially those with a high toughness performance, are developed quickly, and memorable achievements are attained. A summarized approaches and toughening strategies for super tough PLA blends are discussed in Fig 4.

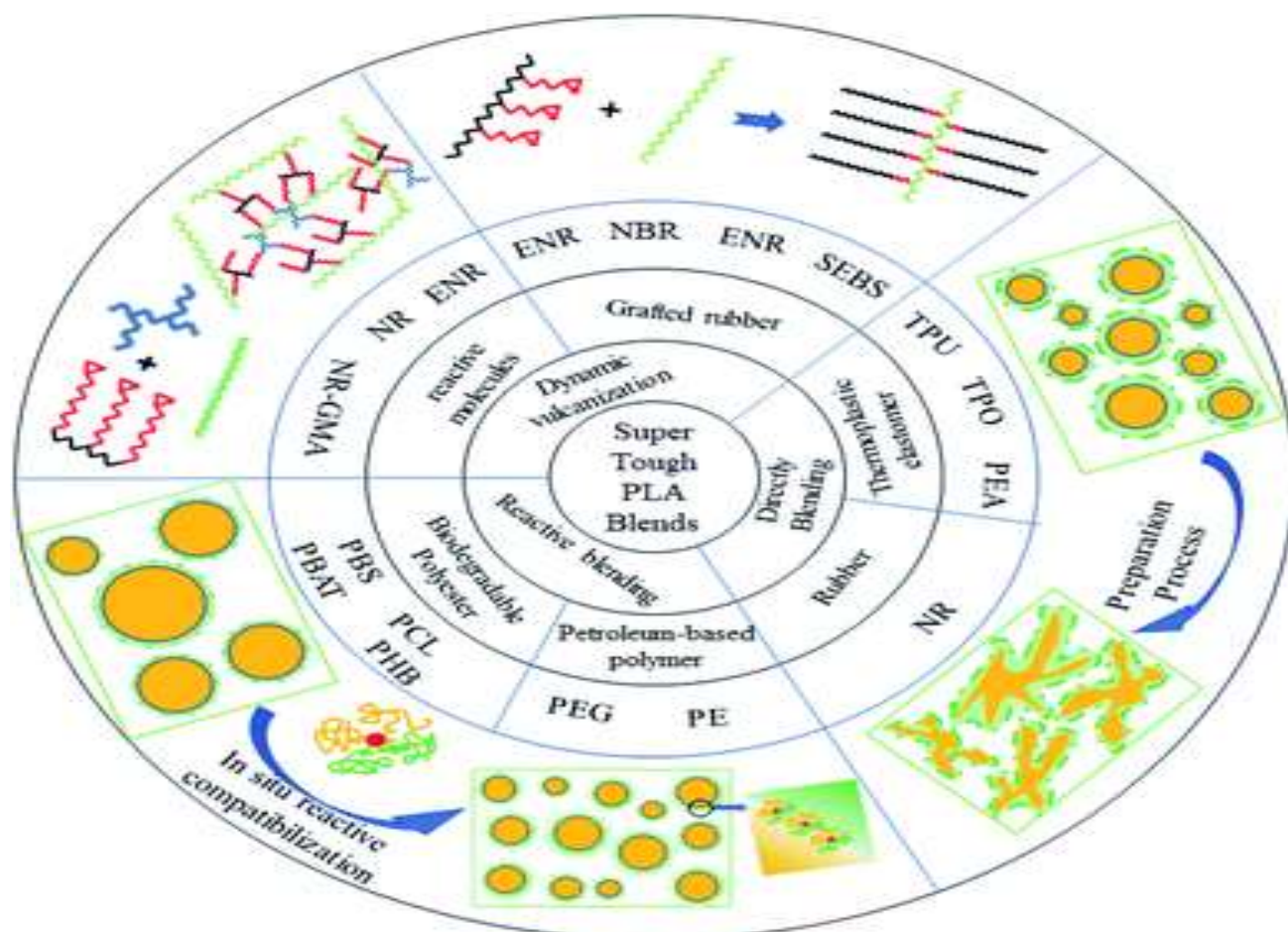


Figure 4: Approaches and toughening strategies for super tough PLA-based blends

Classes of poly blends

- Super tough PLA/ polyolefins blends.
- PLA/ Impact modifier blends.
- PLA/ polyols plastic blends.
- PLA/ engineering plastic blends.

Super tough PLA/ polyolefins blends:

Anderson and Hillmyer (2004) analyzed the influence of PE types with various values of modulus and toughness on the structure and mechanical properties of PLA/PE blends to realize super tough PLA/PE blends [19]. A series of PLA/PE with different modulus blends was prepared by melt blending with different PLA-polyolefin block copolymers (PLLA-PE) as compatibilizers. They recommended that each compatibilizers of

PLA-polyolefin block copolymers effectively improve the interfacial adhesion between PLA and PE. Additionally, the utilization of linear rarity polyethylene (LLDPE) with a modulus of 8 MPa and elongation at break of 960% is conducive to the preparation of super tough blends.

The PLA/LLDPE/PLLA-PE blends containing 80 wt% PLA, 20 wt% LLDPE, and 5 wt% PLLA-b-PE exhibit super toughness with impact strength and elongation of break reaching 760 Jm^{-1} and 31%, respectively, but the lastingness is greatly reduced to 24.3 MPa. The phase morphologies evolution of the blends was presented in and therefore the research works suggested that subtle differences within the degree of adhesion between the matrix and dispersed particles can have a big influence on the resultant toughening in these blends [2].

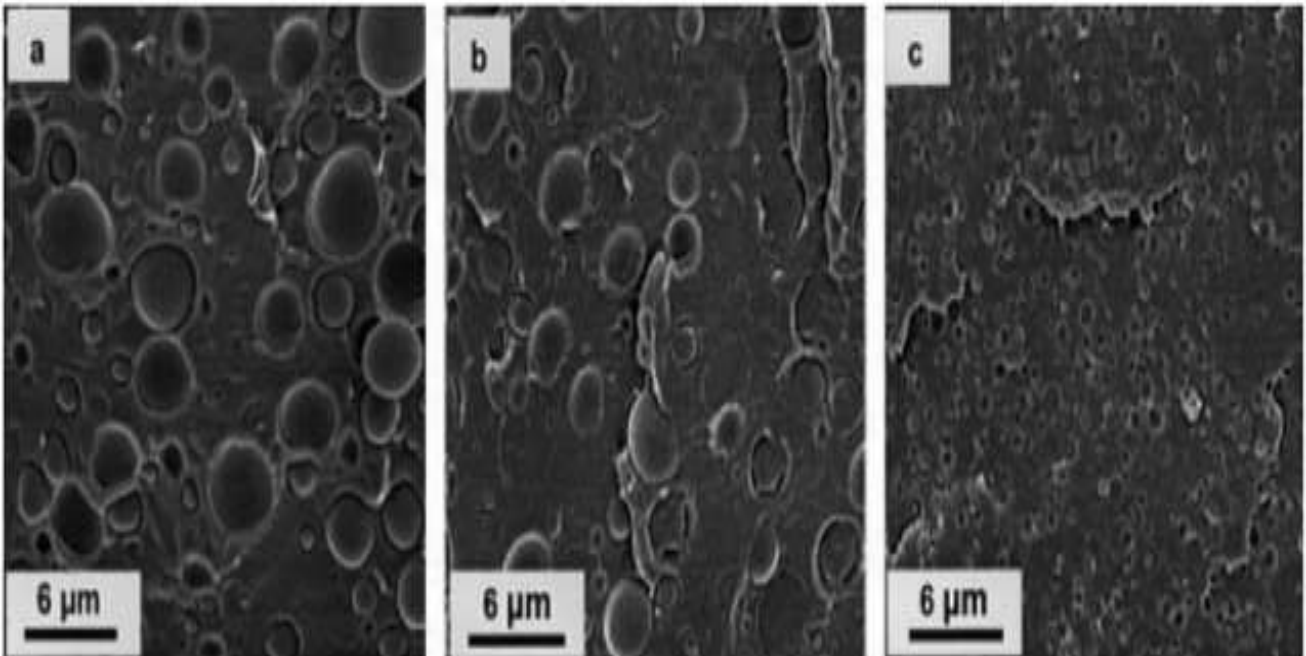


Figure 5: SEM images of cryo-fractured surfaces of (a) PLA/LLDPE (b) PLA/LLDPE/PLLA-PE (5-30) (c) PLA/LLDPE/PLLA-PE

PLA/ Impact Modifier Blends

Li *et al.*, (2015) prepared methyl methacrylate-ethyl acrylate core-shell copolymer (ACR) via seed emulsion polymerization and used it as an impression modifier for melt blending to toughen PLA [20]. The core-shell ratio has a crucial effect on the properties of PLA-based materials. The effect of its ratio of ACR with a core-shell weight ratio starting from 85.5/14.5 to 71.9/28.1 on toughening PLA has been investigated. The particle size and particle size distribution of ACR are often controlled via seed emulsion polymerization.

The agglomeration of ACR particles are often overcome through a synthesis process. When the ACR core-shell ratio is 79.2/20.8, the PLA/ACR (80/20) blend has partial compatibility, and therefore the impact strength and elongation at break reach 77.1 kJ m⁻² and 93.9%, respectively. However, the lastingness is comparatively low, which is merely 31.8 Ma results suggest that the PLA/ACR (80/20) blend has partial compatibility, and ACR is dispersed uniformly within the PLA matrix. Plastic deformation and cavitations are the main mechanisms of toughening blends.

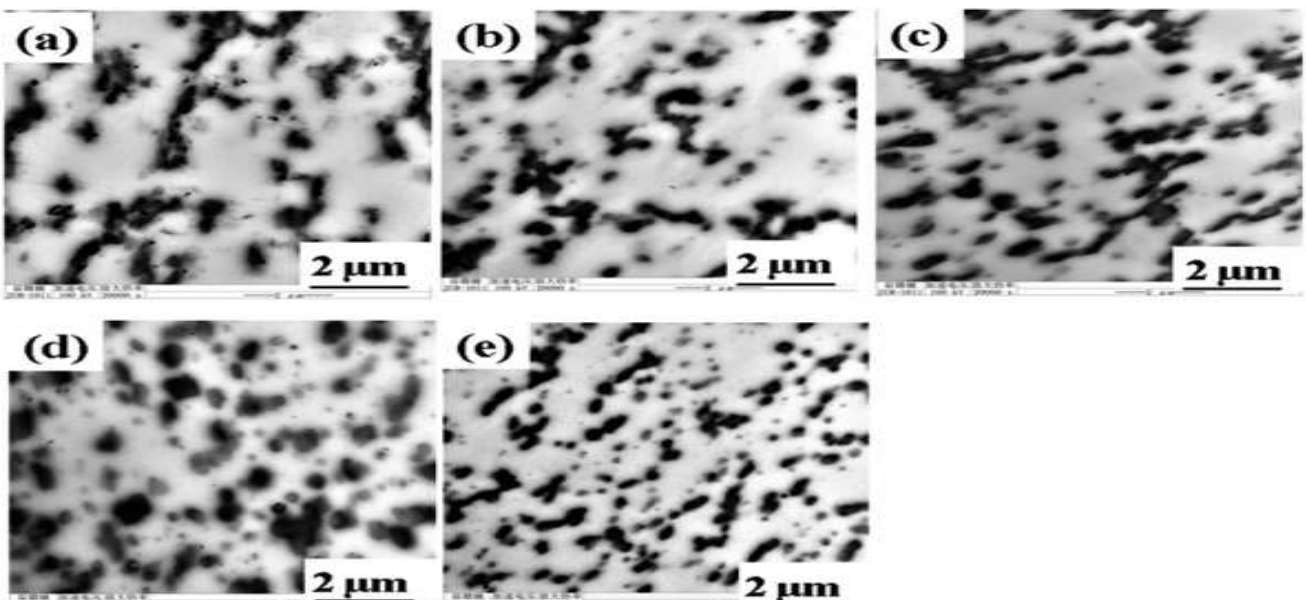


Figure 6: TEM photographs for PLA/ACR blends: (a) PLA/ACR1 (b) PLA/ACR2 (c) PLA/ACR3 (d) PLA/ACR4, and (e) PLA/ACR5

PLA/ Polyols Plastic Blends

Super tough biodegradable PLA blends were prepared by Wang *et al.*, (2017) via the reactive blending of PLA with a poly (ethylene glycol) diacrylate (PEGDA) monomer [21]. During blending, the acrylic group of PEGDA is often polymerized via a radical reaction, and cross-linked PEGDA (CPEGDA) is in place formed. The place in polymerization of PEGDA results in a phase-separated morphology with CPEGDA as the dispersed particle phase dominates.

Because the amount of CPEGDA increases, the viscosity and elasticity of the blend increase. Moreover, the impact strength and elongation at break of PLA/CPEGDA blends reach 50 kJ m⁻² and 140%, respectively, whereas lastingness decreases to 49 MPa. Improvement in toughness is often attributed to the fine dispersion state of CPEGDA particles within the PLA matrix with a mass-average particle diameter of 0.35 μm and a size polydispersity of 1.5. The toughening mechanisms of PLA/CPEGDA blends are often ascribed to the joint contributions of crazing and shear yielding during

deformation supported the analysis of stress-whitening and fracture surface and therefore the measurement of matrix ligament thickness. Two unsaturated functional reactive PWG plasticizers of MAPEG and AcrylPEG are often successfully homooligomerized and grafted onto PLA chains via a reactive extrusion process. Figure 7 shows the chemical reactions routes during the reactive extrusion of the ternary reactive blends. The results reveal that the grafting efficiency of AcrylPEG is far above that of MAPEG.

The functional end-group of the plasticizer significantly affects the grafting efficiency mainly due to the difference within the reactivity between methacrylic and acrylic functional groups. The elongation at break and impact strength of blends significantly increase compared thereupon of pure PLA. For PLA/AcrylPEG binary blends, the inclusion of 20 wt% AcrylPEG into PLA improved the elongation at break and impact strength of pure PLA from 4% and a couple of 8 kJ m⁻² to 230% and 86.0 kJ m⁻², respectively.

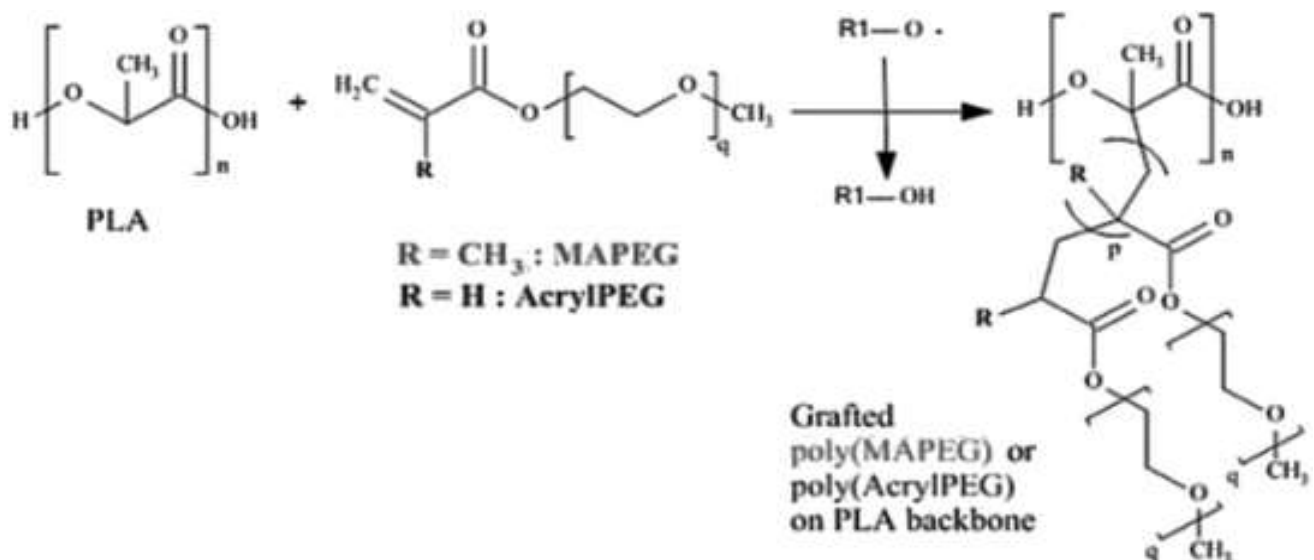


Figure 7: The chemical reactions routes during the reactive extrusion of the ternary reactive blends

PLA/ Engineering Plastic Blend

To simultaneously improve the toughness and warmth resistance of PLA, polycarbonate (PC) incorporated into PLA to organize high-PLA-content (≥66 wt %) PLA/PC blends via in place reactive compatibilization [22]. They enhanced interfacial compatibility of PLA/PC blends by using an industrial copolymer of styrene and glycidyl methacrylate (coded as ADR) as a reactive compatibilizer and

utilized a core-shell impact modifier (BPM) to further improve the impact strength of PLA/PC blends. In their experiment, PLA/PC blends are annealed during a vacuum oven at 120°C for six h to market PLA phase crystallinity and improve the warmth distortion temperature (HDT) TEM images show that the sea-island structure of the PLA/PC/ADR/BPM blends transforms into a lamella-like morphology due to the improved interfacial bonding between PLA and PC. For the annealed PLA/PC/ADR/BPM blends, the

impact strength reach approximately 60 kJ m^{-2} , and therefore the HDT of pure PLA increases from 61°C to 136°C under the many improvement of impact strength for the annealed PLA/PC blends is attributed to the coexistence of shear-yielding and crazing. PC, as a polymer with high T_g and HDT, is taken into account a rigid unit. Hence, a rigid three-dimensional network structure or framework, which may play a superb role in

distortion resistance, are often simultaneously formed in these blends after annealing due to the presence of PC particles and PLA crystals. A model like the network formed in PLA/PC/ADR0.3/BPM5 blends is proposed a) ideal model of the change of PLA structure after annealing. (b) Ideal three-dimensional model for the inner structure of the annealed PLA/PC/ADR0.

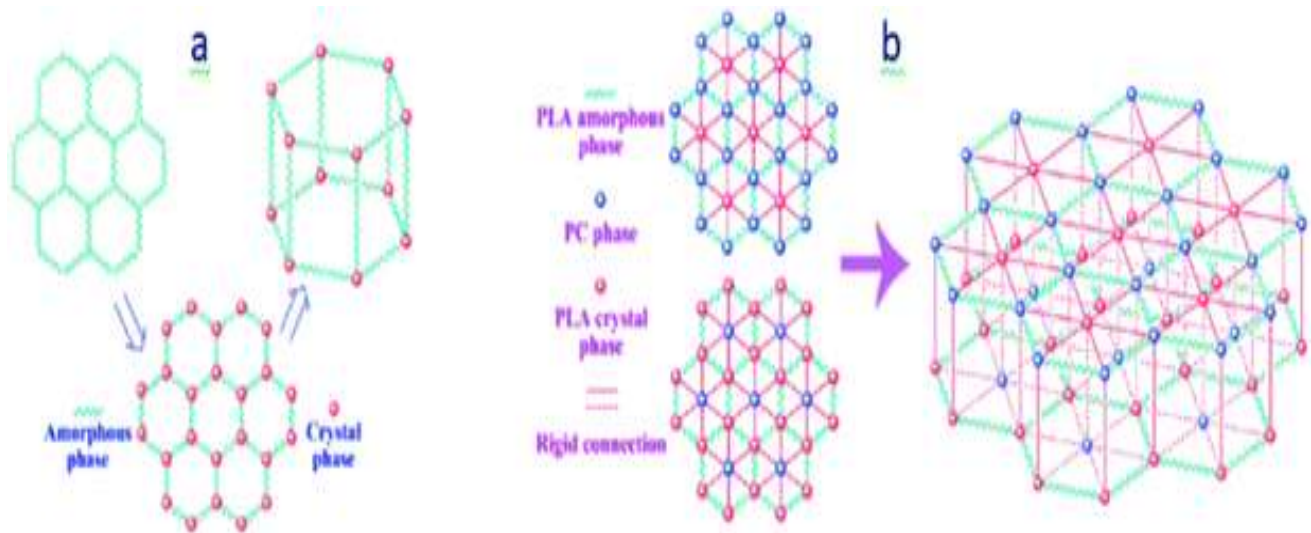


Figure 8: (a) Representative ideal model of the change of PLA structure after annealing. (b) Representative ideal three-dimensional model for the inner structure of the annealed PLA/PC/ADR0.3/BPM5 blend

Biomedical Applications

Poly lactide (PLA) and its copolymers are the aliphatic polyesters having different properties such as good bio-compatibility, biodegradability by enzyme and hydrolysis under physiological conditions, low immunogenicity, etc. They are therapeutically safe. Due to such features they have gained attention and great interest as innovative materials for a wide range of applications in biomedical and pharmaceutical applications, e.g. drug delivery systems, sutures, implants for bone fixation, and widely used in orthopedic medicine, soft tissue repair, synthetic grafts, etc. The first report on PLA as bio-absorbable surgical devices was by Kulkarni [24].

The applications of PLA and its polymeric composites in medical fields such as:

(I) Orthopedics

The investigation of bio-absorbable implants for fixation in orthopedics is rapidly growing. Prime important materials for orthopedic applications are PLA and its co-polymers

with glycolic acid and other hydroxy acids. Since 1965, the use of absorbable materials instead of traditional metallic devices has been prominent. In 1973 first PLA suture used for fracture fixation plates and screws was patented. Bio-absorbable fixation devices are extensively applicable in orthopedic. Such devices are mainly composed of PLA and/or PGA polymers and ultra-high-strength implants. Commonly used for the stabilization of fractures, bone grafting, reattachment of ligaments, tendons, etc. These polymers reduce risks during pre-implant osteoporosis and risks arising due to infections. The intrinsic nature of PLA/PGA copolymers renders promising use for slow release of bioactive agents within the field of orthopedics.

These materials eradicate osteopenia occurring due to stress shielding or additional surgery, but they also suffer from the disadvantage of reduction in cell proliferation. Not only to minimize the problem of osteochondral repair particularly in soft tissues, but also to enhance fixation and repair processes in tendons and ligaments are used PLA

matrix reinforced with phosphate based glass fibers have been employed as bone regenerative implants. After 6 weeks *in vivo* implantation the material becomes more mature [25].

(II) Facial Fracture Repair

Cranio-maxillofacial (CMF) surgery is considered as a part of fracture fixation that involves synthesis and investigating applications of bioabsorbable material which involves safe clinical applications and bio-chemical property studies of bioabsorbable polymeric materials. The application of bioabsorbable materials in cranio-maxillofacial surgery has led to a new era in fracture fixation. Such materials are similar to metal devices, safe in clinical applications, and easy to handle and have proven to be safe in clinical applications.

Now, many polymeric materials like PLA, PGA, and poly dioxanone, are being used in orthognathic surgery, followed by treatment of fractures of the upper facial skeleton. Polymers and copolymers of lactide and glycolide are used as fixation materials in cranio-maxillofacial surgery, as these materials are biocompatible and gradually lose strength. Osteotomies may be effectively fixed with bioabsorbable materials. Self-reinforced (SR) technology based on reinforcing the elements helps in manufacturing these implants of ultra-high strength [9].

(III) Tissue Engineering

Tissue engineering is the medical technology that includes the use of cell combination, engineering and materials methods. Suitable biochemical and physio-chemical factors are also involved to improve or replace biological functions. It arranges for an alternative to the treatment of malfunctioning or lost organs. Patients are treated with their own cells that are grown on a polymer support so that a tissue part is renewed from the natural cells.

PLA composite was synthesized and studied to improve its osteoinductive property. Intestinal crypt cells transplanted as epithelial organoid units on PGA-PLA tubular scaffolds and can survive, alter and renew complex composite tissue. These cells exhibit organ morphogenesis, cyto

differentiation and phenotypic maturation shows resemblance to small intestines. Poly-L-lactic acid can be applied in the successful organization of soft-tissue augmentation. Many non-toxic porous phosphate glass particles incorporated into PLA (95L/5DL) and its composites have been used in bone-tissue engineering. The introduction of glass particles into such polymer affords good mechanical properties and biological response [20].

(IV) Urethral Stent

Ureteral injury is a severe clinical problem. For the discovery of biodegradable ureteral stent is an active and ongoing research. Biodegradable PLA and its composites find wide use as ureteral stents for the treatment of ureteral injury. A biodegradable SR-PLA 96 stent possessing active expansion capacity can be used for stenting after ureteral repair. For ureteral stenting in kidney functioning studies have been focused on screening the usage of poly-L, D-lactide copolymer (SR-PLA 96; L/D ratio 96/4) device [7].

Conclusion

PLA is a leading candidate for consumer and biomedical applications, and the ability to tailor it's mechanical, physical, micro-structural, chemical, and degradation properties for specific applications makes the market capacity of PLA products unlimited and that has catalyzed and extensive and growing amount of research aimed at utilizing these materials in innovative ways and applications. The intention of this work is to give an overview on state of the art of the research activities on PLA's physical and mechanical properties, detailing a wide range of options for properties improvement such as chemical composition manipulation (D/L ratio), processing, additives and plasticizers, and polymeric component blending, production, synthesis and biomedical applications.

This review covered an overall view of PLA. Our vision for PLA's future comes in agreement with the logical belief that there is no one material able to satisfy all design parameters in all applications. So, it can be anticipated that future developments will keep including blends of PLA, copolymers, and impact-modified products, which will

also further expand the applications where this unique polymer can be used.

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