

Literature Review: Ring Opening Polymerization of Polylactide

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Abstract: Poly(lactic acid), PLA is a bio-degradable, thermoplastic polymer. It is highly versatile aliphatic polyesters commonly made from α -hydroxy acid. Literature review of PLA consists of brief introduction of lactide, polylactide, synthesis, and its various properties. Different routes for the synthesis of PLA, polymerization mechanisms are discussed. Ring opening polymerization is the most commonly used method for the synthesis of PLA. PLA Composites and nanoparticles have also been discussed briefly.

IndexTerms - Poly (lactic acid), synthesis, ring opening polymerization, polymerization mechanism

I. INTRODUCTION

Polymers form the backbone of plastic materials and are continually being employed in an expanding range of areas. Polymeric materials are solid and non-metallic compounds of high molecular weights. Plastics are polymeric materials, a material built up from long repeating chains of molecules. During the Second World War, plastics such as nylon and polyethylene were used as a replacement for other materials because the early plastics were not completely chemically stable. However, advances in plastic technology since then, have shown that plastics are a very important and reliable class of materials for product design. Biodegradable polymeric materials are of great interest because these are used in packaging, agriculture, medicine and other areas. Bioplastics are an increasingly well known alternative to petroleum based plastics. They are derived from biological sources instead of petroleum based feed stock. A number of biological materials may be incorporated into biodegradable polymeric materials, with the most common being starch and fiber extracted from various types of plants.

The decade of the 1950s saw the introduction of polypropylene and polycarbonate that, along with nylon, came to form the nucleus of a sub-group in the plastics family known as the "engineering thermoplastics." Their outstanding impact strength and dimensional stability enabled them to compete directly and favorably with metals in many applications. During, 1960s and 1970s several new plastics were introduced, most notable were thermoplastic polyesters with outstanding resistance to gas permeation that made them applicable for use in packaging. During this period, another sub-group of the plastics family called "high temperature plastics," also started to emerge which includes the polyimide, polyamide-imides, aromatic polyesters, polyphenylene sulfide and polyether sulfone. These materials were designed to meet the demanding thermal needs of aerospace and aircraft applications.

The durability of plastics, under both aerobic and anaerobic conditions, contributes to growing waste and waste disposal problems. Even improving recycling rates for many types of plastics have not kept up with increase in overall plastics consumption and in some cases recycling yields new problems associated with concentration of contaminants through the recycling process (Vink *et al.*, 2003).

Poly(lactic acid), PLA is quite an old polymeric material, discovered in the 1890s, but it has only now found a universal route to market in the form of bio-degradable packaging. In 1932, Wallace Carothers, a Dupont scientist, produced a low molecular weight product by heating lactic acid under vacuum. Due to high costs, the focus since then has been mainly on the manufacture of medical grade sutures, implants and films for controlled drug release applications. Until the 1960s, researchers struggled to get high molecular weight polylactide and later found methods to produce high molecular weight polymer which was still relatively expensive to make.

As of Jun 2010, NatureWorks was the primary producer of PLA (bioplastic) in the United States. Other companies involved in PLA manufacturing are PURAC Biomaterials (Netherlands) and several Chinese manufacturers. Galactic and Petrochemicals operate a joint-venture, Futerra, that is developing a

second generation of polylactic acid product. This project includes the building of a PLA pilot plant of 1500 tons/year in Belgium. In 2008, 5000 tons per year of lactides and PLA were produced. Since 2009, Purac has developed a unique business model by starting production of lactides (D and L), the monomers for PLA production, in their Spanish production plant with a capacity of several thousands of tons. First commercial plant at Synbra (NL) for the production of Biofoam (EPLA) was installed in 2010, while in the year of 2011, 75,000 tons per year lactide monomers plant at their production site in Thailand (Rayong Province). Purac has developed the technology to polymerize these lactides with Sulzer, a Swiss engineering company. Purac collaborates with various PLA production partners to develop production scale and new markets for PLA. Due to the availability of D- lactide, Purac partners will be able to use stereo-complex technologies to produce new PLA grades with heat-stability up-to 180 °C, enabling use in higher value application areas. In a tripartite collaboration between Purac, Sulzer and Synbra solutions were developed to allow Synbra to start production of PLA and subsequently E-PLA, an attractive biodegradable and/or bio-based alternative to EPS-foam in a variety of application areas (http://en.wikipedia.org/wiki/Polylactic_acid).

The cost of production of the monomer (lactic acid) has been a deterrent to widespread development of the polymer. Recently, there have been advances in fermentation of glucose, which turns the glucose into lactic acid. This has dramatically lowered the cost of producing lactic acid and significantly increased the interest in the polymer. Cargill, Inc. was one of the first companies to develop polylactic acid polymers. Cargill began researching PLA production technology in 1987, and began production in pilot plants in 1992. In 1997, after a 15 month joint investigation, Cargill formed a joint venture with Dow Chemical Company, Inc., creating Cargill Dow Polymers LLC (CDP). The joint venture was dedicated to further commercializing PLA polymers (Harper, 2000) and they formally launched Nature Works TM PLA technology in 2001. Construction was recently completed on a large-scale PLA manufacturing facility in Blair, Nebraska. The Nebraska facility will be capable of producing up to 300 million pounds (140,000 metric tons) of PLA per year, using 40,000 bushels of corn per day (<http://cargilldow.com/release.asp?id=92>).

Total capacity of lactide in China already comes to over 200,000 t/a. Meanwhile, there are four major polylactide, PLA manufacturers in China as of May 2011, all of them are expanding capacity to 10,000 t/a. It can be predicted that China will become a large production base of lactic acid and PLA worldwide in the future (http://pdf.marketpublishers.com/785/benchmarking_of_lactic_acid_and_polylactic_acid_in_china.pdf).

The economic benefits include an estimated \$2 billion/yr of net income that will accrue to the PLA manufacturing value chain in 2020. About \$367 million/yr of new revenues will go to the agriculture community for harvesting, collection, and transportation of the feedstock. Energy benefits are estimated to save 202 trillion kJ/yr equivalent of fossil derived fuels in 2020 by the displacement of 8 billion/yr of fossil fuel-based polymers with PLA (http://www.oit.doe.gov/cfm/full_article.cfm?id=305).

II. Lactic Acid (Monomer)

Lactic acid was first isolated in 1780 by Swedish chemist, Carl Wilhelm Scheele, who isolated the lactic acid from sour milk as impure brown syrup and gave it a name based on its origins: 'Mjölksyra'. The French scientist Frémy produced lactic acid by fermentation and this gave rise to industrial production in 1881(<http://www.lactic-acid.com/history.html>).

Lactic acid is a chemical compound which plays very important role in several biochemical processes. It has a hydroxyl group adjacent to the carboxyl group, it can lose a proton from the acidic group, producing the lactate ion $\text{CH}_3\text{CH}(\text{OH})\text{COO}^-$. It is miscible with water or ethanol, and is hygroscopic. Lactide is a six member ring, it has significant enough ring strain (22.9 kJ mol^{-1}) that ring opening is favored over reversal of the addition of the alkoxide to the carbonyl (Duda and Penczek, 1990). In 2006, global production of lactic acid reached 275,000 tons with an average annual growth of 10% (<http://www.nnfcc.co.uk/publications/nnfcc-renewable-chemicals-factsheet-lactic-acid>). The lactic acid dimerises to give lactide, which upon ring-opening polymerization yield Poly(lactic acid), PLA.

III. Poly(lactic acid), PLA

Poly(lactic acid), PLA is a bio-degradable, thermoplastic polymer and can be made from renewable resources such as sugarcane and corn. It is highly versatile aliphatic polyesters commonly made from α -hydroxy acid. It is one of the most promising biodegradable polymers (biopolymers) and has been the subject of abundant study over the last two decades. It is relatively cheap and has some remarkable properties, which make it suitable for different applications. High molecular weight polylactide is a colorless, glossy, stiff thermoplastic polymer with properties similar to polystyrene. The physical and mechanical properties of PLA make it a good material as replacement for petrochemical thermoplastics in several application areas. While the high price of PLA long restricted its use to medical applications, recent breakthroughs in lactide polymerization technology opened up possibilities for the production of PLA in bulk for other applications.

The physical characteristics of high molecular weight PLA are to a great extent dependent on its transition temperatures for common qualities such as density, heat capacity, and mechanical and rheological properties. In the solid state, PLA can be either amorphous or semi-crystalline, depending on the stereochemistry and thermal history. The amorphous PLA is soluble in most organic solvents such as tetrahydrofuran (THF), chlorinated solvents, benzene, acetonitrile and dioxane. For amorphous PLAs, the glass transition (T_g) determines the upper use temperature for most commercial applications. For semi-crystalline PLAs, both the T_g (~ 58 °C) and melting point (T_m), 130 - 230 °C (depending on structure) are important for determining the use temperatures across various applications. Above T_g , amorphous PLAs changes from glassy to rubbery and behaves as a viscous fluid upon further heating. Below T_g , PLA behaves as a glass with the ability to creep until cooled to its β -transition temperature of approximately 45 °C. Below this temperature, PLA will only behave as a brittle polymer.

PLA has numerous advantages over other polymers such as: (1) it is produced from renewable resources, (2) permits considerable energy savings, (3) can be recycled back to lactic acid which is a non-toxic and naturally occurring metabolite through hydrolysis or alcoholysis, (4) helps in capturing carbon dioxide, (5) compostable, (6) improvement of farm economics, (7) decline of landfill volumes (Auras *et al.* 2004 and Dorgan *et al.* 2001).

Applications of PLA (<http://cipetians-zone.blogspot.com/2010/09/bio-degradable-plastics-introduction.html>)

- 1) Stereo complex blends of PDLA and PLLA have a wide range of applications, such as woven shirts (iron ability), microwavable trays, hot fill applications and even engineering plastics (in this case, the stereo complex is blended with a rubber like polymer such as ABS). Such blends also have good form-stability and visual transparency, making them useful for low-end packaging applications. Progress in biotechnology has resulted in the development of commercial production of the D enantiomer form that was not possible until recently.
- 2) PLA is currently used in a number of biomedical applications, such as sutures, stents, dialysis media and drug delivery devices. It is also being evaluated as a material for tissue engineering. Because it is biodegradable, it can also be employed in the preparation of bioplastic, useful for producing loose fill packaging, compost bags, food packaging, and disposable tableware. In the form of fibers and non-woven textiles, PLA also has many potential uses, for example as upholstery, disposable garments, feminine hygiene products, and nappies.
- 3) PLA has been used as the hydrophobic block of amphiphilic synthetic block copolymers used to form the vesicle membrane of polymersomes.
- 4) PLA is a sustainable alternative to petrochemical derived products, since the lactide from which it is ultimately produced can be derived from the fermentation of agricultural by-products such as corn starch or other carbohydrate-rich substances like maize, sugar or wheat.
- 5) PLA has also been developed in the United Kingdom to serve as sandwich packaging.
- 6) PLA has also been used in France to serve as the binder in Isonat Natisol, an hemp fiber building insulation.
- 7) PLA is used for biodegradable and compostable disposable cups for cold beverages, the lining in cups for hot beverages, containers for food packaging.

In spite of its good properties, the applications are limited due to its low flexibility and impact strength. Hence it shows some disadvantages too:

- 1) PLA has high cost in comparison to other polymers because of lower scales of production. PLA is more expensive than the majority of commodity polymers.
- 2) The plastic softens at a temperature of about 60 °C, which limits its suitability for the production of cups for hot drinks.
- 3) PLA has moisture sorption properties.
- 4) The primary petroleum based polymers which are derived from alkenes or aromatic monomers are non-polar while PLA is fairly polar, thus increasing degradability but also reducing its water resistance property. When the polymer is used in packaging it can have negative impact on the product inside. Also, when the polymer is used to make a water bottle, water seeps out of the bottle thus decreasing the amount of water inside.

The life cycle of Poly(lactic acid), PLA is shown in Fig. 1 starting with fermentation of starch to give lactic acid, the dimer form lactide is obtained, which is polymerized to give high molecular weight PLA. The PLA on hydrolysis degrades to lactic acid which is further broken to give CO₂ and H₂O.

Among all biodegradable polyesters, PLA is the product that has one of the highest potential due to its availability on the market and its low price (Lunt, 1998, Sinclair, 1996 and Vert *et al.*, 1995). Some commercial biopolyesters like Poly(lactic acid), PLA, Poly (3-hydroxybutyrate-co-3-hydroxyvalerate), PHBV, Polycaprolactone, PCL, Poly (ester amide), PEA, Poly (butylene succinate-co-adipate), PBSA and Poly (butylene adipate-co-terephthalate), PBAT show their different properties like density, glass transition, melting point, crystallinity, modulus etc. in Table 1

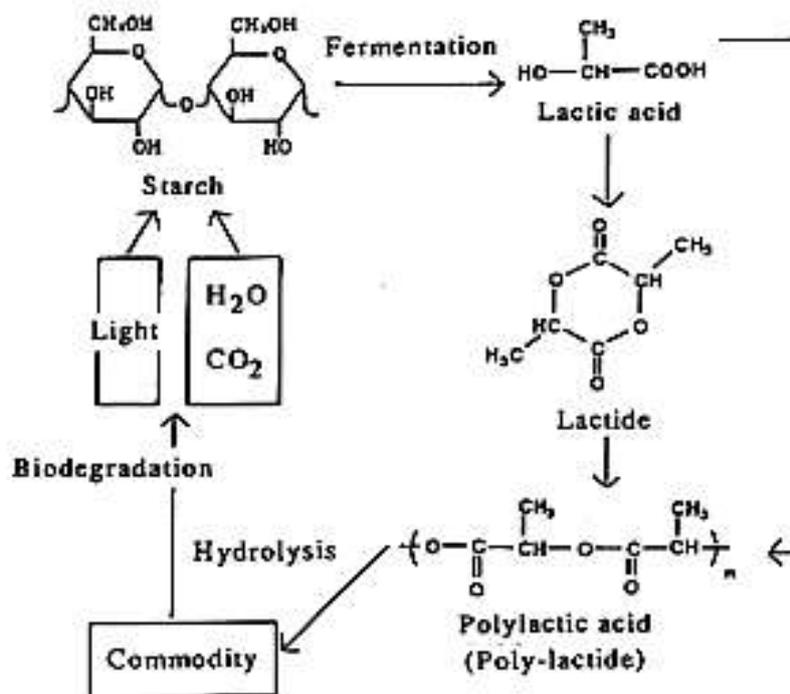


Figure 1 Life cycle of poly(lactic acid)

Table 1 Main Commercial Biopolyesters (<http://www.biodeg.net/bioplastic.html>)

Parameters	Poly(lactic acid), PLA	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate), PHBV	Polycaprolactone, PCL	Poly (ester amide), PEA	Poly (butylene succinate-co-adipate), PBSA	Poly (butylene adipate-co-terephthalate), PBAT
	Dow-Cargill (Nature Works)	Monsanto (Biopol D400G) HV=7 mol%	Solway (CAPA 680)	Bayer (BAK 1095)	Showa (Bionolle 3000)	Eastman (easter bio 14766)
Density	1.25	1.25	1.11	1.07	1.23	1.21
Melting point, in °C (DSC)	152	153	65	112	114	110-115
Glass transition, in °C (DSC)	58	5	-61	-29	-45	-30
Crystallinity (in %)	0-1	51	67	33	41	20-35
Modulus, in MPa (NFT 51-035)	2050	900	190	262	249	52
Elongation at break, in % (NFT 51-035)	9	15	>500	420	>500	>500
Tensile stress at break or max., in MPa (NFT 51-035)	-	-	14	17	19	9
Biodegradation* Mineralization in %	100	100	100	100	90	100
Water permeability WVTR at 25 °C (g/m ² /day)	172	21	177	680	330	550
Surface tension** (g) in mN/m.	50	-	51	59	56	53
gd (Dispersive component)	37	-	41	37	43	43
gp (Polar component)	13	-	11	22	14	11

(*) At 60 days in controlled composting according to ASTM 5336

(**) Determinations from contact angles measurements of probes liquids

IV. Synthesis of PLA from Lactic Acid

There are two major routes to produce PLA from the lactic acid monomer (Fig. 2). The first route involves removal of water by the use of solvent under high vacuum and high temperature (condensation polymerization) to yield low molecular weight of polylactide. In the other route, water is removed under

mild conditions to give an intermediate dimer, the lactide, which on ring-opening polymerization gives high molecular weight PLA (<http://www.nonwoven.co.uk/reports/Prague%202000.html>). In order to get high molecular weight of polylactide, ring-opening polymerization method was used.

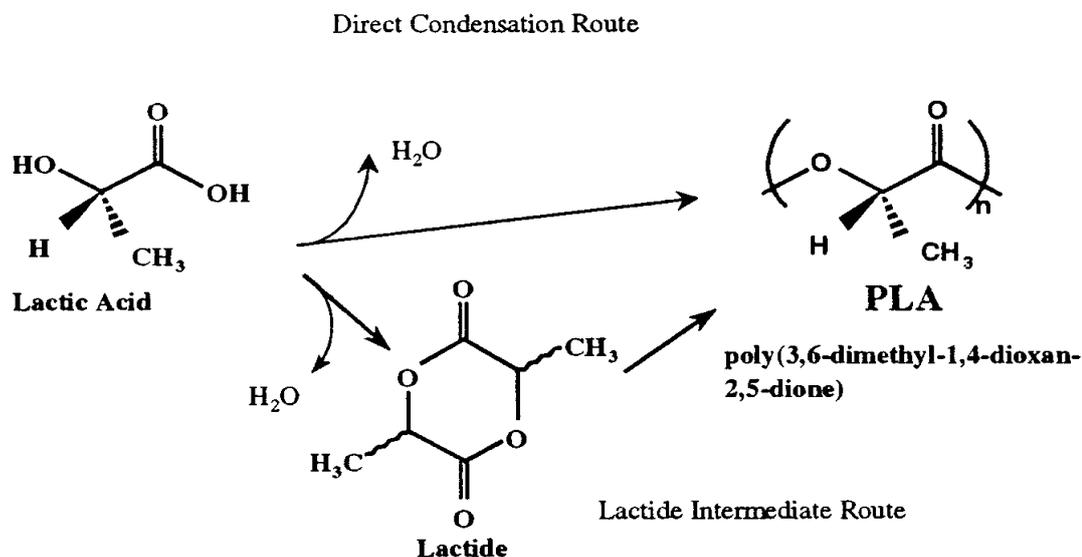


Figure 2 Synthesis of PLA by two routes
(Source: <http://www.nonwoven.co.uk/reports/Prague%202000.html>)

4.1 Synthesis of PLA by Condensation Polymerization

Polycondensation leads to the formation of a polymer by the linking of molecules of a monomer with the release of water, or a similar simple substance. The major disadvantage of this synthesis is that it does not produce high molecular weight PLA due to complication in removing impurity and water. Other drawbacks of these techniques are the need for large reactor, evaporation, solvent recovery and increased racemization (Fisher *et al.*, 1973). The synthesis of PLA through polycondensation of the lactic acid monomer leads to weight average molecular weights lower than 1.6×10^4 , whereas ring-opening polymerization of lactide results in average molecular weights ranging from 2×10^4 to 6.8×10^5 (Hyon *et al.*, 1997). Direct synthesis of poly (L-lactic acid) (PLLA) from an L- lactic acid oligomer has been performed in supercritical carbon dioxide (scCO₂) using an esterification promoting agent, dicyclohexyldimethylcarbodiimide (DCC), and 4-dimethylaminopyridine (DMAP) as a catalyst. PLLA with M_n of 13,500 g/mol was synthesized in 90% yield at 3500 psi and 80 °C after 24 h. The molecular weight distribution of the products was narrower than PLLA prepared with melt–solid phase polymerization under conventional conditions (Yoda *et al.*, 2004).

Lactic acid polymers consist mainly of lactyl units, of only one stereoisomer or combinations of D and L lactyl units in various ratios. There have been studies to obtain a high molar mass polymer by manipulating the equilibrium between lactic acid, water and polylactic acid in an organic solvent (Ajioka *et al.*, 1995) or a multifunctional branching agent was used to give star-shaped polymers (Kim and Kim, 1999). In the presence of bifunctional agents (dipoles and di acids) they form telechelic polymers, which can be further linked to give high molar mass polymers using linking agents like diisocyanate (Hiltunen *et al.*, 1997). In order to reduce the production cost of PLA, L- lactic acid was polymerized by direct polycondensation (DP) under vacuum without initiators, solvents and initiators. Experiments were conducted at polymerization temperatures (T_p) of 150–250 °C. The maximum PLA molecular weight obtained was 90 kDa at 200 °C after 89 h under vacuum. Above 200 °C, PLA is thermally degraded by specific scission (Achmad *et al.*, 2009).

Poly (ester urethane) (PEU) consisting of poly (L- lactic acid) and poly (ethylene succinate) was successfully prepared via chain-extension reaction of poly (L- lactic acid) - diol (PLLA-OH) and poly (ethylene succinate) - diol (PES-OH) using 1,6-hexamethylene diisocyanate (HDI) as a chain extender.

PLLA-OH was obtained by direct polycondensation of L- lactic acid in the presence of 1, 4-butanediol. PESOH was synthesized by condensation polymerization of succinic acid with excessive ethylene glycol. The data of GPC analysis indicated that high molecular weights than $200,000 \text{ g mol}^{-1}$ were easily synthesized through chain-extension reaction (Zeng *et al.*, 2009).

High molecular weight PLA can be synthesized by adopting the process of polycondensation followed by solid state polycondensation. In this method, the residual monomer present in the polymer is substantially less because, during the solid-state polycondensation process, the monomer and catalyst are concentrated in the amorphous regions of the polymer and as a result almost 100 % of the monomer is converted to polymer (Maharana *et al.*, 2009).

Various metal triflates were employed for direct polycondensation of lactic acid to obtain Poly(lactic acid). Screening of the metal triflates was conducted with the polycondensation of lactic acid at $160\text{--}180 \text{ }^\circ\text{C}$ for 16 h under reduced pressure (1.4 kPa) after a pre-dehydration process under an air atmosphere. Examined metal triflates are scandium, yttrium, ytterbium, lanthanum, hafnium, copper, and silver triflates. Polycondensation using scandium triflate afforded poly(lactic acid) with high molecular weights ($M_n = 4.3 \times 10^4$) with good yields (62%) under following conditions; initiator amount = 0.05 mol%, pre-dehydration at $180 \text{ }^\circ\text{C}$ for 2 h, and polycondensation at $180 \text{ }^\circ\text{C}$ for 16 h (Konishi *et al.*, 2010).

4.2 Ring-opening polymerization of PLA

PLA can be prepared by two different methods- by polycondensation of hydroxyl -carboxylic acids or, by ring-opening polymerization (ROP) of cyclic esters. The ROP can be performed either as a bulk polymerization, or in solution, emulsion or dispersion (Sosnowski *et al.*, 1996 and Gadzinowski *et al.*, 1996). An initiator is necessary to start the polymerization. Under rather mild conditions, high molecular weight aliphatic polyesters of low polydispersity can be prepared in short periods of time. The polycondensation technique is less expensive than ROP, but it is difficult to obtain high molecular weight polylactide to achieve specific end groups. Problems associated with condensation polymerization, such as the need for exact stoichiometry, high reaction temperatures and the removal of low molecular weight by products (e.g. water) are excluded in ROP (Brode *et al.*, 1972).

The ROP of lactide has been thoroughly investigated during the last 40 years, due to its versatility to produce a variety of biomedical polymers in a controlled manner. ROP of lactide can be carried out by cationic, anionic, and coordination-insertion mechanisms depending on the initiator. A number of initiators were used for the synthesis of polylactide but among them, stannous octoate is usually preferred because it provides high reaction rate, high conversion rate, and high molecular weights, even under rather mild polymerization conditions. Use of triphenylphosphine (TPP) as co-initiator to enhance the polymerization rate and molecular weight of polylactide resulted in increase in molecular weight from thousands to several ten thousands. Fig. 3 shows the formation of polylactide from lactide by ROP.

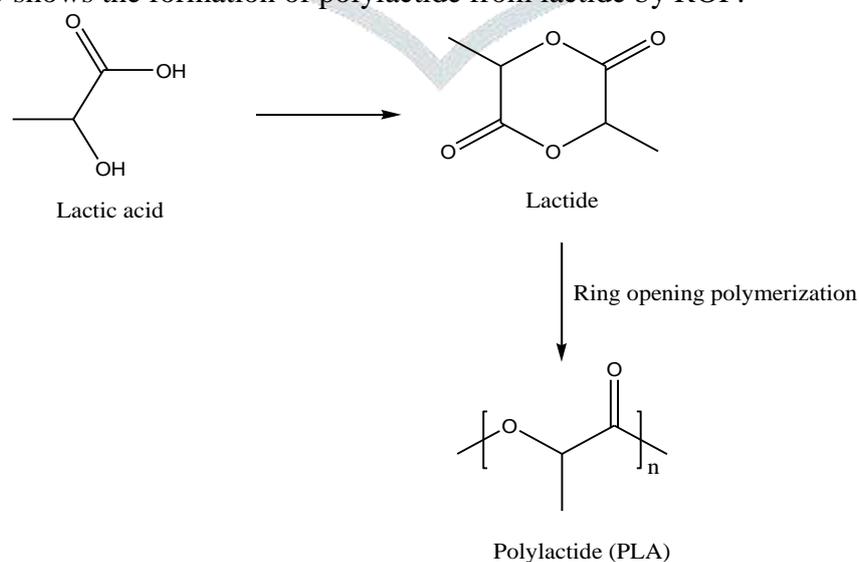


Figure 3 Ring-opening polymerization of lactide

4.3 Synthesis of PLA by Ring-Opening Polymerization

The polymerization of lactones is generally carried out in bulk or in solution (THF, toluene, chloroform etc.), emulsion, (Sosnowski *et al.*, 1996) or dispersion (Gadzinowski *et al.*, 1996). The temperature of bulk polymerization is generally in the range of 100-150 °C, whereas in solution polymerization, low temperatures have been used (0-25 °C) to minimize side reactions (inter and intra molecular transesterification). Racemic lactide was polymerized with various initiators containing Zn and Al. Three groups of initiators can be distinguished in view of their influence on transesterification: ZnCl₂ having the strongest transesterification activity, ZnEt₂ and ZnEt₂/Al (OiPr)₃ having medium activity and Al(acac)₃ with no transesterification activity at all (Bero *et al.*, 1990). The mechanism of polymerization depends on the type of initiator. Three major reaction mechanisms are cationic, anionic, and coordination-insertion. However, high molecular weight polyesters have only been obtained by using anionic or coordination-insertion ring-opening polymerization.

4.3.1 Cationic Ring-Opening Polymerization

The cationic ring-opening polymerization involves the formation of a positively charged species which are subsequently attacked by a monomer. The attack results in ring opening of the positively charged species through the S_N² type process. The cationic ring-opening polymerization reaction of lactones has been achieved using alkylating agents, acylating agents, Lewis acids and protic acids.

Methyl triflate (MeOTf) was found to be a useful initiator for the cationic ring-opening polymerization reaction of L- lactide. The reactions were performed in nitrobenzene for 48 hr and at optimized 50 °C. The methyl ester end groups were formed when methyl triflate was used as the initiator and it was suggested that the polymerization proceeds by cleavage of the alkyl-oxygen bond rather than the acyl-oxygen bond. According to their proposal, reaction propagates through the activation of the monomer by methylation with methyl triflate followed by S_N² attack of the triflate anion on the positively charged lactide ring with the inversion of stereochemistry. Propagation was proposed to proceed by nucleophilic attack by lactide on the activated cationic chain end with inversion, leading to net retention of the configuration (Kricheldorf and Dunsing, 1986). The polymerization proceeded by the cleavage of the alkyl-oxygen bond rather than the acyl-oxygen bond (Fig. 4).

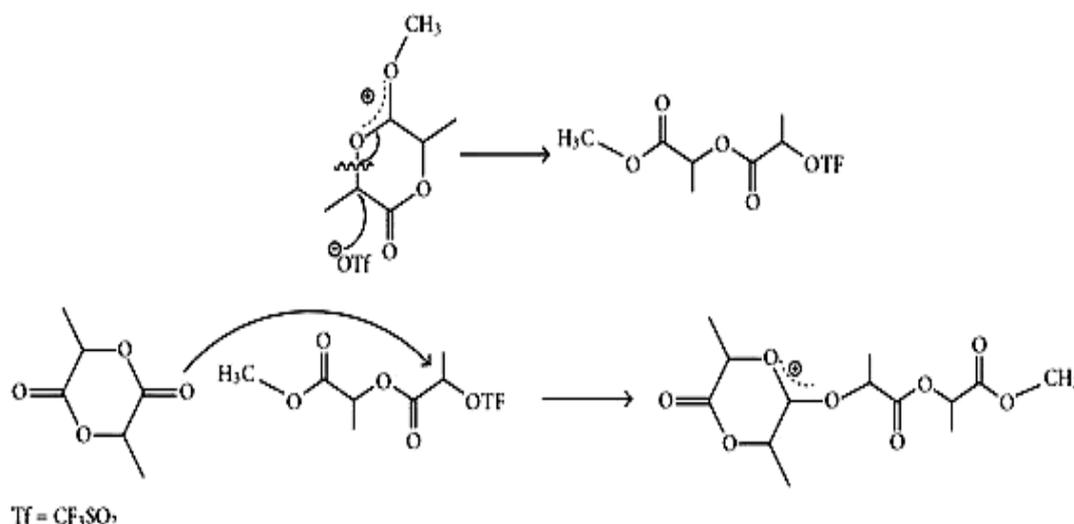


Figure 4 Proposed pathways for cationic ring-opening polymerization of lactone

Atthoff and co-workers reported bulk ring-opening polymerization of lactide at 130 °C using 5 mol% diphenylammonium triflate (DPAT) as an acid-proton initiator in ethanol as initiator. Under these conditions, they were able to get PLA with molecular weight up to 12000 g/mol with dispersity 1.24 to 1.51

in 4 days. They also suggested that such a high dispersity is due to transesterification with prolonged reaction time (Atthoff *et al.*, 2003).

4.3.2 Anionic Ring-Opening Polymerization

The effective initiators for anionic polymerization of lactones are alkali metals, alkali metal oxides, alkali metal naphthalenide complexes with crown ethers, etc. The reaction is initiated by nucleophilic attack of negatively charged initiator on the carbon of the carbonyl group or on the alkyl-oxygen, resulting in formation of linear polyester (Albertsson and Varma, 2003). The polymerization of β - lactones proceeds through alkyl-oxygen or acyl-oxygen cleavage giving both carboxylate and alkoxide end groups (Fig. 5).

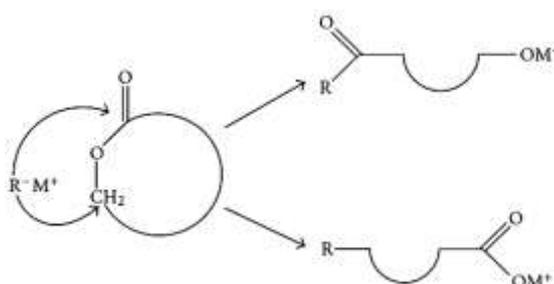


Figure 5 Initiation of ring-opening polymerization of lactones

In larger lactones, such as caprolactone or lactide, the reaction proceeds by the acyl-oxygen scission only thereby leading to the formation of an alkoxide ion as the propagating species (Fig. 6).

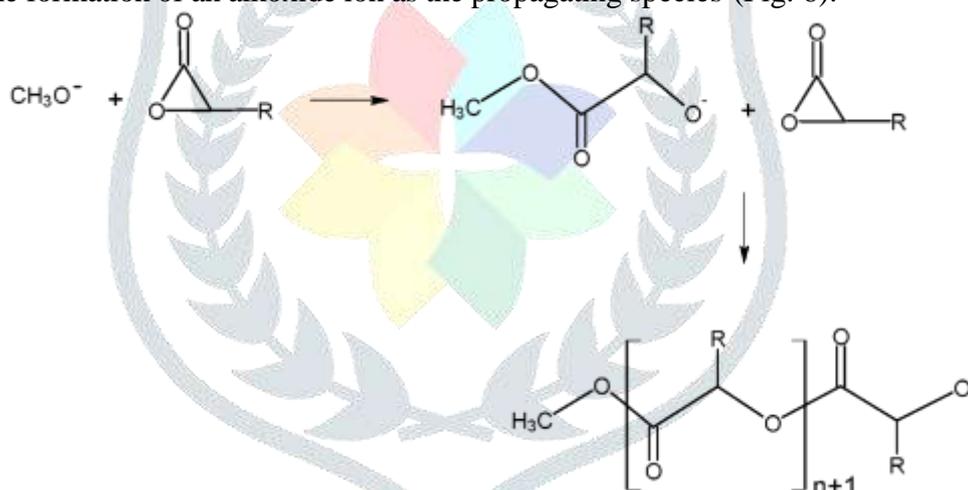


Figure 6 Anionic polymerization of lactone showing acyl oxygen

4.3.3 Co-ordination Insertion Ring-Opening Polymerization

Coordination insertion polymerization has been extensively used for the preparation of aliphatic polyesters with well defined structure and architecture. The most widely used initiators are various aluminum and tin alkoxides and carboxylates. The covalent metal alkoxides or carboxylates with vacant "d" orbital react as coordination initiators and not as anionic initiators in these polymerizations. These initiators are capable of producing stereoregular polymers of narrow MWD and controlled molecular mass, with well defined end groups. The carboxylates are weaker nucleophiles in comparison to alkoxides. The polymerization proceeds via acyl oxygen cleavage of the lactone with insertion of the monomer into the metal-oxygen bond of initiator (Kowalski *et al.*, 1998, Kricheldorf *et al.*, 1995, In't Veld *et al.*, 1997, Du *et al.*, 1995, Schwach *et al.*, 1997, Zhang *et al.*, 1994). The coordination of the exo-cyclic oxygen to the metal results in the polarization and makes the carbonyl carbon of the monomer more susceptible for nucleophilic attack (Fig. 7).

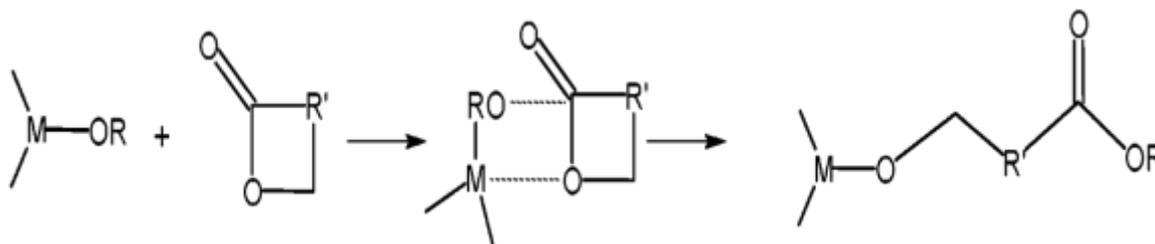
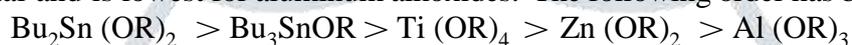


Figure 7 Coordination insertion mechanism of lactone polymerization

Kricheldorf *et al.* (2000) observed the formation of octanoic acid when tin (II) 2-ethylhexanoate was heated above 100 °C. The acid, thus liberated, may bring about the esterification of alcohol (active hydrogen co-initiator) leading to the formation of water, which may react with Sn(Oct)₂ to form stannoxanes and tin hydroxides. Under such conditions, it would be difficult to control the molecular mass and side reactions because the presence of water or other hydroxyl compounds is likely to initiate polymerization. The relative reactivity of different metal alkoxide initiators for transesterification reaction depends on the metal and is lowest for aluminum alkoxides. The following order has been observed:



Stannous octoate has been the most widely used initiator because of high reaction rates, the solubility in the monomer melt and the ability to produce high molecular weight polylactide (Swift 1993, Schwach *et al.*, 1994, Cabaret *et al.*, 2004). The addition of an equimolar amount of Lewis base, particularly triphenylphosphine into 2-ethylhexanoic acid, significantly enhances the lactide polymerization rate in bulk. Triphenylphosphine has two beneficial effects: it increases the polymerization rate and delays the occurrence of the undesirable back biting reactions at monomer/initiator ratios greater or equal to 5000 (Degee *et al.*, 1999).

Engel *et al.* (1997) studied the ring-opening polymerization of lactide cyclic monomers in the bulk in the presence of tin (II) 2-ethylhexanoate. It was reexamined under appropriate conditions for the end-group characterization of growing chains by high-resolution ¹H NMR. The formation of a side product, hydroxytin (II) lactate, was found which appeared to initiate lactide polymerization and to yield a high molecular weight PLA50 polymer. However, the polymerization with stannous octoate was faster than with hydroxytin (II) lactate.

Schwach *et al.* (1998) reported that the polymerization was moisture sensitive and that only a fraction of zinc used was active. Small quantities of a side-product was detected and identified as zinc lactate. This compound appeared to be an efficient initiator of the ring-opening polymerization in the bulk. Initiation by zinc lactate yielded high molecular weight polymers with a high degree of conversion and high polymerization rates.

Kleawkla *et al.* (2005) discussed the co-ordination insertion mechanism of the ring-opening polymerization of the cyclic esters. Originally it was assumed that stannous octoate was the initiator but this was later disproved by the fact that the polymer molecular weight did not depend upon the monomer: stannous octoate molar ratio. Instead it was concluded that hydroxyl containing impurities (e.g. hydroxyl acids) in the system, including any trace amounts of moisture, were the true initiating species with the stannous octoate acting as a initiator to activate the carbonyl of the monomer towards nucleophilic attack by OH group. This was then followed by acyl-oxygen bond cleavage and ring opening of the monomer. It is now believed that rather than effecting simple complexation with the stannous octoate, the alcohol (ROH) actually reacts with it to form a tin alkoxides, Sn(OR)₂, and that it is this Sn(OR)₂ which is the true initiating specie. Thus, the stannous octoate is more correctly termed as initiator and the ROH as the co-initiator.

Copolymers with various compositions were synthesized by bulk ring-opening polymerization of glycolide and ε-caprolactone, using stannous (II) octoate or zirconium (IV) acetylacetonate as initiator. Reaction time and temperature were varied to induce different chain microstructures. Stannous (II) octoate leads to less transesterification than zirconium (IV) acetylacetonate, and lower temperatures lead to less transesterification than higher ones (Dobrzynski *et al.*, 2005).

Aluminum-alkoxide initiated polymerization of lactones proceeds according to a coordination-insertion mechanism. Aluminum isopropoxide coordinates to the exocyclic carbonyl oxygen, and the acyl-oxygen cleavage yields an isopropyl ester end-group. Termination of growing chain with dilute HCl leads to the formation of a hydroxy end-group. A narrow molecular mass distribution and an increase in DP with an increase in $[M]/[I]$ ratio confirmed the living character of the polymerization (Loefgren *et al.*, 1994).

Ferric alkoxides were used as initiators for bulk ring-opening polymerization of lactides. The molecular weight decreased and the molecular weight distribution broadened as the polymerization temperature increased. Intermolecular transesterification took place during polymerization of D, L- lactide as evidenced by the results of MALDITOF MS analysis, and the quantitative evaluation for each initiation system was made by ^{13}C NMR analysis. ^1H NMR, and MALDI-TOF MS analyses indicated that the polymerization of lactides proceeded via a coordination-insertion mechanism involving cleavage of the acyl-oxygen bond of the lactides (Wang *et al.*, 2005). ROP of lactones with these organometallic initiators at high temperatures or long reaction time leads to both inter- as well as intra-molecular transesterification reactions. Both types of transesterification reactions lead to an increase in dispersity of the polyesters (Fig. 8).

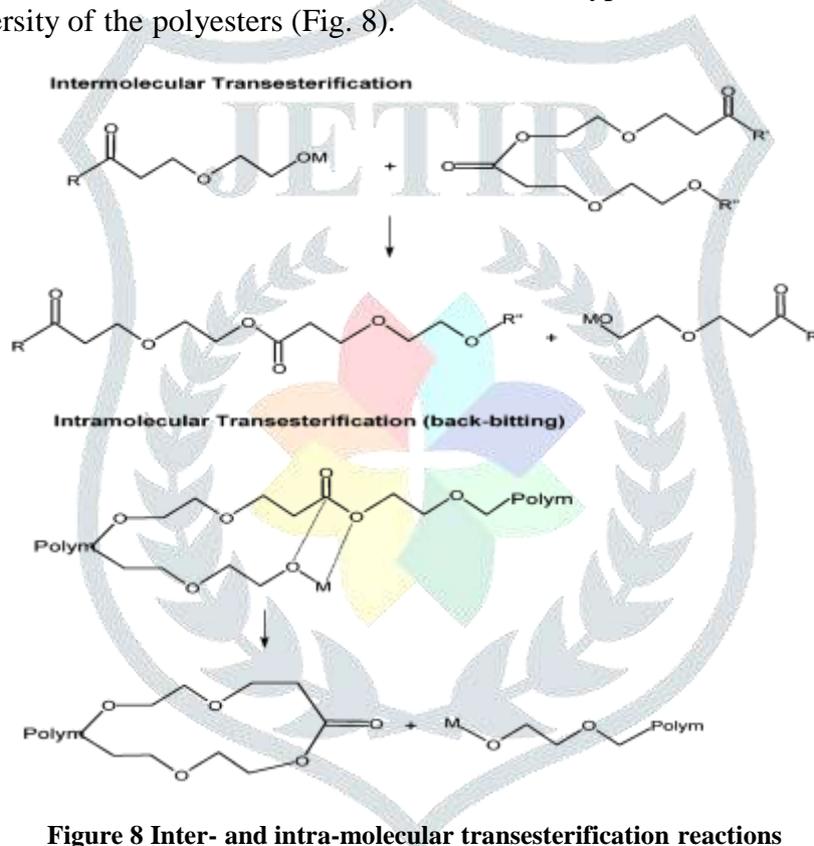


Figure 8 Inter- and intra-molecular transesterification reactions

The reaction parameters which influence transesterification reactions are temperature, reaction time, the type and concentration of initiator and the nature of the lactone or lactide (Dubois *et al.*, 1965). Higher flexibility of the polyester backbone leads to an increase in the extent of side reactions (transesterification).

Bu_3SnOMe and $\text{Bu}_2\text{Sn}(\text{OMe})_2$ are effective transesterification catalysts and cause 'back-biting' degradation even at 90°C . In all series of polymerizations initiated with tin methoxides two tendencies are detectable: increasing randomization of the stereosequence with increasing reaction time and with higher reaction temperatures. In contrast, $\text{Sn}(\text{II})$ octoate does not cause transesterification at $\leq 120^\circ\text{C}$ and even at 180°C randomization of the stereosequences is slow (Kricheldorf *et al.*, 1992). Initiators with higher nucleophilicity are required to initiate lactide and weaker bases such as zinc stearate, potassium phenoxide, and potassium benzoate initiate only at higher temperatures (120°C). Initiations at high temperature are in bulk but accompanied by racemization and other side reaction which are obstacle to propagation (Kricheldorf and Saunders, 1990, Kricheldorf and Boettcher, 1993, Kricheldorf and Serra, 1985 and Kleine and Kleine, 1959).

Poly (L- lactide), PLLA with ultra-high weight average molecular mass and narrow polydispersity index was synthesized by ring-opening polymerization. A synthetic purification method involving a water bath and two time recrystallization could improve the purity of L- lactide to 100%. The yield of L- lactide reached 40.6% and increased 12.1% compared with the recrystallization method. Poly (L-lactide) with a weight average molecular mass of about 102.4×10^4 and a polydispersity index of 1.16 was obtained when polymerization was conducted with molar ratio of monomer to initiator $[M_0]/[I_0]$ of 12000 for 24 h at 140 °C (Zhou *et al.*, 2008).

V. PLA Composites and Nanoparticles

Bioresorbable composite plates have been made from poly (glycolic acid), PGA fibers embedded in a PLA matrixes. These composites are bioresorbable, exhibit good biocompatibility with the tissues in which they are implanted, and have adjustable resorption rates, depending on the relative amounts of L- and D- lactic acid units as well as on the quantities of glycolic acid and lactide repeating units. This concept of bioresorption or biodegradability is an important one in many areas of bioimplants (Boretos and Eden, 1984). Composites of PLA have been made with jute fibers (Ouchi *et al.*, 2003) and bioactive glass (Roether *et al.*, 2002).

Lipase catalyzed ring opening graft copolymerization can be employed to graft hydrophobic polyesters onto hydrophilic cellulose based polymers. The reaction resulted in polyester grafted HEC with DSs between 0.10 and 0.32 in terms of per anhydroglucose unit (Li *et al.*, 1999). Organoclay plays an important role in the preparation of polymer/clay nanocomposites and dispersing the clay into less polar polymer matrixes (Maiti *et al.*, 2002). New polylactide (PLA)/layered silicate nanocomposites have been prepared by simple melt extrusion of PLA and organically modified montmorillonite. The d spacing of both the organically modified montmorillonite and intercalated nanocomposites were investigated by wide-angle X-ray diffraction (WAXD) analysis, and the morphology of these nanocomposites was examined by transmission electron microscopy (TEM) (Ray *et al.*, 2002). PHB/layered silicate nanocomposites were prepared successfully through melt extrusion (Maiti *et al.*, 2007).

PLA nanocomposites with nano-sized precipitated calcium carbonate (NPCC) and organically modified montmorillonite (MMT) clay were prepared by melt extrusion. Morphologies, tensile mechanical properties, dynamic mechanical and rheological properties, polymer–nanoparticles interactions, and toughening mechanisms of the PLA/NPCC and PLA/MMT nanocomposites were compared. MMT and NPCC showed significantly different effects on the strength, modulus and elongation of the PLA nanocomposites (Jiang *et al.*, 2007).

The specific moduli of both solid and microcellular components were improved by addition of nanoclay into bio-based polylactide and facilitated the formation of smaller cell sizes and higher cell densities. Addition of nanoclay also reduced the strain at break and the specific toughness of solid polylactide nanocomposite components. However, the strain at break and specific toughness of microcellular polylactide nanocomposite components were largely improved in comparison with microcellular polylactide components, especially when the loading level of the nanoclay was at 3% and 5%, presumably due to the lack of large voids, as well as the smaller cell size and higher cell density (Kramschuster *et al.*, 2007).

Poly(lactic acid)/organo-montmorillonite (OMMT) nanocomposites were prepared by melt intercalation technique. Maleic anhydride-grafted ethylene propylene rubber (EPMgMA) was added into the PLA/OMMT in order to improve the compatibility and toughness of the nanocomposites. The samples were prepared by single screw extrusion followed by compression molding. The thermal properties of the PLA/OMMT nanocomposites have been investigated by using differential scanning calorimeter (DSC) and thermo-gravimetry analyzer (TG). The melting temperature (T_m), glass transition temperature (T_g), crystallization temperature (T_c), degree of crystallinity (χ_c), and thermal stability of the PLA/OMMT nanocomposites have been studied. It was found that the thermal properties of PLA were greatly influenced by the addition of OMMT and EPMgMA (Chow and Lok, 2009).

Poly(lactic acid) PLA and polycaprolactone (PCL) nanocomposites prepared by adding two organically modified montmorillonites and one sepiolite were obtained by melt blending. Materials were

characterized by Wide Angle X-ray analysis (WAXS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Differential Scanning Calorimetry (DSC), Thermo Gravimetric Analysis (TGA) and Dynamic-Mechanical Thermal Analysis (DMTA) (Fukushima *et al.*, 2009). A new manufacturing process similar to papermaking, which enables the production of thin sheets made of uniformly dispersed microfibrillated cellulose (MFC) with polylactic acid (PLA) fibers was devised, and the composites were obtained by compression molding of the stacked sheets (Nakagaito *et al.*, 2009).

The Taguchi method of experimental design (TMED) was used for the preparation of PLA nanoparticles via a nano precipitation technique. The effect of four pertinent parameters, such as concentration of PLA, solvent to non solvent (S/NS) volume ratio, molecular weight of PLA and type of solvent, were studied on the yield and size of nanoparticles. The size of PLA nanoparticles obtained was around 100 nm (Maharana *et al.*, 2010).

Jonoobi *et al.*, (2010) develop cellulose nanofiber (CNF) reinforced polylactic acid (PLA) by twin screw extrusion. Nanocomposites were prepared by premixing a master batch with high concentration of CNFs in PLA and diluting to final concentrations (1, 3, 5 wt. %) during the extrusion. The tensile modulus and strength increased from 2.9 GPa to 3.6 GPa and from 58 MPa to 71 MPa, respectively, for nanocomposites with 5 wt.% CNF.

VI. Polymerization Mechanism

Poly(lactic acid), PLA can undergo cationic, anionic and co-ordination insertion polymerization mechanisms. The mechanism through which the initiator works has been suggested for some systems. Trifluoromethane sulfonic acid (triflic acid) and methyl trifluoromethanes sulfonic acid (methyl triflate) are the only cationic initiators to polymerize lactide (Kricheldorf and Kreiser, 1987, Kricheldorf and Sumbel, 1989 and Dittrich, 1971). The polymerization proceeds via triflate ester end-groups instead of free carbenium ions, which yields, at low temperatures (<100 °C), an optically active polymer without racemization. The chain growth proceeds by cleavage of the alkyl oxygen bond. The propagation mechanism begins with the positively charged lactide ring being cleaved at the alkyl-oxygen bond by an SN^2 attack by the triflate anion. The triflate end-group reacts with a second molecule of lactide again in an SN^2 fashion to yield a positively charged lactide. Then the triflate anion again opens the charged lactide, and polymerization proceeds (Kricheldorf and Dunsing, 1986). The cationic polymerization mechanism with methyl trifluoromethanes sulfonic acid (methyl triflate) initiator is shown in Figure 9.

Zhang *et al.* (1994) studied the effect of hydroxyl and carboxylic acid substances on lactide polymerization in the presence of stannous octoate. Stannous alkoxide, a reaction product between stannous octoate and alcohol, was proposed as the substance initiating the polymerization through coordinative insertion of lactide. Alcohol could affect the polymerization through reactions leading to initiator formation, chain transfer, and transesterification. Carboxylic acids affect the polymerization through a deactivation reaction.

Aluminum isopropoxide is an effective initiator for the polymerization of lactides in toluene at 70 °C. The ring-opening polymerization proceeds through a coordination-insertion mechanism. The mechanism involves the insertion of the lactide into the aluminum-alkoxide bond with lactide acyl-oxygen cleavage is shown in Figure 10 (Dubois *et al.*, 1991).

Nijenhuis *et al.* (1992) studied the kinetics and mechanism of L- lactide bulk polymerization using stannous octoate and zinc bis (2,2-dimethyl-3,5-heptanedionate-O,O'). Up to 80% conversion, the rate of polymerization using tin compound was higher than that with zinc-containing catalyst, while at conversions beyond 80%, the latter catalyst gave the higher rate of polymerization. Crystallization of the newly formed polymer has an accelerating effect on the polymerization. The differences in the rate of polymerizations at high conversion for the two catalysts have been suggested to be caused by a difference in crystallinity of the newly formed polymer. It is further suggested that contaminants in the catalyst (such as tin-oxy or tin-hydroxyl contaminants) and the monomer are the true initiators. Initiation as well as polymerization proceeds through a Lewis acid catalyzed transesterification reaction between an activated lactone and a hydroxyl group.

Schwach *et al.* (1997) reexamined the ring-opening polymerization of PLA in the presence of stannous octoate under conditions allowing for the end-group characterization of growing chains by high-

resolution $^1\text{H-NMR}$. For low values of monomer to initiator ratios, the DL- lactide ring was opened to yield lactyl octoate-terminated short chains.

Various authors have described mechanisms for the tin octoate catalyzed polymerization of lactide but only a few have incorporated the effect the impurities on the polymerization. Figure 11 is a hypothetical reaction mechanism put forth by (Du *et al.*, 1995) which includes the effect of different hydroxylic compounds.

Stannous (II) trifluoromethane sulfonate and scandium(III) trifluoromethane sulfonate have also been studied as catalysts for PLA synthesis (Moller *et al.*, 2001). It was found that polymers of predictable molecular weights and narrow polydispersities could be obtained. The addition of base either as a solvent or as an additive significantly enhanced the polymerization rate with minimal loss to the polymerization control.

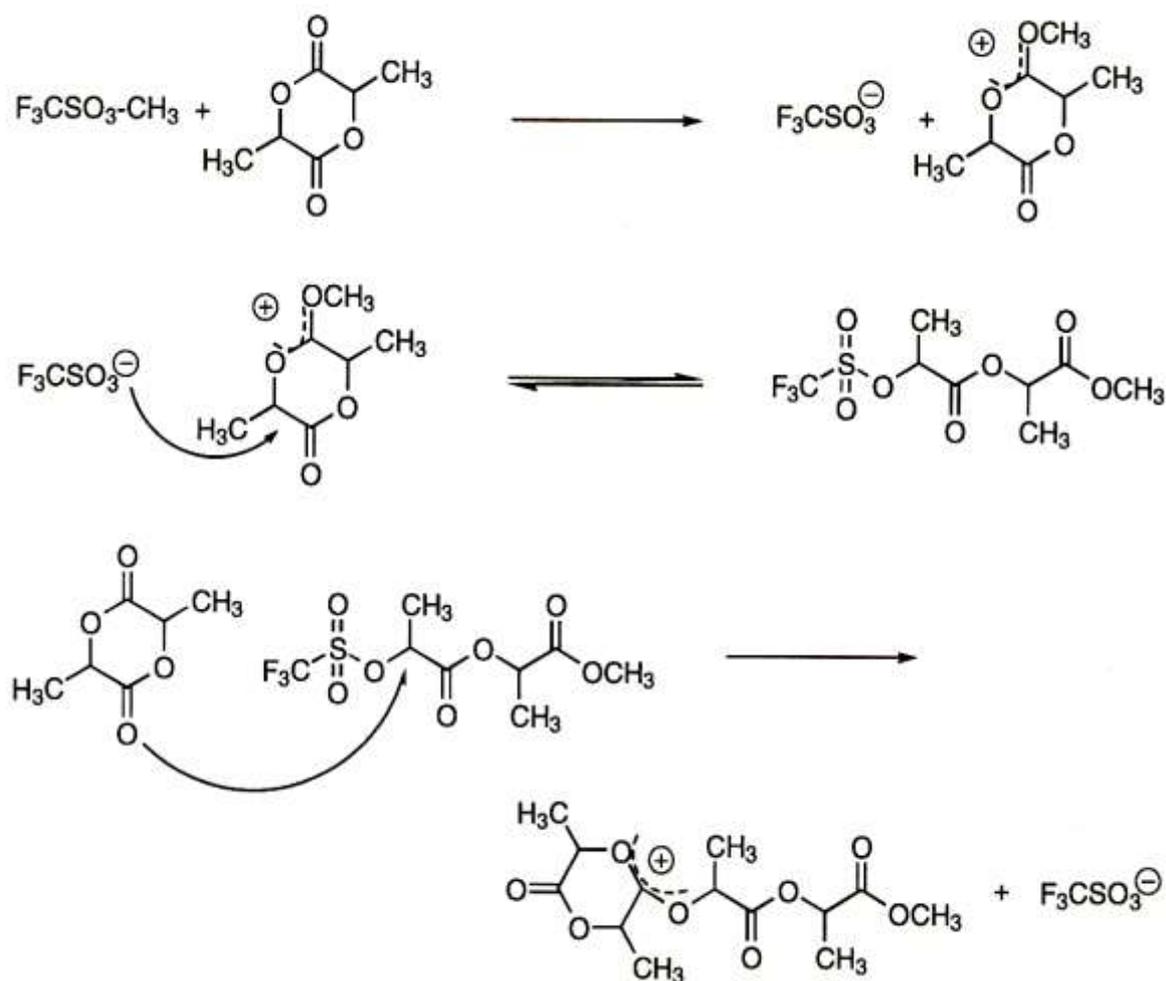


Figure 9 Cationic ring-opening polymerization mechanism of PLA using methyl triflate
(Source: Kricheldorf and Dunsing, 1986)

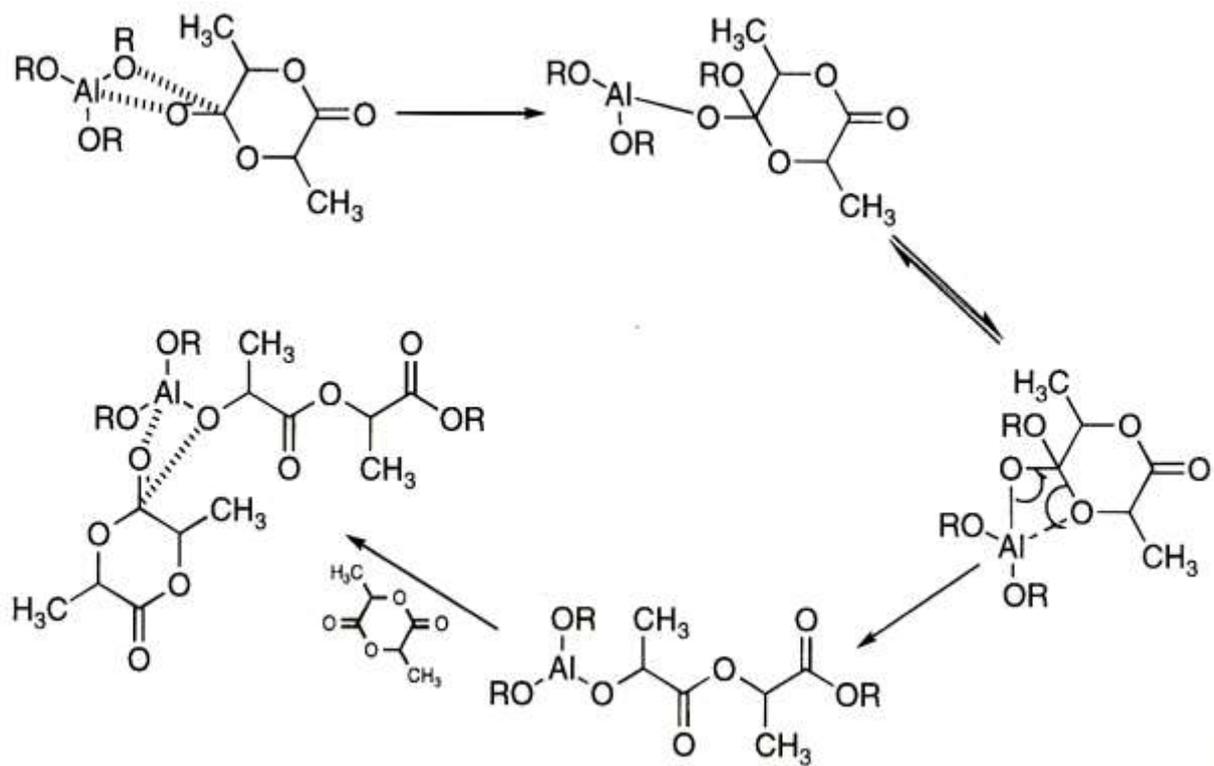
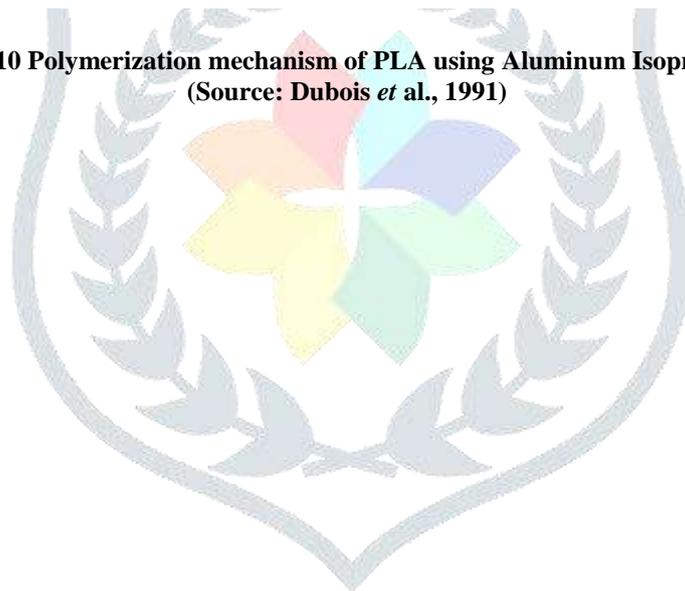


Figure 10 Polymerization mechanism of PLA using Aluminum Isopropoxide
(Source: Dubois *et al.*, 1991)



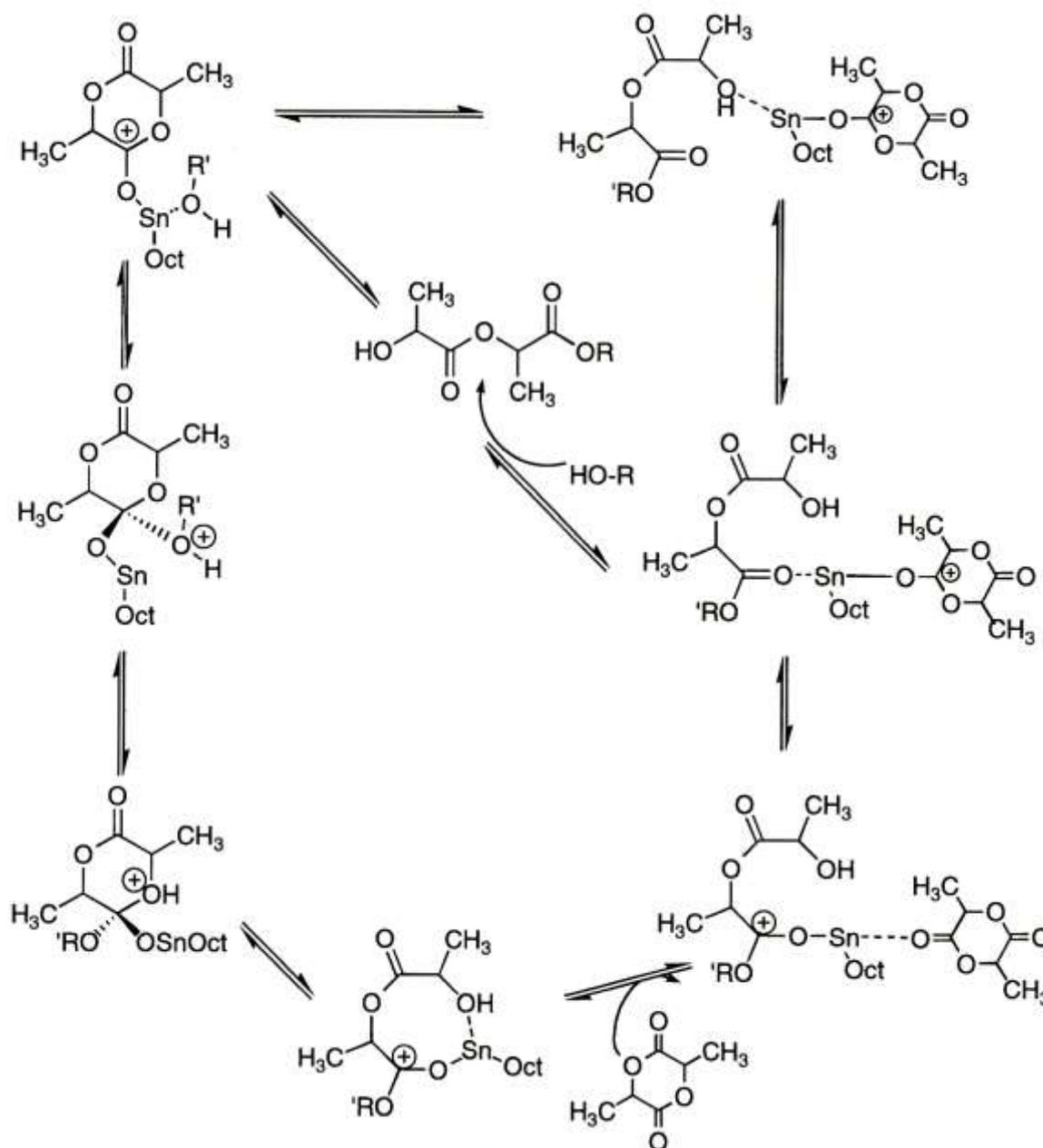


Figure 11 Polymerization mechanism of lactide in presence of stannous octoate
(Source: Du *et al.*, 1995)

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