Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review☆

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ABSTRACT

Poly(lactic acid) (PLA), so far, is the most extensively researched and utilized biodegradable aliphatic polyester in human history. Due to its merits, PLA is a leading biomaterial for numerous applications in medicine as well as in industry replacing conventional petrochemical-based polymers. The main purpose of this review is to elaborate the mechanical and physical properties that affect its stability, processability, degradation, PLA-other polymers immiscibility, aging and recyclability, and therefore its potential suitability to fulfill specific application requirements. This review also summarizes variations in these properties during PLA processing (i.e. thermal degradation and recyclability), biodegradation, packaging and sterilization, and aging (i.e. weathering and hygrothermal). In addition, we discuss up-to-date strategies for PLA properties improvements including components and plasticizer blending, nucleation agent addition, and PLA modifications and nanoformulations. Incorporating better understanding of the role of these properties with available improvement strategies is the key for successful utilization of PLA and its copolymers/composites/blends to maximize their fit with worldwide application needs.

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Contents

1. Introduction

Poly(lactic acid) or polylactide (PLA) is the most extensively researched and utilized biodegradable and renewable aliphatic polyester. PLA has a proven potential either to replace conventional petrochemical-based polymers for industrial applications or as a leading biomaterial for numerous applications in medicine [1,2].

Environmental, economic, and safety challenges have provoked packaging scientists and producers to partially substitute petrochemical-based polymers with biodegradable ones [3]. PLA as a leading candidate, is a thermoplastic, high-strength, high-modulus polymer that can be made from annually renewable resources to yield different components for use in either the industrial packaging field or the biocompatible/bioabsorbable medical device market. It is easily processable on standard plastic equipment to yield molded parts, film, or fibers [4,5].

As a bioabsorbable polymer, PLA, is one of the most promising biopolymers 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 [6,7]. Lactic acid (2-hydroxypropionic acid, LA), a PLA constituent unit, since it is a chiral molecule, exists as two enantiomers, L- and D-lactic acid (Fig. 1), PLA has stereoisomers, such as poly(L-lactide) (PLLA), poly(D-lactide) (PDLA), and poly(DL-lactide) (PDLLA) [1]. Lactic acid can be made by fermentation of sugars obtained from renewable resources as such sugarcane or corn starch [4]. Therefore, PLA is an eco-friendly product with better features for use in the human body (nontoxicity). PLA is the first commodity polymer produced from annually renewable resources [8]. It is classified as generally recognized as safe (GRAS) by the United State Food and Drug Administration (FDA) and is safe for all food packaging applications [3,9]. The research on lactic acid based polymers intended for medical applications has accelerated since FDA approval, and during the last two decades an increasing utilization of large scale industrial lactic acid based polymers for other uses has occurred [10–12].

PLA was synthesized in 1932 by Carothers (at DuPont). He was only able to produce a low molecular weight (Mw) PLA by heating lactic acid under vacuum while removing the condensed water. The problem at that time was to increase the Mw of the products; and, finally, by ring-opening polymerization of the lactide, high-Mw PLA was synthesized (Fig. 2) [3,7]. Today, although there are multiple ways to fabricate PLA, none of them is simple or easy to execute. PLA synthesis requires rigorous control of conditions (temperature, pressure and pH), the use of catalysts and long polymerization times [6,7]. PLA can be prepared by different polymerization processes from lactic acid including: polycondensation, ring opening polymerization and by direct methods like azeotopic dehydration and enzymatic polymerization [5]. Currently, direct polymerization and ring opening polymerization are the most used production techniques. Fig. 2 shows the main methods for PLA synthesis.

In comparison to other biopolymers, the production of PLA has numerous advantages [3], including: 1) Eco-friendly — apart from being derived from renewable resources (e.g., corn, wheat, or rice), PLA is biodegradable, recyclable, and compostable [2,13]. Its production also consumes carbon dioxide [14]. 2) Biocompatibility — the most attractive aspect of PLA, especially with respect to biomedical applications. A biocompatible material should not produce toxic or carcinogenic effects in local tissues. Also, the degradation products should not interfere with tissue healing. PLA hydrolyzes to its constituent α-hydroxy acid when implanted in living organisms, including the human body. It is then incorporated into the tricarboxylic acid cycle and excreted. Moreover, PLA degradation products are non-toxic (at a lower composition) making it a natural choice for biomedical applications [15]. The FDA has also approved PLA for direct contacting with biological fluids [16]. 3) - Processibility — PLA has better thermal processibility compared to other biopolymers such as poly(hydroxyl alkanoate) (PHA), poly(ethylene glycol) (PEG) and poly(γ-caprolactone) (PCL). It can be processed by injection molding, film extrusion, blow molding, thermoforming, fiber spinning, and film forming [17]. 4) Energy savings — PLA requires 25–55% less energy to produce than petroleum-based polymers and estimations show that this can be further reduced to less than 10% in the future [15]. Lower energy use makes PLA production potentially advantageous with respect to cost as well. Although, despite the above positive features, PLA has drawbacks as well, which limit its use in certain applications, mainly: 1) Poor toughness — PLA is a very brittle material with less than 10% elongation at break [19]. Although its tensile strength and elastic modulus are comparable to poly(ethylene terephthalate) (PET) [17,18], the poor toughness limits its use in the applications that need plastic deformation at higher stress levels (e.g., screws and fracture fixation plates) [15]. 2) Slow degradation rate — PLA degrades through the hydrolysis of backbone ester groups and the degradation rate depends on the PLA crystallinity, Mw and its distribution, morphology, water diffusion rate into the polymer, and the stereoisomeric content [20]. The degradation rate is often considered to be an important selection criterion for biomedical applications [21]. The slow degradation rate leads to a long in vivo life time, which could be up to years in some cases (mostly 3–5 years) [15]. The slow degradation rate is a serious problem with respect to disposal of consumer commodities as well. 3) Hydrophobicity — PLA is relatively hydrophobic, with a static water contact angle of approximately 80 °C. This results in low cell affinity, and can elicit, in some cases, an inflammatory response from the living host upon direct contact with biological fluids [22]. 4) Lack of reactive side-chain groups — PLA is chemically inert with no reactive side-chain groups making its surface and bulk modifications a challenging task.

In recent times, several PLA-based technologies have emerged with an emphasis on achieving chemical, mechanical, and biological properties equivalent or superior to conventional polymers. The frequent need for a chemical or physical modification of PLA to achieve suitable properties for its intended consumer and biomedical applications, has demanded significant attention in the last decade. The successful implementation of PLA in consumer and biomedical applications relies not only on mechanical properties being better than or comparable to conventional plastics, but also on controlled surface properties (e.g., hydrophilicity, roughness, and reactive functionalities). PLA has been bulk modified
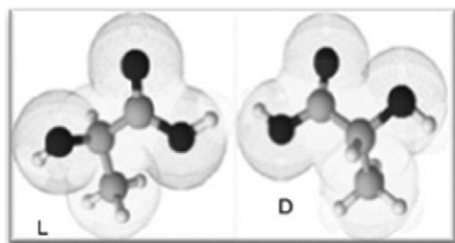

Fig. 1. Atomic chemical structure of L- and D-lactic acid. (Reprinted from [6]).
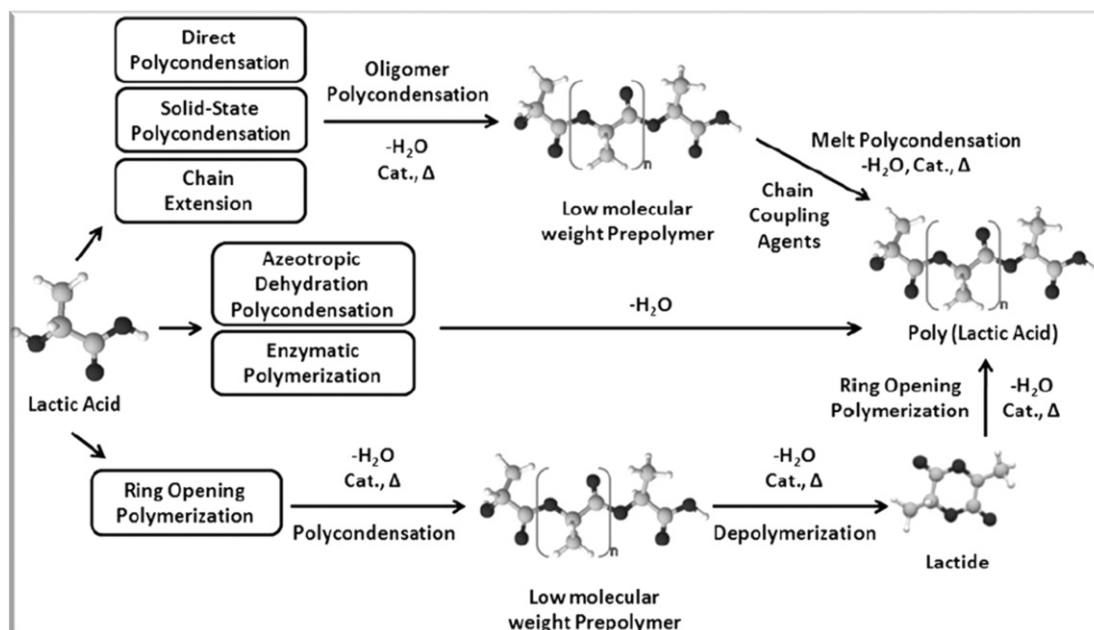
Fig. 2. Synthesis methods for poly(lactic acid).
(Adapted from [1,5,7]).

mainly to improve toughness and degradation rate while surface modification has been attempted to control hydrophilicity, roughness, and to introduce reactive groups. Toughness improvement is a crucial necessity for many consumer applications, while the improvements in hydrophilicity and introduction of reactive groups are beneficial for biomedical applications. Improvements in degradation rate could also be important in both consumer and biomedical applications [15].

Several reviews have been written which include details on the properties and characteristics of PLA [8,12,23]. Here in this work, our focus is on elaborating the mechanical and physical properties that affect PLA's stability, processability, degradation, PLA-other polymers immiscibility, aging and recyclability, and therefore its potential suitability to fulfill specific application requirements. PLA's property variations during PLA processing, biodegradation, packaging and sterilization, and aging were studied and summarized. In the second part of the review we discuss up-to-date strategies for PLA property improvements including components and plasticizer blending, nucleation agent addition, and PLA modifications and nanoformulations. These aspects rarely have been found discussed together. Several examples on PLA property functions in widespread applications are also given in the last part. The main review goal is combining better understanding of the role of these properties with available improvement strategies for successful utilization of PLA and its copolymers/composites/blends to maximize their applications.

2. Properties of lactic acid-based polymers

PLA's properties have been the subject of extensive research [1,6,24]. Here, in this section, is a brief overview on the main studied PLA properties, followed by deep consideration of PLA's physical and mechanical properties in the following sections.

Properties of PLA depend on its component isomers, processing temperature, annealing time and Mw [6,24,25]. The stereochemistry and thermal history have direct influence on PLA crystallinity, and therefore, on its properties in general. A very important property of polymers is the rate of crystallinity where crystallinity is the indication of amount of crystalline region in the polymer with respect to amorphous content. Crystallinity influences many polymer properties including hardness, modulus, tensile strength, stiffness, crease and melting points. So,

while selecting a polymer for a required application, its crystallinity plays the foremost role [3].

PLA crystals can grow in 3 structural positions called α, β, and γ forms. They are characterized by different helix conformations and cell symmetries, which develop upon different thermal and/or mechanical treatments [1]. The α form grows upon melt or cold crystallization, the β form develops upon mechanical stretching of the more stable α form, and the γ form, which recently has been reported to develop on hexamethylbenzene substrate [26]. PLA properties may be controlled through the use of special catalysts of isotactic and syndiotactic content with different enantiometric units [16]. PLA with PLLA content higher than 90% tends to be crystalline, while the lower optically pure is amorphous. The melting temperature (T_m), and the glass transition temperature (T_g) of PLA decrease with decreasing amounts of PLLA [7].

Physical characteristics such as density, heat capacity, and mechanical and rheological properties of PLA are dependent on its T_g [8]. For amorphous PLA, the T_g is one of the most important parameters since dramatic changes in polymer chain mobility take place at and above T_g. For semicrystalline PLA, both T_g and T_m are important physical parameters for predicting PLA behavior [17,27,28]. The melt enthalpy estimated for an enantiopure PLA of 100% crystallinity (ΔH°_m) is 93 J/g; it is the value most often referred to in the literature although higher values (up to 148 J/g) also have been reported. The T_m and degree of crystallinity are depended on the molar mass, thermal history and purity of the polymer [29]. The density of amorphous and crystalline PLLA has been reported as 1.248 g/ml and 1.290 g/ml, respectively. The density of solid PLA was reported as 1.36 g/cm^3 for L-lactide, 1.33 g/cm^3 for *meso*-lactide, 1.36 g/cm^3 and 1.25 g/cm^3 for crystalline and amorphous PLA, respectively [17].

PLA solubility — in general, PLA products are soluble in dioxane, acetonitrile, chloroform, methylene chloride, 1,1,2-trichloroethane and dichloroacetic acid. Ethyl benzene, toluene, acetone and tetrahydrofuran only partly dissolve PLAs when cold, though they are readily soluble in these solvents when heated to boiling temperatures. Lactic acid-based polymers are not soluble in water, alcohols such as methanol, ethanol and propylene glycol and unsubstituted hydrocarbons (e.g. hexane and heptane). Crystalline PLLA is not soluble in acetone, ethyl acetate or tetrahydrofuran [6,10].

PLA degrades primarily by hydrolysis, after several months of exposure to moisture. PLA degradation occurs in two stages. First, random non-enzymatic chain scission of the ester groups leads to a reduction in Mw. In the second stage, the Mw is reduced until the lactic acid and low Mw oligomers are naturally metabolized by microorganisms to yield carbon dioxide and water [17,30]. The polymer degradation rate is mainly determined by polymer reactivity with water and catalysts. Any factor which affects the reactivity and the accessibility, such as particle size and shape, temperature, moisture, crystallinity, % isomer, residual lactic acid concentration, Mw, water diffusion and metal impurities from the catalyst, will affect the polymer degradation rate [2,17,31–33]. The in vivo and in vitro degradation have been evaluated for PLA surgical implants. In vitro studies showed that the pH of the solution does play a role in the in vitro degradation, and that, an in vivo study can be used as a predictor of the in vivo degradation of PLA [17,34].

The Mw has a significant impact on the properties of polymers such as degradation, mechanical strength and solubility. High Mw PLA has a complete resorption time of 2 to 8 years. This prolonged existence in vivo in some organs may lead to inflammation and infection [35]. Therefore, production of low Mw PLA is desirable as it provides a shorter degradation rate. Mainil-Varlet studied the degradation rate of low Mw PLLA (60,000 g/mol) and found that the implants were able to maintain mechanical properties for a period of time usually required for bone fracture healing. Low Mw PLAs that are used for drug delivery have a weak retarding effect. They degrade by hydrolysis relatively fast into lactic acid, which reduces the risk of material accumulation in tissue [34]. For example, PLA with Mw between 2000 and 20,000 g/mol was used by Andreopoulos as an implantable antibiotic release system. They found that the sustained release of antibiotics in low and high Mw implants lasted 33 days and more than 3 months, respectively [36]. Jabbari and He, developed an injectable and bioresorbable macromer using PLLA (number-average molecular weight (Mn) 1200 g/mol) as a starting material. It is reported that an injectable hydrogel can be prepared by the addition of acrylate or fumarate units to low Mw PLLA. This particular functionalized PLA has a favorable biodegradation rate [37].

By modification of the chain architecture through the introduction of branching, different melt flow properties will be obtained [1]. Thermal and rheological properties of 2 commercial types of PLA, linear and branched, were investigated by Dorgan and others [38]. The crystallization kinetic of the branched polymer was faster than that of the linear analog. Longer relaxation times in the terminal region of the branched material introduced it as a higher zero shear rate viscosity. They concluded that by utilizing the structure modifications through polymer branching the ability of using PLA in many processing operations will be extended.

PLA stereocomplexes can be produced by enantiomers with identical chemical composition but with different steric structures. Since preparation in 1987, the stereocomplex between PLLA and PDLA has been intensively studied by utilizing different preparations, structures and functional properties, enhanced characteristics have been reported especially for drug delivery applications [39].

PLA can also be tailored by formulation involving co-polymerization of the lactide with other lactone-type monomers, hydrophilic macromonomers (PEG), other monomers with functional groups (such as amino and carboxylic groups), or blending PLA with other materials [6,40]. Blending can radically alter the resultant properties, which depend sensitively on the mechanical properties of the components as well as the blend microstructure and the interface between the phases [41]. Broz prepared a series of blends of the biodegradable polymers PDLLA and PCL by varying mass fraction across the range of compositions. It was found that polymers made from ε-caprolactone were excellent drug permeation products [41].

Optical properties of PLA are important in dyeing operations for textiles and in various packaging applications where clarity is desirable.

Hutchinson and others determined the optical properties of PLA with different amounts of stereoisomer proportions by ellipsometric measurements. They developed an equation for index of refraction of PLA with a wide range of stereoisomer proportions (L-content) within the range of wavelengths from 300 to 1300 nm by using Cauchy coefficients [42].

PLA barrier properties — one of the most important factors in food packaging polymers is their barrier or permeability performance against transfer of gases, water vapor, and aroma molecules. Gas permeation properties of PLA (L:D ratio 96:4) have been studied by Lehermeier and others [38,43,44] and these values are summarized in Fig. 3. The authors concluded that polymer chain branching and small changes in L:D stereochemical content have no effect on permeation properties, but film crystallinity profoundly impacted the permeation of the mentioned gases. For example, due to higher crystallinity of biaxially oriented PLA film, CH_4 permeation is 4.5 times lower than that of the other films. In an earlier study by Shogren the water vapor transmission rate (WVTR) of crystalline and amorphous PLA in 6, 25, and 49 °C was reported as 27, 82, and 333 g/m^2 per day for the crystalline form and 54, 172, and 1100 g/m^2 per day for the amorphous form, respectively [45]. He reported activation energies of 5 and −0.1 kJ/mol for amorphous and crystalline PLA, respectively [45]. In a more detailed study by Tsuji and others [46], the effects of D-lactide content, degree of crystallinity, and Mw of PLA films on WVTR were studied. They observed the WVTR of PLA films decreased monotonically with increasing crystallinity from 0% to 20%, while leveled off for crystallinity exceeding 30%; so they suggested this change due to the higher resistance of restricted amorphous regions to water vapor permeation compared with that of the free amorphous regions. They also concluded that changes in Mn of PLA films in the range of 9×10^4 to 5×10^5 g/mol and D-lactide unit content of PLA films in the range of 0% to 50% have insignificant effects on their WVTR values [3,46]. In a study by Auras and others [47], oriented PLA (OPLA) was investigated with PET and oriented polystyrene (OPS) with regard to physical, mechanical, and barrier properties. They concluded, in terms of water vapor barrier, that PET gave the best performance, followed by OPS and OPLA. In the case of oxygen barrier properties, PET showed the lowest oxygen permeability coefficients, followed by OPLA and OPS that showed very poor oxygen barrier performance. According to these results, the barrier properties of PLA are remarkable and better than those of OPS. As a consequence, PLA is suitable for packaging a wide range of food applications [3,47]. A very important property is the water content or water uptake of the biopolymer resin. PLA resins were tested and they were found to be situated near 0.5% [48].

Fragmented data on several other useful properties could be found: crimp [49], melt flow indices [49–52,58], impact properties [49,53,54], hardness [48], vapor transmission characteristics (mainly for film
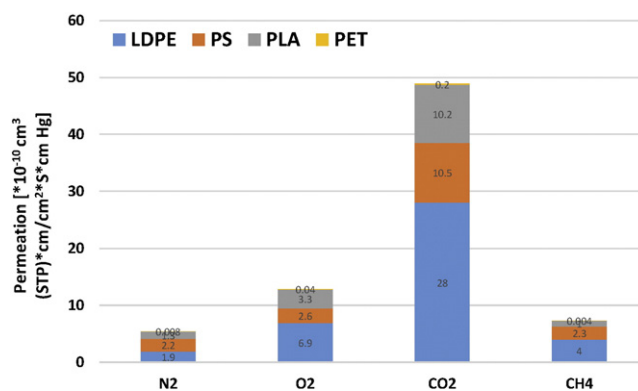

Fig. 3. Barrier properties of PLA in comparison to other common polymers, Low-density polyethylene (LDPE), polyethylene terephthalate (PET) and polystyrene (PS) at 30 °C (a) N_2, (b) O_2, (c) CO_2, and (d) CH_4.
Data collected from [38,43,44].

applications) [55–58], compostabilities [51,52,55–58], coefficients of friction [58], surface energies and contact angles with water [58,59]. Since data on these and other properties were so fragmentary, they were nearly impossible to evaluate.

There are many PLA resins for different applications with varied properties; the general characteristics of the widely-leading commercial amorphous PLA produced by NatureWorks Co., prepared by injection mold and having a 96:4 L:D ratio content, are summarized in Table 1.

2.1. Physical properties

Physical properties are important; one must know the dimensions, size, and weight requirements for a desired part or product. For example, if used by a surgeon, it must be light enough to handle precisely as implementation of material also becomes much easier and less hazardous when lighter [4]. Density can also be a very important design parameter since elevated density values imply high transportation costs

Table 1
General characteristics of a commercial amorphous PLA, injection mold grade (96:4 L:D ratio content produced by NatureWorks Co. [3]).

Characteristics	Unit	Amount	Reference
Physical:			
Mw	g/mol	66,000	[5]
Specific gravity	–	1.27	
Solid density	g/cm³	1.252	
Melt density	g/cm³	1.073	
T_g	°C	55	[60]
T_m	°C	165	
Specific heat (Cp)	J/kg °C		
190 °C		2060	
100 °C		1955	
55 °C		1590	
Thermal conductivity	W/m °C		
190 °C		0.195	[61]
109 °C		0.197	
48 °C		0.111	
Optical:			
UV light transmission			[17]
190 to 220 nm		<5%	
225 to 250 nm		85%	
>300 nm		95%	
Visible light transmission		95%	
Color			
L∗		90.64 ± 0.21	
a∗		−0.99 ± 0.01	
b∗		−0.50 ± 0.04	
Mechanical:			
Tensile strength	Mpa	59	
Elongation at break	%	7	
Elastic modulus	MPa	3500	
Shear modulus	MPa	1287	
Poisson's ratio	–	0.36	[61]
Yield strength	MPa	70	
Flexural strength	MPa	106	
Unnotched izod	J/m	195	
Notch izod impact	J/m	26	
Rockwell hardness	HR	88	
Heat deflection temp	°C	55	
Vicat penetration	°C	59	
Ultimate tensile strength	MPa	73	
Percent of elongation	%	11.3	
Young's modulus	MPa	1280	
Rheological:			
Cross WLF viscosity model:			
n		0.25	
Tau	Pa	$1.00861 * 10^5$	[61]
D1	Pa-s	$3.31719 * 10^9$	
D2	K	373	
D3	K/P	0	
A1		20.2	
A2	K	51.6	

(e.g. light car parts reduce energy consumption). Density is often used for the calculation of 'specific properties', i.e. dividing mechanical properties by the appropriate density. These specific properties consequently give a better notion of the intrinsic strength of the construct one wants to build [48]. The density of PLA in comparison to a series of biopolymers is given in Table 2.

Polymers may be either semicrystalline or amorphous. Semicrystalline polymers have regular repeating units that allow the chains to fold into dense regions called crystallites. These act as crosslinks giving the polymer higher tensile strengths and higher modulus (stiffness) as compared to an amorphous analog. No polymer can completely organize into a fully crystalline material so there are still amorphous areas in semicrystalline polymers [62]. Characteristic temperatures of a polymer can be determined in several ways, but DSC (differential scanning calorimetry) is the most cited one. The flexibility of amorphous polymers is reduced drastically when they are cooled below a characteristic transition temperature called the T_g. At temperatures below T_g, there is no segmental motion and any dimensional changes in the polymer are the result of temporary distortions of the primary valence bonds. Amorphous plastics, such as all the D,L-PLA containing ones perform best below T_g, but elastomers must be used above the brittle point [63]. The T_g can be very important when studying mechanical properties (Table 2). These properties are always obtained in standard conditions (comparable to room temperature), but one should know that they may decrease at higher temperatures and that the T_g may be a limit above which mechanical properties may degrade drastically [48].

The T_m is a more important parameter. Above it, whole polymer chain mobility occurs and the mechanical properties are virtually reduced to zero. Together with the melt points one should also look at the process temperatures. These are by definition significantly higher than the melt points because at these higher temperatures viscosity is reduced drastically in order to improve processability. These temperatures for PLA are ranging from 190 to 250 °C [49,51,52,55–58].

In the solid state, PLA can be either amorphous or semicrystalline, depending on the stereochemistry and thermal history. For amorphous PLAs, the T_g determines the upper use temperature for most commercial applications. For semicrystalline PLAs, both the T_g (~58 °C) and T_m, (130–230 °C, depending on structure) are important for determining the use temperatures across various applications. Both of these transitions, T_g and T_m, are strongly affected by overall optical composition, primary structure, thermal history, and Mw. Above T_g amorphous PLAs transition from glassy to rubbery and will behave 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 [8].

Polymers prepared from *meso-* or *rac-*lactide are in general amorphous, but by applying stereoselective catalyst, polymers having tacticity high enough for crystallization have been obtained [10]. The melt enthalpy estimated for an enantiopure PLA of 100% crystallinity ($\Delta H°_m$) by Fischer et al. [64], were 93 J/g, is the value most often referred to in the literature although higher values (up to 14 t J/g) also have been reported [65]. The T_m and degree of crystallinity are dependent on the molar mass, thermal history, and purity of the polymer, and the crystallization kinetics, and melting behavior of PLAs of different optical purity has been investigated in several studies [66–68]. It has been observed that an optical purity of at least 72–75%, corresponding to about 30 isotactic lactyl units, is required for the crystallization to take place [66]. Though, Sarasua et al. [69] have been able to crystallize a PLA of as low as 43% optical purity, when polymerizing using Salen-Al-OCH₃ (a complex resulting when reacting a Schiff base on AlEt₂Cl) as an initiator, which was explained by the preference for the formation of long isotactic sequences. Enantiomeric oligomers of fewer lactyl units only showed a molar mass dependent T_g. By utilizing stereoselective catalysts in the polymerization, semicrystalline polymers have been prepared both from *meso-*lactide [70] and *rac-*lactide [71,72]. After annealing, a T_m of 152 °C was obtained for the *meso-*PLA. The *rac-*PLA prepared by using

Table 2
Physical properties of PLA and various biopolymers.
[48].

Properties[a]	Type of biopolymer								
	Unit	PLA	PLLA	PDLLA	PGA	PDLLA/PGA 50/50	PDLLA/PGA 50/50	PCL	PHB
ρ	g/cm^3	1.21–1.25	1.24–1.30	1.25–1.27	1.50–1.71	1.30–1.40	1.3	1.11–1.146	1.18–1.262
σ	MPa	21–60	15.5–150	27.6–50	60–99.7	41.4–55.2	41.4–55.2	20.7–42	40
E	GPa	0.35–3.5	2.7–4.14	1–3.45	6.0–7.0	1–4.34	1.38–4.13	0.21–0.44	3.5–4
ε	%	2.5–6	3.0–10.0	2.0–10.0	1.5–20	2.0–10.0	2.5–10	300–1000	5.0–8.0
σ^*	Nm/g	16.8–48.0	40.0–66.8	22.1–39.4	40.0–45.1	30.9–41.2	31.8–42.5	18.6–36.7	32.0–33.9
E^*	kNm/g	0.28–2.80	2.23–3.85	0.80–2.36	5.00–4.51	0.77–2.14	1.06–2.12	0.19–0.38	2.80–2.97
T_g	°C	45–60	55–65	50–60	35–45	40–50	50–55	(−60)–(−65)	15.0–5.0
T_m	°C	150–162	170–200	am[b]	220–233	am	am	58–65	168–182

[a] ρ — Polymer density, σ — tensile strength, E — tensile modulus, ε — ultimate strain, σ^* — specific tensile strength, E^* — specific tensile modulus, T_g — glass transition temperature and T_m — melting temperature.
[b] am — amorphous and thus no melt point.

a racemic aluminum alkoxide catalyst was reported to have a T_m of 191 °C with a ΔH of 42 J/g [71]. The high T_m was believed to be the result from co-crystallization of enantiomerically pure D- and L-PLA leading to a stereocomplex formation. PLA stereocomplexes were first reported by Ikada et al. [73], when they discovered that the T_m of blended PLLA and PDLA is about 50 °C higher than for the pure enantiomeric polymers. Since that, stereocomplexes have been further investigated for both PLA oligomers and high molar mass polymers [74–76]. Table 3 lists the effects of stereochemistry and crystallinity on the mechanical properties of amorphous L-PLA, annealed L-PLA, and amorphous D,L-PLA [5,77]. Perego et al. [78] studied the effects of Mw and crystallinity on the mechanical properties of PLA by polymerizing pure L-lactide and D,L-lactide to create amorphous or semicrystalline polymers. They found that the T_g wasn't greatly affected by the stereo chemical makeup or the range of Mws tested and that PLA with a Mw of 22,000 g/mol has a T_g of 55 °C, which is only 4–5 °C lower than that predicted for PLA of infinite Mw [5,78]. Other physical properties can be important including transparency/opacity, color (some items might use color to aid in identification), esthetics, water absorption, lubricity, and wear resistance. Most of these properties are oriented to specific applications and the data were too fragmentary to be included in the tables and graphs.

2.2. 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. Semicrystalline PLA is preferred over the amorphous polymer when higher mechanical properties are desired. Semicrystalline PLA has an approximate 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% [10,79].

Different from thermal properties, the mechanical properties and crystallization behavior of PLA are very dependent on the Mw and

stereo chemical makeup of the backbone [5]. For example, it has been shown that tensile modulus of PLLA increases by a factor of 2 when the Mw is raised from 50 to 100 kDa [10], and tensile strengths of 15.5, 80 and 150 MPa, for varying the Mw from 50 over 150 to 200 kDa respectively [48]. On the other hand, the stereo chemical makeup is very easily controlled by the polymerization with D-lactide, L-lactide, D,L-lactide, or *meso*-lactide, to form random or block stereocopolymers, while the Mw is directly controlled by the addition of hydroxylic compounds (i.e., lactic acid, water, alcohols) [77]. The ability to control the stereochemical architecture allows precise control over the speed and degree of crystallinity, the mechanical properties, and the processing temperatures of the material.

Pure PDLA or PLLA has a crystalline equilibrium T_m of 207 °C but typical T_m are in the 170–180 °C range [80]. This is due to small and imperfect crystallites, slight racemization, and impurities. It has also been observed that a 1:1 mixture of pure PLLA with pure PDLA will yield an insoluble gel formed by the stereocomplexation (racemic crystallite) of the two polymers during crystallization or polymerization [75,76]. Superior mechanical properties have been achieved by stereocomplexation of enantiomeric PLAs, which was ascribed to formation of stereocomplex crystallites giving intermolecular crosslinks. This pure stereocomplex has a T_m of 230 °C and mechanical properties greater than either pure polymer [5,75,76,81]. Using low Mw PLA, it has been reported that ultimate tensile strengths were 50 MPa for the 1:1 stereocomplex versus 31 MPa for pure L-PLA. Variations such as block and star copolymers of D- and L-lactide show this same stereocomplexation [77].

In the early 90's, Lalla and Chugh polymerized D,L-lactide using 2% (*w/v*) and 0.1% (*w/v*) zinc oxide and stannous chloride catalyst systems, respectively, and having studied their mechanical properties [82] (Table 4), they found that the wide variance in the oriented properties is due to the degree of orientation and stereo chemical composition of various PLA samples. Table 3 lists the effects of stereochemistry and

Table 3
Effects of stereochemistry and crystallinity on mechanical properties.
[5,77,78].

Properties		Annealed		
		PLLA	PLLA	PDLLA
Tensile strength	MPa	59	66	44
Elongation at break	%	7	4	5.4
Modulus of elasticity	MPa	3750	4150	3900
Yield strength	MPa	70	70	53
Flexural strength	MPa	106	119	88
Unnotched izod impact	J/m	195	350	150
Notched izod impact	J/m	26	66	18
Rockwell hardness		88	88	76
Heat deflection temperature	°C	55	61	50
Vicat penetration	°C	59	165	52

Table 4
Comparison of physical properties of high Mw PLA.
[5].

Properties		Unoriented	Oriented[a]
Ultimate tensile strength	psi $* 10^3$, MPa	6.9–7.7, 47.6–53.1	6.9–24, 47.6–166
Tensile yield strength	psi $* 10^3$, MPa	6.6–8.9, 45.5–61.4	N/A
Tensile modulus	psi $* 10^3$, MPa	500–580, 3447–4000	564–600, 3889–4137
Notched izod impact	ft-lb./in	0.3–0.4	N/A
Elongation at break	%	3.1–5.8	15–160
Rockwell hardness		82–88	82–88
Specific gravity	g/cm^3	1.25	1.25
T_g	°C	57–60	57–60

[a] Results depend on degree of orientation and isomer content.

crystallinity on the mechanical properties of amorphous PLLA, annealed PLLA, and amorphous PDLLA. On annealing, the impact resistance increased due to the crosslinking effects of the crystalline domains, while the tensile strength increased, presumably due to the stereo regularity of the chain [77,78].

The mechanical properties of PLA that are the most intensively studied in comparison to a series of biopolymers include tensile properties: tensile strength (σ, in MPa), tensile modulus (E, in GPa) and ultimate strain (ε, in %) and polymer density (ρ, in g/cm^3). Data summary are given in Table 2 [48]. It has been found that tensile properties are clearly best for the densest reported polymers, especially for poly(glycolic acid) (PGA). PCL, on the other hand, seems to be the weakest polymer with a remarkable high strain at failure. The data on flexural properties was too limited to be used for comparison. However, flexural and tensile properties are mostly correlated anyway and the tendencies found here are probably the same as found when comparing flexural properties [48].

PLA-specific mechanical properties — specific tensile strength (σ^*, in Nm/g) and specific tensile modulus (E^*, in kNm/g) are obtained by dividing the original mechanical properties by the polymer density: In Table 2, PLA specific tensile strength and tensile modulus ranges compared to different biopolymers are given. It is a useful tool in the case of intending to use the biopolymers as structural elements without needing reinforcement. These specific properties are important as they determine the dimensions necessary for a certain mechanical strength or stiffness. Contrary to usefulness as a composite matrix, in this case, PGA and PLLA seem the best choices, whilst PCL and also polyhydroxybutyrate (PHB, σ^* 8.8 MPa and E^* 7.8 MPa) are clearly the worst ones [48].

It should be emphasized that the mechanical properties of polymers of similar Mw, but prepared by different polymerization processes, have been shown not to differ. This has been noticed for PLAs prepared by both polycondensation and ring-opening polymerization [83].

3. PLA property variation during

3.1. Processing, thermal degradation and recyclability

Although PLA can be processed on standard converting equipment with minimal modifications, its unique properties must be taken into consideration in order to optimize the conversion of PLA to molded parts, films, foams, and fibers, etc. Several processing technologies for PLA have been developed for large-scale production lines, depending on the intended application, including drying and extrusion [8,84], injection molding [85–87], injection stretch blow molding [2,88,89], casting (film and sheet) [89–91], extrusion blown film [92–94], thermoforming [47,95,96], foaming [97–102], fiber spinning [103–107], electro spinning [108–116], blending [117–120], compounding [11,121–124] and nanocompositing [125–137]. Lim et al. [138] reported, in a comprehensive study, on these techniques for PLA processing highlighting the large scale production challenges and performance improvements. Due to the fact that the first 4 aforementioned techniques are the most common processing technologies and the most studied, we have focused on these techniques for highlighting the thermal and mechanical PLA changes during processing.

Processing effects on PLA is an important issue and independent research field where the polymer must possess adequate thermal stability to prevent degradation of its Mw and physical properties. PLA undergoes thermal degradation at temperatures above 200 °C (392 °F) and by hydrolysis, lactide reformation, oxidative main chain scission, and inter- or intramolecular transesterification reactions. PLA degradation is dependent on time, temperature, low-Mw impurities, and catalyst concentration [5]. Catalysts and oligomers decrease the degradation temperature and increase the degradation rate of PLA. In addition, they can cause viscosity and rheological changes, fuming during processing, and poor mechanical properties. PLA homopolymers have a T_g and T_m of about 55 °C and 175 °C, respectively. They require processing temperatures in excess of 185–190 °C [139]. At these temperatures, unzipping and chain scission reactions leading to loss of Mw, as well as thermal degradation, are known to occur. Consequently, PLA homopolymers have a very narrow processing window. The most widely used method for improving PLA processability is based on T_m depression by the random incorporation of small amounts of lactide enantiomers of opposite configuration into the polymer (i.e., adding a small amount of D-lactide to the L-lactide to obtain PDLLA). On the other hand, unfortunately, the T_m depression is accompanied by a significant decrease in crystallinity and crystallization rates [139].

Maspoch and coworkers [140] extensively studied the chemical structure, crystallinity, thermal stability and mechanical properties of PLA after being processed by means of industrial thermoplastic processing methods (injection and extrusion followed by injection) with or without a further thermal treatment (i.e. annealing) (Table 5). They found that processing of PLA was responsible for a decrease in Mw, as determined by GPC, due to chain scission. The degree of crystallinity was evaluated by means of DSC and X-ray diffraction. It was found that mechanical processing led to the quasi disappearance of crystal structure whereas it was recovered after annealing. 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 proportion of methyl groups increased, thus indicating the presence of a different molecular environment. The thermal stability of various materials was established by calculating characteristic temperatures from thermograms and conversion derivative curves. Finally, the mechanical behavior was determined by means of tensile testing (Young's modulus, yield strength and elongation at break). They found that fast cooling after injection molding did not allow the polymer chains to rearrange into a crystalline structure. For this reason, presupposed bands were not present for injected and extruded/injected materials. On the contrary, after annealing, an important crystalline structure was created. These findings were corroborated by DSC (degrees of crystallinity of 4% for injected material, 8% for extruded/injected material and 33–35% for annealed materials) and X-ray diffraction (45–47% for annealed materials). Thermal decomposition occurred within the temperature range of 325–375 °C. Raw material exhibited slightly higher thermal stability (~331 °C) than processed materials (323–325 °C) (Table 5). After annealing, samples showed an increase in Young's modulus (5–11%) and in yield strength (15–18%), which is explained by the higher degree of crystallinity of annealed materials, with its subsequent decrease in chain mobility. Extruded/injected materials showed a significant increase in elongation at break (32–35% higher), compared to injected materials. It is attributed to a higher number of chains, due to chain scissions in reprocessed materials, Table 6.

For the case of injection molding of PLA a Mw decrease of 14–40% was reported [78]. Coupled extrusion and injection molding also resulted in a Mw reduction. As found by viscosity studies using the Mark–Houwink equation:

$$[\eta] = 5.50 * 10^{-4} \, Mv^{0.639}. \tag{1}$$

Viscosimetric studies revealed that there was a 21.85% and 41.00% Mw decrease when the PDLLA was injection molded and extruded,

Table 5
DSC parameters for the thermal transitions observed concerning injected (PLA-I) and extruded/injected (PLA-EI) materials (without/with-A-annealing).
[140].

Sample	Heating	T_g (°C)	Cold Crystallization		Melting		XRD
			T_c (°C)	Xc-c (%)	T_c (°C)	Xc-c (%)	Xc (%)
PLA-I	1st	65	125	4.1	154	4.5	
PLA-I	2nd	64	133	0.3	156	0.3	
PLA-IA	1st	67	–	–	154	33	45.1
PLA-EI	1st	64	128	8.4	154	7.8	
PLA-EI	2nd	64	133	2	156	1.9	
PLA-EIA	1st	68	–	–	154	34.5	47.3

Table 6
Main mechanical properties of processed PLA (Young's modulus, yield strength and elongation at break) processed by injection (PLA-I) and extrusion/injection (PLA-EI) without or with annealing (PLA-EIA).
[140].

Property	Unit	PLA-I	PLA-EI	PLA-IA	PLA-EIA
E	GPa	3.7 ± 0.1	3.9 ± 0.1	4.1 ± 0.1	4.1 ± 0.1
σ_y	MPa	65.6 ± 1.3	65.2 ± 0.9	75.4 ± 0.9	77.0 ± 1.1
ε_b	%	4.0 ± 0.8	5.4 ± 0.6	2.5 ± 0.2	3.3 ± 0.3

respectively. A possible explanation for the increase in the viscosity-average Mw of the injection-mold-grade PDLLA is that during processing there was polymer chain entanglement, which led to an increase in the hydrodynamic volume, intrinsic viscosity, and, hence, the Mw of the polymer.

Bigg [141] reported the effect of temperature on the degradation of PLA and its copolymers. PLA quickly loses its thermal stability when heated above its T_m. A significant level of molecular degradation occurred when PLA was held 10 °C above its T_m (~160 °C) for a sustained period of time, Fig. 4. Migliaresi and coworkers showed that thermal degradation was due to chain splitting and not hydrolysis. They observed Mw reductions greater than 50% and concluded that large Mw reductions were unavoidable. Oxidation of PLA didn't occur to a measurable extent during thermal degradation [142].

The PLLA has a narrow window of processing, (12 °C), whereas a 10/90 PDLLA copolymer has a much wider range of processing (40 °C) due to its lower T_m. Bigg [141] reported tables, graphs, and DSC thermograms of various investigated PLA samples following processing methods. The effect of temperature on the Mw of PLA, and processing conditions on the mechanical properties of PLA are summarized in Fig. 4 and Table 7 respectively.

PLA Thermal degradation — One of the drawbacks of processing PLA in the molten state is its tendency to undergo thermal degradation, which is related both to the process temperature and the residence time in the extruder and hot runner. PLA is thermally unstable and exhibits rapid loss of Mw and consequent erosion of its mechanical properties as well. PLA thermal degradation partially starts at temperatures lower than the T_m of the polymer, but the degradation rate rapidly increases above the T_m. The ester linkages of PLA tend to degrade during thermal processing or under hydrolytic conditions [143].

Different factors like particle/device size and polymer shape, temperature, moisture, crystallinity, % D-isomer, residual lactic acid concentration, Mw and its distribution, water diffusion, and metal impurities from the catalyst will affect the polymer degradation rate [3]. Thermal degradation of PLA is very complex and various mechanisms have been postulated, including various non-radical and radical reactions including random chain scission reactions, depolymerization, oxidative degradation, intramolecular and intermolecular transesterifications, hydrolysis, pyrolytic elimination and radical reactions [5,17, 144–148]. The degradation of PLA during the melt is mainly caused by intramolecular transesterification reactions leading to cyclic oligomers of lactic acid and lactide. Simultaneously, there is a recombination of the cyclic oligomers with linear polyesters through insertion reactions, while molecules with longer chain lengths are favored. In the case of intermolecular transesterification, a reaction between two ester molecules exchanges their radicals, thus leading to a variation of the distribution of Mws [140]. Only a few studies considered the intermolecular transesterification [149,150] as a mechanism present during degradation in the melt, which can be minimized by the addition of benzoyl peroxide [151], 1,4-dianthraquinone [152] and other stabilizers. Kopinke et al. proposed that above 200 °C, PLA can degrade through intra- and intermolecular ester exchange, cis-elimination, radical and concerted non-radical reactions, resulting in the formation of CO, CO_2, acetaldehyde and methylketene [138,153]. In contrast, McNeill and Leiper proposed that thermal degradation of PLA is a non-radical, "back-biting" ester interchange reaction involving the –OH chain ends [152]. Depending on the point in the backbone at which the reaction occurs, the product can be a lactide molecule, an oligomeric ring, or acetaldehyde plus CO (Fig. 5). The formation of acetaldehyde is expected to increase with increasing process temperature due to the increased rate of the degradation reactions. Above 230 °C a thermal degradation of acetaldehyde was reported by McNeill and Leiper [152], involving a complex chain reaction to form methane and CO at the elevated temperature (Fig. 5). McNeill and Leiper also proposed that the formation of butane-2,3-dione, another detected byproduct, is likely caused by the radical combination of acetyl radicals from the chain reaction (Fig. 5) [152]. PLA hydrolysis lead to the cleavage of ester linkages, with the production of acid and alcohol groups. Ester splitting depends on water content, while pyrolytic elimination leads to the formation of an acid and a molecule with acrylic end groups. This is a less important side reaction [140]. The pyrolytic elimination results in species containing conjugated double bonds due to the carbonyl groups [147]. PLA radical degradation only needs be taken into consideration at temperatures above 250 °C. These reactions can be assumed to start with either an alkyl-oxygen or an acyl-oxygen homolysis [153].
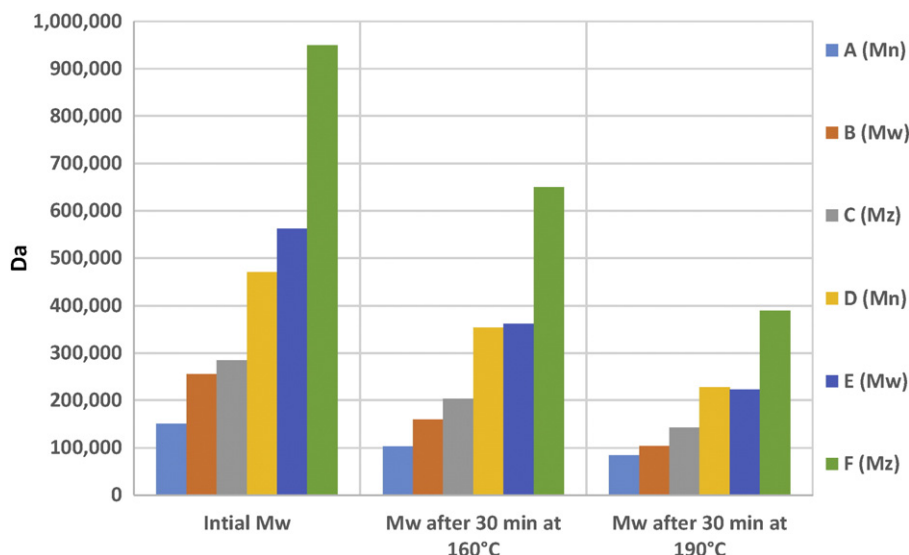

Fig. 4. Effect of temperature on the molecular weight (Mw) and number-average molecular weight (Mn) of 90/10 PLA copolymer.

Table 7
Effect of processing conditions on the mechanical properties of PLA copolymers.
[5,141].

Copolymer ratio (L/D,L)-PLA	Process condition	Tensile strength, MPa	Young's modulus, GPa	Elongation, %	Mw, g/mol
100/0	Injection molded, crystallized	64.8	4	–	800,000
90/10	Injection molded, amorphous	53.4	1.03	4.6	–
90/10	Injection molded, crystallized	58.6	1.29	5.1	–
90/10	Extruded, biaxially oriented, strain crystallized	80.9	3.41	41.2	145,000
90/10	Extruded, biaxially oriented, strain crystallized, heat set	70.1	2.76	20.7	145,000
95/5	Extruded, biaxially oriented, strain crystallized	68.6	1.88	56.7	120,000
95/5	Extruded, biaxially oriented, strain crystallized, heat set	60.7	1.63	63.8	120,000
80/20	Injection molded, amorphous	51.7	2.1	5.7	268,000
80/20	Extruded, biaxially oriented, strain crystallized	84.1	2.94	18.2	268,000
80/20	Extruded, biaxially oriented, strain crystallized, heat set	80.1	2.54	32.3	268,000

Yu and others [148] have developed a mathematical model to describe the Mw and polydispersity index (PDI) in PLA thermal degradations. They claimed model ability to predict these parameters changes for PLLA assigned for thermal degradation. Their model was based on the random chain scission mechanism, effects of temperature, and time on the Mw and PDI.

PLA recycling — PLA thermo-mechanical recycling has been extensively studied. The general trend is a slight decrease of its mechanical properties after several injections or molding processes according to the nature of the polymer [140]. The major problem of recycling is the thermal stability of PLA, which has been reported as a complex process [154]. This serious issue raises the question of recyclability of industrial production waste and packaging wastes as well. Grohens and coworkers reported on the evolution of rheological and mechanical properties of polymer with the number of recycling cycles up to 7 cycles [155]. They found that only the tensile modulus remains constant with the thermo-mechanical cycles. In contrast, stress and strain at break, rheological factors and the modulus and hardness probed by nanoindentation decrease for PLA (Table 8). Stress at break was found to decrease from 66.5 to 56.0 and 23.0 MPa, and strain at break from 0.060 to 0.025 and 0.005 mm/mm after 3 and 7 injection cycles respectively [155]. This dramatic effect is ascribed to a large decrease in the Mw due to several different complex degradation processes which are discussed (Fig. 6). Reprocessing of PLA induces an increase of crystallization during cooling with the number of injection cycles. This can be explained by higher chain mobility due to chain scission during injection (Table 9). The addition of stabilizers suppresses this crystallization during cooling. Moreover, most of the mechanical performances of PLA become rapidly too weak for an industrial application of the polymer. This decrease could be explained by the strong degradation of PLA during processing which yields large chain scission evidenced by rheological experiments and Mw measurements (Fig. 6 and Table 8).

Several solutions have been studied to avoid this issue mainly to minimize the PLA thermal degradation by several routes: 1) free radicals stabilizer (i.e. Quinone) [155], was found to be an efficient stabilizer to trap free radicals and maintain PLA chain length with time at the processing temperatures. 2) Reinforcement biocomposite (i.e. flax fibers $20 \le X < 30\%$) as reported by Endo and coworkers [154]. They have found that Flax/PLLA biocomposites have been shown to be very promising biocomposites and exhibit interesting recycling properties, especially if it can be considered that in the industrial process recycled material would include both virgin and recycled matter (Tables 8 and 9). Furthermore, with natural fibers as reinforcement end-of-life composting is possible. Finally, PLA industrial waste can support moderate recycling as well as other polyesters which is a significant improvement of the environmental impacts of this polymer. Although to be complete, biodegradation of this stabilized or reinforced PLA has to be confirmed in forthcoming studies.

3.2. Biodegradation

Polymer degradation occurs mainly through scission of the main chains or side chains of macromolecules. In nature, polymer degradation is induced by thermal activation, hydrolysis, biological activity (i.e., enzymes), oxidation, photolysis, or radiolysis [156]. Biodegradation has been accomplished by synthesizing polymers that have
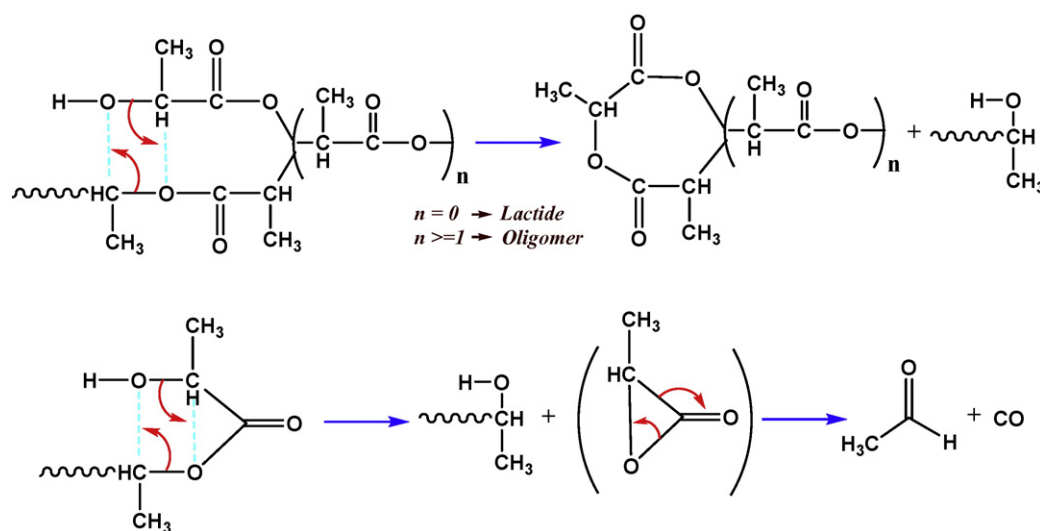
Fig. 5. Thermal degradation of PLA.
Adapted from McNeill and Leiper [152].

Table 8
Evolution of mechanical properties of flax/PLLA biocomposites at different fiber contents during recycling.

Mechanical properties after	Mechanical properties	Material		
		PLLA	Flax/PLLA biocomposites (20%)	Flax/PLLA biocomposites (30%)
1 cycle	E (MPa)	3620 ± 67	6395 ± 515	7320 ± 380
	σ (MPa)	60.1 ± 1.7	55.5 ± 4.1	53.1 ± 2.8
	ε (%)	2.4 ± 0.4	1.4 ± 0.2	1.1 ± 0.1
6 cycles	E (MPa)	3518 ± 192	5633 ± 247	6760 ± 183
	σ (MPa)	27.8 ± 8.9	29.8 ± 3.9	16.3 ± 2.7
	ε (%)	0.9 ± 0.4	0.7 ± 0.1	0.2 ± 0.1
Evolution of mechanical properties cycles 1 to 6 (%)	E (MPa)	−2.8	−12	−7.7
	σ (MPa)	−53.8	−46.3	−69.4
	ε (%)	−72.5	−47.6	−77.7

hydrolytically unstable linkages in the backbone. The most common chemical functional groups are esters, anhydrides, orthoesters, and amides [157]. As a polyester, PLA's biodegradation behavior is a critical characteristic of the material and the most important reason for the high interest in its use in medical applications and industry. PLA degradation was studied in animal and human bodies for medical applications like implants, surgical sutures, and drug delivery materials. In these environments, PLA is initially degraded by hydrolysis and the soluble oligomers formed are metabolized by cells [44]. As illustrated in Fig. 7A, cleavage of the ester linkages by absorbed water produces a successive reduction in Mw. The rate of this hydrolytic degradation is primarily temperature- and humidity-dependent. Fig. 7A also illustrates the rate of hydrolytic degradation as a function of temperature [12]. PLA has a relatively long half-life of hydrolysis due to steric effects where the alkyl group hinders the attack by water, for example, PLLA stent or fibers exposed to in vivo conditions do not begin to degrade until after approximately 12 months [158,159]. On the other hand, PLA degradation upon disposal in the environment (environmental degradation) is more challenging because PLA is largely resistant to attack by microorganisms in soil or sewage under ambient conditions. The polymer must first be hydrolyzed at elevated temperatures (about 60 °C) to reduce the Mw before biodegradation can commence. Under conditions of high temperature and high humidity, as in active compost, for example, PLA will degrade quickly and disintegrate within weeks to months [8]. The primary mechanism of degradation occurs by a two-step process starting also with hydrolysis, followed by bacterial attack on the fragmented residues. During the initial phases of degradation, the high Mw polyester chains hydrolyze to lower Mw oligomers. As the average Mw reaches approximately ~10,000 Da, micro-organisms present in the soil begin to digest the lower Mw lactic acid oligomers, producing carbon dioxide and water (Fig. 7B) [12]. The rate of hydrolysis is accelerated by acids or bases and is dependent on moisture content and temperature. PLA products rapidly degrade in both aerobic and anaerobic composting conditions [8].

The process is also dependent upon the chemical and physical characteristics of the polymer. These include diffusivity, porosity,

morphology, crosslinking, purity, chemical reactivity, mechanical strength, thermal tolerance, and resistance to electromagnetic radiation in some cases [160]. PLA degradation has been found to be dependent on a range of factors, such as Mw, crystallinity, purity, temperature, pH, presence of terminal carboxyl or hydroxyl groups, water permeability, and additives acting catalytically that may include enzymes, bacteria or inorganic fillers [161]. Under typical use conditions, PLA is very stable and will retain its Mw and physical properties for years. This is typified by its growing use in clothing and durable applications. High Mw PLA is also naturally resistant to supporting bacterial and fungal growth, which allows it to be safely used for applications such as food packaging and sanitation. A review done by Tsuji gives an excellent account of PLA degradation studies [23].

For implantable medical devices, once implanted in the body, the biodegradable device should maintain mechanical properties until it is no longer needed and then be degraded, absorbed, and excreted by the body, leaving no trace. However semi-crystalline PLA biodegradation occurs in two phases. In the first phase, water penetrates the bulk of the device, preferentially attacking the chemical bonds in the amorphous phase (due to the ability of water to permeate within the amorphous phase but not the crystalline phase) and converting long polymer chains into shorter, ultimately water-soluble fragments. Because this occurs in the amorphous phase initially there is a reduction in Mw without a loss in physical properties as the device matrix is still held together by the crystalline regions. The reduction in Mw is soon followed by a reduction in physical properties as water begins to fragment the device [62]. Yield strain, yield stress, and elongation to failure all decrease. These changes can have consequences for devices which are load bearing throughout their degradation process [162]. In the second phase, enzymatic attack of the fragments occurs. The metabolizing of the fragments results in a rapid loss of polymer mass (illustrated by Fig. 8) [62].

However stereochemistry, crystallinity, Mw, and applied loads are the main factors influencing the rate of degradation of PLA [163]. The degradation–absorption mechanism is the result of many interrelated factors, including 1) the chemical stability of the polymer backbone, 2) the presence of catalysts, 3) additives, impurities or plasticizers, 4) the geometry and location of the device. The balancing of these factors to tailor an implant to slowly degrade and transfer stress to the surrounding tissue as it heals at the appropriate rate is one of the major challenges facing researchers today [62].

The factors which accelerate polymer degradation are the following: 1) More hydrophilic monomer. 2) More hydrophilic, acidic end groups. 3) More reactive hydrolytic group in the backbone. 4) Less crystallinity. 5) Smaller device size. The location of the device can play an important role in the degradation rate of implants. Large devices implanted in areas with poor vascularization may degrade and overwhelm the body's ability to flush away degradants. This leads to a buildup of acidic by-products. An acidic environment will catalyze the further degradation and cause further reduction in pH and may also be responsible for adverse tissue reactions [164]. It has recently been shown that the rate of degradation is also dependent on the magnitude of the applied stress
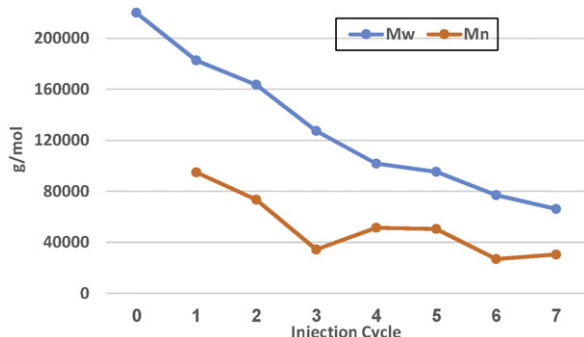

Fig. 6. Evolution of molecular weight (Mw) and of PLLA as a function of injection cycles.

Table 9
Evolution of thermal properties of PLLA, flax/PLLA biocomposites 20% and 30% as a function of injection cycles [154].

Material	Injection cycles	T_g (°C)	First cooling		Second heating				
			T_c (°C)	ΔH_c (J/g)	T_c (°C)	ΔH_c (J/g)	T_m (°C)	ΔH_m (J/g)	χ (%)
PLLA	1	66.5	–	–	123.3	36.5	175.1	36.3	38.7
	3	59.9	93.6	15.9	104.3	16.4	171.1	38.4	41
	6	56.5	97.7	38.9	89.8	0.6	167.3	49.9	53.2
flax/PLLA biocomposites (20%)	1	61.1	–	–	110.9	36.5	170.7	37.2	39.7
	3	56.9	89.1	16.8	90.4	21.6	167.4	44.2	47.1
	6	54.9	92.4	41.3	–	–	163.9	47.1	50.2
flax/PLLA biocomposites (30%)	1	62.2	114.5	45.6	–	–	170.4	44.0	47
	3	57.8	112.5	45.6	–	–	163.9	51.9	55.3
	6	41.7	87.1	35.9	85.1	5.1	152.3	40.2	43.2

T_g, T_c, ΔH_c, T_m, ΔH_m and χ represent, respectively, the glass transition temperature, the crystallization temperature, the crystallization enthalpy, the melting temperature, the melting enthalpy and the degree of crystallinity.

[165]. Implants under stress degrade faster. It was proposed that the stressed implant may form microcracks increasing the surface area exposed to water [164].

Lactide commercially available devices and sutures degrade by bulk erosion [166]. This two-stage degradation mechanism has led one researcher to report that the degradation rate at the surface of large lactide-glycolide implants is slower than the degradation in the interior [62]. Initially, degradation does occur more rapidly at the surface due to the greater availability of water. The degradation products at the surface are rapidly dissolved in the surrounding fluid and removed from the bulk polymer. In the interior of the device the inability of large polymeric degradation products to diffuse away from the bulk device results in a local acidic environment in the interior of the implant. The increased acidic environment catalyzes further degradation resulting in accelerated hydrolysis of the ester linkages in the interior. Athanasiou and coworkers [167] showed that low-porosity implants from 50/50 PDLLG degrade faster than high-porosity implants. They have attributed this to the quick diffusion of low pH degradants from the interior of the high-porosity devices. Polymer scientists have used this knowledge to tailor the degradation rates of biodegradable polymers. Hydrolysis of the crystalline domain occurs mainly by a surface erosion mechanism. Bulk hydrolysis occurs faster than surface hydrolysis. PLA first degrades in the more loosely packed chain folding regions. In the later stages of hydrolysis, the more persistent crystalline region's Mw approaches that of the lamellar thickness, and the degradation mechanism will change to that of surface erosion [8].

Certain impurities and classes of additives increase the rate of PLA hydrolysis, including lactide and oligomers and some acidic and basic additives. Strategies for stabilizing PLA to hydrolysis include reducing the level of residual monomer to as low a level as possible and lowering the water concentration in PLA and preventing autocatalysis. The equilibrium moisture content can be decreased by controlling morphology (highly crystalline, oriented, fibular structure). Reduction in the rate of autocatalysis has been accomplished by incorporation of basic, buffering salts such as $CaCO_3$ [8]. A second approach to preventing autocatalysis was reported by Lee et al. [168] by functionalizing the PLA end group chemistry. End groups studied included OH–, COOH–, Cl–, and NH_2–. NH_2- and Cl-terminated PLAs were more resistant to thermal and hydrolytic degradation. The thermal stability of the OH-terminated PLA was poor (likely due to lactide formation), and the hydrolytic stability of the COOH-terminated PLA was also poor. Alternatively, storage stability, at lower temperatures and/or lower humidities of the PLA products are considered to be acceptable [12].

Tsuji and Suzuki also studied stereocomplex degradation over the course of 30 months, in 7.4 pH buffer solution using 1:1 blends and nonblended films prepared from PLLA and PDLA [169]. Properties and Mw were monitored with GPC, tensile tests, DSC, SEM, optical polarizing microscopy, x-ray diffractometry, and gravimetry. They found that the rate of Mw loss, tensile strength, Young's modulus, melting temperature, and mass remaining of the films in the course of hydrolysis was more stable for the stereocomplex film than for the nonblended films [169].
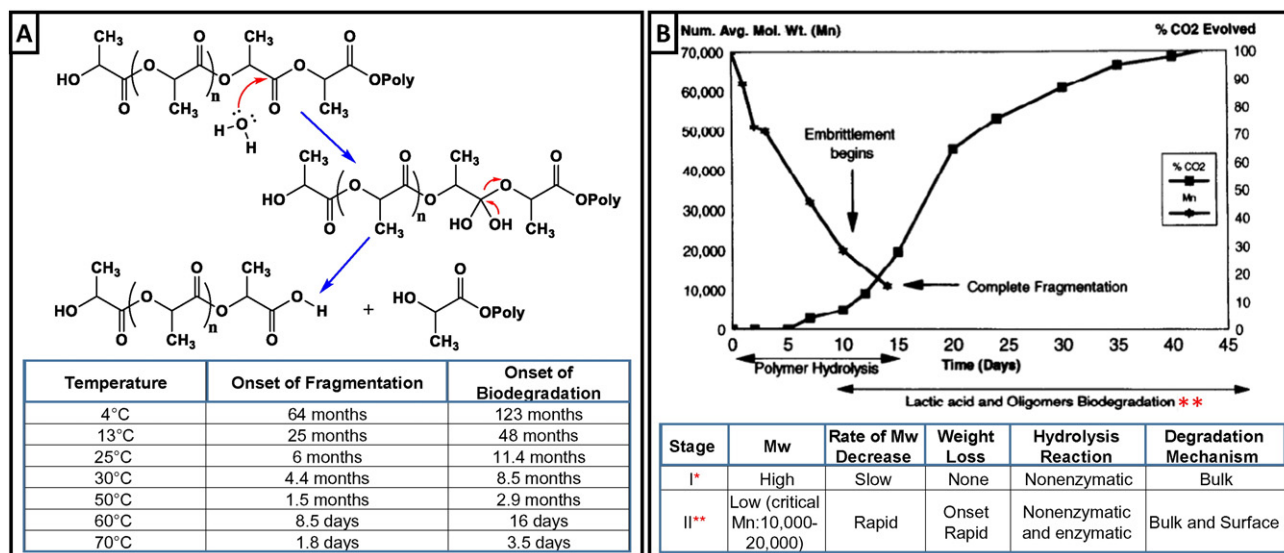

Fig. 7. (A) Hydrolysis of PLA and length of time taken to degrade to PLA in water. (B) Biodegradation of polylactic acid in 60 °C compost. (Adapted from [12]).
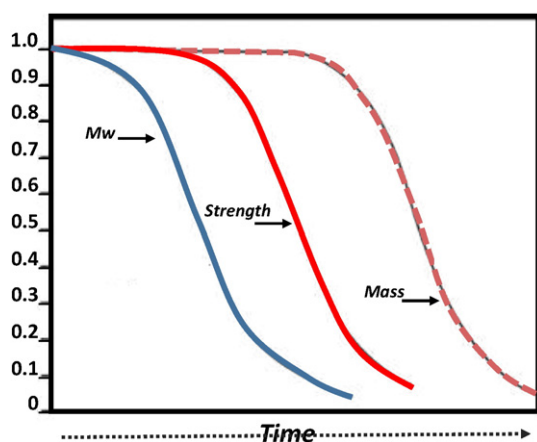
Fig. 8. Generic curves showing the sequence of polymer-molecular weight (Mw), strength, and mass-reduction over time.
(Adapted from [62]).

3.3. Packaging and sterilization

Packaging materials need to show sufficient flexibility and resilience to compensate for the reduction in volume to preventing irreversible deformations [170]. A big effort for reducing packaging waste has encouraged the exploration of new bio-based packaging materials, such as edible and biodegradable films from renewable resources. Unfortunately, so far the use of biodegradable films for packaging applications has been strongly limited because of the poor barrier properties and weak mechanical properties shown by natural polymers. For this reason natural polymers were frequently blended with other synthetic polymers or, less frequently, chemically modified with the aim of extending their applications in more special or severe circumstances [170]. PLA offer numerous opportunities in packaging applications. So far, the large-scale use of biodegradable PLA as packaging material is partially hampered by its high cost as well as low performances.

In the field of packaging, 2 specific areas have received close attention, namely high-value films and rigid-thermoformed containers. PLA brings a new combination of attributes to packaging, including stiffness, clarity, dead fold and twist retention, low-temperature heat sealability, as well as an interesting combination of barrier properties including flavor, and aroma barrier characteristics. For extending PLA applications, the properties like impact strength or flexibility, stiffness, barrier properties, thermal stability, and production costs must be improved. Generally, modifiers have been studied to improve stiffness at elevated temperatures, reduce cost, or increase the degradation rate of PLA. Some efforts of PLA modifications in the field of packaging are presented in Table 10 [3]. Alternative approaches have been reported also with the help of nanotechnology and providing safe PLA nanocomposites so that many of its weakness compared to petrochemical-based polymer improvement such as gas barrier, mechanical and thermal properties will be resolved and expand its application [172,173].

Sterilization is an important aspect where many reusable, disposable, packaging and implant materials will need to be sterilized before use [4]. For example, in the medical field, it is essential to sterilize all medical implants after fabrication and prior to their surgical placement to reduce the risk of infections and associated complications [203]. So far various methods for sterilization have been developed like steam, dry heat, ethylene oxide (EtO), electron beam, γ-radiation, UV, a combination of these methods or other less-known techniques such as plasma etching [62,164,166,204]. PLA based polymers in addition to being susceptible to damage by moisture and radiation, are heat sensitive due to their thermoplastic nature. Thus, the selection of the correct sterilization technique for PLA for implants is crucial to their physical and mechanical properties, and hence to their performance in vivo and in some cases it may cause early implant failure [203]. Accordingly, PLAs must be able to withstand sterilization conditions and still maintain their properties for the intended use [4]. Of particular importance is hydrolytic stability for steam sterilization, thermal resistance to

Table 10
Summary of PLA modifications for packaging applications.

Type of modification	Treatment or added material	Effect	Reference
Modifier	Citrate esters	$\downarrow T_g$ and improving the elongation at break	[174]
	Triacetine or tributyl citrate	$\downarrow T_g$ and $\uparrow$crystallinity	[175]
	Oligomeric malonate esteramides	$\downarrow T_g$ and improvement of the strain at break	[176]
	4,4-Methylene diphenyl diisocyanate	$\uparrow T_g$ to 64 °C, $\uparrow$tensile strength to 5.8 MPa good nucleating agent for PLA crystallization	[177]
	Polyglycerol esters	Improving the elongation at break	[178]
	Polyethylene glycol and acetyl triethyl citrate	$\downarrow T_g$ and $\uparrow$crystallization rate	[179]
	Talc	$\uparrow$Ductility at more than 10%	[179]
	Bifunctional cyclic ester	Enhance PLA toughness	[180]
	Poly(1,3-butylene adipate)	$\downarrow$Storage modulus and T_g but $\uparrow$elongation at break	[181]
	Polycarbodiimide	Improve the thermal stability at 210 °C for up to 30 min	[182]
Blending with:	Polyvinyl acetate	$\uparrow$Tensile strength and percent elongation	[183]
	Poly ethylene oxide (PEO)	Elongation at break of more than 500%	[184]
	Poly ε-caprolactone (PCL)	High improvement in mechanical properties	[185]
	Poly ethylene glycol (PEG)	Enhance the crystallinity of PLA and biodegradability	[186]
	Starch with different plasticizers	Lowering the price, $\downarrow T_g$, and $\uparrow$crystallinity and $\uparrow$biodegradability	[187–189]
	Polyvinyl alcohol and starch	$\uparrow$Tensile strength	[190]
	Ethylene vinyl alcohol (EVOH)	Improvement of mechanical, thermal, and biodegradability properties	[191]
	Polycarbonate	Improvement of mechanical properties and biodegradation rate	[192]
	Polyethylene glycidylmethacrylate (PEGMA)	Production of super-tough PLA materials	[193]
Copolymerization of PLA and:	DL-mandelic acid	$\uparrow T_g$ and improving mechanical properties	[194]
	ε-Caprolactone	Improving the decomposition temperatures and crystallinity	[195]
	Polyvinyl chloride	Improving strength and toughness	[196]
	Acrylonitrile butadiene styrene	Improved impact strength and elongation at break with a slight loss in modulus and tensile strength	[197]
Physical treatment	Vacuum compression-molding and solid-state extrusion techniques	Flexural strength and flexural modulus were improved up to 221 MPa and 8.4 GPa, respectively.	[198]
	Orientation	Significant improvement in tensile and impact properties	[199]
	Annealing	$\uparrow$Toughness	[200]
	Aging	$\uparrow T_g$	[201]
	Drawing	Improvement in tensile and fracture properties	[202]

steam and autoclave conditions, chemical resistance to EtO, and resistance to high-energy radiation including electron beam, γ, and UV [205].

In an early study examining the effects of 7 different steam sterilization techniques on PLLA, it was determined that all the evaluated techniques significantly changed at least one material property of the polymer. The Mw decreased in all cases, although in most cases the elastic modulus tended to increase [206]. Autoclaving and dry heating are usually performed at temperatures equal to or higher than 120 °C. For example, PLLA at 129 °C for 60 s resulted in minimal change in tensile properties of the tested PLLA. However, this method resulted in a significant decrease in the Mw, which would affect the degradation kinetics of the polymer [4]. PLA and PLGA implants are susceptible to hydrolysis and their deformation at higher temperatures therefore precludes the use of these sterilization methods. For radiation sterilization of bioresorbable polymers, temperature and dose conditions need to be closely controlled to avoid chain scission and significant degradation. Gamma sterilization at dry ice temperatures is more preferred [4]. Chemical sterilization by gases such as ethylene oxide (EO) is often used for polymers that are sensitive to heat and moisture such as the case in PLA based polymers [203]. However, chemical sterilization can potentially leave residues in harmful quantities on the surface and within the polymer, so great care is used to ensure that all gas is removed from the device before final packaging usually by extremely long vacuum aeration times to fully remove the residual EtO gas [62,166]. EtO sterilization is performed at temperatures of 50–60 °C, which can lead to Mw loss, and in some cases as well EtO is chemically highly reactive and acts as a plasticizer for PLA based polymers, which can lead to changes in the polymer structure. However, detrimental effects of chemical sterilization on the mechanical properties of the PLA based polymers have rarely been reported in the literature. Table 11 gives an overview of sterilization techniques used for PLA based biomaterials and lists their general advantages and disadvantages [203].

For summary, the specific effects of different techniques are determined by the sterilization parameters, the method used for fabrication, as well as the polymeric composition itself. Thus, it is imperative that choice of a particular sterilization regimen be made only subsequent to a careful study. Also, very important for medical devices is sterilization method compatibility including consideration of single vs. repeat sterilization [4].

3.4. Aging

PLA performance in terms of durability are limited by multiple chemical aging mechanisms such as thermal decomposition [207,208], hydrolysis [209,210], photo-oxidation [211,212], natural weathering [213] and thermo oxidation at high temperature [214,215]. Due to biodegradable applications, numerous studies dealing with hydrolytic aging are available (i.e. [210]). Ideally, composite materials and their structures that are intended for long term use should be tested in real time and with realistic in-service environments. Often this is not viable because the time involved would significantly delay product development and therefore, accelerated aging techniques are required [216].

Foreman and coworkers reported the influence of accelerated weather aging on the mechanical and physical properties of neat PLA and untreated long hemp fiber/PLA (AUL) and aligned alkali treated long hemp fiber/PLA (AAL) composites [216]. During accelerated weathering, measured variables can include exposure time, exposure to UV irradiation over a specific wavelength range, and exposure to moisture as number of cycles or time. In this reported study accelerated aging was carried out using UV irradiation and water spray at 50 °C for four different time intervals (250, 500, 750 and 1000 h) and samples were studied for micro and macroscopic changes. The changes in mechanical properties due to accelerated aging for different time periods are summarized in Table 12. Fig. 9A represents a visual example of the samples after exposure to accelerated aging environments were slightly deteriorated the surface texture in the form of decoloration, surface softness and matrix cracks. A reduction in tensile strength (TS), flexural strength, Young's modulus (YM), and flexural modulus from their mean values for neat PLA and composites with increased aging duration was observed (Table 12). The greatest overall reduction in TS, flexural strength, YM, and flexural modulus was observed for AUL composites than for AAL composites. Impact strength (IS) of neat PLA was found to decrease with increased accelerated aging time while mode I fracture toughness (K_{Ic}) was found to decrease for all samples with increased weathering time (Table 12). Foreman and coworkers assumed that the resulting reduction in TS, flexural strength, YM, and flexural modulus for neat PLA with increased duration of accelerated aging to be due to plasticization, swelling effect [217] and photochemical degradation [218]. They also have assumed that the reduction of IS and K_{Ic} of neat PLA with weathering of up to 750 h could be due to PLA chain scission and formation of surface cracks (sample was found too soft for further testing), which can be seen in Fig. 9B.

Another comprehensive study was done by Baley and coworkers [219], where they studied accelerated hygrothermal aging of PLA and flax/PLA biocomposites where samples were aged in natural seawater at different temperatures in order to understand the mechanisms which govern the long-term durability in the marine environment in order for future adoption for marine structures. During hydrothermal aging of PLLA the Mw reduction is greater when the temperature and water uptake increase. Their study continued for 3 months immersion. Results from mechanical tests on wet unreinforced PLLA are shown in Table 13. The results indicate that the elastic modulus is not affected by aging but the tensile strength decreases significantly. The results showed also that flax/PLLA composites undergo permanent changes after immersion in seawater. According to this study, the absorption of water was resulted in several degradation mechanisms: hydrolysis (reduction in Mw), structural changes, degradation of the fiber/matrix interface, differential swelling at the fiber–matrix interface and degradation of fibers and therefore in a reduction in mechanical properties. The stiffness of unreinforced PLLA was found to hardly be affected by water, but the biocomposites lose tensile stiffness and strength progressively as water enters the material, suggesting that fiber/matrix interface weakening is the main damage mechanism induced by wet aging [219].

Recently, Fayolle and coworkers have reported PLA aging in atmospheric conditions with the absence of water and UV light [220]. They

Table 11
Standard sterilization techniques and their applicability to lactic acid based polymers.

Sterilization technique	Conditions	Advantages	Disadvantages
Steam sterilization	High steam pressure, 120–135 °C	No toxic residues	Deformation/degradation due to water attack, limited usage for lactic acid based polymers
Dry heat sterilization	160–190 °C	No toxic residues	Melting and softening of polymer, not usable for lactic acid based polymers
Radiation	Ionizing or γ	High penetration, low chemical reactivity and quick effect	Instability and deterioration, crosslinking/breakage of polymer chains
Gas sterilization	Ethylene oxide	Low temperature range	Lengthy process due to degassing residues are toxic

Table 12
Effect of accelerated aging on neat PLA, AUL and AAL composites.

Accelerated Aging (h)	Neat PLA				
	TS (MPa)	YM (GPa)	FS (MPa)	FM (GPa)	IS (KJ/m^2)
0	48.0 ± 5.0	4.6 ± 1.1	87.4 ± 6.5	3.7 ± 0.3	2.5 ± 0.5
250	45.5 ± 5.0	4.2 ± 1.1	84.1 ± 5.6	2.6 ± 0.4	2.5 ± 0.3
500	42.3 ± 3.3	3.7 ± 1.0	80.0 ± 4.1	2.3 ± 0.6	2.2 ± 0.1
750	28.1 ± 3.3	2.9 ± 0.9	59.8 ± 5.4	1.7 ± 0.4	1.1 ± 0.0
1000	N.T.	N.T.	N.T.	N.T.	N.T.

Accelerated Aging (h)	AUL PLA				
	TS (MPa)	YM (GPa)	FS (MPa)	FM (GPa)	IS (KJ/m^2)
0	60.0 ± 5.1	7.7 ± 1.6	114.9 ± 5.9	5.8 ± 0.8	12.5 ± 3.0
250	53.1 ± 3.0	7.6 ± 1.1	71.1 ± 7.0	2.8 ± 0.7	43.9 ± 5.4
500	41.0 ± 5.0	6.3 ± 1.1	64.1 ± 6.9	2.0 ± 0.7	51.7 ± 3.9
750	36.0 ± 3.9	5.1 ± 0.9	54.2 ± 6.9	1.7 ± 0.5	52.2 ± 5.2
1000	8.1 ± 3.9	1.1 ± 0.4	12.1 ± 4.0	1.5 ± 0.2	18.0 ± 2.5

Accelerated Aging (h)	AAL PLA				
	TS (MPa)	YM (GPa)	FS (MPa)	FM (GPa)	IS (KJ/m^2)
0	83.6 ± 9.9	11.0 ± 1.9	144.1 ± 5.8	6.5 ± 1.0	8.0 ± 1.9
250	57.1 ± 2.6	8.7 ± 1.2	87.1 ± 5.7	3.2 ± 0.3	36.5 ± 3.1
500	50.0 ± 2.1	8.1 ± 1.1	82.1 ± 5.0	3.0 ± 0.3	42.5 ± 3.2
750	49.9 ± 1.8	7.3 ± 0.7	73.2 ± 6.0	2.6 ± 0.4	51.6 ± 3.1
1000	34.2 ± 1.5	5.0 ± 0.3	44.3 ± 4.8	2.4 ± 0.5	34.1 ± 3.2

(TS)-Tensile strength, (YM)-Young's modulus, (FS)-Flexural strength, (FM)- Flexural modulus, (IS)-Impact strength, (K$_{Ic}$)-Fracture toughness, and (N.T.)- not tested.

studied the oxidative degradation of PLA induced at moderate temperatures (i.e. below the PLA T_m) for more than 500 h. By comparing aging in air and in water at 70 °C, the authors concluded that the hydrolysis aging can be neglected in air. At temperatures higher than 100 °C in air, aging mechanism is undoubtedly oxidation. They also concluded that the thermal oxidation mechanism of PLA at low temperatures (T < 160 °C) leads to a random chain scission process, responsible for the decrease of the PLA Mw as found by SEC measurements. Oxidation affects the physical and mechanical properties of the polymer. These results come in agreement with some common behaviors observed during polyolefin oxidative aging. Consequently, knowing the chain scission kinetics, it will be possible to predict the embrittlement time, in other words the time when Mn is below 40 kg/mol: this time is around 150 h, 250 h and 500 h for the PLA aged at 150, 130 and 100 °C respectively [220].

4. PLA properties improvement

4.1. Plasticizer and polymer blending

PLA is characterized by excellent optical properties and high tensile strength but unfortunately, it is rigid and brittle at room temperature (RT) due to its T_g ~ 55 °C [138]. Potentially, PLA fulfills the packaging industry's requirements for most of the rigid objects but the polymer needs to be plasticized to be used as soft films [155]. Indeed, developing packaging materials requires high flexibility at RT and thus, there is no tolerance for the polymer film tearing or cracking when subjected to stresses during package manufacturing or use [138,221]. Other requirements which include transparency, low crystallinity and desired barrier properties are also relevant for these applications [155]. To improve the ductility of PLA-based materials, a large number of investigations have been made to modify PLA properties via plasticization or polymer blending (see Section 3.3/Table 10).

Plasticizers are widely used to improve processability, flexibility and ductility of polymers. In the case of semicrystalline polymers like PLA, an efficient plasticizer has to reduce the T_g but also to depress the T_m and the crystallinity [155,222]. Lactide monomer, for instance, is a good candidate to plasticizing PLA but it tends to migrate to the material's surface causing a stiffening of the films in time [155]. Rather than lactide, many kinds of ester-like plasticizers for PLA have been studied such as glycerol, sorbitol, bishydroxymethyl malonate (DBM) [223], glucose monoesters and partial fatty acid esters, and citrates [79]. However, the low Mw plasticizers have the problem of migrating, owing to their high mobility within the PLA matrix. Therefore, plasticizers with rather high Mw and low mobility are necessary. At least five kinds of plasticizers with high Mw and being miscible to PLA without any compatibilizer have been reported so far, i.e. PEG [79,224,225], poly(propylene glycol) (PPG) [226], atactic poly(3-hydroxybutyrate)
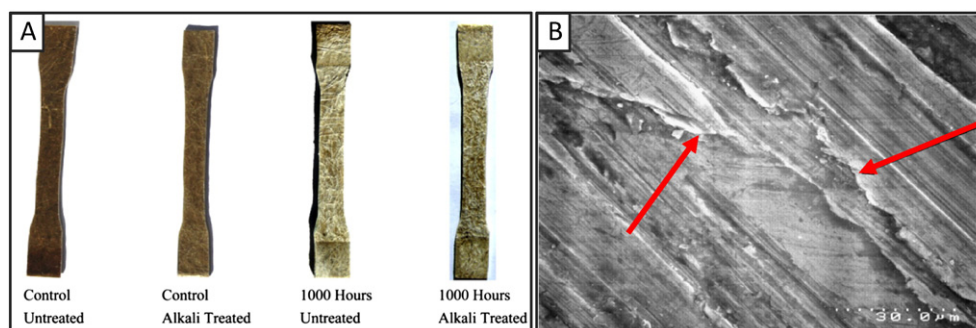

Fig. 9. (A) Visual change during aging of AUL and AAL composites. (B) SEM image of neat PLA surface after weathering for 750 h, surface cracks are marked with red arrows, scale bar 30 μm. (Adapted from [216]).

Table 13
Mechanical properties of PLLA before and after accelerated hygrothermal aging [219].

T (°C)	Young's modulus (MPa) at t = 0	Young's modulus (MPa) at t = 3 months	Evolution of properties (%)
20	3655 ± 87	3682 ± 113	+1
40	–	3316 ± 216	−9

T (°C)	Stress max (MPa) at t = 0	Stress max (MPa) at t = 3 months	Evolution of properties (%)
20	60.5 ± 0.9	46.6 ± 0.1	−23
40	–	41.9 ± 3.7	−31

T (°C)	Strain at break (%) at t = 0	Strain at break (%) at t = 3 months	Evolution of properties (%)
20	2.5 ± 0.4	10.8 ± 1.2	+335
40	–	1.3 ± 0.4	−48

(a-PHB) [227], polyester diol (PED) as poly(diethylene adipate) (PDEA) [228], tributyl citrate-oligoester (TbC-oligoesters), diethyl bishydroxymethyl malonate oligoester (DBM-oligoester) and oligoesteramide (DBM-oligoesteramide) [223,229,230]. Despite the wide diversity, the choice of plasticizer used as a modifier for PLA is limited by the legislative or technical requirements of the application, and in this context, its selection becomes more difficult [223,230,231]. In fact, the plasticizer used for PLA has to be biodegradable, non-toxic for food contact (for food packaging applications) and/or biocompatible (for biomedical applications). So far the most common plasticizers used for PLA are low MW PEG [79,188,222,224,225,232,233], citrate [175,229,230,234] and oligomeric lactic acid, giving the best results, while glycerol was found to be the least efficient plasticizer [15,235,236].

Typically, 10–20% w/w amount of plasticizers are required to provide both a substantial reduction of T_g of PLA matrix and adequate mechanical properties. Regarding sustainability, the preferred plasticizer for PLA should be biodegradable/bioresorbable, sufficiently non-volatile, and with a relatively low Mw to produce the desired decrease of Young's modulus value and increase of the impact strength. Moreover, the addition of more than 20–30% (depending on the plasticizer) of plasticizers into PLA matrix leads to a phase separation which needs to be avoided. The plasticization is thus limited by the amount of plasticizer to be blended with PLA [231].

Grohens and coworkers reported a comprehensive study aimed to determine thermal and mechanical properties of PLA (Mw 74,000 g/mol) with PEG and several other oligomeric plasticizers (Fig. 10) that can be used in food packaging [155]. The authors discussed the thermo-mechanical PLA performances assessed for blends containing 10, 20,

and 30% w/w of plasticizers. Summaries of the T_g, melting enthalpies, crystallization temperature of pure components and blends with PLA are given in Tables 14 and 15. The study outcome was that plasticizers blended with PLA lowered the T_g and modified the melting and crystallization characteristics. The PEGs are the most efficient plasticizers used for PLA for the T_g reduction and it clearly appears that for compositions higher than 20% of plasticizer, all the blends presented a limit of miscibility and the T_g reaches a plateau value. Results of static tensile experiments are summarized in Fig. 11. It was found that the mechanical characteristics of these materials showed a decrease in modulus and stress at break. Nevertheless, the PLA blended to PEGs becomes very brittle as a function of plasticizer content and Mw. The more efficient plasticizers are PBOH, AGM and DBS that give mechanical characteristics that can be consistent with soft packaging applications [155].

Recently, David and coworkers have reported in situ reactive grafting of hydroxy-terminated PEG plasticizer onto the maleic anhydride modified PLA in PLA/PEG blends [231]. The authors declared that grafting did not lead to a dramatic drop of PLA Mw by thermal degradation or hydrolysis of ester chains while lowering significantly the T_g compared to the blends without grafting (neat PLA + PEG) and a negligible effect on viscoelastic and viscoplastic mechanical behaviors of PLA was found.

Another study done by Sun and coworkers investigated the effects of the plasticizer 1,2-cyclohexane dicarboxylic acid diisononyl ester (Hexamoll® DINCH) on the thermal stability and degradation of PLA and compared with tributyl citrate (TBC) and montmorillonite (MMT) [235]. The authors found that the addition of Hexamoll® DINCH, TBC, and MMT can efficiently decrease the T_g of PLA and improve the crystallinity of PLA polymer.

Although, huge attempts to improve PLA physical–mechanical properties for packaging or medical applications using plasticizers have been reported, there is limited information found regarding aging under several conditions for these blends. Assessment of the property enhancement on the stability of the plasticized material and the prevention/limitation of the plasticizer migrating from the bulk is crucial for intended material usage and should be further studied in the future.

4.2. Nucleation agents

The presence of additives in a pristine polymer resin can influence the crystalline morphology and kinetics, so it can be used as a tool for controlling/designing specific physical and mechanical properties by providing nucleation sites for crystallization to initiate. Nucleating agents can be chemical or physical in nature. So far several studies have reported a variety of physical nucleating agents for PLA, including talc and nanoclays [127,144,179,237–247]. Talc is often chosen due to
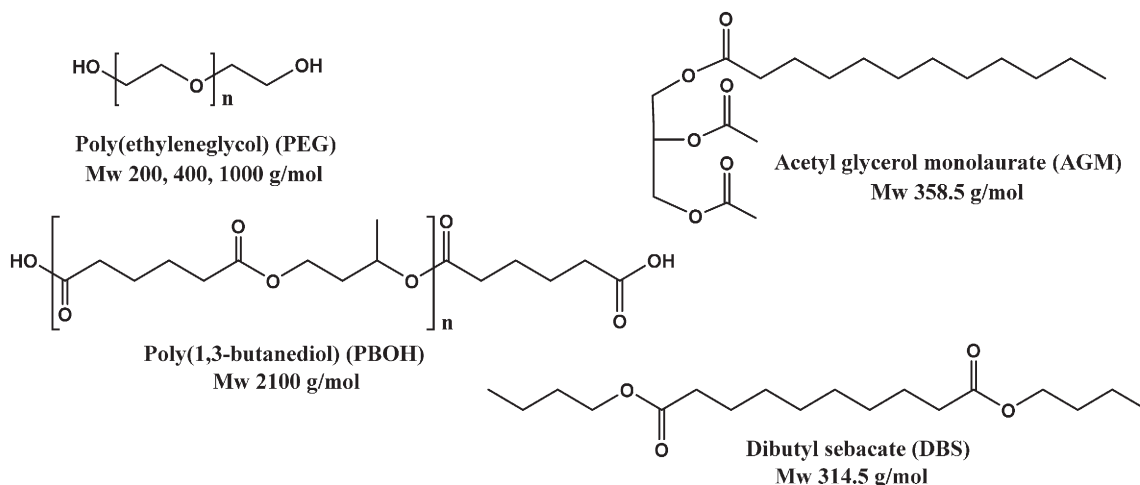

Fig. 10. Chemical structures of plasticizers that have been studied by Grohens and coworkers [155].

Table 14
T_g of pure components and of blends between PLA and plasticizers.
[155].

Components	T_g (°C) of PLA blends						
	100%	10%		20%		30%	
		T_{g1}	T_{g2}	T_{g1}	T_{g2}	T_{g1}	T_{g2}
Neat PLA	59.2	–	–	–	–	–	–
PEG 200	−81.8	35.8	N.T.	–	–	–	–
PEG 400	−65.7	37.1	N.T.	18.6	−50.2	–	–
PEG 1000	−81.0	40.2	N.T.	22.4	−62.7	29.9	−68.9
PBOH	−64.7	47.6	N.T.	30.1	−48.5	29.4	−45.0
AGM	−82.0	45.8	N.T.	24.3	−65.8	12.9	−56.9
DBS	−81.7	39.9	N.T.	26.1	−66.9	29.2	−56.5

T_{g1} corresponds to the PLA rich phase and T_{g2} corresponds to the plasticizer rich phase.
N.T., not tested.

both its low cost as well as its additional reinforcement effect. Angela and Ellen have studied the relationship between crystallinity level and mechanical performance in injection molded specimens of PLA [248]. They have used talc and ethylene bis-stearamide (EBS) as physical nucleating agents, and they have done isothermal and nonisothermal crystallization experiments and evaluated the final crystalline content. Mechanical performance was assessed through flexural and heat distortion measurements. The study outcome showed for the first time that an increase in the crystallinity through an optimized injection molding process and the addition of nucleating agents can result in a direct and significant improvement in mechanical performance of a commercial grade of PLA [248]. The overall crystallization rate and final crystallinity of PLA were controlled by the addition of physical nucleating agents as well as optimization of injection molding processing conditions. Talc and ethylene bis-stearamide (EBS) nucleating agents both showed dramatic increases in crystallization rate and final crystalline content as indicated by isothermal and nonisothermal crystallization measurements (Table 16), [248]. Isothermal crystallization halftimes were found to decrease nearly 65-fold by the addition of just 2% talc. Process changes also had a significant effect on the final crystallinity of molded neat PLA, which was shown to increase from 5 to 42%. The combination of nucleating agents and process optimization not only resulted in an increase in final injection molded crystallinity level, but also allowed for decreased cycle processing times and reduced energy requirements in the injection molding process. The authors also reported significant improvements in mechanical performance of PLA, achieved by increasing the overall material crystallinity. An increase of over 30 °C in the heat distortion temperature and improved strength and modulus by upwards of 25% were achieved. The materials with higher crystallinity showed correspondingly increased mechanical properties and are thought to have improved durability and degradability as well.

Other studies have reported the self-nucleation of PLA by adding small crystallites of the stereocomplex which were formed from blending up to 15% PDLA into PLLA [237,249]. In comparison of self-nucleation with the heterogeneous nucleation obtained from the addition of talc, self-nucleation was found much more efficient and reduced the crystallization half time by nearly 40-fold, in the best case, while a similar loading of talc only decreased the half time by just over 2-fold.

5. PLA's properties functions in applications

This part summarizes the applications of PLA and deeply discusses the connection between the mechanical/physical properties of PLA and the required features for medical and non-medical applications, as well as pointing out current challenges which need further investigation for PLA performance improvement.

5.1. Medical application

PLA offers unique features of biodegradability, biocompatibility, thermoplastic processability and eco-friendliness that offer potential and being a bioresorbable polymer that play an increasingly important role in biomedical applications due to their unique ability to be completely resorbed in pre-designed time frames ranging from months to a few years [162]. Furthermore, the ability to tailor their mechanical, microstructural, chemical, and degradation properties for specific applications has catalyzed an extensive and growing amount of research aimed at utilizing these materials in innovative ways and applications [250]. PLA is used in a wide range of biomedical applications such as stents [250–253], surgical sutures [254], plates and screws for craniomaxillofacial bone fixation [255], interference screws in ankle, knee, and hand; tacks and pins for ligament attachment, anchors [256], spinal cages [250,257], soft-tissue implants, tissue engineering scaffolds, tissue cultures, drug delivery devices [258], and craniofacial augmentations in plastic surgery [259]. In all of these applications, lactic acid based polymers are exposed to different devices with specific load environments. Each of these applications demands materials with specific physical, chemical, biological, biomechanical and degradation properties to provide efficient therapy [1]. The diversification of PLA applications is such that a single polymer may prove useful in many applications by simple modifications of its physical–chemical structure. In many cases the PLA can be blended or copolymerized with other polymeric or non-polymeric components to achieve the desired behavior [16,40].

The general criterion for selecting a polymer for use as a biomaterial is to match the mechanical properties and the time of degradation to the needs of the application. The mechanical properties match the application so that sufficient strength remains until the surrounding tissue has healed. The selection starts by planning crystallinity level as it influences many polymer properties including hardness, modulus, tensile strength, stiffness, crease point, and melting point [3]. For example, in applications where an implant will be under substantial load the family of semicrystalline biodegradable polymers would typically be chosen [62].

Table 15
Melting and crystallization temperatures and enthalpies of pure components for PLA in PLA/plasticizers blends.
[155].

%Plasticizer	100%			10%			20%			30%		
	T_m (°C)	ΔH_m (J/g)	T_c (°C)	T_m (°C)	ΔH_m (J/g)	T_c (°C)	T_m (°C)	ΔH_m (J/g)	T_c (°C)	T_m (°C)	ΔH_m (J/g)	T_c (°C)
Neat PLA	154	0.5		–	–		–	–		–	–	
PEG 200	–	–	[a]	148.0	34.1	90.6	–	–		–	–	
PEG 400	6.9	113.0	[a]	150.8	32.4	102.2	18.6	−50.2	61.8	–	–	
PEG 1000	39.8	149.4	[a]	153.0	32.1	110	22.4	−62.7	87.4	149.3	41.3	
PBOH	−15.5	1.8	−26.1	152.5	1.3	128.5	30.1	−48.5	110.4	151.0	34.3	98.2
AGM	−8.3	71.9	[a]	150.3	1.6	126	24.3	−65.8	99.3	143.4	31.4	67.8
DBS	−6.9	160.8	[a]	148.8	2.2	122.5	26.1	−66.9	78.2	143.4	32.0	85.4

PLA melting enthalpies are normalized by the PLA content in the blends.
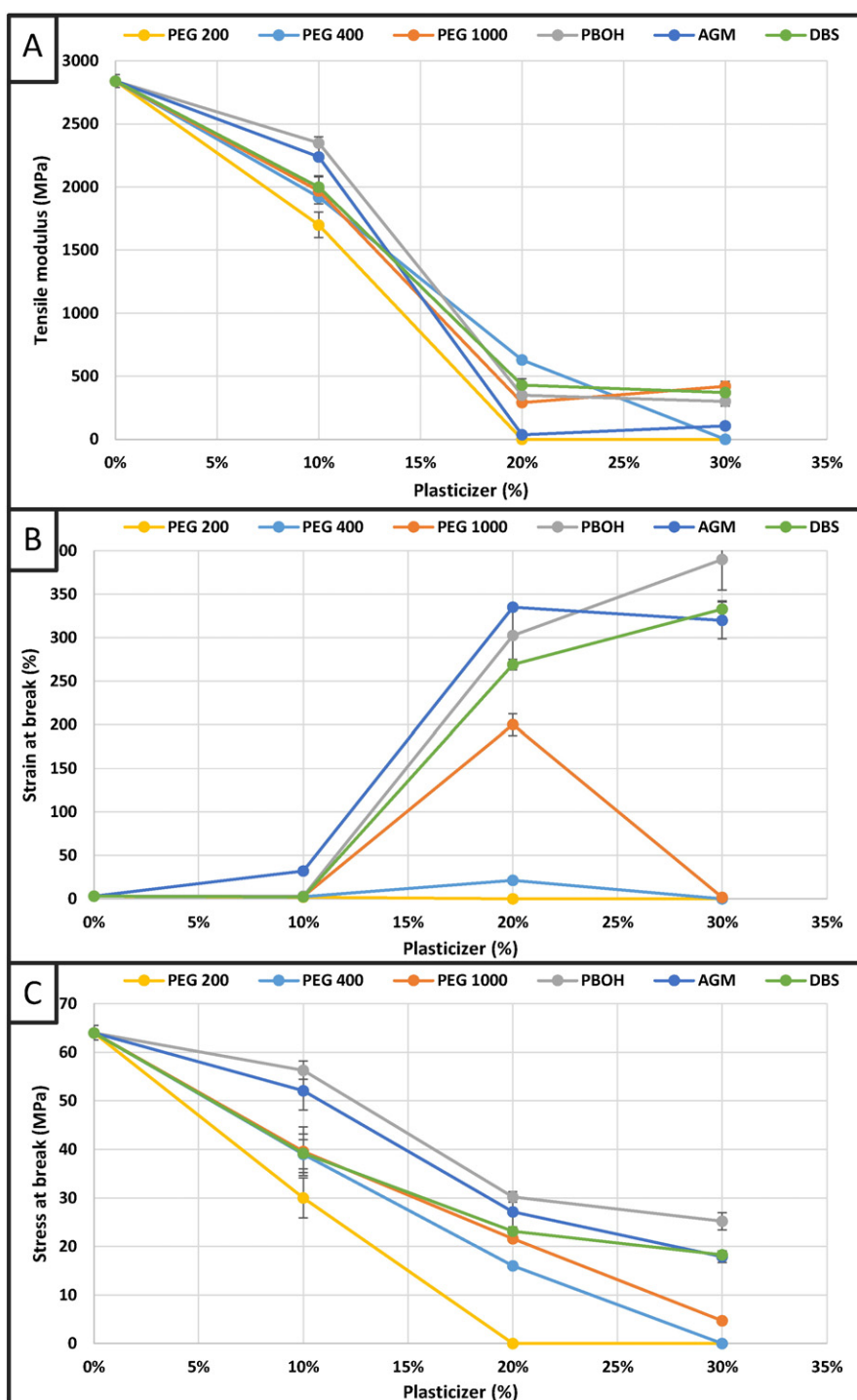[a] Only classical crystallizations are observed for pure plasticizers.

Fig. 11. (A) Tensile modulus (MPa) of pure PLA and plasticized PLA, (B) strain at break (%) of pure PLA and plasticized PLA, (C) stress at break (MPa) of pure PLA and plasticized PLA.

For a medical product, physical properties are important as well where the designer should consider product dimensions, size, and weight requirements. For example, to be light enough so a surgeon can handle precisely while the design should maintain the loads, stresses, and impact that the product might be face with during its use [4]. Other physical properties can be important including transparency/opacity, color (some items might use color to aid in identification), esthetics, water absorption, lubricity, and wear resistance. Important mechanical properties are tensile strength, tensile elongation, tensile modulus, impact resistance (all for toughness), and flexural modulus. Accordingly, usage conditions such as temperature, chemical contact and resistance, and applied stresses during use, are considered where PLA mechanical and physical properties can be tailored for use in a variety of processes and applications [8]. For example in tissue engineering, the biostability of many scaffolds depends on the factors such as strength, elasticity, and absorption at the material interface and its chemical degradation [260]. The scaffold should have proper mechanical properties and degradation rate with the bioactive surface to encourage the rapid regeneration of the tissue. It is highly essential to retain the mechanical strength of the scaffold structure after implantation for the reconstruction of hard, load bearing tissues such as bone and cartilage [261]. To be used successfully, it is critical that a biomaterial scaffold

Table 16
Effects of nucleating agents on thermal properties of injection molded PLA. [248].

Samples	Additive weight (%)	$T_g{}^a$ (°C)	$T_{c1}{}^a$ (°C)	$T_m{}^a$ (°C)	$T_{c2}{}^b$ (°C)	$X_c{}^a$ (%)
Neat PLA	0	64.3	115.9	172.4	n/a	10.0
PLA + EBS	2	63.6	93.2	169.4	97.4	18.5
PLA + talc	2	64.8	99.6	172.1	106.9	17.9
PLA + talc	5	62.7	95.2	171.5	110.9	15.4
PLA + talc	10	63.4	95.2	171.5	111.1	12.3
PLA + talc	20	60.8	92.9	171.6	112.6	20.8

Samples molded at room temperature.
 ^{a} DSC program: heat at 10 °C/min to 220 °C.
 ^{b} DSC program: heat at 10 °C/min to 220 °C, hold for 20 min, cool at 10 °C/min to 25 °C.
T_{c2} was determined from the final cooling ramp.

temporarily withstands and conducts the loads and stresses that the new tissue will ultimately bear. Therefore, it is important to evaluate one or more of the following rheological parameters: (i) elastic modulus: measured strain in response to a given tensile or compressive stress along the force; (ii) flexural modulus: measured the relationship between a bending stress and the resulting strain in response to a given tensile or compressive stress perpendicular under load; (iii) tensile strength: maximum stress that the material can withstand before it breaks; and (iv) maximum strain: ductility of a material or total strain exhibited prior to fracture.

The mechanical properties and structural integrity of bulk biomaterials are altered by their processing into scaffolds of various pore sizes and volume, shape, orientations and connectivity, and further that these properties will rapidly diminish as a function of implantation time [262]. It is critically important to understand these behaviors and how they influence the material response in order to properly design a medical device, and to analyze the device response under realistic in vivo conditions.

Mechanical properties and degradation: The degradation behavior of PLA is a critical characteristic of the material and the most important reason for the high interest in its use in medical applications. The stereochemistry, crystallinity, Mw, and applied loads are the main factors influencing the rate of degradation of PLA [163,263]. It has recently been shown that the rate of degradation is also dependent on the magnitude of the applied stress [165]. During degradation the yield strain, yield stress, and elongation to failure all decrease. These changes in yield stress, yield strain and elongation at failure can have consequences for devices which are load bearing throughout their degradation process [162,264]. For example in stent application, although the artery is

Fig. 12. Young's modulus and engineering strain to failure for different PLA materials. (Reprinted from [162]).

thought to remodel after approximately 6 months, device fractures or viscoplastic flow may cause uneven loading in the vessel which could have a negative impact on a tissue which is highly sensitive to changes in the mechanical environment.

PLLAs exhibit high tensile strength and low elongation and consequently have high modulus that makes them more applicable than the amorphous polymers for load-bearing applications such as in orthopedic fixation and sutures. PDLLA is an amorphous polymer having a random distribution of both isomeric forms of lactic acid and accordingly is unable to arrange into an organized crystalline structure. This material has lower tensile strength and higher elongation and much more rapid degradation time making it more attractive as a drug delivery system [62]. PLLA is about 37% crystalline with a T_m of 175–178 °C and a T_g of 60–65 °C [265]. The degradation time of PLLA is much slower than that of PDLLA requiring greater than 2 years to be completely absorbed [35]. Copolymers of L-lactide with PCL, glycolide or DL-lactide have been prepared to disrupt the L-lactide crystallinity accelerating the degradation process or include plasticizers to increase the ductility [266]. Fig. 12 summarizes the correlation between Young's modulus and elongation to failure at RT for large intervals of PLA materials with the aforementioned microstructural states [162].

The following section details the required PLA properties and challenges to fit potential applications in the medical industry.

5.1.1. Wound management and stent applications
PLA and its copolymers were used in a wide range of applications related to wound management, such as surgical sutures [254], healing dental extraction wounds, and preventing postoperative adhesions. For sutures it has recently been shown that the rate of degradation of PLA is dependent on the magnitude of the applied stress [165,254]. An additional complication is that PLA can exhibit premature failure at stress magnitudes that are significantly lower than both the yield strength and the ultimate tensile strength of the material due to viscoplastic flow causing creep rupture or fatigue failure. As a result, in some applications device failure can occur long before the material is expected to fail due to degradation in vivo [162,264]. Another example, a bioresorbable PLA stent, is exposed to very large stresses and strains during the crimp and expansion steps. After deployment the stent typically contains large viscoplastic residual strains. Additionally it needs to maintain its mechanical integrity when exposed to a large number of load cycles with low stress and strain amplitudes. The use of degradable, non-linear, viscoplastic materials presents many new challenges to the development and use of bioresorbable stents by altering the mechanical response of the devices to their in vivo environments. Accordingly, the most commonly used material for bioresorbable scaffolds/stents is PLLA [267,268]. However, due to the lower stiffness and strength of PLLA compared to metals, the struts are typically required to be thicker than what is used with conventional metal stents in order to obtain the desired radial strength. This may lead to poor deliverability, platelet deposition, and vessel injury [250–253,162]. In order to address these challenges it is necessary to fully understand the mechanical response of PLA implant/device. This requires in-depth characterization of how the strength and stiffness of the material change due to time-dependent microstructural mechanisms, how the material response changes during degradation, and how the material undergoes non-linear viscoplastic deformations at finite deformations. Similar to stents, other applications require a longer retention of strength, such as ligament and tendon reconstruction as well as urological surgery, where PLLA fibers are the preferred material as well [1,269].

5.1.2. Drug delivery system-based PLA
PLAs have been utilized for continuous drug release for different periods of time including prolonged administration of a wide variety of medical agents such as contraceptives, narcotic antagonists, local anesthetics, vaccines, peptides and proteins [270,271]. Polymeric drug release can occur in one of three ways: erosion, diffusion and swelling.
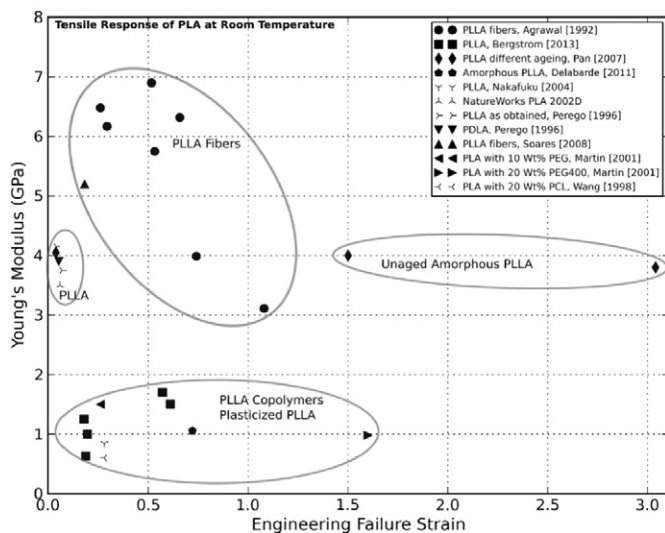
For PLA, the breakage of ester bonds occurred randomly through hydrolytic ester cleavage, leading to subsequent erosion of the device. The hydrolytic products from such degradation process are then transformed into non-toxic subproducts that are eliminated through normal cellular activity and urine [6]. PLA and their copolymers in the form of micro or nano-particles were used in the encapsulation process of many drugs, such as psychotic [272], restenosis [273], hormones [274], oridonin [275], dermatotherapy [276], and protein (BSA) [277]. PLA particles were prepared using solvent evaporation technology and found ideal candidates for the design of drug delivery systems. It has been found that the challenge of controlled drug release can be tuned by mechanical stability and crystallinity degree of PLA in the formulation [44].

5.1.3. Orthopedic and fixation devices

The challenges associated with PLA usage for orthopedics are highly dependent on the location and type of device intended to be used [162]. While typical devices are composed of steel or titanium to ensure that the devices are capable of withstanding in vivo loading over long periods of time [278], polymers have advantages over metal implants in that they transfer stress over time to the damaged area, allowing healing of the tissues [62]. Another important advantage is avoiding a second surgical procedure to remove unnecessary hardware, which reduces medical costs and allows for the gradual recovery of tissue function as the device is degraded simply by hydrolysis without any use of enzymes or catalysts (Fig. 13) [1,44,279]. Historically, the PLA polymer was used to produce biodegradable screws and fixation pins, plates, and suture anchors. These types of absorbable screws and pins have been gaining widespread clinical use, particularly in cases where high mechanical stiffness or strength was not required. Pertinent orthopedic areas might include the knee [280–282], shoulder, foot and ankle [283, 284], hand, wrist [285], elbow [286], pelvis, and zygomatic fractures. In some other cases, high performance PLA is needed and it was found quite challenging to achieve. Haers et al. [279] reported an improvement of the mechanical properties of PLA through the control of the L/D ratio in the polymer, where the ratio of L/D 85/15 was polymerized, and the prepared PLA was used for the manufacture of screws and fixation plates used in fracture fixation. The results showed that it was possible to use the plates without the need for additional support for the fixation of fractures (Fig. 13). These degradable devices in comparison to their metallic counterparts were found to exhibit similar rates of success [8,287,288]. However, in these applications it is important that the applied stress never gets so large that the implant undergoes significant permanent deformation, or premature failure due to viscoplastic flow or fracture [162].

Since materials for bone fixation require high strength, close to that of bone, PLLA has a large application in this field. In Barber's review, 22 of the listed 40 orthopedic devices were composed of PLLA (Table 17) [62,289]. Another application of PLLA in the form of injectable microspheres for temporary fillings in facial reconstructive surgery has also been reported [6].

Table 17
List of commercial biodegradable devices. [62,289].

| Application	Trade name	Composition	Manufacturer
Fracture fixation	SmartPins	SR-PLLA SR-PGA	Bionx Implants
	SmartScrew SmartTack	SR-PLLA	
	Phantom SofThread Soft	PLLA	DePuy
	Tissue Fixation Screw		
	Orthosorb Pin	PDO	J & J Orthopedics
Interference screws	Full Thread Bio-Interference Screw	PLLA	Arthrex
	Sheathed Bio-Interference Screw		
	Phantom Interference Screw		DuPuy
	Biologically Quiet Interference Screw	85/15 PDLLGA	Instrument Makar
	BioScrew	PLLA	Linvatec
	Sysorb		Sulzer Orthopedics
	Endo-Fix Screw	PGA-TMC	Smith and Nephew
Suture anchors	Bankart Tack SmartAnchor-D SmartAnchor-L	SR-PLLA	Bionx Implants
	Phantom Suture Anchor	PLLA	DuPuy
	BioROC EZ 2.8 mm BioROC EZ 3.5 mm		Innovasive Devices
	Biologically Quiet Biosphere Biologically Quiet Mini-Screw	85/15 PDLLGA	Instrument Makar
	Bio-Anchor GLS Panalok Panalok RC	PLLA	Linvatec Mitek Products
	Suretak 6.0 Suretak 8.0 Suretak II w spikes TAG 3.7 mm Wedge TAG Rod II	PGA-TMC	Smith and Nephew
	SD sorb 2 mm SD sorb 3 mm SD sorb E-Z TAC	82/18 PLLGA	Surgical Dynamics
	Bio-Statak	PLLA	Zimmer
Meniscus repair	Menicus Arrow	SR-PLLA	Bionx Implants
	Clearfix Meniscal Dart Clearfix Meniscal Screw Meniscal Stinger	PLLA	Innovasive Devices Linvatec
	SD sorb Meniscal Staple	82/18 PLLGA	Surgical Dynamics
ACL reconstruction	Biologically Quiet Staple	85/15 PDLLGA	Instrument Makar
Craniomaxillofacial fixation	LactoSorb Screws and Plates	82/18 PLLGA	Biomet
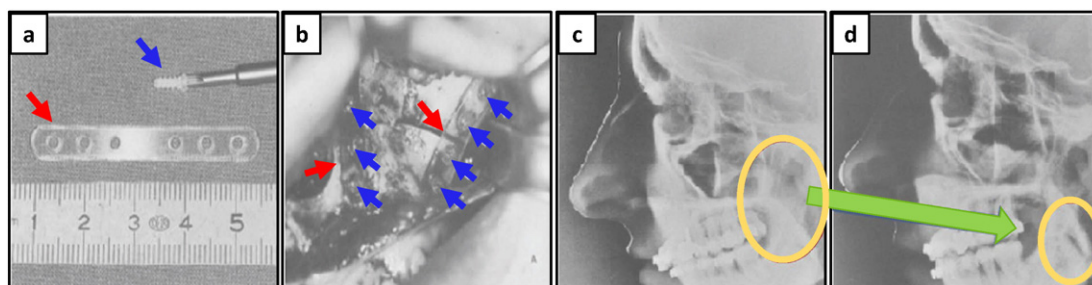
Fig. 13. (a) Screws and plate made of PLA (b) upper jaw with the plates and screws in situ (c) and (d) lateral cephalogram, with the screws and plate, taken immediately postoperatively and 6 weeks postoperatively, respectively.
(Adapted from [44,279]).

5.1.4. Tissue engineering and regenerative medicine

Tissue engineering is one of the most exciting interdisciplinary and multidisciplinary research areas where PLA usage has grown exponentially over time. Scaffold materials and fabrication technologies play a crucial role in tissue engineering and regeneration [260]. PLA matrix materials have found enormous interest as supports because of the fact that the support disappears from the transplantation site with the passage of time, leaving behind a perfect patch of the natural neo-tissue [1,16]. PLA has been investigated for tissue engineering applications, such as bone scaffolds, because of the good biocompatibility of this polymer [290]. However different tissue nature requires relative material strength with a pre-planned biodegradation profile. The mechanical properties of PLA were reported to be improved for tissue engineering using a range of methods, such as blending, composites forming (i.e. [291]), and co-polymerization [44]. Three dimensional porous scaffolds of PLA have been created for culturing different cell types, using in cell based gene therapy for cardiovascular diseases; muscle tissues, bone and cartilage regeneration and other treatments of cardiovascular, neurological, and orthopedic conditions [292–294]. Another two studies have reported osteogenic stem cells seeded on scaffolds of this material and implanted in bone defects or subcutaneously for recapitulating both developmental processes of bone formation: endochondral ossification and intramembranous ossification [295,296]. Due to the high strength of PLLA mesh, it is possible to create 3D structures such as trays and cages [297]. The PLA may take 10 months to 4 years to degrade, depending on the microstructural factors such as chemical composition, porosity and crystallinity that may influence tensile strength for specific uses [1]. Moreover, lactic polymers can stimulate isolated cells to regenerate tissues and release drugs such as painkillers, anti-inflammatories and antibiotics, which have recently motivated their study as scaffolds for cell transplantation [6,298,299].

PLA scaffold degradation — scaffolds should maintain their mechanical properties until it is no longer needed. In consecutive order, the scaffold degraded, absorbed, and excreted by the body, leaving no trace [62]. Scaffolds gradually degrade by predetermined periods to be replaced by newly grown tissue from the adhered cells [300]. Degradation results in scaffold dismantling and material dissolution/resorption through the scaffold bulk and/or surface types of degradation [62,260]. The biodegradation rate of a biopolymer depends mainly on its intrinsic properties, including, chemical structure, the presence of hydrolytically unstable bonds, level of hydrophilicity/hydrophobicity, crystalline/amorphous morphology, T_g, copolymer ratio, and its Mw [301]. Other interrelated factors should be taken into account for predicting the mechanism of bioerosion, including a) the presence of catalysts, additives, impurities or plasticizers, b) the geometry of the device and c) the location of the device. Also implants under stress have been reported to degrade faster. A potential explanation to this phenomena have proposed that in stressed implant a microcracks may form, leading to an increase in the exposed surface area to water [164,165]. For summary, balancing all of these factors to tailor an implant for slow degradation and transfer stress to the surrounding tissue as it heals at the appropriate rate are the keys for biomedical device success.

PLA and 3D printing — Merging the 3D printing technology with intrinsic properties of PLA was found to be a promising way to produce complex biomedical devices according to computer design using patient-specific anatomical data as well as in wide range of industrial and architectural applications [302]. Specifically, in biomedical application, PLA 3D printing has slowly evolved to create one-of-a-kind devices and also improvement in implants and scaffold performance for tissue engineering, diagnostic platforms, and drug delivery systems [303]. PLA printing was found feasible for the aforementioned applications mainly by using direct or indirect 3D printing and fused deposition modeling technologies. Helena and Benjamin have reported an excellent summary on the recent progress in PLA 3D printing technologies for tissue engineering [303].

Fueled with the recent advances in cell manipulation technology and nano-machinery it can be anticipated that the interest in combining stem cells with custom PLA 3D scaffolds for personalized regenerative medicine is the growing spot of PLA 3D printing. However, before PLA 3D printing can be used routinely for the regeneration of complex tissues (e.g. bone, cartilage, muscles, vessels, nerves in the craniomaxillofacial complex), and complex organs with intricate 3D microarchitecture (e.g. liver, lymphoid organs), several technological limitations and balancing between physical/mechanical properties and biodegradation must be addressed. Deep understanding of these limitations should motivate future research and advance this fascinating field for advanced manufacturing.

5.1.5. Other applications

Other applications for PLA and its copolymers have been reported [304,305]. These studies have reported for the first time the use of lactic acid based polymers for fabrication of implantable biodegradable inflatable balloons. These balloons were designed for reducing radiation adverse effects in prostate cancer by prostate–rectum separation (up to 9 mm) or as a sub-acromial spacer in the treatment of massive irreparable rotator cuff tears (Fig. 14) [304–306]. Balloon's shape, mechanical and chemical properties were premeditated to withstand the different surrounding tissue stress following minimally invasive balloon deployment and in situ inflation, up to a desired period of time (weeks–months) and then gradually biodegrade. For these applications, they have controlled the balloon mechanical stability by its wall thickness and Mw. The balloon's safety and efficacy was established in a mammalian model and they have maintained their performance along the study followed by biodegradation without toxicity [304,305]. Recently, clinical studies have evaluated the safety and efficacy of these balloons for long term performance (up to 3 years of post-implantation) and the results were found promising, no safety issues were raised [306–308]. This example represents a good model for PLA property optimization and device fabrication to fulfill medical need, starting with proper polymer composition, implant degradability–mechanical stability balancing and proper sterilization technique development.

5.2. Non- medical application

Globally, bioplastics make up nearly 300,000 metric tons of the plastic market. Even though it sounds like a lot, this only accounts for less than 1% of the 181 million metric tons of synthetic plastics the world produces each year. Nevertheless, the bioplastic market is growing by 20–30% each year [160]. As we proceed forward into the 21st century, an increased utilization of renewable resources will be one of the strong drivers for sustainable products. Reduced energy consumption, waste generation, and emission of greenhouse gases will take on greater emphasis. PLA is the first commodity plastic to incorporate these principles and is currently the most promising and popular material with the brightest development prospect and is considered as the 'green' eco-friendly material [8,160]. PLA is ideally suited for many applications in the environment where recovery of the product is not practical, such as agricultural mulch films and bags. Composting of post-consumer PLA items is also a viable solution for many PLA products. Biodegradable plastics, packaging and paper coatings, sustained release systems for pesticides and fertilizers and compost bags etc. are also examples of PLA usage in non-medical application. However, the large growth seen for PLA in many applications does not depend solely upon the biodegradability of the material. Each grade is optimized for both processing and end use performance in its intended application.

Currently, Nature Works LLC is the leader in lactic polymer technology and markets. Over the past 10 years, this company has done extensive work on the development of lactic acid-based products, which are of two types-the PLA-based resins (Nature-Works PLA) used for plastics or packaging applications, and the Ingeo™ polydilactide-based fibers that are used in specialty textiles and fiber applications [160]. Fiber
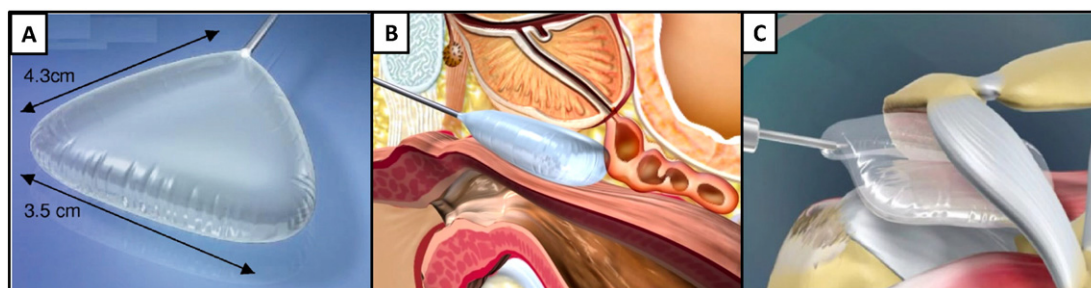
Fig. 14. (A) Prostatic lactic acid based balloon was preshaped to separate and retract prostate from nearby rectum to reduce radiation adverse effects in patients with prostate cancer (adapted from [305]). (B) Schematic representation of lactic acid based balloon (ProSpace™) inflated with a physiological saline and sealed in situ in between the rectum wall and the prostate gland spacing up to 9 mm between the two organs (adapted from [304]). (C) Schematic representation of lactic acid based balloon (InSpace™) deployment and inflation in the sub-acromial space through an insertion tube.
(Adapted from [306]).

manufacturing is one of the largest potential application areas for PLA. PLA is readily melt spinnable, stress crystallizes upon drawing, and can be designed for many fiber applications. Some of the current fiber uses include hollow fiberfill for pillows and comforters, bulk continuous filament for carpet, filament yarns, and spun yarns for apparel, spun bond, and other nonwovens and bicomponent fibers for binders and self-crimping fibers. In the form of non-woven textiles, PLA also has many potential uses, for example as upholstery, disposable garments, awnings, feminine hygiene products, and nappies. Most fiber applications require polymer with high optical purity (OP) to allow high levels of crystallinity to develop and to have adequate heat resistance in the application. Binder fibers are unique in that low crystallinity in the sheath layer is desired to allow ease of melting and adhesion to other fibers; thus, high (8–20%) D- or *meso*-lactide content is incorporated [8]. PLA can be processed on standard thermoplastic fiber spinning equipment with the appropriate temperature profiles relative to its crystal melting point. Melt temperatures of 200–240 °C are typically used. PLA is replacing PET in these applications because of its superior performance and the fact that the disposable products can be produced from fibers that are from 100% renewable resources and fully biodegradable. Some of the beneficial characteristics of PLA fiber products include its natural soft feel, ease of processing, and unique stain and soil resistance. PLA excels at resistance to stain in standard tests with coffee, cola, tea, catsup, lipstick, and mustard. PLA also burns with low smoke generation, has good ultraviolet resistance, is easily dyeable, and brings good wickability of moisture to applications [8].

Films are the second largest application area for PLA. Films are transparent when stress crystallized and have acceptance by customers for food contact. PLA films also have superior dead fold or twist retention for twist wrap packaging [8]. Different types of PLA resins with different application ranges are being produced and each customer should specify packaging demands and match them with PLA data sheets. For example, PLA in food packaging applications is ideal for fresh products and those whose quality is not damaged by PLA oxygen permeability [3]. PLA is a growing alternative as a "green" food packaging polymer. New applications have been claimed in the field of fresh products, where thermoformed PLA containers are used in retail markets for fruits, vegetables, and salads. For a few years, natural foods purveyors have been quietly using some PLA products, but the material got its biggest boost when Wal-Mart, the world's largest retailer, announced that they will sell some produce in PLA containers [160]. That field of application of biodegradable polymer in food-contact articles includes also disposable cutlery, drinking cups, salad cups, plates, overwrap and lamination film, straws, stirrers, lids and cups, plates and containers for food dispensed at delicatessen and fast-food establishments. These articles will be in contact with aqueous, acidic and fatty foods that are dispensed or maintained at or below room temperature, or dispensed at temperatures as high as 60 °C and then allowed to cool

to *RT* or below. So accordingly PLA based polymer's optical, physical and mechanical properties should be tailored [309]. The market capacity of these products packaged in PLA is unlimited. For today, the major PLA application is in packaging (nearly 70%), while the estimation for 2020 shows the increase of other applications especially in fibers and fabrics (up to 50%) [3]. In this field, as a native form or in a blend, PLA contributes tremendously to packaging material stiffness, clarity, deadfold and twist retention, low-temperature heat sealability, and special barrier characteristics (i.e. aroma and flavor). The functional properties and benefits of PLA in these areas are presented in Table 18 [3,310]. Although complete replacement of synthetic packaging films with eco-friendly packaging films is still far from full achievement, at least for specific applications like food packaging the use of bioplastics should be the future.

PLA challenges for the non-medical application and modifications — besides the main challenge of lowering the PLA manufacturing cost to hit 1.0 US$/kg or lower, other major technical challenges to widespread acceptance of bio-based polymers are difficulties achieving mechanical and barrier properties comparable with conventional synthetic polymers while maintaining biodegradability. Another challenge: PLA inferior moisture barrier properties compared to synthetic polymers [160]. So management of moisture penetration and hydrolytic degradation of PLA is extremely important during the manufacturing, shipping, storage, and end-use of PLA products [311]. The inherent brittleness of PLA has also been a major bottleneck for its large-scale commercial applications.

To improve the barrier properties several approaches are available (i.e. Table 10): i) use of coating with materials which would add hydrophobicity to the packaging material, ii) lamination of two or more biopolymers (co-extrusion), iii) use of an edible coating with the required barrier properties for the food and subsequently use biopolymers as primary packaging, iv) development of blends of biopolymers with different properties, some examples include PLA/PEG blends, PLA/PHA blends and PLA/PCL blends, v) chemical and/or physical modification of biopolymers, and vi) development of micro- and nanocomposites based on biopolymers [170,312]. Co-extruded laminated films are already widely used in food packaging applications. The major drawbacks of these methods are the substantial decreases in the strength and modulus of the toughened PLA. So, a PLA based material having good stiffness–toughness balance along with high biobased PLA content is still elusive [160]. For example: flexibility improvement was achieved by plasticizing PLA with its own monomers, PLA becomes increasingly flexible so that a continuous series of products can be prepared that can mimic PVC, LDPE, LLDPE, PP, and PS. For food contact applications a number of plasticizers or polymers have been reported [155], PLA has been blended with polymers such as poly(hydroxybutyrate), poly(vinylacetate), poly(ethylene oxide) and polysaccharides [189, 313,314]. However, these polymer blends generally exhibit phase separation in the whole or part of the composition range similar to

Table 18
PLA functional properties for packaging.
[3,310].

Functional property	Packaging improvement	Comment
Dead fold, twist, and crimp[a]	Improved folding and sealing	OPLA has excellent dead fold and twist retention
High gloss, and clarity	Package esthetics	Comparable with PET and cellophane, 3 times more than nylon and PP, 10 times more than LDPE
Barrier properties	Grease and oil resistance	Good resistant to oils and terpenes
Renewable resource	Made from CO_2 and H_2O	
Flavor and aroma properties	Reduced taste/odor issues	
Low temperature heat seal	Stronger seals at lower temperatures	PLA can provide an "easy-open" package
High tensile and modulus	Wet paper strength, ability to down gauge coating	
Low coefficient of friction, polarity	Printability	Excellent printability, metallizable, antifogging ability
GRAS status	Food contact approved	

[a] The ability to hold a crease or fold, or the ability to retain a twist that is imparted in order to close the edges of the film around a small object.

plasticizer usage especially at higher % (above 20%) [155]. Nevertheless it is important to take into account that product shelf life is favored by decreasing plasticizer content and/or orientation [160].

Another typical investigative approach is the use of nanometric additives [315], which have been reported to dramatically change rheological properties of polymer melts and to improve functional properties such as barrier to gases and vapors, mechanical properties and thermal stability, for example, nanocomposites of the aPLA and aPLA/PCL blends were obtained by melt-mixing with a properly modified kaolinite showed an improvement in these properties with regard to the polymers and blends without clay [312]. It was found that PLA based nanocomposites have exhibited higher rates of PLA biodegradation in compost by the addition of nanoclays, which was attributed to the high relative hydrophilicity of the clays, allowing an easier permeability of water into the polymer matrix and activating the hydrolytic degradation process [316]. Zhou and Xanthos studied the size effect and the kinetics of the thermal degradation of PLAs and they have concluded that, in general, the thermal stability of PDLLA and its composites is higher than that of PLLA and its composites and the thermal stability of the nanocomposites is higher than that of the microcomposites [215]. This new generation of PLA-based nanocomposites exhibits significant improvements in modulus, dimensional stability and solvent or gas resistance with respect to the pristine polymer at very low filler content (0.5–5% w/w), also offer extra benefits like low density, transparency, good flow, better surface properties and recyclability. Various inorganic nano-particles have been recognized as possible additives to enhance the polymer performance [171]. So with the help of nanotechnology and providing safe PLA nanocomposites, many of its weakness compared to petrochemical-based polymer will be resolved and increase the application potential of PLA-based nanocomposites in food packaging, besides medical applications, and tissue cultures [3]. Potentials and problems associated with the use of nanoscaled fillers to PLA have been recently reviewed [115,171,315,317]. The research and development of bio-nanocomposite materials for packaging applications is expected to grow in the next years, due to the possibility of improving both packaging performance and process technology of biopolymers.

For PLA's fiber performance improvement, it was found that it can be combined with natural or regenerated fibers including cotton, wool, silk, viscose, lyocell, and others along with synthetic fibers made from PET, nylon, and other petroleum-based synthetics [8].

PLA and active packaging applications — active packaging realizes certain extraordinary and vital functions other than providing an inert barrier between product and external conditions. Active substances that are important and considered for novel bioactive packaging include antimicrobials, vitamins, phytochemicals, prebiotics, marine oils, and immobilized enzymes [318]. Specifically, antimicrobial packaging trends have been widely reported. The innovative strength of PLA antimicrobial packaging has a direct impact on consumer health by creating safer and more wholesome packaged foods as well as prolong the shelf life of packaged food products by slowing down or inhibiting those

mechanisms that are responsible for packaged food products unacceptability [170]. A whole range of active additives, including silver-substituted zeolite, organic acids and their salts, bacteriocins such as nisin and pediocin, enzymes such as lysozyme, a chelator like ethylenediaminetetraacetic acid (EDTA), lactoferrin, and plant extracts have already been successfully incorporated in antimicrobial active packaging [319]. Successful introduction of a new active packaging requires careful attention to the interactions in the active agent, packaging, and food triangle. The most widely used bacteriocin in active food packaging is nisin due to its GRAS status [320]. Fig. 15 shows schematic representation of PLA film for food packaging with nisin as an active agent incorporated and release strategy. The mechanical and physical properties of the PLA are the key role for effective and preplanned release of nisin.
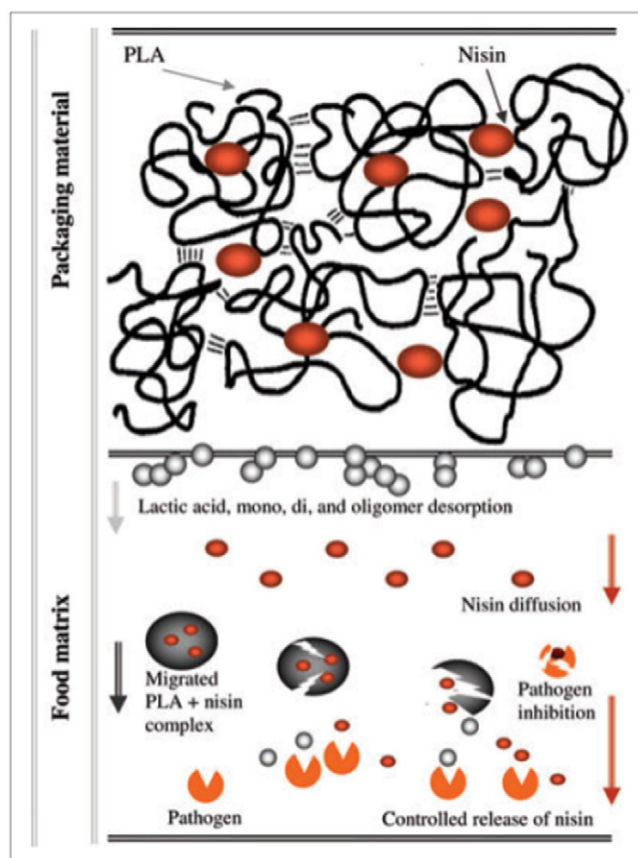

Fig. 15. Schematic representation of PLA film with nisin as an active agent incorporated and release thereof.
(Reprinted from [3]).

The incorporation of antimicrobial agents into PLA packaging material slows down their release and helps to maintain high concentrations of the active compounds against pathogenic bacteria like *Listeria monocytogenes* [321]. In the last decade, the above-mentioned slow release approach has been used for PLA. In this regard, major antimicrobial agents include bacteriocins, predominantly nisin [321], lactic acid [322], lysozyme [323], and chitosan [324,325]. Solvent casting technique was extensively reported for starch, zein and PLA-based antimicrobial film production [319,326–328]. However, the use of extrusion-based processing, industrially employed for the manufacturing of packaging films, could affect the functionalities of antimicrobial compounds embedded in the polymeric matrix [3].

Although the above-mentioned PLA systems reduced resistant bacterial strain development and guaranteed a higher level of microbial protection for certain food products, their casting and preparation were still complicated and challenging due to reported cases of processing inactivation. Up until now, a literature study reveals that relatively low attention has been given to micro-encapsulated active agents in foods. Active agent-loaded polymeric micro-/nanoparticles give the impression of being promising formulations to achieve long-lasting antimicrobial activity as they will prevent the invasion of bacteria and micro-organisms [329], and should be further focused on and it can be enlarged to the applications of other active agents like antioxidants for oil rich foods and antisticking/antifogging agents for cheese slices and fresh fruits, respectively. Controlling and manipulation of physical and mechanical properties of PLA (i.e. D/L ratio and Mw) is the key role for long lasting successful active packaging.

6. Summary and outlook

PLA is a leading candidate for consumer and biomedical applications, and the ability to tailor its mechanical, physical, microstructural, chemical, and degradation properties for specific applications makes the market capacity of PLA products unlimited and that has catalyzed an 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. This review has also covered the major concerns about PLA physical and mechanical property variation during processing, recycling, biodegradation and aging, as well as discussed the thermal instability impact on these properties. The last part of this review has provided an overview on PLA's physical and mechanical properties' role and function in widespread application.

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. Besides that, we do expect for the nearby future increasing research interest in the following four areas:

a) PLA blends stability: recently, several PLA blends based synthetic or natural components have been reported and found very efficient in PLA properties improvement [235,330–343]. However, very limited attention have been given for studying blends stability under different aging conditions (e.g. in different environments, during storage, during reprocessing), this part is highly essential and should be further focused on impartial evaluation of these new compositions advantage, in terms of durability and applicability, in comparison to classical reported compositions (PLA:PGA, PLA:PCL, etc.).

b) PLA-based nanocomposites: the linkage of a 100% bio-originated material and nanomaterials opened new windows for becoming independent from petrochemical-based polymers and many of PLA's weakness have been resolved [172,173]. This new generation of PLA based nanocomposites was found to exhibits significant improvements, at very low filler contents (0.5–5% w/w), with the help of nanotechnology and providing safe PLA nanocomposites. The research and development of bio-nanocomposite materials for packaging applications (especially for direct food contact packaging materials) is expected to grow in the next years, due to the possibility of improving both packaging performances and process technology of biopolymers. In this area, we have also found that less attention has been given to inorganic nano-particles while various have been recognized as possible additives to enhance the polymer performance, their potential in combination with PLA should be further studied.

c) Composites of fiber mixtures: such mixtures combine the positive properties of different fibers [334–343]. Learning from nature what the function of a fiber in a plant is we can design the composite properties by adding seed fibers with high elongations for improved impact or stem fiber for improved stiffness. The role of the reinforcing fiber should be more focused in future research activities of PLA composites. Playing with the different fiber characteristics a design of composite properties is possible. The results have shown so far that the investigated composites with their various characteristics can be used for different technical applications, each suiting specific requirements.

d) Computational modeling of PLA behavior for different applications: the magnitude of experimentally observed nonlinear behaviors of PLA's properties increases the importance of computational modeling to both understand how a device-based lactic acid will behave in a given environment, and to optimize the device for a given application. A number of carefully developed constitutive models are now under development for predicting the material response in different load environments (i.e. simulating PLLA stent fixed inside artery). These models, if applied properly, can provide great insight into the response of various materials and designs. Due to the high interest in this area from both academia and industry, we can only expect computational modeling to become even more powerful in the coming years.

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