Review: Numerous biodegradable polymers have been developed in the last two decades. In terms of application, biodegradable polymers are classified into three groups: medical, ecological, and dual application, while in terms of origin they are divided into two groups: natural and synthetic. This review article will outline classification, requirements, applications, physical properties, biodegradability, and degradation mechanisms of representative biodegradable polymers that have already been commercialized or are under investigation. Among the biodegradable polymers, recent developments of aliphatic polyesters, especially polylactides and poly(lactic acid)s, will be mainly described in the last part.

Polarizing optical photomicrograph of a PLLA film annealed at 140 °C after melting at 200 °C

Biodegradable polyesters for medical and ecological applications

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1. Introduction

Polymer degradation takes place mostly through scission of the main chains or side-chains of polymer molecules, induced by their thermal activation, oxidation, photolysis, radiolysis, or hydrolysis. Some polymers undergo degradation in biological environments when living cells or microorganisms are present around the polymers. Such environments include soils, seas, rivers, and lakes on the earth as well as the body of human beings and animals[1–18]. In this article, biodegradable polymers are defined as those which are degraded in these biological environments not through thermal oxidation, photolysis, or radiolysis but through enzymatic or non-enzymatic hydrolysis.

In a strict sense, such polymers that require enzymes of microorganisms for hydrolytic or oxidative degradation are regarded as biodegradable polymers. This definition does not include polylactides in the category of biodegradable polymers, because polylactides are hydrolyzed at a relatively high rate even at room temperature and neutral pH without any help of hydrolytic enzymes if moisture is present. This often gives rise to confusion when we say that polylactides are biodegradable. As will be shown later, polylactides, especially polyglycolide, are readily hydrolyzed in our body to the respective monomers and oligomers that are soluble in aqueous media[2]. As a result, the whole mass of the polymers disappears, leaving no trace of remnants. Generally, such a polymer that loses its weight over time in the living body is called an absorbable, resorbable, or bioabsorbable polymer as well as a biodegradable polymer, regardless of its degradation mode, in other words, for both enzymatic and non-enzymatic hydrolysis. To avoid this confusion, some people insist that the term "biodegradable" should be used only for such ecological polymers that have been developed aiming at the protection of earth environments from plastic wastes, while the polymers applied for medical purposes by implanting in the human body should not be called biodegradable but resorbable or absorbable. In this article, however, the term "biodegradable" is used in spite of this confusion, since the term has been widely utilized in the biomaterial world for the biomedical polymers that are absorbed in the body even

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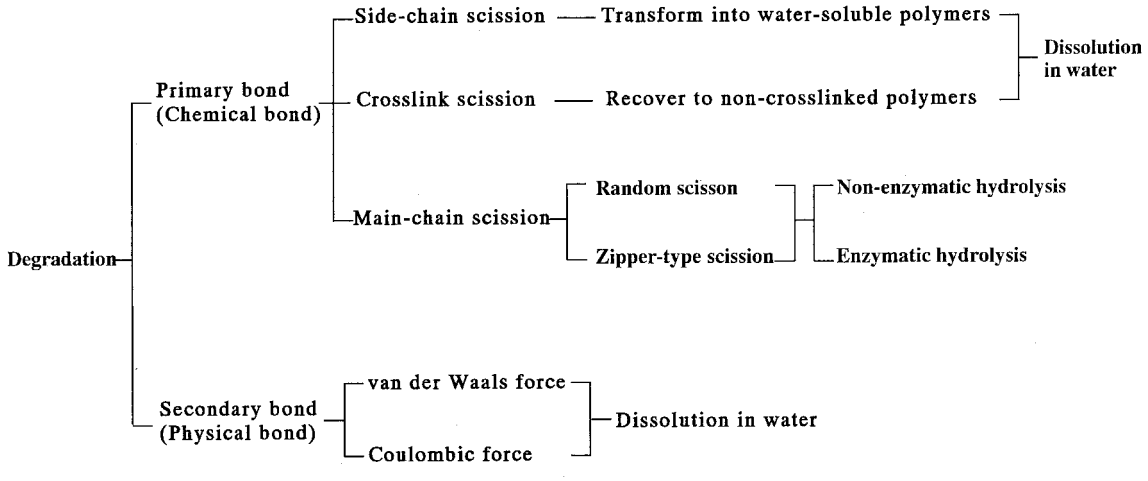

Fig. 1. Modes of resorption of polymers

Tab. 1. Classification of biodegradable polymers

Natural Polymers		Synthetic Polymers	
Sub-classification	Examples	Sub-classification	Examples
1. Plant origin		1. Aliphatic polyesters	
1.1 Polysaccharides	Cellulose, Starch, Alginate	1.1 Glycol and dicarbonic acid polycondensates	Poly(ethylene succinate), Poly(butylene terephthalate)
2. Animal origin		1.2 Polylactides	Polyglycolide, Polylactides
2.1 Polysaccharides	Chitin (Chitosan), Hyaluronate	1.3 Polylactones	Poly(ε-carpolactone)
		1.4 Miscellaneous	Poly(butylene terephthalate)
2.2 Proteins	Collagen (Gelatin), Albumin	2. Polyols	Poly(vinyl alcohol)
3. Microbe origin		3. Polycarbonates	Poly(ester carbonate)
3.1 Polyesters	Poly(3-hydroxyalkanoate)		
3.2 Polysaccharides	Hyaluronate	4. Miscellaneous	Polyanhydrides, Poly(α-cyanoacrylate)s, Polyphosphazenes, Poly(orthoesters)

through non-enzymatic hydrolysis. In other words, the term "biodegradable" is used here in broad meaning that the polymer will eventually disappear after introduction in the body, without references to the mechanisms of degradation. Fig. 1 shows a variety of mechanisms responsible for polymer resorption.

These biodegradable polymers have currently two major applications; one is as biomedical polymers that contribute to the medical care of patients and the other is as ecological polymers that keep the earth environments clean. Most of the currently available biodegradable polymers are used for either of the two purposes, but some of them are applicable for both, as illustrated in Fig. 2. Biodegradable polymers can be also classified on the basis of the origin, that is, naturally occurring or synthetic. Tab. 1 lists biodegradable polymers classified according to the polymer origin.

The purpose of this article is to give a brief overview on representative biodegradable polymers that have

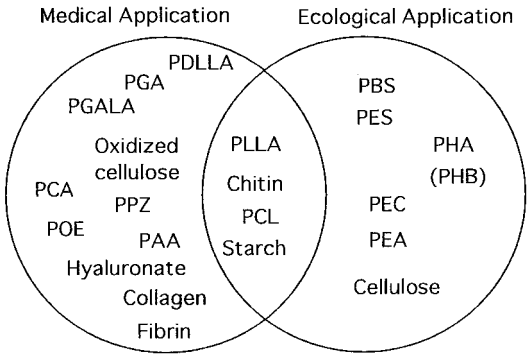

Fig. 2. Application of biodegradable polymers. PAA: Poly(acid anhydride); PBS: Poly(butylene succinate); PCA: Poly(α-cyanoacrylate); PCL: Poly(ε-caprolactone); PDLLA: Poly(DL-lactide), Poly(DL-lactic acid); PEA: Poly(ester amide); PEC: Poly(ester carbonate); PES: Poly(ethylene succinate); PGA: Poly(glycolide), Poly(glycolic acid); PGALA: Poly(glycolide-*co*-lactide), Poly(glycolic acid-*co*-lactic acid); PHA: Poly(hydroxyalkanoate); PHB: Poly(3-hydroxybutyrate); PLLA: Poly(L-lactide), Poly(L-lactic acid); POE: Poly(orthoester)

already been commercialized or are under investigation for biomedical and ecological applications.

2. Biomedical applications

2.1 Biomaterials

A variety of polymers have been used for medical care including preventive medicine, clinical inspections, and surgical treatments of diseases[19–23]. Among the polymers employed for such medical purposes, a specified group of polymers are called polymeric biomaterials when they are used in direct contact with living cells of our body. Typical applications of biomaterials in medicine are for disposable products (e.g. syringe, blood bag, and catheter), materials supporting surgical operation (e.g. suture, adhesive, and sealant), prostheses for tissue replacements (e.g. intraocular lens, dental implant, and breast implant), and artificial organs for temporary or permanent assist (e.g. artificial kidney, artificial heart, and vascular graft). These biomaterials are quite different from other non-medical, commercial products in many aspects. For instance, neither industrial manufacturing of biomaterials nor sale of medical devices are allowed unless they clear strict governmental regulatory issues. The minimum requirements of biomaterials for such governmental approval include non-toxicity, sterilizability, and effectiveness, as shown in Tab. 2. Biocompatibility is highly desirable but not indispensable; most of the clinically used biomaterials lack excellent biocompatibility, although many efforts have been devoted to the development of biocompatible materials by biomaterials scientists and engineers. A large unsolved problem of biomaterials is this lack of biocompatibility, especially when they are used not temporarily but permanently as implants in our body. Low effectiveness is another problem of currently used biomaterials.

The biological materials composing our living body as skeleton, frame, and tissue matrix are all biodegradable in a strict sense and gradually lose the mass unless additional treatments are given when our heart ceases beating.

Recently, biodegradable medical polymers have attracted much attention[7, 10, 22]. There are at least two reasons for this new trend. One is the difficulty in developing such biocompatible materials that do not evoke any significant foreign-body reactions from the living body when receiving man-made biomaterials. At present we can produce biomaterials that are biocompatible if the contact duration of biomaterials with the living body is as short as several hours, days, or weeks[24]. However, the science and technology of biomaterials have not yet reached such a high level that allows us to fabricate biocompatible implants for permanent use. On the contrary, biodegradable polymers do not require such excellent biocompatibility since they do not stay in our body for a long term but disappear without leaving any trace of foreign materials.

Tab. 2. Minimal requirements of biomaterials

1. Non-toxic (biosafe)
   Non-pyrogenic, Non-hemolytic, Chronically non-inflammative, Non-allergenic, Non-carcinogenic, Non-teratogenic, etc.
2. Effective
   Functionality, Performance, Durability, etc.
3. Sterilizable
   Ethylene oxide, γ-Irradiation, Electron beams, Autoclave, Dry heating, etc.
4. Biocompatible
   Interfacially, Mechanically, and Biologically

The other reason for biodegradable polymers attracting much attention is that nobody will want to carry foreign materials in the body as long-term implants, because one cannot deny a risk of infection eventually caused by the implants.

Although biodegradable polymers seem very promising in medical applications, these kinds of polymers currently do not enjoy large clinical uses, because there is a great concern on biodegradable medical polymers. This concern is the toxicity of biodegradation by-products, since the causes of toxicity of biomaterials are mostly due to low-molecular-weight compounds that have leached from the biomaterials into the body of patients. They include monomers remaining unpolymerized, ethylene oxide remaining unremoved, additives such as anti-oxidant and pigments, and fragments of polymerization initiator and catalyst. The content of these compounds in currently used biomaterials is below the level prescribed by regulations. Water-insoluble polymers generally are not able to physically and chemically interact with living cells unless the material surface has very sharp projections or a high density of a cationic moiety[24].

However, biodegradable polymers always release low-molecular-weight compounds into the outer environment as a result of degradation. If they can interact with the cell surface or enter into the cell interior, it is possible that the normal condition of the cell is disturbed by such foreign compounds. One can say that an implanted biomaterial induces cyto-toxicity if this disturbance is large enough to bring about an irreversible damage to the cell. Purified polyethylene and silicone are not toxic but also not biocompatible, because thrombus formation and encapsulation by collagenous fibrous tissues take place around their surface when implanted[24]. The largest difference in terms of toxicity between biodegradable and non-biodegradable polymers is that biodegradable polymers inevitably yield low-molecular-weight compounds that might adversely interact with living cells while any leach-

ables or extractables eventually contaminating non-biodegradable polymers can be reduced to such a low level as required by governmental regultaions, if the polymers are extensively and carefully manufactured and purified.

2.2 Surgical use

Application of biodegradable polymers to medicine did not start recently and has already a long history. Actual and possible applications of biodegradable polymers in medicine are shown in Tab. 3. Tab. 4 lists representative synthetic biodegradable polymers currently used or under investigation for medical application. As is seen, most of the applications are for surgery. The largest and longest use of biodegradable polymers is for suturing. Collagen fibers obtained from animal intestines have been long used as absorbable suture after chromium treatment[6]. The use of synthetic biodegradable polymers for suture started in USA in the 1970's[2,7]. Commercial polymers used for this purpose include polyglycolide, which is still the largest in volume production, together with a glycolide-L-lactide (90:10) copolymer[2,7]. The sutures made from these glycolide polymers are of braid type processed from multi-filaments, but synthetic absorbable sutures of mono-filament type also at present are commercially available.

The biodegradable polymers of the next largest consumption in surgery are for hemostasis, sealing, and adhesion to tissues[25]. Liquid-type products are mostly used for these purposes. Immediately after application of a liquid to a defective tissue where hemostasis, sealing, or adhesion is needed, the liquid sets to a gel and covers the defect to stop bleeding, seal a hole, or adhere two separated tissues. As the gelled material is no longer necessary after healing of the treated tissue, it should be biodegradable and finally absorbed into the body. The biomaterials used to prepare such liquid products include fibrinogen (a serum protein), 2-cyanoacrylates, and a gelatin/resorcinol/formaldehyde mixture.

2-Cyanoacrylates solidify upon contact with tissues as a result of polymerization to polymers that are hydrolyzable at room temperature and neutral pH, but yield formaldehyde as a hydrolysis by-product [2]. Regenerated collagen is also used as a hemostatic agent in forms of fiber, powder, and assemblies.

Another possible application of biodegradable polymers is the fixation of fractured bones. Currently, metals are widely used for this purpose in orthopaedic and oral surgeries in the form of plates, pins, screws, and wires, but they need removal after re-union of fractured bones by further surgery. It would be very beneficial to patients if these fixation devices can be fabricated using biodegradable polymers because there would be no need for a re-operation. Attempts to replace the metals with biodegradable devices have already started, as will be described later.

Tab. 3. Medical applications of bioabsorbable polymers

Function	Purpose	Examples
Bonding	Suturing	Vascular and intestinal anastomosis
	Fixation	Fractured bone fixation
	Adhesion	Surgical adhesion
Closure	Covering	Wound cover, Local hemostasis
	Occlusion	Vascular embolization
Separation	Isolation	Organ protection
	Contact inhibition	Adhesion prevention
Scaffold	Cellular proliferation	Skin reconstruction, Blood vessel reconstruction
	Tissue guide	Nurve reunion
Capsulation	Controlled drug delivery	Sustained drug release

2.3 Pharmaceutical use

In order to deliver drugs to diseased sites in the body in a more effective and less invasive way, a new dosage form technology, called drug delivery systems (DDS), started in the late 1960's in the USA using polymers. The objectives of DDS include sustained release of drugs for a

Tab. 4. Representative synthetic biodegradable polymers currently used or under investigation for medical application

Polymers	Structure	$\overline{M}_w$ / kD	Degradation rate	Medical application
Poly(glycolide)	Crystalline	–	100% in 2–3 months	Suture, Soft issue anaplerosis
Poly(glycolic acid-*co*-L-lactic acid)	Amorphous	40–100	100% in 50–100 days	Suture, Fracture fixation, Oral implant, Drug delivery microsphere
Poly(L-lactide)	Semicrystalline	100–300	50% in 1–2 years	Fracture fixation, Ligament augmentation
Poly(L-lactic acid-*co*-ε-caprolactone)	Amorphous	100–500	100% in 3–12 months	Suture, Dural substitute
Poly(ε-caprolactone)	Semicrystalline	40–80	50% in 4 years	Contraceptive delivery implant,
Poly(*p*-dioxanone)	Semicrystalline	–	100% in 30 weeks	Suture, Fracture fixation
Poly(orthoester)	Amorphous	100–150	60% in 50 weeks (saline, 37 °C)	Contraceptive delivery implant

desired duration at an optimal dose, targeting of drugs to diseased sites without affecting healthy sites, controlled release of drugs by external stimuli, and simple delivery of drugs mostly through skin and mucous membranes. Polymers are very powerful for this new pharmaceutical technology. If a drug is administered through a parenteral route like injection, the polymer used as a drug carrier should be preferably absorbable, because the polymer is no longer required when the drug delivery has been accomplished. Therefore, biodegradable polymers are widely used, especially for the sustained release of drugs through administration by injection or implantation into the body. For this purpose, absorbable nanospheres, microspheres, beads, cylinders, and discs are prepared using biodegradable polymers[26–28]. The shape of the most widely used drug carriers is a microsphere, which incorporates drugs and releases them through physical diffusion, followed by resorption of the microsphere material. Such microspheres can be prepared with a solvent-evaporation method using glycolide-lactide copolymers.

Naturally occurring biodegradable polymers are also used as drug carriers for a sustained release of drugs. If the drug carrier is soluble in water, the polymer need not to be biodegradable, because this polymer will be excreted from the body, associated with urine or feces although excretion will take a long time if the molecular weight of the polymer is extremely high.

2.4 Use for tissue engineering

Tissue engineering is an emerging technology to create biological tissues for replacements of defective or lost tissues using cells and cell growth factors[23]. Also, scaffolds are required for tissue construction if of the lost part of the tissue is so large that it cannot be cured by conventional drug administration. At present, such largely diseased tissues and organs are replaced either with artificial organs or transplanted organs, but both of the therapeutic methods involve some problems. As mentioned earlier, the biocompatibility of clinically used artificial organs is mostly not safisticatory enough to prevent severe foreign-body reactions and to fully perform the objective of the artificial organs aimed for patients. The biofunctionality of current artificial organs is still poor. On the contrary, the biofunctionality of transplanted organs is as excellent as healthy human organs, but the patients with transplanted organs are suffering from side-effects induced by immuno-suppresive drugs administered. Another major problem of organ transplantation is shortage of organ donors.

The final objective of tissue engineering is to solve these problems by providing biological tissues and organs that are more excellent in both biofunctionality and biocompatibility than the conventional artificial organs.

Biodegradable polymers are required to fabricate scaffolds for cell proliferation and differentiation which result in tissue regeneration or construction[23]. Biodegradable polymers are necessary also for a sustained release of growth factors at the location of tissue regeneration. Generally, scaffolds used in tissue engineering are porous and three-dimentional to encourage infiltration of a large number of cells into the scaffolds[14]. Currently, the polymers used for scaffolding include collagen, glycolide-lactide copolymers, other copolymers of lactide, and crosslinked polysaccharides.

3. Ecological applications

3.1 Processing of plastic wastes

The other major application of biodegradable polymers is in plastic industries to replace biostable plastics for maintaining our earth environments clean.

The first choice for processing of plastic wastes is reuse, but only some plastic products can be re-used after adequate processing, and many of them are very difficult to recycle. In these cases, wastes are processed by landfill or incineration, but these processes often pollute the environments. If biodegradation by-products do not exert adverse effects on animals and plants on the earth, biodegradable plastics can be regarded as environment-friendly or ecological materials. Therefore, much attention has been focused on manufacturing biodegradable plastics which, however, should address several requirements. They are to be low in product cost, satisfactory in mechanical properties, and not harmful to animals and plants when biodegraded. The biodegradation kinetics are also an important issue of biodegradable plastics.

Expected applications of biodegradable polymers in plastic industries are listed in Tab. 5. As can be seen, the applications cover a wide range of industries including agriculture, fishery, civil engineering, construction, out-

Tab. 5. Ecological applications of biodegradable polymers

Application	Fields	Examples
Industrial applications	Agriculture, Forestry	Mulch films, Temporary replanting pots, Delivery system for fertilizers and pesticides
	Fisheries	Fishing lines and nets, Fishhooks, Fishing gears
	Civil engineering and construction industry	Forms, Vegetation nets and sheets, Water retention sheets
	Outdoor sports	Golf tees, Disposable plates, cups, bags, and cutlery
Composting	Food package	Package, Containers, Wrappings, Bottles, Bags, and Films, Retail bags, Six-pack rings
	Toiletry	Diapers, Feminine hygiene products
	Daily necessities	Refuge bags, Cups

Tab. 6. Classification of aliphatic polyesters

Polymers	Chemical structure	Examples
Poly(*α*-hydroxylacid)s	—(O—CHR—CO)$_n$—	R : H Poly(glycolide) (PGA) R : CH_3 Poly(L-lactide) (PLLA)
Poly(3-hydroxyalkanoate)s	—(O—CHR—CH_2—CO)$_n$—	R: CH_3 Poly(3-hydroxybutyrate) (PHB) R : CH_3, C_2H_5 Poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV)
Miscellaneous Poly(*ω*-hydroxyalkanoate)s	—[O—$(CH_2)_m$—CO]$_x$— m = 3–5	m = 3 Poly(*γ*-butyrolactone) m = 4 Poly(*δ*-valerolactone) m = 5 Poly(*ε*-caprolactone)
Poly(alkylene dicarboxylate)	—[O—$(CH_2)_m$—O—CO—$(CH_2)_n$—CO]$_x$—	m = 2, n = 2 Poly(ethylene succinate) (PES) m = 4, n = 2 Poly(butylene succinate) (PBS) m = 4, n = 2,4 Poly(butylene succinate-*co*-butylene adipate) (PBSA)

door leisure, food, toiletry, cosmetics, and other consumer products. It is possible that the waste left as a result of outdoor activity and sports will stay for a long time in natural environments, possibly damaging them. On the other hand, when plastics are used indoors as food containers that are difficult to separate from the food remaining after use, the waste can be utilized as compostable if it is biodegradable.

3.2 Classification of ecological plastics

Biodegradable ecological plastics are defined as polymers that maintain mechanical strength and other material performances similar to conventional non-biodegradable plastics during their practical use but are finally degraded to low-molecular-weight compounds such as H_2O and CO_2 and non-toxic byproducts by microorganisms living in the earth environments after their use[29]. Therefore, the most remarkable feature of ecological plastics is their biodegradability.

In the infancy stage of ecological plastics, natural polymers, especially polysaccharides, were promising candidates for biodegradable polymers. They included starch, chitin, cellulose, and mucopolysaccharides, but not much attention is now paid to these polysaccharides except for cellulose and its derivatives because of their low processability in molding. However, chemically substituted, grafted, and blended starch and cellulose have been intensively studied to improve processability and physical properties[30, 31]. For example, cellulose acetate has been proven to be a thermoplastic and exhibit good barrier properties to grease and oil though chemical substitution of cellulose is well known to slow down its biodegradation, while starch-poly(vinyl alcohol) (PVA) blend has been investigated for relacement of low density polyethylene (LDPE) and polystyrene (PS).

Among the biodegradable polymers that have been most intensively investigated are aliphatic polyesters of both natural and synthetic origins. Their chemical structures are given in Tab. 6. They are except for poly(*α*-hydroxyacid)s[32, 33] degraded by enzymes excreted from microorganisms.

The synthesis of poly(*α*-hydroxyacid)s such as polyglycolide or poly(glycolic acid) is carried out by direct condensation polymerization of HO—R—COOH or ring-opening polymerization of —R—CO—O—R—CO—O—[4]. The former polymerization generally yields oligomers while the latter results in high-molecular-weight polymers. Poly(hydroxyalkanoate)s (PHA) are biosynthesized by microorganisms such as *Bacillus megaterium* using starch from corn and potato as raw materials, while poly(*ω*-hydroxyalkanoate)s are synthesized by ring-opening polymerization of lactones[9, 16]. Poly(alkylene dicarboxylate)s are generally produced by condensation of prepolymers having hydroxyl or carboxyl terminal groups using chain extenders such as diisocyanate[34]. Direct condensation polymerization between low-molecular-weight HO—R_1—OH and HOOC—R_2—COOH generally produces only low-molecular-weight polymers.

3.3 Physical properties of ecological plastics

Fig. 3 shows the melting and glass-transition temperatures as well as the tensile moduli of representative biodegradable polymers without any special treatments, along with those of typical conventional polymers. As is apparent, biodegradable polymers can be divided into two groups, that is, polyethylene(PE)-like and poly(ethylene terephthalate) (PET)-like polymers. The biodegradable polymers with a relatively large number of methylene groups and planar zigzag structure in a molecule are PE-like, including poly(*ε*-caprolactone) and poly(butylene succinate) (PBS), while PET-like polymers such as poly(3-hydroxybutyrate) (PHB) and poly(L-lactide) (PLLA) have helix structures and bulky side-chains. However, the elongation-at-break of PHB and PLLA observed at tensile testing is much lower than that of PET, resulting in low toughness and poor impact strength[9, 16]. This means that some modifications, for

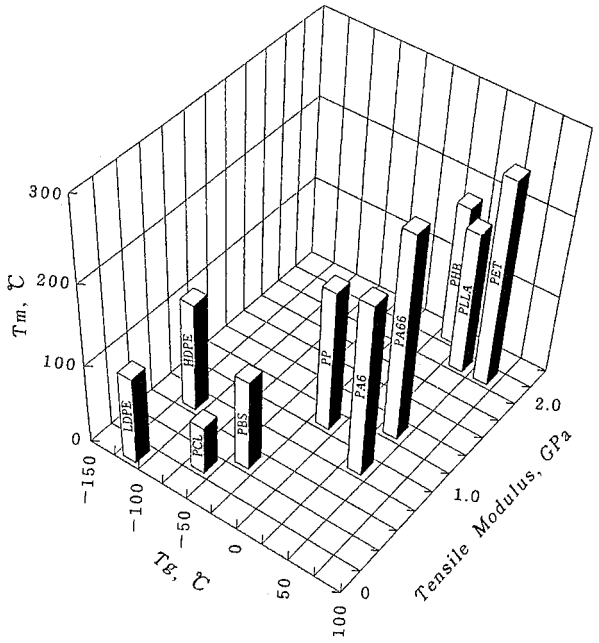

Fig. 3. Melting and glass-transition temperatures and tensile modulus of representative biodegradable and typical conventional polymers. HDPE: High-density polyethylene; LDPE: Low-density polyethylene; PA6: Nylon-6; PA66: Nylon-66; PBS: Poly(butylene succinate); PCL: Poly(ε-caprolactone); PET: Poly(ethylene terephthalate); PHB: Poly(3-hydroxybutyrate); PLLA: Poly(L-lactide); PP: Poly(propylene)

instance, copolymerization, blending, or addition, will be required for a large industrial production of these biodegradable polymers as real ecological plastics.

Another disadvantage of biodegradable polymers is their low crystallization temperature, which lowers the crystallization rate. This property brings about low processability when fibers are manufactured from these polymers.

Tab. 7 shows the moisture barrier, oxygen barrier, and mechanical properties of representative biodegradable polymers, together with their cost[31]. Evidently, physical properties as well as the cost of these polymers depend on their chemical and physical structures. This table will give important information to determine which polymer has a low cost/performance for respective end uses.

3.4 Biodegradability

Similar to biodegradation of cellulose and chitin by cellulase and chitinase, aliphatic polyesters undergo enzymatic degradation. Esterases are the enzymes responsible for hydrolytic degradation of aliphatic polyesters[35]. As this enzymatic reaction is of heterogeneous type, hydrolytic enzyme molecules first adsorb on the surface of substrate polymers through the binding site of enzyme molecules[35–38]. Then, the active site of the enzyme comes into direct contact with the ester bond of the substrate molecule. Different activities of different hydrolytic enzymes for the same substrate polymer may be due to different binding capacities of the enzymes to the substrate, as there is no large difference in the hydrolytic activity among enzymes. The enzymes excreted from microorganisms may hydrolyze polymers to low-molecular-weight compounds which will serve as a source of nutrients to the mother microorganisms.

An important group of esterases for biodegradation of aliphatic polyesters are lipases[32, 33]. These enzymes are known to hydrolyze triacylglycerols (fat) to fatty acid and gycerol. It seems probable that lipase can hydrolyze aliphatic polyesters in contrast with aromatic polyesters,

Tab. 7. Moisture barrier, oxygen barrier, mechanical properties, and cost of representative biodegradable polymers[31]

Materials	Moisture barrier[a]	Oxygen barrier[b]	Mechanical Properties[c]	Cost ($/lb)
Collagen	Poor	Good	Moderate	49.00–54.00[d]
Gelatin	Poor	Good	NA	2.40–2.60[e]
High Amylose Starch	Poor	Moderate	Moderate	0.60–0.70[e]
Methyl Cellulose	Moderate	Moderate	Moderate	4.50–7.00[e]
Cellulose Acetate	Moderate	Poor	Moderate	1.60–2.10[f, g]
Starch/PVA	Poor	Good	Good	1.50–3.00[f]
P(3HB-4HV)	Good	Good	Moderate	3.00–6.00[f]
PLA	Moderate	Poor	Good	1.00–5.00[f]

[a] Test conditions: ≈38 °C, 0–90% RH (RH = relative humidity). Poor: 10–100 g · mm/mm² · d · kPa; Moderate: 0.1–10 g · mm/mm² · d · kPa; Good: 0.01–0.1 g · mm/mm² · d · kPa (LDPE: 0.08 g · mm/mm² · d · kPa).

[b] Test conditions: ≈25 °C, 0–50% RH. Poor: 100–1000 cm³ μm/m² · d · kPa; Moderate: 10–100 cm³ μm/m² · d · kPa; Good: 1–10 cm³ μm/m² · d · kPa. (Ethylene vinyl alcohol copolymer: 0.1 cm³ μm/m² · d · kPa)

[c] Test conditions: ≈25 °C, 50% RH. Moderate tensile strength (σ_B): 10–100 MPa, Moderate elongation-at-break (ε_B): 10–50% (LDPE: σ_B = 13 MPa, ε_B = 500%; Oriented PP: σ_B = 165 MPa, ε_B = 60%).

[d] Finished film cost from supplier.

[e] Material cost range from suppliers.

[f] Compares to $/lb resin (and finished film) costs for LDPE: $0.50 ($1.00); PS: $0.55 ($2.00); PET: $0.75 ($3.00).

[g] Finished film cost from supplier is $4.00/lb.

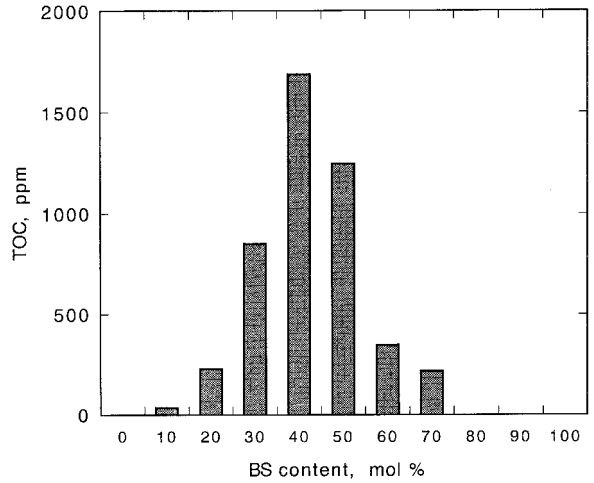

Fig. 4. Increase in total organic carbon (TOC) after hydroysis of films prepared from copolymers of butylene succinate (BS) and ethylene succinate (ES) by lipase from *Phycomyces nitens* at 30 °C for 16 h as a function of the BS content in the copolymers[43)]

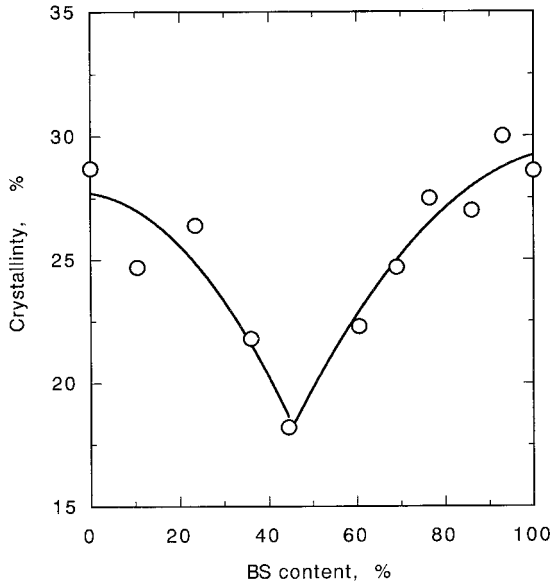

Fig. 5. Crystallinity of films prepared from copolymers of butylene succinate (BS) and ethylene succinate (ES) as a function of the BS content in the copolymers[43)]

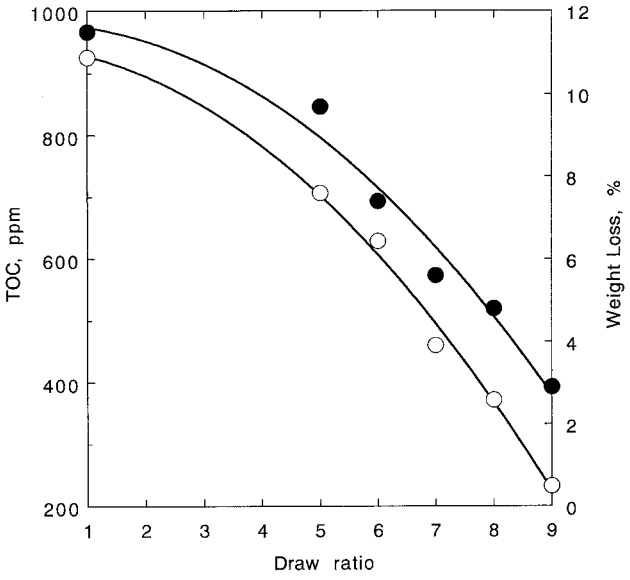

Fig. 6. Increase in total organic carbon (○) and weight loss (●) of PCL filaments after hydrolysis by lipase from *Phizopus arrhizus* at 30 °C for 16 h as a function of the draw ratio of the filaments[43)]

because the flexibility of the main-chain and the hydrophilicity of aliphatic polyesters is so high to allow intimate contact between the polyester chain and the active site of lipases in marked contrast with the rigid main-chain and hydrophobicity of aromatic polyesters.

The biodegradability of polyesters is investigated in terms of the hydrophilic/hydrophobic balance of polyester molecules, since their balance seems to be crucial for the enzyme binding to the substrate and the subsequent hydrolytic action of the enzyme. Interestingly, lipases are not able to hydrolyze polyesters having an optically active carbon such as PHB and PLLA[32, 33, 39)].

The hydrolysis of PHA is catalyzed by PHA depolymerase which has a sequence of -Asn-Ala-Trp-Ala-Gly-Ser-Asn-Ala-Gly-Lys- as the active center[40)]. It is reported that PHB is hydrolyzed by PHA depolymerase more quickly than a copolymer of 3-hydrolxybutyrate (3HB) and 3-hydroxyvalerate (3HV) [P(3HB-3HV)] but more slowly than the copolymer of 3HB and 4-hydroxyvalerate (4HV) [P(3HB-4HV)][41)]. This difference in hydrolysis rate may be explained in terms of bulkiness of the side-chain of PHA which hinders the enzymatic attack on the ester bond of PHA through a steric hindrance effect.

Both lipases and PHA depolymerase are enzymes of the endo-type which breaks bonds randomly along the main-chain of the substrate polymer, in contrast to enzymes of the exo-type which attack zipper-like the bonds at the end of the main-chain[42)].

Finally, effects of the physical structure of the substrate polymers on their hydrolysis should be mentioned. Fig. 4 gives the hydrolysis rate of films prepared from copolymers of butylene succinate (BS) and ethylene succinate (ES) by lipase from *Phycomyces nitens*as a function of the BS content in the copolymers[43)]. It seems that the enzymatic hydrolysis of the copolymers greatly depends on the chemical composition. However, the more direct factor influencing the hydrolysis is not the chemical composition but the crystallinity of the copolymer films, since there is a linear correlation between the hydrolysis rate and the crystallinity of the films, as is obvious from comparison of Fig. 4 and Fig. 5[43)], where the film crystallinity is plotted against the chemical composition of the films. Such a clear dependence of polymer hydrolysis on the substrate crystallinity can be also recognized in Fig. 6,

Tab. 8. Physical properties of PGA, PLLA, PDLLA, and PCL

	PGA	PLLA	PDLLA	PCL
T_m/°C	225–230	170–190	–	60
T_m^{0}[a]/°C	–	200–215	–	71, 79
T_g/°C	40	50–60	50–60	–60
ΔH_m (x_c = 100%)/(J/g)	180–207	93	–	142
Density/(g/cm^3)	1.50–1.69	1.25–1.29	1.27	1.06–1.13
Solubility parameter (25 °C)/(J/cm^3)$^{0.5}$	–	22.7	21.1	20.8
$[a]_{25}^{D}$ in chloroform	–	–155 ± 1	0	0
WVTR[b]/(g/m^2/day)	–	82–172	–	177
σ_B[c]/(kg/mm^2)	8–100[d]	12–230[d]	4–5[e]	10–80[d]
E[f]/(kg/mm^2)	400–1400[d]	700–1000[d]	150–190[e]	–
ε_B[g]/%	30–40[d]	12–26[d]	5–10[e]	20–120[d]

[a] Equilibrium melting temperature.
[b] Water vapor transmission rate at 25 °C.
[c] Tensile strength.
[d] Oriented fiber.
[e] Non-oriented film.
[f] Young's modulus.
[g] Elongation-at-break.

where the hydrolysis rate of PCL filaments is given as a function of the draw ratio of the filaments[44]. Obviously, an increase in draw ratio promotes the crystallization of the filaments.

4. Dual applications

4.1 Polylactides and PCL

There is a group of polymers that is used for both medical and ecological applications. Among them are PLLA and PCL. Both aliphatic polyesters are synthesized by ring-opening polymerization. PLLA is degraded non-enzymatically in both earth environments and the human body, while PCL is enzymatically degraded in earth environments, but non-enzymatically in the body[45–48]. Here, focus is given on polylactide, i.e., poly(lactic acid) (PLA) alone, because PLA has much more applications than PCL and, hence, has attracted much more attention. The general term "polylactides" include not only PLLA, poly(DL-lactide), and poly(DL-lactic acid) (PDLLA), but also PGA.

4.2 Synthesis of PLA

The monomers used for ring-opening polymerization of lactides are synthesized from glycolic acid, DL-lactic acid, L-lactic acid, or D-lactic acid. Among them, only L-lactic acid is optically active and produced by fermentation using *Lactobacilli*[49].The raw materials for this fermentation are corn, potato, sugar cane, sugar beat, etc.[49] All of them are natural products, similar to those of PHA. This is a great advantage over conventional polymers, which consume oil as their starting material. Natural products can be supplied without limit, whereas oil is thought to be exhausted sooner or later in the future, though some processing energy for fermentation is needed for the production of lactic acids. The effects of producing biodegradable polymers on natural environments should be discussed not only by consumption of natural resources but also by energy consumption and effects of by-products. However, no sufficient information concerning this issue has been obtained so far.

There is a debate on the future potential of PLLA and PHA. Some researchers think that PHA will dominate PLLA in the future when plants modified with gene technology will become capable of producing PHA on a large scale, while others say that ring-opening polymerization in chemical industries is more controllable and produces a larger amount of polymer than biosynthesis in the outdoor field. It seems too early to give a conclusion on this issue, although it is clear that the most important influential factor is the production cost of these polymers, and this is a complex issue depending on many factors.

The widely used catalyst for ring-opening polymerization of PLA is stannous octoate and the regulator of chain length is lauryl alcohol[50–52]. By changing the concentration of these additives, bulk polymerization of lactides around 120–140 °C yields PLA with molecular weights ranging from several thousands to several millions[53]. Ajioka et al. succeeded in the synthesis of PLLA by a one-step condensation polymerization of L-lactic acid using azeotropic solvents such as diphenyl ether[54].

4.3 Physical properties of PLA

Physical properties of polymeric materials depend on their molecular characteristics as well as ordered struc-

tures such as crystalline thickness, crystallinity, spherulitic size, morphology, and degree of chain orientation. These physical properties are very important, because they reflect the highly ordered structure of the materials and influence their mechanical properties and their change during hydrolysis. Tab. 8 summarizes the physical properties of PGA PLLA, PDLLA, and PCL.

4.3.1 Molecular weight effect

T_m increases with a rise in $\bar{M}_w$ and approaches a constant value around 180 °C, while x_c decreases gradually with the increasing $\bar{M}_w$. A physical property *(P)* of a polymeric material in general can be expressed using $\bar{M}_n$ by Eq. (1):

$$P = P_0 - K/\bar{M}_n \quad (1)$$

where K is a constant and P_0 is the physical property of the polymer with infinite $\bar{M}_n$. Fig. 7 shows the physical properties of solution cast PLLA and PDLA films including tensile strength (σ_B), Young's modulus *(E)*, and elongation-at-break (ε_B) as a function of $1/\bar{M}_n$[55]. Evidently, PLLA films have non-zero tensile strength when their $1/\bar{M}_n$ is lower than 2.2×10^{-5}, in other words, $\bar{M}_n$ is higher than 4.5×10^4. The tensile properties almost linearly increase with a decrease in $1/\bar{M}_n$ below 2.2×10^{-5}.

4.3.2 Copolymerization effect

T_m and x_c of PLA are generally reduced by a decrease in tacticity. DSC thermograms of poly(L-lactide-*co*-glycolide) [P(LLA-GA)] and poly(D-lactide-*co*-glycolide) [P(DLA-GA)] having different L-lactide(LLA) and D-lactide(DLA) contents (X_{Ll} and X_{Dl}, respectively) are shown in Fig. 8[56]. It is obvious that T_m and x_c decrease with increasing fraction of the GA unit, finally losing the crystallizability of P(LLA-GA) and P(DLA-GA) for X_{Ll} and X_{Dl} below 0.75. Similarly, PLA stereocopolymers lose their crystallizability for DLA contents (X_D) below 0.83 and above 0.15[57,58]. This result and Eq. (1) suggest that the crystalline thickness (L_c) of copolymers decreases with increasing comonomer content. The result of crystallizability tests of PLA stereocopolymers having different X_D from the melt implies that the critical isotactic sequence length of PLA for crystallization is approximately 15 isotactic lactate units.

The weight of poly(DL-lactide-*co*-glycolide) [P(DLLA-GA)] remaining after their in vitro hydrolysis is shown in Fig. 9[59]. A rapid decrease of the remaining weight is observed for P(DLLA-GA) having high GA contents. This is probably due to the high hydrophilicity of the GA unit compared to the DL-lactide (DLLA) unit, which will accelerate the hydrolysis rate of the copolymers having high GA contents.

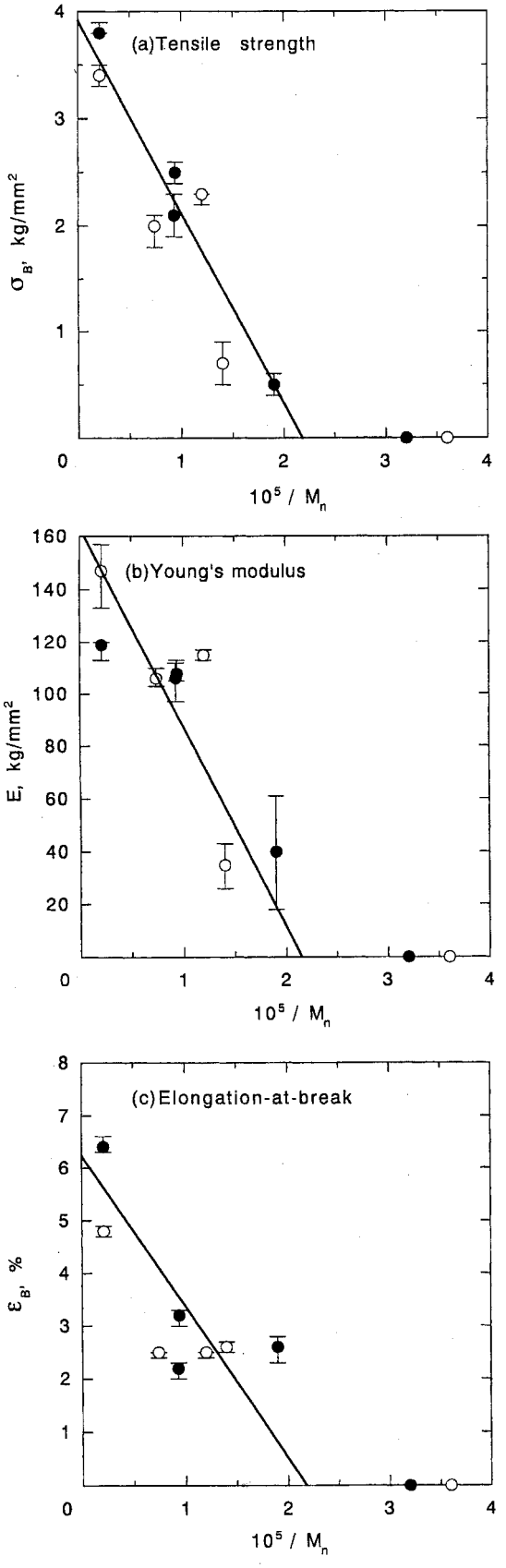

Fig. 7. Tensile strength (σ_B), Young's modulus (E), and elongation-at-break (ε_B) of solution cast PLLA (○) and PDLA (●) films as a function of $1/\bar{M}_n$[55]

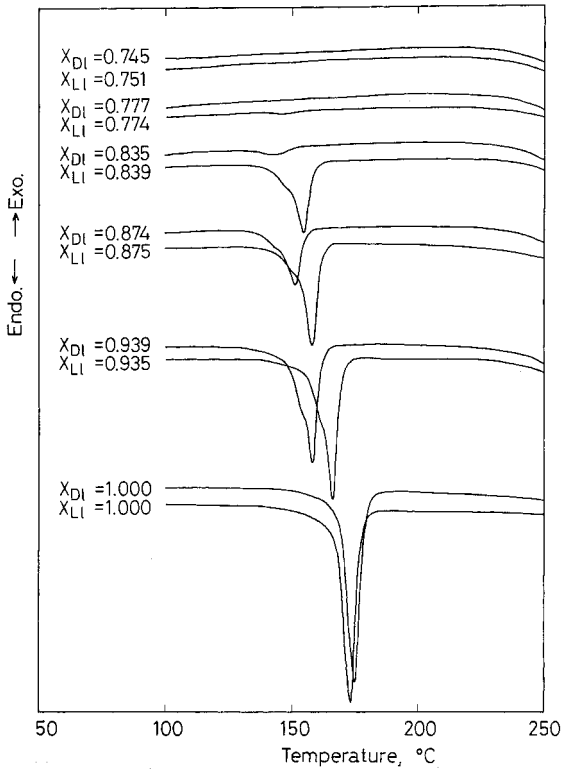

Fig. 8. DSC thermograms of P(LLA-GA) and P(DLA-GA) having different L- and D-lactide contents (X_{LI} and X_{DI}, respectively)[56]

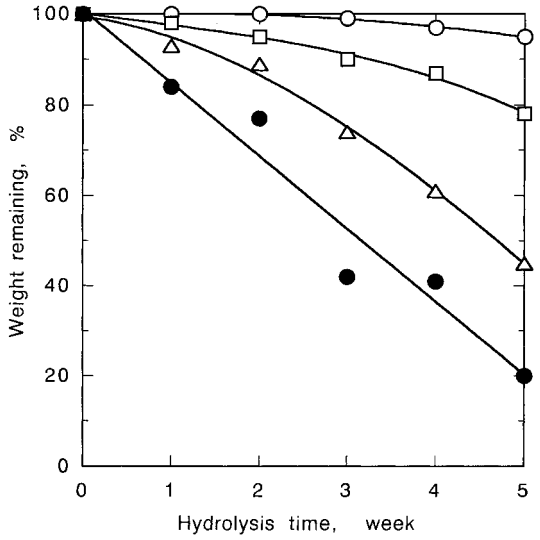

Fig. 9. Weight remaining for P(DLLA-GA) with DLLA contents of 100 (○), 66 (□), 42 (△), and 27% (●) as a function of hydrolysis time[59]

4.3.3 Annealing effect

Changing the annealing or crystallization conditions such as annealing temperature and time (T_a and t_a, respectively) alters the ordered structures, i.e., L_c, x_c, and spherulite size and morphology, even if the solid specimens are fabricated from a single polymer (Tab. 9)[60–64]. In addition, annealing effects of PLLA films depend on pretreatments such as melting before annealing. Fig. 10 shows T_m of PLLA films subjected to different thermal processes as a function of T_a[62]. T_m increases linearly with an increase in T_a above 130 °C, when the PLLA specimens were melted before annealing [Fig. 10(B) and (C)]. This result means that L_c increases with a rise in T_a. On the other hand, the change in T_m induced by altering T_a is very small without melting before annealing [Fig. 10(A)]. The equilibrium melting temperatures (T_m^0), estimated by extrapolation of T_m plotted against T_a above 120 °C to $T_m = T_a$, are 181, 212, and 211 °C for the PLLA films exposed to different thermal processes.

Tab. 9. Physical properties of PLLA films annealed at temperature T_a for time t_a after melting at 200 °C[62]

T_a / °C	t_a / min	x_c / °C	Temperature / °C			Mechanical properties		
			T_g	T_c[a]	T_m	σ_B[b] / kg/mm²	E[c] / kg/mm²	ε_B[d] / %
0	600	0	60	114	177	5.0	174	27
100	600	40			177	6.2	194	11
120	600	47			177	6.2	190	7
140	600	54			183	5.8	192	6
160	600	63			191	4.5	211	6
140	5	0	58	108	177	4.6	168	22
140	10	0	58	108	177	4.5	172	19
140	20	6	58	106	177	4.6	163	21
140	30	30	58	108	181	5.0	192	18
140	60	54			182	5.6	184	12
140	600	54			183	5.8	192	6

[a] Crystallization temperature.
[b] Tensile strength.
[c] Young's modulus.
[d] Elongation-at-break.

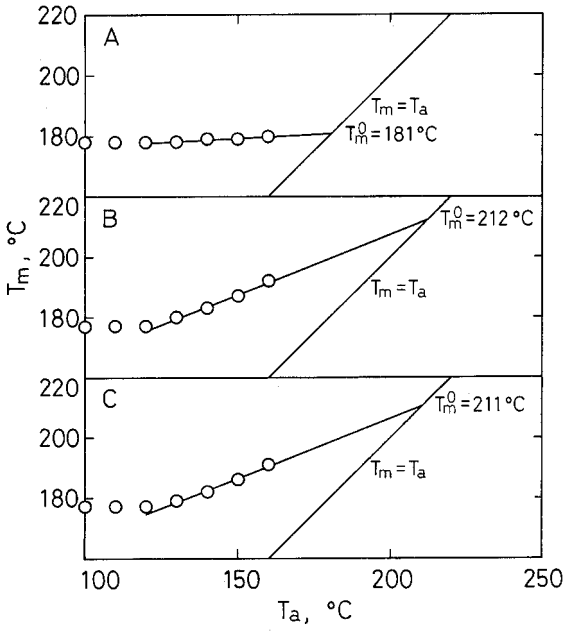

Fig. 10. T_m of PLLA films subjected to different thermal processes as a function of T_a[62]: (A) direct annealing; (B) melting (200 °C) – annealing; (C) melting (200 °C) – quenching (0 °C) – annealing

Fig. 11 shows polarizing optical photomicrographs of the PLLA films annealed at different T_a after melting at 200 °C[62]. The spherulite size increases with a rise in T_a. Fig. 11 suggests that the decrease in σ_B of PLLA films prepared at high T_a may be ascribed to the formation of large size spherulites and crystallites in the film at high T_a.

4.3.4 Orientation effect

PLLA is known to exhibit strong piezoelectricity when polymer chains are highly oriented. Fig. 12 shows piezoelectric constants of PLLA films as a function of the draw ratio at room temperature[65]. It is seen that both piezoelectric constants increase with an increase in draw ratio and become maximal at a draw ratio around 4–5. Interestingly, healing of a fractured bone was clearly promoted under increased callus formation when drawn PLLA rods were intramedullarily implanted in the cut tibiae of cats for its internal fixation. This promotion effect is probably ascribed to the piezoelectric current generated by the strains accompanying leg movement of the cats.

Molecular orientation increases also the mechanical strength of PLLA plastics. If the orientation is performed at low temperatures by drawing or extrusion under hydraulic pressure, the resulting plastics have an enhanced strength without any significant increase in crystallinity. Fig. 13 shows an example of drawing of a PLLA rod[66]. Bone fixation devices such as screw and pin can be fabricated from this PLLA rod. These biodegradable devices are clinically used to replace metallic screws and pins that require re-operation to remove them after bone healing.

4.3.5 Blending effect

No high-$\bar{M}_n$ polymers that are highly miscible with PLA are reported so far. Koyama and Doi reported that PLLA was miscible with PHB when the $\bar{M}_n$ of PLLA was as low

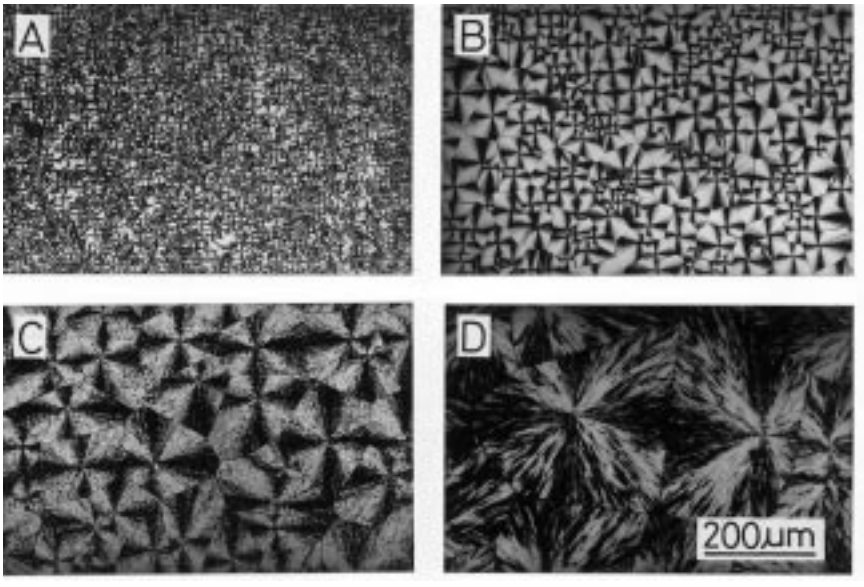

Fig. 11. Polarizing optical photomicrographs of PLLA films annealed at 100 (A), 120 (B), 140 (C), and 160 °C(D) after melting at 200 °C[62]

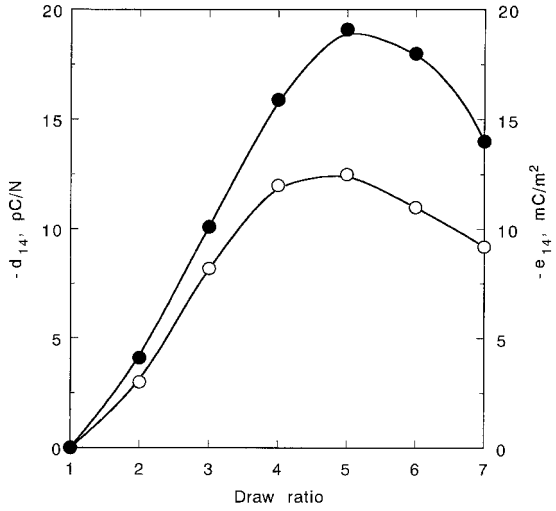

Fig. 12. Piezoelectric constants of PLLA films at room temperature as a function of the film drawing ratio. (○) d_{14}, (●) e_{14}[65]

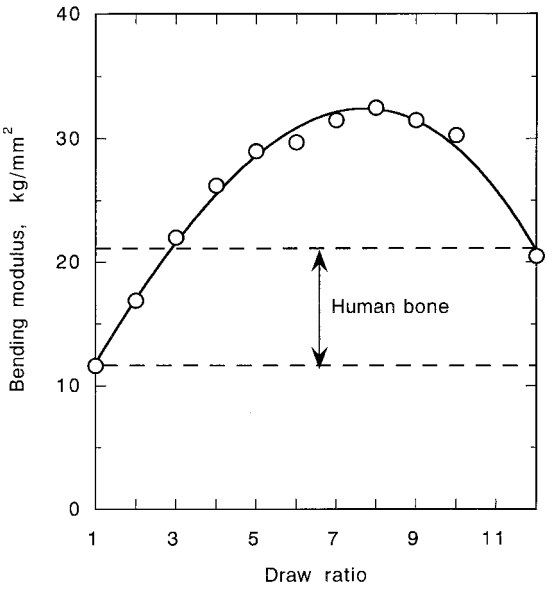

Fig. 13. Bending strength of PLLA rods as a function of draw ratio[66]

as 9×10^3[67]. In this case the increased density of polar terminal groups and the entropy of mixing may be responsible for the high miscibility between the two polymers.

Blending of two enantiomeric polymers results in the formation of a stereocomplex, which has a melting temperature 50 °C above homo-crystallites of non-blended PLLA and PDLA[52, 56, 68]. DSC thermograms of blends from PLLA and PDLA having different PDLA contents (X_D) are shown in Fig. 14[52]. The stereocomplex crystal has a triclinic unit cell with: a = 0.916 nm, b = 0.916 nm, c = 0.870 nm, α = 109.2°, β = 109.2°, and γ = 109.8°, where the PLLA and PDLA chains are packed side-by-side as shown in Fig. 15[69].

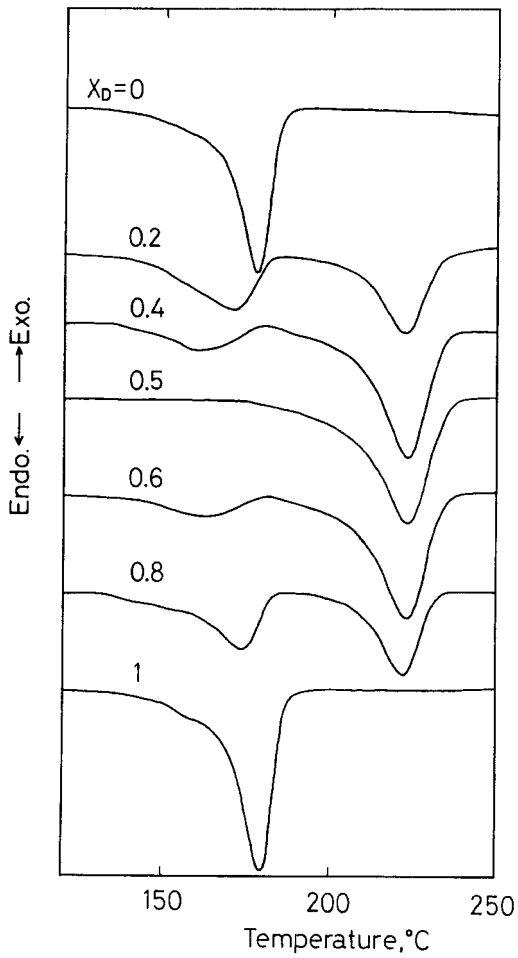

Fig. 14. DSC thermograms of blends from PLLA and PDLA having different PDLA contents (X_D)[52]

5. Conclusion

As outlined above, a wide range of biodegradable polymers are currently available. Generally, natural biodegradable polymers are hydrophilic and low in mechanical strength, while synthetic biodegradable polymers are hydrophilic and have good mechanical properties. There are exceptions such as chitin and PHA. Applications of biodegradable polymers in medicine and plastics industry depend on their physical, chemical, and biological properties. Although many people consider biodegradable polymers very attractive and necessary for the co-existence of the human society with the nature, global production of biodegradable polymers is not as large as expected. The major reason for this seems to be not their poor properties as materials but their high production costs. Consumers do not want to pay much for conventional daily products even if they are urgently required to keep our environments both inside and outside the human body safe and clean. The largest challenge to polymer scientists is to manufacture at a reasonably low cost biodegradable polymers having well-balanced biodegrad-

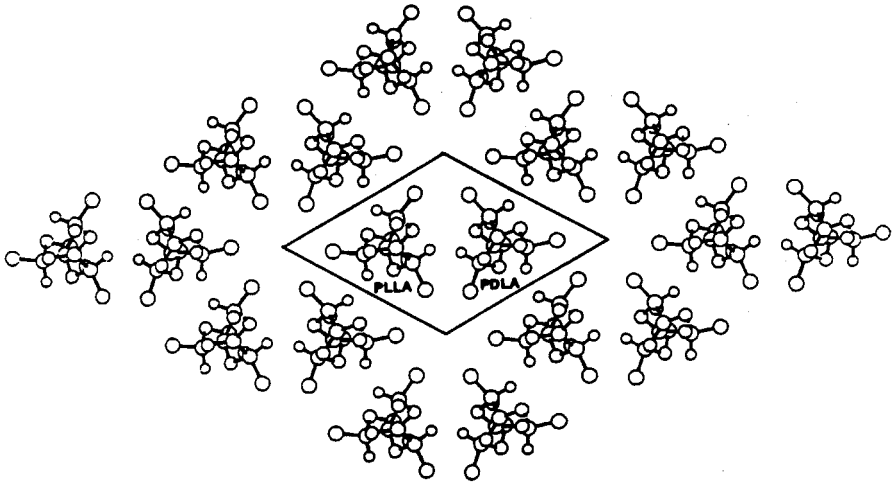

Fig. 15. PLLA and PDLA molecular arrangements in a stereocomplex crystal projected on the plane normal to the chain axis[69)]

ability and mechanical properties. The most appropriate biodegradable polymer for the targeted end use will be selected taking into account the ratio polymer cost/performance.

Abbreviations

Polymers
- HDPE: High-density polyethylene
- LDPE: Low-density polyethylene
- PAA: Poly(acid anhydride)
- PA6: Nylon-6
- PA66: Nylon-66
- PBS: Poly(butylene succinate)
- PCA: Poly(*α*-cyanoacrylate)
- PCL: Poly(*ε*-caprolactone)
- PDLA: Poly(D-lactide), Poly(D-lactic acid)
- P(DLA-GA): Poly(D-lactide-*co*-glycolide)
- PDLLA: Poly(DL-lactide), Poly(DL-lactic acid)
- P(DLLA-GA): Poly(DL-lactide-*co*-glycolide)
- PEA: Poly(ester amide)
- PEC: Poly(ester carbonate)
- PES: Poly(ethylene succinate)
- PET: Poly(ethylene terephthalate)
- PGA: Poly(glycolide), Poly(glycolic acid)
- PGALA: Poly(glycolide-*co*-lactide), Poly(glycolic acid-*co*-lactic acid)
- PHA: Poly(hydroxyalkanoate)
- PHB: Poly(3-hydroxybutyrate)
- P(3HB-3HV): Poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate)
- P(3HB-4HV): Poly(3-hydroxybutyrate-*co*-4-hydroxyvalerate)
- PLA: Poly(lactide), Poly(lactic acid)
- PLLA: Poly(L-lactide), Poly(L-lactic acid)
- P(LLA-GA): Poly(L-lactide-*co*-glycolide)
- POE: Poly(orthoester)
- PP: Poly(propylene)
- PS: Poly(styrene)
- PVA: Poly(vinyl alcohol)

Monomers
- BS: Butylene succinate
- CL: *ε*-Caprolactone
- DLA: D-lactide
- DLLA: DL-lactide
- ES: Ethylene succinate
- GA: Glycolide
- LA: Lactide
- LLA: L-lactide
- 3HB: 3-Hydroxybutyrate
- 3HV: 3-Hydroxyvalerate
- 4HV: 4-Hydroxyvalerate

Others
- DSC: Differential scanning calorimetry
- E: Young's modulus
- K : Constant
- L_c: Crystalline thickness
- $\overline{M}_n$: Number-average molecular weight
- $\overline{M}_w$: Weight-average molecular weight
- P: Physical property
- P_0: Physical property for infinite $\overline{M}_n$
- T_a: Annealing temperature
- t_a: Annealing time
- T_c: Crystallization temperature
- T_g: Glass transition temperature
- T_m: Melting temperature
- T_m^0: Equilibrium melting temperature
- TOC: Tortal organic carbon
- WVTR: Water vapor transmission rate
- x_c: Crystallinity
- X_{Dl}: Mol fraction of DLA in P(DLA-GA) [DLA/(GA+DLA)]

X_D: DLA content in PLA stereocopolymer [DLA/(LLA+DLA)] or PDLA content in enantiomeric polymer blends from PLLA and PDLA [PDLA/(PLLA+PDLA)]
X_{Ll}: Mol fraction of LLA in P(LLA-GA) [LLA/(GA+LLA)]
ΔH_m: Enthalpy of melting
ε_B: Elongation-at-break
σ_B: Tensile strength

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