Poly(lactic acids) : A potential solution to plastic waste dilemma

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SUMMARY : With mechanical properties that can be tuned at will to mimic a large range of conventional petrochemically produced thermoplastics, poly(lactic acids) (PLA) are also totally biodegradable and biocompatible polyesters. Moreover, PLA can be advantageously produced from renewable raw materials such as sugar beets, sugar cane, and maize, which, in turn, might strengthen the agricultural sector by allowing it to enter the non-food market. Through the description of the main characteristics of PLA, the development strategy of the main intervening industrial players, the economical interests and supports, it is pointed out how probable and close is PLA becoming a commodity plastic.

Introduction

Because of the ever-increasing amount of plastic wastes that are discarded in landfills, considerable R&D efforts have been devoted to the need for specific single-use materials and to the search for biodegradable substitutes of conventional commodity thermoplastics. Among the various families of biodegradable polymers, aliphatic polyesters have a leading position since hydrolytic and/or enzymatic chain cleavage yields ω-hydroxyacids, which in most cases are ultimately metabolized. For instance, poly(lactic acids) (PLA) can be defined as chemical derivative of lactic acid, which is nowadays widely produced by fermenting carbon hydrates, such as sugar or starch. When disposed in landfills, PLA biodegrades into water and carbon dioxide, i.e. compounds which re-enter the biological life-cycle.

In 1997, the potential market for biodegradable polymers has been evaluated by the European Union to 1,145 millions tons [1)] and PLA is clearly among the most promising ones. If one attempts to figure out its potential in a near future, one may reasonably expect a PLA-only share of 390.000 tons by 2008, inasmuch sales prices drop progressively to reach a stable EUR 1.75 /kg.

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Results and discussions

Plastics made from synthetic, petrochemical, conventional polymers are essentially stable, i.e. they remain for a very long time in their initial chemical and physical state. This property is a consequence of the very strong bonds existing between constituting monomer units and the lack of micro-organisms able to digest them. Hence, after their use, items made from these polymers are nearly unaffected by time. This beneficial attribute for objects built to last, presents however severe drawbacks when these items are of a single-use type, such as in food packaging applications. Solutions such as recycling and incineration have been proposed, but they are not yet completely satisfying since not economically and/or environmentally viable. A better solution would be to develop plastic materials which can be completely degraded by a natural process, leaving only harmless, and possibly even useful, residues. In other words, biodegradable polymers are an actual alternative to solve the plastic waste disposal problem.

When discussing the biodegradability property of polymers, it is necessary to first define precisely what one should understand by this concept. Indeed, a substance may have its internal chemical and physical structure undergoing changes due to a biological process and be decomposed into more elementary constituents, without emphasis on the future of the resulting products. It is also requested that all these resulting products do have the capacity to undergo further biological changes ending up with harmless and reusable substances.

Some materials claimed to be biodegradable, are nothing more than fragmentable under defined conditions leaving by-products in the environment which are far from being totally safe. Other substances may disintegrate to a certain point and then remain in an intermediary state without releasing any natural chemical element or compound which might again enter the natural life cycle. In such conditions, the waste problem is only partially solved as there is still need to find ways of discarding the residues.

Biodegradability is a supplementary property for a product whose primary characteristic is to be a material which is stable during its first use and then, after a certain induction time, become degradable until its complete assimilation. Thus, the degradation residues must be taken over by micro-organisms to be completely assimilated. The tricky part is to produce a solid material with good mechanical properties, which will not degrade when first used. PLA, for instance, starts degrading only when in contact with water and under specific conditions (pH, T°, …).

Biodegradable polymers appeared in successive generations starting early during the 1980s.

The *first-generation* "biodegradable" polymers did not satisfy public's expectations of complete degradation. They were indeed an intermediary solution where synthetic and natural polymers were compounded to form heterogeneous structures with weak intermolecular bonds to facilitate degradation. Certain starch-based polymers fall into this category. They contain only a small percentage of starch (about 5%), the rest of the material being non-degradable synthetic polymers.

The *second-generation* biodegradable polymers went a step further in biodegradability although not far enough to be entirely acceptable. These polymers included thermoplastic starch and mixtures of starch and synthetic poly(ε-caprolactone) (MATER-BI®). As far as biodegradability is concerned, it was already an improvement, but the starch component entailed major limitations in terms of mechanical properties.

The *third-generation* biodegradable polymers are based on lactic acid polymers – poly(lactic acids), PLA – or polyhydroxybutyrates – PHB. They display excellent biodegradability and mechanical properties.

PLA synthesis intermediates : lactic acid and lactide

Lactic Acid chemistry

Lactic acid, 2-hydroxypropionic acid ($C_3H_6O_3$), is present in nearly every form of organized life and was likely present in the first forms of primitive life that existed on earth. Its most important function in animals and humans is related to the supply of energy to muscle tissues. Metabolic turnover of lactic acid in an adult man, called the Cori cycle, has been estimated to range around 120 to 150 g per day[2)]. This water-soluble weak organic acid is one of the smallest chemical molecules with an asymmetrical atom and therefore exists under two stereoisomerical. If the L(+) form can be found in many different animal organisms, its levo-rotating counterpart D(-)is, on the contrary, very uncommon in nature.

Lactides are formed by the cyclic condensation of two lactic acid units and therefore, exist in three different forms, i.e. L,L-lactide, D,D lactide, and meso-lactide. It is also often referred to a racemic mixture of L,L- and D,D-lactides, called D,L-lactide.

The molecule's chirality is an essential property because it allows a certain adjustment of the degradation speed of resulting polymers. In addition, the D(+)/L(-) lactic acid ratio contained in a PLA fibers will affect its crystallinity. A polymer containing simultaneously both D(+) and L(-) lactic acid units might be amorphous and will not crystallize. In contrast, poly(L-

lactic acid) is semi crystalline after molding, but a fast cooling prevents crystallization and makes it amorphous.
In addition to its optical activity, the lactic acid molecule holds simultaneously carboxylic and hydroxyl groups. This double functionality initiates spontaneous condensation leading to a thermodynamic equilibrium depending on concentration and age of aqueous solutions
Lactic acid is produced in two different ways: chemical synthesis from oil-based non-renewable resources or biochemical processes starting from agricultural renewable resources. Only this last route, which implies more or less 80% of the actual market, can ensure high stereochemical purity by an careful choice of producing strain and purification procedures.

Lactide production method

As will be seen hereafter, poly-(α-hydroxy-acids) such as PLA can be synthesized either starting from the related α-hydroxy acids by polycondensation, or from cyclic dimers by ring-opening polymerization.
The most common way of synthesizing lactides from a lactic acids aqueous solutions consists in extracting free water and part of intermolecular water until one obtains lactic acids oligomers. In a second step, formation of lactides cycles is achieved by depolymerization of these oligomers at high temperature (higher than 200°C) in the presence of a suitable catalyst, under reduced pressure. However, taking into account this way of preparing lactide, the crude product is contaminated by impurities which can further disturb the ring-opening polymerisation of lactides into poly(lactic acid). This requires a careful purification of lactides. In that purpose, different approaches have been suggested among which the repeated recrystallization of the monomer, fractional distillation with aromatic non-solvents and treatment by basic dessicants.

Market and applications

The food sector for human and animal consumption counts currently for the major output of lactic acid and its derivatives with more than 70% of the total lactic acid market (about 100.000 tons/year). Beside nutrition, non-food industrial applications cover a wide spectrum : metallic surfaces cleaning, electroplating on plastic materials, synthesis of acrylate, alkyl and phenolic resins, formulation for soldering fluxes, treatment of textiles, synthesis of herbicides, solvents for inks, paints and coatings, cleaning and degreasing agent for electronic industry, etc. ...The global market for lactic acid and lactates (polymers excluded) ranges at about

100.000 tons/year and shows an annual 15% growth rate. The main companies involved in the world-wide lactic acid business are listed in Table 1. Concerning lactides, despite some specific applications, it has to be considered as an intermediate and linked to the PLA market.

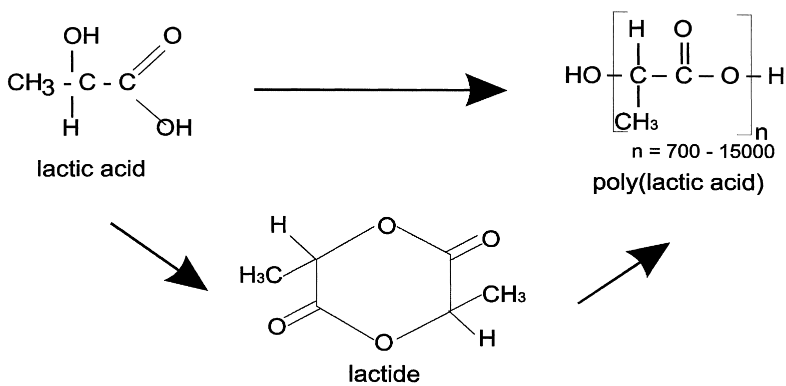
Table 1 : Main companies active in world-wide lactic acid business

Company	**Plant location**	**Production Capacity (mTons)**	**Lactic acid production process**
Purac	Holland, Spain, Brazil	80 000	fermentation
Purac/Cargill JV	USA	starting	fermentation
Galactic	Belgium	15 000	fermentation
ADM	USA	10 000	fermentation
Musashino	Japan	8 000	Chemical synthesis

PLA synthesis routes and properties

The synthesis of poly(lactic acids) is basically possible following two routes : either by means of direct polycondensation of lactic acid units, or by producing the cyclic dimer of lactic acids (lactides), followed by the ring-opening polymerization in the presence of catalyst (figure 1). Stannous carboxylates are often mentioned as catalysts for this reaction.

Figure_1: Two routes to synthesize PLA



As the direct polycondensation only produces polymers having low molecular weights (10,000 to 20,000), the ring-opening polymerization is usually preferred because it results in polymers with a much higher molecular weight (min. 50,000) and mechanical properties required for the main applications. It must be noted that some other processes are carrying out polycondensation of lactic acids in the presence of aromatic solvents to eliminate intramolecular water and, consequently, obtaining the higher molecular weights.

From the point of view of its physico-chemical and mechanical properties, semi-crystalline PLA is a stiff and brittle material with a glass transition temperature close to 55°C and a melting temperature close to 180°C. Typical values for the mechanical properties of such a polyester are elasticity modulus of over 3500 M Pa, tensile strength close to 60 M Pa and elongation at break of only 3 %. Therefore, PLA is as stiff and brittle as polystyrene which elasticity modulus and tensile strength are respectively, 1900 and 50 M Pa.

Four different approaches have been followed to modulate the mechanical properties of PLA:

1. controlling synthesis parameters (catalyst concentration, polymerization temperature, residence time, raw material isomeric purity, reactor shape,…)
2. co-polymerization giving many options inasmuch the co-monomer used in conjunction with lactide is itself biodegradable and/or bioresorbable.
3. compounding differing from co-polymerization by the fact that there is no chemical bond between the polymer components.
4. using additives and/or plasticizers.

For instance, with suitable plasticizers such as glucose monoesters or polyethylene glycol, similar to the approach used in traditional polyvinyl chloride industry, it is possible to mimic properties of polypropylene (elasticity modulus of 1200M Pa and tensile strength of 28 M Pa). Moreover, tremendous enlargement of the available range of PLA mechanical properties, from a brittle thermoplastic to a rubbery-like polymer, can be reached through the random copolymerization of lactide and ε-caprolactone.

Among the most important properties of PLA and some of its copolymers, biocompatibility opens the way to medical and pharmaceutical applications, while biodegradability prompts them to a promising future as substitutes of conventional commodity plastics with respect to the environment.

The actual state of knowledge indicates that PLA degrades, at least initially, exclusively by hydrolysis without enzymatic catalysis[)]. However, as far as surgical implants based on poly(lactic acids) are concerned, other degradation mechanisms, like phagocytosis, seems to gain importance, at least during the final phase, as soon as the implant has been disintegrated into small fragments [3)]. The first step of pure hydrolytical degradation is controlled by the penetration of water into the amorphous polymeric structure. Subsequently, ester bonds are cleaved, producing polymers having shorter chains. Since these fragments are non-soluble until they reach very low molecular weight, the shape of the implant is preserved. It has to be emphasized that the decomposition velocity not only depends on the polymer composition, but on its surface and porosity as well as on its surrounding. Indeed, lactic acid based polymers show considerable differences in their degradation behaviour when compared to other degradable polymers like poly(hydroxybutyrate-co-valerate). For instance, poly(hydroxybutyrate-co-valerate) shows poor water absorption capability but strong bacterial and/or enzymatic decomposition [4)]. Finally, when incinerated, PLA burns with a clean blue flame without releasing of any corrosive gases [5)].

PLA applications

With mechanical properties similar to those of several conventional thermoplastics produced by the petrochemical industries, PLA and its copolymers are biocompatible which allows to use them for medical, hygiene and pharmaceutical applications. Biodegradable PLA is also a very promising material for use in agriculture as mulch films or as clips in vineyards. It can also be used by the textile industry as woven fabrics for clothes and non-woven items. Another example of sound application for PLA is packaging, including films, blow moulded bottles for drinks and injection molded items for food and non-food uses. Table 2 presents some of the main applications of PLA with the processing techniques related.

Table 2 : Main applications for PLA in the commodities sector

Process	**End-Products**
Nonwoven fibers	Personal hygiene, protective clothing, filtration
Oriented films	Container labels, tape
Extrusion coating	Dinnerware, food packaging, mulch film
Flexible film	Food wrap, trash bags, shrink wrap
Cast sheet	Deli trays
Injection moulding	Rigid containers, daily containers
Foam	Clam shells, meat trays

Because of its vast range of single-use products, the non-woven sector is very well suited for the commercial development of biopolymers. Indeed, several applications provide additional benefits when using biodegradable polymers and more specifically PLA : in the field of personal hygiene, products such as baby-diapers, sanitary napkins, face flannels or in the field of medical care, products such as operative fields, surgical masks, blouses, dressings and compresses, the use of PLA-based voiles allows to avoid contamination or skin secondary reaction. One should remember that lactic acid is a common component of cosmetics used to treat acne and for personal hygiene products.

A second field is agriculture and horticulture where the use of non-woven cloth allows natural cultivation without pesticides or herbicides. Cultivation of lettuce or other vegetables is a good example: by putting a non-woven and very light voile above seed –beds, one creates a micro-climate where temperature and moisture are easily monitored and controlled. The faster growth of plants is obtained together with protection against frost, hail and certain parasites. Interstices between non-woven cloth fibers prevent insects from penetrating but allow air and rain to reach plants. Plants may thus grow without interference and the environment is preserved. The latter will be even more protected if one uses PLA voiles. Indeed, the degradation of the voile being initiated by a simple hydrolysis process, the molecular mass of fibers will progressively decrease to, finally, end up in fragmentation and releasing of lactic acid oligomers which will penetrate the soil (within a period of 50 days). In addition of suppressing the need to recover the voile, it was shown that these oligomers are promoting the plants' germination before decomposing into water, CO_2 and humus [6)].

Biopolymers for coated paper are also well established. Paper is coated with either polymeric or wax coatings, for various reasons. These reasons include increasing the strength of the paper stock, imparting water resistance, enhancing gloss or improving barrier properties. In light of depleting sources of cellulosic fiber over the last decade, repulping of paper and the reuse of the cellulosic fiber recovered has accelerated. A problem that occurs with repulping coated paper is the disposal or recycling of the coating which is liberated during the process. Currently, coatings such as polyethylene are popular for their superior properties. However in repulping processes, paper coated with polyethylene are not easily repulsed since polyethylene is typically not broken down by the process conditions. Special polymer were developed but the coating was not clear or glossy and could be sensitive to water. Disposal is a major problem associated with both repulping and non repulsable coating. For coating which are recovered during the repulp process, there is no value in the recovered material and therefore these coatings represent waste generally disposed of in a landfill. For the coatings which pass through the filters and screens of the process, these materials end up in the waste and may pose a problem for the waste water treatment plants. PLA is a polymeric material which offers unique advantages as a paper coating not only in the repulping process, but in the application process and the coated paper's performance.

1. The repulping process can be realized under conditions of neutral pH and moderate temperature. Poly(lactide) will break up more easily than polyethylene coating. The fragments of PLA may be recovered in the screens and either recycled for their lactic acid value or composted. Under the more severe repulping conditions which includes pH of 10 or greater, high temperature, and optional surfactants, PLA will degrade to the extent that it will disperse in water and pass through the screen. But because of poly(lactide)'s ability to biodegrade, the polymer should pose no problems in the waste water treatment stage.
2. PLA adhesion to the paper is better than polyethylene adhesion. Two characteristics of polylactides lend themselves enhanced adhesion : low viscosity and high polarity
3. The surface energy of PLA is higher than this of polyethylene. The latter films have a surface energy in the range of 30-33 dynes/cm. In order to produce a satisfactory printing surface, these films must first be modified to raise their surface energy to 35-38 dynes/cm. This not only increases the costs associated with production of the films, but the modification treatment will diffuse into the film and will produce an unsatisfactory surface. The surface energy of PLA can be about 44 dynes/cm, which leads to a surface with satisfactory printing characteristics without modification. Fillers may reduce the surface energy down to 35 dynes/cm. Additionally, inks which are typically more difficult to apply onto paper coatings, like water based inks, may be applied directly to polylactide. Furthermore, it is believed that the ability of the coating to maintain a smooth, coherent film despite the roughness of the paper is related to the surface energy of the coating. PLA gives therefore a coating which is smooth, with high gloss.
4. PLA of a relatively low viscosity which allows the extrusion coating to be done at lower temperatures.

In another field, in recent years, marine pollution caused by disposed plastics has developed into an international problem, and treaties that ban the disposal of plastic in the ocean have gone into effect. Given these trends, it is desirable to use biodegradable plastics for the manufacture of fishing nets and lines, which are likely to be carried away by water currents during use.

Because of the high prices of PLA based polymers on the market till now (450 – 900 EUR/kg), they found uses, almost exclusively, in the medical field as surgical implants or matrix for controlled release of drugs and pharmaceuticals. Properties of biodegradability, biocompatibility and thermoplasticity, in addition to the fact that the degradation velocity can be varied and consequently adapted to pathologies, authorise the use of such kind of polymers as orthopaedic repair material. They are also used in the same field and for the same reasons in the form of fibers as suture material [3].

Yolles [7] and Sinclair [8] were the first, already in the 70's to suggest the use of lactic/glycolic copolymers as degradable matrix for continuous and controlled liberation of bioactive substances. Current developments concentrate on many types of treatments (diabetes, drug addiction, fertility, ...) because insertion of polar bioreactive substances remains possible thanks to the polar structure of such bioplastics. The agrochemical sector is also interested in these properties for the controlled liberation of pesticides and herbicides, for instance [9].

PLA: impact on environment and agriculture

Impact on environment

From the 110 millions tons of plastics consumed each year, about 40% are disposed of in dumps. It is estimated that 2 billion tons of non-degradable plastics waste are in the world's dumping grounds [10]. In Western Europe, plastic waste amounts are estimated to about 7% in terms of weight and 22% in terms of volume.

As far as plastic waste disposal is concerned, three alternative strategies are considered : incineration, recycling and composting. Energy recovered by incinerating plastics is estimated to 60% of the total energy used for their elaboration or about one fifth of a ton of oil-equivalent per ton of plastic. However there remains 300 kg of solid residues which need to be disposed of in landfills in addition to the emission, in certain cases, of volatile products (chlorhydric acid, dioxines,...).

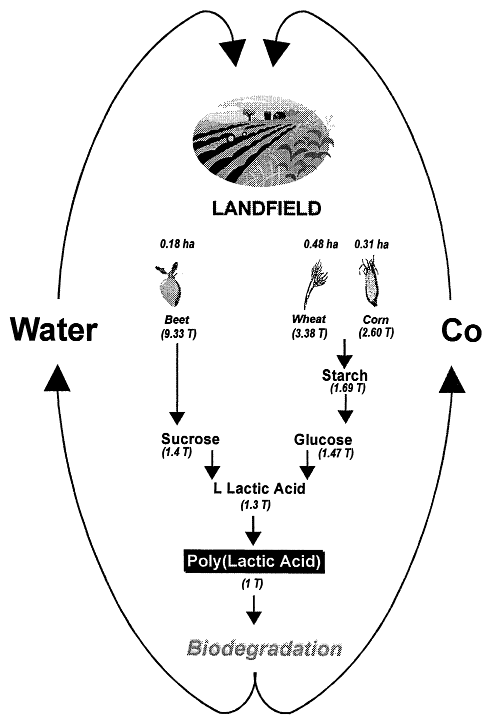


Figure 2 : Material balance to produce PLA

Investment in new incinerators with energy recovery should amount to EUR 7 billions for the next ten years for Europe alone. On the other hand, if plastic waste recycling would amount to about 2.7 million tons from now to 2006, or 10.6% of the total waste volume, this path presents unavoidable limits such as the progressive loss of mechanical properties, limited applications in the food sector and the possible discrepancy between the need for recycling and the demand for recycled products. Launching a recycling strategy will lessen the acuity of the problem but certainly not solve it.

Resorting to biodegradable products in composting conditions together with efficient strategies to collect compostable refuse is therefore an indispensable complement to other disposal techniques for the daily plastic volume originating from our habits as consumers.

Impact on agriculture

The lactic acid needed to make PLA is currently mainly produced by fermenting carbon hydrates from agriculture, namely saccharose and hydrolyzed starch (glucose).
Other raw materials have been suggested in order to decrease PLA's production costs, with a particular emphasis on agrochemical wastes like molasses or whey, instead of using refined materials, but purification costs increase dramatically with a reduction of substrate purity.
In Europe, saccharose is produced from sugar beets, while starch is mainly obtained from wheat and, to a lower extend, from potatoes or corn. In the US, it is this latter cereal which is the main source of starch.
If one looks at the material balance shown on figure 2, the 390.000 tons of PLA in 2008 would entail the cultivation of 70,000 ha, 187,000 ha or 121,000 ha of farm land, respectively, for sugar beets, wheat and corn (corresponding to 3.3%, 1.9% or 2.9% of average acreage used for these three commodities in the 15-states European community) (table 3). In addition, a study published by the European Community evaluates at 25%, the agricultural farm land soon not anymore needed to produce foodstuff which amounts to 30 millions ha [4]. According to this scheme, if the advent of biopolymers is not fair to provide the final answer, it would nevertheless afford non-negligible sources of revenues for E.U.'s agricultural sector.

Table 3 : Area to cultivate and volume to harvest to produce 390,000 tons of PLA as compared to European averages (Eurostat, 2 – 1998)

	Sugar beet	Wheat	Corn
Harvested area (.000 ha) Year 96			
- EUR 15	2 108	9 774	7 174
- EUR 12	1 961	-	3 995
Area needed for PLA	70.2	187.2	120.9
Production (.000 tons) Year 96			
- EUR 15	112 250	67 915	35 466
- EUR 12	105 792	-	33 730
Volume needed for PLA	3 738	1 318	1 014
Turnover (prices : Nov. 98)			
- prices (Euro/ton)	42.14	116.51	136.55
- turnover (millions Euro)	157.53	153.56	138.46

PLA markets : current - prospective

The current PLA market, mainly in the biomedical field (surgical suture thread, orthopaedic prosthesis components,…), remains a speciality market of high value materials with quite small production quantities (a few tons each year). This application requires very high molecular weights which are not systematically required for other applications being developed. The latter are calling for a "commodity status" requiring production costs to be drastically reduced, so that to warrant adequate profitability and to provide sales prices very similar to those of conventional petrochemical plastics.

Table 4 shows the main companies active in PLA sector with the products they commercialize. Although few data are available for the biomedical PLA market, it seems relatively stable in volume and value, since several years. For the surgical implants, it would amount to EUR 8.8 millions (USD 10 millions) , estimate based on 200.000 surgical operations of the mandible, face and femoral collar with an average price of EUR 45 (USD 50) per set of surgical screws [5)]. According to other sources, the PLA offer for medical applications would be of the order of 50 tons per year [11)].

Table 4 : Main companies involved in lactic acid and PLA biomedical fields

Company	Country	Lactic acid	Lactide	PLA (co)polymers	End products
Galactic Laboratories	Belgium	✖	✖	✖	
Bioscience	Finland				✖
Phusis	France		✖	✖	✖
Boehringer Ingelheim	Germany		✖	✖	
Purac	Netherlands	✖	✖	✖	
ICI	U. Kingdom				✖
BPI	USA				✖
Davis & Geck	USA				✖
Etnor	USA				✖
Henley Chemicals	USA		✖		
Johnson & Johnson	USA				✖
Medisorb Technoologies	USA			✖	

Table 5 shows the main companies active in the PLA sector with the products they commercialize. Notwithstanding the large development potential of PLA, numerous companies have put an end to their efforts for strategic reasons generally having to do with their internal reorganization (concentration on core business, the case of Chronopol, USA, and Neste Chemicals, Finland, for instance).

It is however worth recalling that PLA as commodity is still in infancy. Currently, numerous applications are being developed by the major producers in co-operation with certain customers representing the 7 most feasible potential uses of this polymer (nonwoven and fibres, oriented films, flexible films, extrusion coating, injection molding, cast sheets and foams).

Table 5 : Main companies involved in lactic acid and PLA for commodities

Company	**Country**	**Lactic acid**	**Lactide**	**PLA (co)polymers**	**End products**
Galactic Laboratories	Belgium	✖	✖	✖	
Dai-Nippon Ink Chemicals	Japan			✖	
Mitsui Chemicals	Japan			✖	
Shimadzu Corp.	Japan			✖	
Toyobo	Japan			✖	
Hycail	The Netherlands			✖	
Cargill Dow Polymers	USA			✖	

Other biopolymers are, or have been developed. BIOPOL™ made by Monsanto based on poly(hydroxybutyrate-co-valerate) (PHBV) produced from transgenic plants or by bacterial fermentation (Alcaligenes entropus) has been sold for a price between EUR 13 and 18/kg (USD 15 –20) until Monsanto announced that it would stop this project in January 1999. Metabolic Inc. is however still working on this project.

Poly(caprolactone) initially developed by Union Carbide (TONE™) and currently also sold by Solvay (CAPA™), BIONOLLE™ made by Showa Highpolymer, MATER-BI™ from Novamont, BIOTEC from Biotec/Melitta are all biodegradable resins which are currently available at prices varying according to the different mechanical properties and biodegradability rates. New developments at Bayer (degradable polyester amide made of hexamethylene diamine, butane diol and adipic acid, WALOCOMP™), Eastman Chemical Co. (EASTAR™), BASF (ECOFLEX™) and Dupont (BIOMAX™) show tremendous interest in that new age for plastics [12)]. However, only some of them are produced from renewable resources.

For the PLA as such, different information prompt to think that the market would reach about 390.000 tons at the 2008 horizon with a price target of about EUR 1.75/kg (USD 2),

Competitivity of biopolymers.

Generally speaking, the biopolymer's competitivity as compared to conventional plastics should be attained by controlling three essential factors :

1. production costs
2. scale factor
3. legislative and environmental constraints.

Controlling production costs obviously means to operate cost-effective processes, to select the appropriate raw material and the adequate geographical location with regard to this resource and to the markets in order to limit transportation costs, and, in certain cases, the impact of import duties. The scale-factor is also a key-parameter as one remembers that operating a 10-fold higher capacity only requires investments 4.6 times higher, while reducing by 50% the fixed part (depreciation expenses) of production costs. Finally, an increasing legislative and environmental pressure promotes the use of biopolymers, as can be observed in German-speaking and Scandinavian countries. As an example, a German initiative decreases to about EUR 0.4/kg (DEM 0.8) the tax imposed on household plastic waste if it is compostable and made from renewable resources, compared to EUR 1.5/kg (DEM 3.00) for conventional petrochemical plastics. It thus allows a EUR 1.1/kg leverage for biodegradable plastics made from renewable resources.

A price/market model, developed by The PST Group, allows to compute a first approximation of the market size for poly(lactic acids) in function of its selling price, compared to conventional thermoplastics. In perfect agreement with observations, the resulting curve remains quite stable during the last 20 years, even if the individual position of each polymer tended to change during that time. Table 6 shows the possible growth-trend for the PLA market versus its sales price (estimates by Galactic laboratories). The trend shows that the potential market might grow rapidly during the first years and then level off starting year 2006. SRI Consulting expects an annual growth rate of 70% in the next five years for the use of biodegradable polyesters [12)]. We do not think however that, in 2001, poly(lactic acids) will be produced in the amount of 38,000 tons/year but such a potential market will set an average price of about 4.1 EUR/kg. In addition, certain simulations show that such price levels remain acceptable compared to estimated production costs (plant and equipment depreciation charges included) for market shares of 10 to 20% per production unit.

Table 6 : Sales prices versus market volume for poly(lactic) acids.

Year	**Market potential** *[Tons]*	**Sales price for PLA** *[EUR/kg]*
2001	*38,000*	4.09
2002	70,000	3.17
2003	160,000	2.23
2004	250,000	2.03
2005	305,000	1.92
2006	360,000	1.86
2007	375,000	1.81
2008	390,000	1.75

Conclusion

It is to be believed that PLA will soon come out as one of the best alternative to conventional plastics in the industrial sectors making intensive use of these materials such as the packaging industry, for instance. Mechanical and, more generally, physical properties of PLA are comparable to the ones of popular petrochemical plastics and this truly biodegradable material can be processed with existing machinery of the plastic industry. The remaining problem, i.e. production cost, is soon to be solved when mass production plants come on line.

PLA will significantly contribute to both the environment protection, by biodegrading into nature's simple building blocks, and the economy, by making use of overabundant agricultural crops. This will thus improve the farmers income and lessening the burden of farm-subsidies paid from the E.U. budget.

It is hence a product which plainly justifies the hopes of environment- and economy-conscious citizens, producers and authorities.

However, if PLA is now technically ready to meet numerous industrial requirements, its market will only develop simultaneously with the setting up of biodegradable selective waste collection systems, of additional composting plants and of humus scattering schemes coupled with consumers coaching and awareness. Therefore, it is accepted that the most mature market, thus the one most likely to foster PLA development, is in Western Europe, more particularly in the German-speaking and Scandinavian countries.

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