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# Making Plastics from Garbage

## A Novel Process for Poly-L-Lactate Production from Municipal Food Waste

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### Keywords

biodegradable plastic  
biopolymer  
lactic acid fermentation  
municipal solid waste (MSW)  
recycling  
poly-L-lactate (PLLA)

### Summary

We propose a novel recycling system for municipal food waste that combines fermentation and chemical processes to produce high-quality poly-L-lactate (PLLA) biodegradable plastics. The process consists of removal of endogenous D,L-lactic acid from minced food waste by a propionibacterium, L-lactic acid fermentation under semisolid conditions, L-lactic acid purification via butyl esterification, and L-lactic acid polymerization via LL-lactide. The total design of the process enables a high yield of PLLA with high optical activity (i.e., a high proportion of optical isomers) and novel recycling of all materials produced at each step, with energy savings and minimal emissions. Approximately 50% of the total carbon was removed, mostly as L-lactic acid, and 100 kg of collected food waste yielded 7.0 kg PLLA (about 34% of the total carbon). The physical properties of the PLLA yielded in this manner were comparable to those of PLLA generated from commercially available L-lactic acid. Evaluation of the process is also discussed from the viewpoints of material and energy balances and environmental impact.

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## Introduction

The exhaustion of finite fossil resources as a source of energy and chemicals, as well as shortages of food and feed, are serious problems to be overcome if society is to be sustained. In addition, an environmentally friendly mode of treating municipal refuse is required. Of about 50 MMT of waste<sup>1</sup> that is generated annually in Japan, around 20% is high-moisture-content refuse from kitchens and the food industry. Such wastes readily decompose, generate odors, and sometimes cause illness. Municipal solid wastes (MSWs), including food waste, are usually incinerated or landfilled, but these processes generate many problems. Incineration facilities can be damaged by temperature fluctuations when food waste with high water content is burned in a semicontinuous process. In addition, it is difficult to recover energy from such waste incineration processes because the heating value of food waste is low (Harrison et al. 2000). Also, landfill space is limited, and uncontrolled fermentation of organic wastes in landfills causes secondary problems, such as methane emissions (Camobreco et al. 1999). Under these circumstances, the food-recycling law was promulgated in Japan in 2001, thus putting pressure on managers of food waste to improve the process of recycling waste food (Food Recycling Law 2000).

Treatment of biological solid waste<sup>2</sup> via microbiological processes improves these wastes and reduces the need for both landfill space and fuel used in waste incineration. Direct composting and methane fermentation, which produce fertilizers and biogas, are alternative ways to reuse food waste, but these processes have been applied only in rural areas. On the other hand, our previous study, which aimed to develop an economical means of converting solid domestic and industrial food wastes into valuable products, showed that municipal food waste is a good source of natural lactic acid bacteria (Sakai et al. 2000). This finding indicated another route of food waste reuse suitable for use in urban areas.

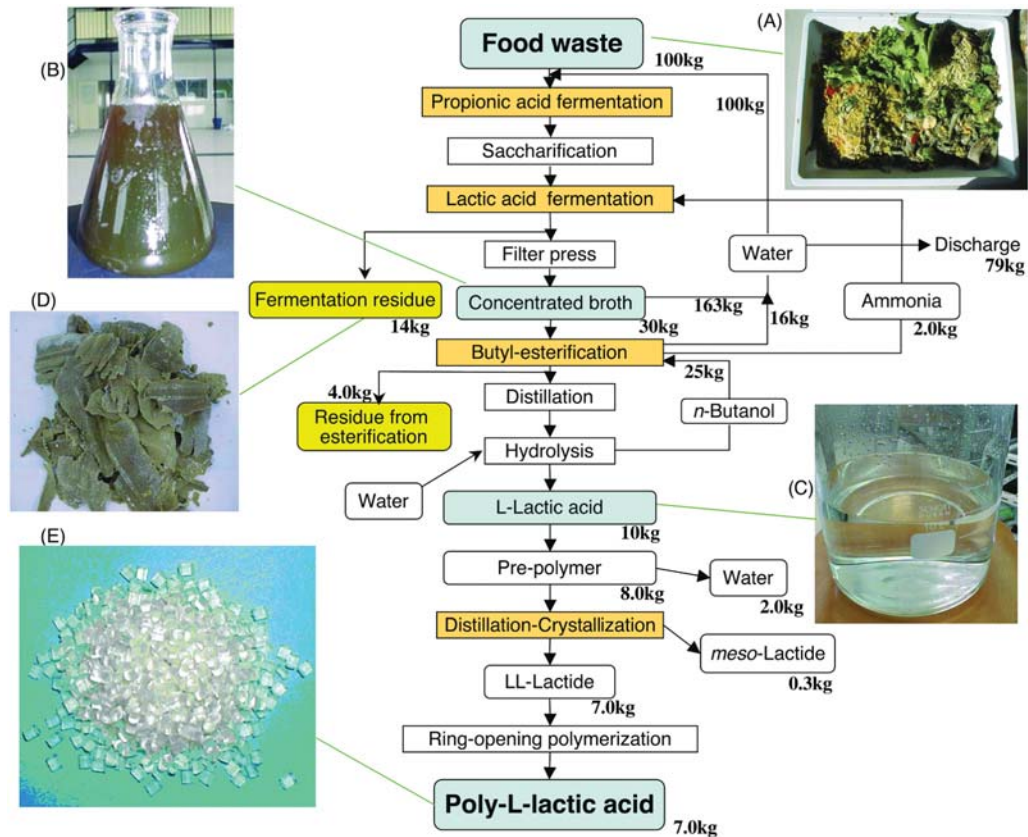
Lactic acid has both hydroxyl and carboxyl groups with one chiral carbon atom, and it is widely used in the food, pharmaceutical, and general chemical industries (Litchfield 1996). In

addition, lactic acid can be polymerized to form the biodegradable and recyclable polyester polylactic acid, which is considered a potential substitute for plastics manufactured from petroleum (Ohara and Sawa 1994). Although the ester bond of poly-L-lactate (PLLA)<sup>3</sup> is susceptible to some enzymes, including proteinases and lipases, and PLLA has been recognized as a biodegradable plastic (Sakai et al. 2001), its biodegradation in soil is rather slow and depends on morphology and thickness (Miyazaki and Harano 2001). Therefore, PLLA may better be developed as a chemically recyclable plastic with an appropriate collection system for the used materials and not as a single-use plastic. The industrial production of PLLA from cornstarch has recently begun (Lunt 1998), and its potential use as a "green plastic" has been discussed (Gerngross 1999; Gerngross and Slater 2000). Such materials are expected to come into worldwide use, but PLLA and other plant-derived plastics are costly, thus preventing their widespread application. In addition, the process uses cornstarch feedstock, which is also a source of food for humans and other animals.

During the past decade, many authors have described lactic acid production from wastes, including molasses (Aksu and Kutsal 1986), bakery waste (Oda et al. 1997), waste waterpaper (Schmidt and Padukone 1997), MSW (Zhou et al. 1996), and sugarcane pressmud (Xavier and Lonsane 1994). These studies, however, have operated using extracted liquids from the wastes, which contain well-known, uniform components, and these approaches have never been developed into practical industrial processes. Here we demonstrate a novel process in which high-quality PLLA, a recyclable plastic, is produced from actual (collected) municipal food waste by combining two fermentation and chemical steps, thus creating a system for total reuse of municipal food waste. We also discuss the practicability of the system in terms of materials and energy balances, as well as environmental impact.

## Materials and Methods

Figure 1 shows a schematic diagram of the process for production of PLLA from food waste.



**Figure 1** Process outline of PLLA production from food waste. See experimental protocol. Photos adjacent to the figure show food waste (A), concentrated broth after lactic acid fermentation (B), purified L-lactic acid (C), fermentation residue (D), and pellets of PLLA (E). Average amounts of intermediates and products yielded from 100 kg food waste are also included.

### Food Waste

To investigate the amount of food waste generated by the food industry, we sent questionnaires to companies with over 20 employees in Kitakyushu City, a city in southern Japan with a population of approximately 1 million. Of 851 mailings, 15.2% of the replies were valid. We then calculated the amount of food waste disposed in 2001 per employee (basic unit) in each type of food business. We estimated from these basic units and the numbers of workers in Kitakyushu the potential amount of food waste disposed by each type of food business in Kitakyushu. The total amount of food waste available for PLLA production was estimated by summing the food waste generated by companies that annually discarded over 100 tons.

Food waste samples were collected from various types of food businesses including hotels, restaurants, and hospitals (20 samples from 15 sites). After recording the approximate food composition, the samples (12 to 50 kg,<sup>4</sup> 30.4 kg average) were minced in an equal amount of water using an extruder. We then analyzed the proportions of water, D- and L-lactic acids, total soluble sugars, glucose, and CHN elements.

### Propionic Acid and Lactic Acid Fermentation

The minced food waste was autoclaved in a 90 L fermentor (Marubishi Bioengineering Co., Japan) (121°C for 20 min) and then inoculated with *Propionibacterium freundenreichii*. The sus-

pension was gently rotated at 60 revolutions/min (rpm) for 12 hr at pH 5.5 (37°C) to consume naturally produced D- and L-lactic acids. After the first fermentation, the temperature was increased to 50°C and glucoamylase (Glucoteme, Yanase Sangyo Co., Japan) (20,000 units/g) was added to the suspension to obtain a concentration of 300 ppm. Saccharification proceeded for 2 hr, and then *Lactobacillus rhamnosus* KY-3 was seeded at an initial cell density of 10<sup>6</sup> cells/mL. The culture (pH 6.5 automatically maintained using 7% ammonia) was incubated at 37°C for 3 or 4 days to complete fermentation.

#### Purification of L-Lactic Acid

The fermented suspension was passed through a filter press to separate solid residue from the fermented liquid, which contained an average of 60 g/L L-lactic acid. The filtrate was concentrated using a rotary vacuum evaporator (10 L) to yield an average of 40% ammonium lactate. The condensate was placed in a 20 L reactor equipped with an agitator and a distillation column. The internal diameter of the column was 500 mm, and the theoretical stage number was 5. After *n*-butanol (3 mol/mol lactic acid) was added, the condensate was heated in an oil bath at 150°C to 160°C and rotated at 80 rpm. The azeotropic vapor of water and *n*-butanol was collected by a condenser connected to the top of the distillation column and separated into water and *n*-butanol phases in a separator. The *n*-butanol, as the upper phase, was refluxed to the top of the column, whereas the lower water phase was extracted. The ammonia gas liberated and vaporized in the reactor was collected using an ammonia absorber. The reaction mixture was filtered to remove solid precipitates, and the filtrate (butyl lactate) was evaporated using a rotary vacuum evaporator. The butyl lactate purified by distillation was placed with water in the hydrolyzing vessel and heated to between 95°C and 110°C. The water phase was refluxed to the top of the column, and the *n*-butanol phase was separated from L-lactic acid in the vessel.

#### Polymerization of L-Lactic Acid

The purified L-lactic acid was heated to 135°C, 150°C, and 160°C in a stepwise manner

and totally refluxed under a reduced pressure of 10 mmHg. Tin isoocotate was added as a catalyst at a concentration of 30 grams per liter and the resulting lactide (cyclic dimer of lactic acid) was reactive distilled at 180°C and 5 mmHg. To purify the lactide, four cycles of crystallization at 60°C to 90°C, partial melting at 65°C to 95°C, and total melting at 70°C to 100°C proceeded using a melt crystallizer (Sulzer Chemtech Ltd., Switzerland) equipped with four pipes (70 mm inside diameter and 400 cm in length). Tin isoocotate (0.5% w/v of sample) was added as a catalyst to a 50 L reactor (Kansai Chemical Engineering Co., Hyogo, Japan) to open the ring of the cyclic LL-lactide, and the continuous polymerization was done using an extruder (S1-KRC, Kurimoto Ltd. Osaka, Japan) (200°C, 15 min retention time).

#### Chemical Analysis

Short-chain fatty acids (formic, acetic, propionic, lactic, and butyric acids) in the supernatant obtained by centrifugation of fermented food waste (3,000 rpm, 20 min) were evaluated using an organic acid analysis system (Shimadzu, Kyoto). Optical isomers of lactic acid were analyzed by using D- and L-specific lactate dehydrogenase (Roche Diagnostics Inc., Tokyo), according to the protocol recommended by the manufacturer. The concentration of total soluble sugars was analyzed using phenol-sulfuric acid (Dubois et al. 1956), and that of glucose was enzymatically determined using a glucose oxidase kit (Glucose Test Wako, Wako Chemicals, Tokyo). The elemental carbon and nitrogen composition in the dried food waste were analyzed using a CHN analyzer (PE2400 series 2, Perkin Elmer Japan).

## Results and Discussion

#### The Process

Figure 1 shows the four steps required to produce PLLA from food waste and the balance of materials obtained. These steps consisted of (1) removal of endogenous D,L-lactic acids from minced collected food waste by a propionibacterium, (2) L-lactic acid fermentation under semi-solid conditions, (3) purification of L-lactic acid

by butyl esterification, and (4) polymerization of L-lactic acid via LL-lactide. The process was applied to food waste collected from commercial kitchens. The yield and composition of collected food waste is discussed first. The specific points of each step are then addressed, followed by an evaluation of the entire process from material, energetic, and environmental perspectives.

#### Amount and Composition of Actual Food Waste

The questionnaire sent to food-related companies indicated that about 350 tons/day of food waste was discarded in the year 2000 in Kitakyushu. The estimated sum of food waste by companies that discarded over 100 tons/yr was 62 tons/day, which could be used for PLLA production. The water content of 20 samples from 15 different kitchens averaged 78.5% (table 1). Dry matter consisted of 35% vegetable, 23% meat and fish, and 42% cooked carbohydrates, including rice, bread and noodles. Although the carbohydrate concentration varied between 28% and 63%, the total amount of soluble sugar after glucoamylase digestion was 0.14 kg/kg wet waste. Clearly, considerable potential feedstock for lactic acid fermentation is being disposed of on a daily basis.

The collected food waste also contained on average 1.6 g/kg wet waste of endogenous D- and

L-lactic acids, produced by native lactic acid bacteria during transfer and storage of the waste. The presence of D-lactic acid decreases the optical activity (i.e., proportion of the quantity of optical isomers) of accumulated lactic acid and decreased PLLA crystallinity.

#### Removal of Endogenous D(L)-Lactic Acid by Propionibacterium

We found that *P. freudenreichii* preferentially consumes D- and L-lactic acids before sugars as a carbon source under acidic conditions. Figure 2A shows that lactic acid in the refuse paste was quickly degraded and diminished within 10 hr at pH 6.5, whereas glucose began to decrease after several hours of lag and was then consumed gradually. This was observed more clearly at pH 5.5 (figure 2B). The microorganisms assimilate only lactic acid, and most of the glucose remained even after 24 hr. These characteristics of *P. freudenreichii* were useful for selective removal of optically inactive lactic acid, with little effect on the amount of sugar availability for subsequent L-lactic acid fermentation.

#### L-Lactic Acid Fermentation under Semisolid Conditions

After the optically inactive lactic acid was consumed, polysaccharides including starch were

**Table 1** Product yields and carbon balance

	Content and yield		Carbon yield (%)
	(kg/kg wet waste)	(kg/kg dry waste)	
Dry material <sup>a</sup>	0.215	1.	—
Carbon content <sup>a</sup>	0.101	0.470	100
Total soluble sugar <sup>a,b</sup>	0.143	0.665	—
Lactic acid in culture filtrate <sup>c</sup>	0.118	0.549	47
Purified L-lactic acid <sup>c</sup>	0.099	0.459	37
PLLA <sup>c</sup>	0.069	0.320	34
Fermentation residue <sup>d</sup>	0.14	0.101	27
Esterification residue <sup>d</sup>	0.04	0.038	16

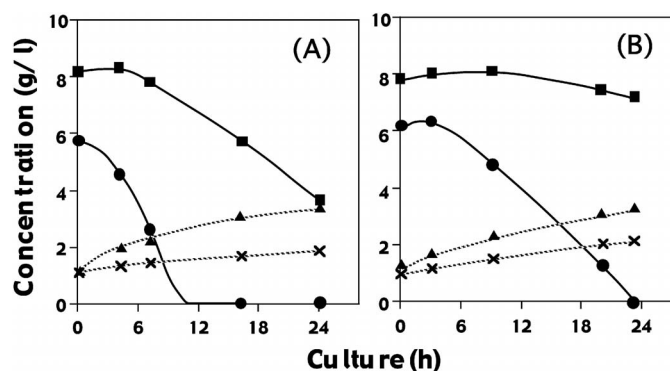
<sup>a</sup> Average of 20 samples from 15 companies.

<sup>b</sup> Average concentration in saccharified samples.

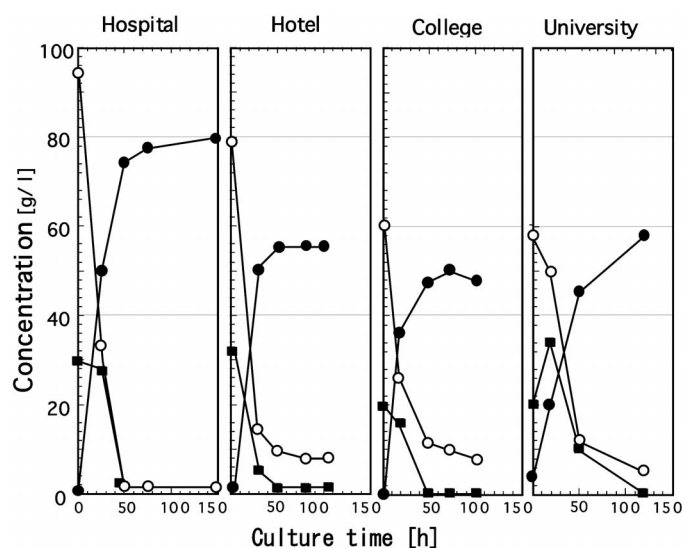
<sup>c</sup> PLLA was experimentally produced from three representative culture filtrate samples. Average yield was calculated using efficiencies of each step (purified L-lactic acid from culture filtrate, 78.7%; PLLA from purified L-lactic acid, 91.9%).

<sup>d</sup> Representative data. Water contents of fermentation residue and esterification residue were 38% and 6.4%, respectively.

**Figure 2** Selective degradation of endogenous lactic acid in food waste by *P. freudenreichii* at pH 6.5 (A) and pH 5.5 (B). Food waste from a university kitchen (500 g) was minced with an equal amount of water, and the pH was adjusted using 7% ammonia. It was then inoculated with *P. freudenreichii* (10 mL preculture) and was gently shaken (60 rpm) at 37°C for 12 hr. Symbols: circle, lactic acid; square, glucose; triangle, acetic acid; cross, formic acid.



**Figure 3** Representative transients showing L-lactic acid fermentation of food waste collected from various sources. Food waste samples from a hospital (42.5 kg), a hotel (36 kg), a college (23.7 kg), and a university (50 kg) were used. Each sample was minced with an equal amount of water, which was autoclaved and treated with 0.3 grams per liter glucoamylase at 50°C for 6 hr. It was then inoculated with *L. rhamnosus* and incubated at 37°C. Symbols: open circle, lactic acid; closed circle, total sugar; square, glucose.

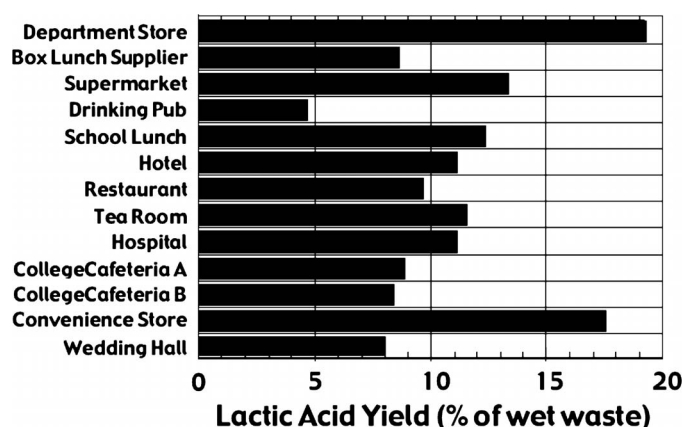


solubilized by glucoamylase. *L. rhamnosus*, which is an L-forming homo-fermentative strain, was then inoculated into the treated refuse paste. As reported previously (Sakai et al. 2000), nutrient-rich food waste appears to be a superior growth medium for fastidious lactic acid bacteria that generally require a variety of nutritional elements. The amount of water added was minimized to reduce energy input for its distillation from the fermented broth; an equal proportion of water to refuse was sufficient to yield the highest productivity of L-lactic acid. The concentration of total sugar after solubilization averaged 74 g/L, meaning that the estimated concentration of carbohydrate in the food waste available for lactic acid fermentation was estimated to be

143 g/kg wet waste. Figure 3 shows some examples of lactic acid fermentation using the refuse collected from various sources.

Solubilized sugars including glucose seemed to be involved in the lactic acid fermentation because over 82% of the total was converted to L-lactic acid (an average of 61 g/L), with an average optical purity of over 98% (97.2% to 98.9%).<sup>5</sup> The amount of accumulated L-lactic acid was dependent on the C/N ratio of the sample, in addition to the amount of total sugar. Refuse with an extremely high or low C/N ratio, such as extracted tea residue or fish residues, yielded rather less L-lactic acid (data not shown). Although the amount of accumulated L-lactic acid varied depending upon the source of the

**Figure 4** Yield of L-lactic acid from food waste generated from various kinds of commercial kitchens. For experimental conditions, see the discussion in the section on materials and methods.



food waste, an average lactic acid yield of more than 10% per total weight of refuse was confirmed by semisolid, two-step fermentation (figure 4).

#### Purification of L-Lactic Acid

The filtered and concentrated broth containing approximately 35% L-lactic acid was esterified with *n*-butanol (150°C to 160°C) and distilled in the form of butyl lactate (130°C, 98% yield), which was then hydrolyzed between 95°C and 110°C. Soluble proteins and salts were precipitated with *n*-butanol. Esters, such as those of acetic acid and propionic acid, were separated during this part of the process. The optical purity of lactic acid did not change during these purification steps. Ammonia stripped at the esterification step was reused to adjust the culture pH at the fermentation step described above. Condensed water and *n*-butanol were recycled for subsequent esterification. This step consumed a relatively high amount of energy (23.4 MJ/kg PLLA) but yielded L-lactic acid of very high purity. Purification of L-lactic acid by butyl esterification is advantageous in that a wastewater treatment process is not required. In contrast, wastewater treatment is crucial in a conventional precipitation using methanol and calcium sulfate (Filachione and Costello 1952).

#### Polymerization of L-Lactic Acid via LL-Lactide

The prepolymer was first synthesized from L-lactic acid by increasing the reaction tempera-

ture in a stepwise manner (135°C to 160°C, 10 mmHg), and the lactide produced was then reactively distilled (180°C, 5 mmHg). As the lactide obtained through the reactive distillation contained a small amount of linear products that inhibit active polymerization, the LL-lactide was further purified by four steps of crystallization with successive partial and total melting (60°C to 100°C). Small amounts of the *meso*-lactide (melting point 52.0°C) were separated from the LL-lactide (melting point 97.8°C) during this step. We also separated a racemic eutectic mixture of LL- and DD-lactide, which has a melting point of 124.0°C. Consequently, LL-lactide at high optical purity (98.8%) was obtained (95% yield). On the other hand, our preliminary experiments showed that one-step synthesis of prepolymer decreased the optical purity of lactide to 88.0%.

Using tin isoocotate as a catalyst (Zhang et al. 1994), 97.5% optically pure PLLA was synthesized at 95.1% yield. The PLLA had an average molecular weight of 200 kilodaltons (kDa), a melting point of 175°C, and a glass transition temperature of 58°C (table 2). These physical properties are comparable to those of PLLA produced from commercially available L-lactic acid.

#### Material and Energy Balances for the Process

The material balance and energy requirements of the total process are summarized in tables 1 and 3, respectively. Table 1 shows that the overall experimental process yielded 68.8 g PLLA from 1 kg food waste (1.0 kg PLLA/14.6 kg food



waste). This means that 34% of total carbon in the food waste was recovered as PLLA. The amount of water added to the food waste was optimized to generate the highest yield of L-lactic acid, as well as to minimize the size of the fermentation facility and the energy input for water removal by evaporation during the subsequent processing. Furthermore, the process was designed to have low environmental impact. The fermentation residue is rich in nitrogen (C/N = 6.5; concentrations of N, P, and K were 75, 2.6, and 0.7 mg/g dry matter, respectively), reduced in weight to 14% of that of the untreated food waste, and the precipitated residue produced at the esterification step contains high concentrations of phosphorus and potassium (C/N = 7.7; concentrations of N, P, and K were 39, 28, and 23 mg/g dry matter, respectively). These stable residues were confirmed to be useful fertilizers (unpublished data). Condensed water, ammonia, and butanol were reused during the process. The removed lactide by-product with low optical purity could also be used in molding applications where no crystallinity of the polymer is required. Consequently, nearly all materials are converted to valuable resources or recycled in the process.

Production of plastics worldwide consumes around 270 MMT of fossil fuel each year (Gerngross and Slater 2000), with around 45% of this used as feedstock; the balance is used as process energy (Kurdikar et al. 2000). Because petroleum resources are limited and the combustion of fossil fuels releases greenhouse gases with the potential to change our environment, the use of fossil energy resources is a global issue. Table 3 shows that about 44.4 MJ (12.3 kWh) of process energy was required to yield 1 kg of PLLA, supplied mainly as electricity in these laboratory-scale experiments. For comparison, the first commercial PLLA plant, operated by Cargill Dow Polymers,<sup>6</sup> reportedly requires gross fossil process energy<sup>7</sup> of 39.5 MJ/kg (Vink et al. 2003). Meanwhile, the process energy required for production of bottle-grade polyethylene terephthalate (PET) and high-density polyethylene (HDPE) using petrochemicals is 27 MJ/kg (Boustead 2002) and 23 MJ/kg (Boustead 2000), respectively.

Although the process energy required for PLLA production is significantly larger than that required for some petrochemical polymers, it has

**Table 2** Characteristics of PLLA produced from collected food waste

Optical purity	97.5%
Average molecular weight	200 kDa
Melting point	175°C
Glass transition temperature	58°C

the advantage that the energy content of the feedstock is entirely renewable, resulting in lower total fossil energy use. For example, the fossil energy embodied in the feedstock of PET and HDPE is 39 MJ/kg (Boustead 2002) and 49 MJ/kg (Boustead 2000), respectively. Thus the cradle-to-factory-gate fossil energy required for production of PET and HDPE is 77 MJ/kg (Boustead 2002) and 80 MJ/kg (Boustead 2000), respectively. For comparison, the cradle-to-factory-gate fossil energy requirement of the first commercial PLLA plant is 54.1 MJ/kg (Vink et al. 2003). As currently practiced by Cargill Dow, the cradle-to-factory-gate polylactide production system uses 20% to 50% fewer fossil resources than required for competing petrochemical polymers (Slater et al. 2003).

The PLLA process proposed here has an energy advantage over even the Cargill Dow polylactide process, because the feedstock is a waste stream. In the Cargill Dow process, nearly 30% of gross fossil energy use goes into producing and processing corn to provide dextrose to feed the lactic acid fermentation. Because the feedstock to the proposed PLLA process is food waste that must otherwise be disposed of, the only upstream fossil energy allocated to the production of PLLA would be that required for collection of the separated waste (approximately 2 MJ/kg in Kitakyushu City).

Because polylactide production technology is in its infancy, and the PLLA process proposed here is still in laboratory development, there are many opportunities for substantial reductions in fossil energy use. The most energy-intensive steps in our process are the concentration, esterification, and distillation of L-lactic acid (8.04 kWh/kg PLLA; table 3). These are the key steps required for separating L-lactic acid from the complex materials in refuse and are appropriate targets for efficiency improvements.

**Table 3** Energies required at each step of PLLA production from food waste

Step	Electricity consumed <sup>a</sup> (kWh/kg PLLA)	Energy type	Energy in MJ <sup>b</sup> (MJ/kg PLLA)	Temperature (°C)	Alternative energy type
Fermentation/filtration	2.54	Electricity	9.1	125	Heat/electricity
Evaporation	3.25	Electricity	11.7	80	Heat
Esterification	3.08	Electricity	14.1	150–160	Heat
Deesterification	1.71	Electricity	6.2	95–110	Heat
Polymerization	<u>1.71</u>	Electricity	<u>6.2</u>	60–200	Heat
Total	12.33		44.4		

<sup>a</sup> PLLA yield was 68.8 g/kg wet waste.

<sup>b</sup> Calculated from electricity (kWh/kg PLLA)  $\times$  3.6 MJ/kWh.

As table 4 shows, the amount of fossil fuel required by our process could be improved by substituting steam heat for electricity in many stages of the process, because most of the energy required is heat below 150°C (table 3). For example, if 80% of the total energy were supplied by steam rather than electricity, the process energy use would be reduced from 3.53 kg Fossil Fuel Equivalent (FFE)/kg of PLLA to 1.42 kg FFE/kg.<sup>8</sup>

As in current commercial operations, it is producing lactic acid and PLLA that is the most energy-intensive part of our process, and thus process energy is expected to dominate the environmental impact of the overall scheme. One way to reduce this impact is to use a renewable form of process energy. This can be done by generating electricity and heat energy through combustion of the nonfood waste portion of the MSW stream. Because over 60 tons/day of refuse would be available for PLLA production in Kitakyushu City, 18,000 tons/yr of food waste could be treated to produce  $1.2 \times 10^3$  tons of PLLA per year, requiring  $1.5 \times 10^7$  kWh of electricity.<sup>9</sup> Using the data of Harrison and colleagues (2000), the rate of electricity generation from MSW combustion that contains 4.9% food waste is 0.584 kWh/kg wet waste.<sup>10</sup> If the electricity for PLLA production (20% of total energy) is provided by combusting such MSW, then 5,100 tons of wet waste<sup>11</sup> would be required. This figure corresponds to around 1/50th of the MSW burned annually in Kitakyushu City (data not shown). The remaining 80% of the energy required for PLLA production could be recovered as waste heat from the MSW combustion. Thus, the solid

waste stream could easily provide the feedstock as well as the electricity and heat energy required for PLLA production from food waste. In addition, closely coupling PLLA production with waste heat utilization during MSW combustion would be beneficial because it would provide a valuable use for low-quality waste heat from the combustion process and reduce total infrastructure requirements.

If process energy were derived from MSW combustion, it might be that from a greenhouse gas perspective PLLA would be preferable to petrochemical polymers such as polyethylene (PE) only because of the use of biomass power. A similar result was found for polyhydroxyalkanoate (PHA) produced using biomass power (Kurdikar et al. 2000). This seems quite possible because PLLA production requires substantially more process energy than many comparable petrochemical polymers. Such life-cycle comparisons of petrochemical and biobased plastics are also frequently quite sensitive to assumptions regarding end-of-life disposition (Patel et al. 2003). For example, PE that is landfilled sequesters carbon, but if combusted, it releases its fossil feedstock carbon into the atmosphere. In contrast, PLLA biodegrades when landfilled or composted, but the quantity and form of this carbon release is both variable and uncertain. A life-cycle assessment of the proposed PLLA process addressing these issues is now in progress, and results will be reported elsewhere.

In conclusion, the innovative practical process described here can produce high-quality PLLA from food waste. The system was designed as a total material recycling process for municipal

**Table 4** Fossil fuel required in producing PLLA from food waste

Form of energy	Fossil fuel required (kg FFE/kg PLLA)
100% electricity <sup>a</sup>	3.53
80% heat, 20% electricity <sup>b</sup>	1.42

<sup>a</sup> Using the factor of U.S. average for producing 1 kWh electrical power described by Gerngross (1999): 12.33 kWh/kg PLLA  $\times$  0.272 kg FFE/kWh = 3.53 kg FFE/kg PLLA.

<sup>b</sup> Using the factor of heat energy from natural gas cited by Gerngross (1999): (47.2 MJ/kg FFE)/(3.6 MJ/kWh) = 0.0763 kg FFE/kWh, 12.33 kWh/kg PLLA  $\times$  (0.0763  $\times$  0.8 + 0.272  $\times$  0.2) = 1.42 kg FFE/kg PLLA.

food waste, with minimal environmental emissions and energy savings. It also has the potential to produce from MSW a valuable, renewable product that can substitute for currently produced nonrenewable, petrochemical polymers. This system would also be applicable to the production of PLLA from other waste streams that contain fermentable sugars with a high proportion of water, such as agricultural wastes.

### Acknowledgments

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### Notes

- One metric ton = 1 Mg (SI)  $\approx$  1.102 short tons. Unless otherwise noted, all tons in this article refer to metric tons.
- Biological waste in this context refers to the portion of MSW composed of food waste, yard waste, and, in some cases, paper and related biodegradable materials. It is often labeled “organic waste” in the United States and “biowaste” in Europe.
- Editor’s note: “Poly(lactide)” or “PLA” means a polymer derived from the condensation of lactic acid or by the ring opening polymerization of lactide. The terms “lactide” and “lactate” are used interchangeably. Polylactide or polylactate is a commercial, biodegradable polymer that is used for a variety of packaging, medical and other materials applications. Lactic acid, lactide and polylactide all occur as chiral molecules. Chiral molecules are molecules that are so asymmetric that they are nonsuperimposable on their mirror images. That is, they have “handedness” in the way gloves are left- or right-handed. Lactide occurs in three forms: the two chiral isomers of lactide, L-lactide and D-lactide, and an achiral form known as meso-lactide. The predominant stereoisomer in the lactide polymer product is L-lactide. Thus, the terms “polylactide” or “PLA” used in the article in this issue by Gruber (2003) and “poly-L-lactate” or “PLLA” used in this article are both used to describe the same material.
- One kilogram  $\approx$  2.204 lb.
- The degree of stereochemical (optical) purity is important for commercial applications because the properties of PLA such as melting point, mechanical strength, and crystallinity, are determined by the different proportions of L-, D-, or meso-lactide in the polymer (as well as its molecular mass). PLA resins with 50–93% content of L-lactide are amorphous (non-crystalline), while resins containing over 93% L-lactide are semi-crystalline. PLA that is too crystalline however, can be brittle, and so a small number of stereo-defects can improve the polymer’s mechanical properties.
- Editor’s note: For a description of the Cargill Dow joint venture in the *Journal of Industrial Ecology*, see the corporate profile by Gruber (2003).
- This gross process energy term includes energy used in the fermentation and polymer plant and also the energy to run the wastewater treatment plant and produce and deliver various supplies such as nitrogen and water. It also includes the energy required to produce the process energy used in the PLLA production process. The process energy accounting for the PLLA process described in this article is not as complete but does include the largest energy requirements.
- This calculation is based on the conversion factor of Gerngross (1999), which assumes steam generated by ideal combustion of natural gas with no heat loss.
- PLLA production and associated electricity requirements are calculated as follows:  $1.2 \times 10^3$  ton PLLA/yr = ([18,000 ton/yr]/[14.6 kg waste/kg PLLA]);  $1.5 \times 10^7$  kWh = 12.3 kWh/kg PLLA  $\times$  1,200 tons of PLLA.
- Note that 0.584 kWh/kg = 10,512 (Btu/kg wet waste)/18,000 (Btu/kWh); 1 Btu = 0.00106 MJ.
- 5,100 tons =  $0.2 \times 1.5 \times 10^7$  (kWh)/0.584 (kWh/kg wet waste).

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