A Membrane-Integrated Fermentation Reactor System: Its Effects in Reducing the Amount of Sub-Raw Materials for \( \delta \)-Lactic Acid Continuous Fermentation by *Sporolactobacillus laevoiaceticus*

Takashi MIMITSUKA, Kyungsu NA, Ken MORITA, Hideki SAWAI, Shinichi MINEGISHI, Masahiro HENMI, Katsushige YAMADA, Sakayu SHIMIZU, and Tetsu YONEHARA

1New Frontiers Research Laboratories, Toray Industries, Inc., 6-10-1 Tebiro, Kamakura, Kanagawa 248-8555, Japan
2Global Environment Research Laboratories, Toray Industries, Inc., 1-1-1 Sonoyama, Ohtsu, Shiga 520-8558, Japan
3Department of Bioscience and Biotechnology, Faculty of Bioenvironmental Science, Kyoto Gakuen University, 1-1 Otani Nanjyou Sogabe, Kameoka, Kyoto 621-8555, Japan

Received July 4, 2011; Accepted October 2, 2011; Online Publication, January 23, 2012

Continuous fermentation by retaining cells with a membrane-integrated fermentation reactor (MFR) system was found to reduce the amount of supplied sub-raw material. If the amount of sub-raw material can be reduced, continuous fermentation with the MFR system should become a more attractive process for industrialization, due to decreased material costs and loads during the refinement process. Our findings indicate that the production rate decreased when the amount of the sub-raw material was reduced in batch fermentation, but did not decrease during continuous fermentation with *Sporolactobacillus laevoiaceticus*. Moreover, continuous fermentation with a reduced amount of sub-raw material resulted in a productivity of 11.2 g/L/h over 800 h. In addition, the index of industrial process applicability used in the MFR system increased by 6.3-fold as compared with the conventional membrane-based fermentation reactor previously reported, suggesting a potential for the industrialization of this \( \delta \)-lactic acid continuous fermentation process.

Key words: continuous fermentation; *Sporolactobacillus laevoiaceticus*; membrane; lactic acid

Lactic acid (2-hydroxypropionic acid) is a widely used chemical in the food and pharmaceutical industries. It has recently been highlighted as a raw material for polylactic acid (PLA). PLA, made from the lactic acid derived from biomass, was developed as an environmentally friendly biodegradable plastic that can substitute for synthetic plastics derived from petroleum feedstocks, but lactic acid must be produced at a lower cost if synthetic plastics are to be replaced by PLA in the future.

PLA can be divided into poly (\( L \)-lactic acid) (PLLA), poly (\( \delta \)-lactic acid) (PDLA), and poly (\( \delta \)-lactic acid) (PDLLA). Polymers of \( L \)-lactic acid, \( \delta \)-lactic acid, and \( \delta \)-lactic acid. Both of the homopolymers, PLLA and PDLA, are crystalline and have the same melting temperature of about 170 °C. However, more commonly used PLA plastics require melting temperatures in excess of 185–190 °C. It was recently discovered that the enantiomers of lactic acid form stable stereocomplexes. Stereocomplex-type PLA (sc-PLA) is characterized by its high melting temperature, about 50 °C higher than the homopolymers. This finding increased the importance of \( \delta \)-lactic acid production.

Before sc-PLA can be considered for industrial production, a process must be developed whereby lactic acid can be manufactured at high optical purity and high chemical purity at low cost.

On the other hand, we have developed a membrane-integrated fermentation reactor (MFR) system to achieve high productivity using maximum membrane performance by continuous fermentation. The concept of critical flux was applied to the continuous fermentation process as an operational strategy to reduce the flux decline caused by membrane fouling. However, when the culture liquid properties change greatly during the culture period, the long-term operation becomes difficult even if it uses the MFR system. For example, an increase in cell density, leads to increasing viscosity and waste material accumulation, causes membrane fouling. Levent and Taya have reported that cell density increased sharply, resulting in a decreased membrane permeate flux. Hence we aimed at stable long-term continuous fermentation by a reduction in sub-raw materials so as not increase the density more than necessary, but lactic acid bacteria are complex auxotrophs, and this makes it difficult to reduce sub-raw materials, such as yeast extract and peptone, which are usually expensive. According to Tejayadi and Cheryan, the nutrient sources account for about 38% of the total production cost. For example, Hurok *et al.* reported that the yeast extract concentration plays an important role in lactic acid fermentation with *Enterococcus faecalis* RKY1. Their results indicated that lactic acid productivity is linearly correlated with the yeast extract concentration at up to 25 g/L, but they found that it is possible to reduce the yeast extract concentration by repeated batch operation. Furthermore, Choudhury and Swaminathan reported that cell density can be controlled by the

---

1 To whom correspondence should be addressed. Tel: +81-467-32-9652; Fax: +81-467-32-8364; E-mail: Katsushige.Yamada@nts.toray.co.jp

Abbreviations: PLA, polylactic acid; PLLA, poly (\( L \)-lactic acid); PDLA, poly (\( \delta \)-lactic acid); PDLLA, poly (\( \delta \)-lactic acid); sc-PLA, stereocomplex-type PLA; MFR, membrane-integrated fermentation reactor
reducing the yeast extract concentration, but that this severely affected productivity with Lactobacillus rhamnosus NRRL B445 in continuous fermentation with a membrane bioreactor.\(^{10}\)

Hence we selected Sporolactobacillus laevolacticus JCM 2513 as \(\delta\)-lactic acid production bacterium. Sporolactobacillus, a spore-forming lactic acid bacterium,\(^{11}\) shows a lower level of amino acid auxotrophy than other lactic acid bacteria.\(^{12}\)

If sub-raw materials can be reduced, continuous fermentation by the MFR system would be an attractive fermentation process, because it would lead to both decreased material costs and decreased loads in the refinement process.

In this study, we examined reduction of sub-raw materials to improve the potential of the \(\delta\)-lactic acid continuous fermentation process with \(S.\) laevolacticus using the MFR system.

Materials and Methods

Bacteria and culture medium. The microorganism used in this study was \(S.\) laevolacticus strain JCM 2513. The medium used for \(\delta\)-lactic acid production contained, per liter, 10 g of yeast extract (Becton, Dickinson and Company, New Jersey, USA), 2 g of MgSO\(_4\)\(\cdot\)7H\(_2\)O, 0.1 g of MnSO\(_4\)\(\cdot\)4H\(_2\)O, 0.1 g of FeSO\(_4\)\(\cdot\)7H\(_2\)O, 100 g of raw cane sugar (Muso, Osaka, Japan), and 20 g of CaCO\(_3\). The medium was sterilized at 121 °C for 20 min.

Batch fermentation. Batch fermentation experiments were carried out in a 2-L fermenter (Able-Biot, Tokyo). An initial media broth volume of 1 L was used at a temperature of 37 °C and an agitation speed of 120 rpm, and nitrogen was introduced into the broth at 50 mL/min to maintain anaerobic conditions. The seed broth was incubated at 37 °C for 24 h on a shaking incubator at 100 rpm. Then 100 mL of seed broth was transferred to the 2-L fermenter. The neutralizer, Ca(OH)\(_2\) slurry (equivalent to 5 m), was automatically added to maintain a pH of 6.0 using a peristaltic pump. A series of fermentations was run at various yeast extract concentrations. Samples were withdrawn for analysis of organic acids, ethanol, residual sugar, and cell concentration, and these were stored at 4 °C for further analysis.

Continuous fermentation with the MFR system. Continuous fermentation was carried out using the MFR system, which consisted of a 2-L fermenter (working volume 1.5 L) and the microfilter element previously reported.\(^5\) The fermentor containing the microrfilter element was sterilized at 121 °C for 20 min before cultivation. A separation membrane, reported by Morikawa H et al.,\(^{13}\) was used in continuous fermentation. \(S.\) laevolacticus was cultured continuously in the fermentor, cultures were kept at 37 °C at pH 6, and nitrogen gas was introduced at 100 mL/min. Filtration and a medium supply were started at 24 h after inoculation. The permeate flow from the membrane was controlled with a peristaltic pump. The filtration condition was set at a flux below the critical flux of individual bacteria, and intermittent filtration was performed, in which filtration was stopped for 1-min intervals over 9 min. The critical flux of the \(S.\) laevolacticus batch cultivated broth determined according to the sapewise flux method was 0.600 m\(^3\)/m\(^2\)/d. Thus the filtration conditions comprised constant dilution rates: 0.17 h\(^{-1}\) and flux, 0.530 m\(^3\)/m\(^2\)/d. The permeation rate was equal to the rate at which a medium plus an alkali was added to maintain a constant working volume (1.5 L) in the fermentor. Continuous fermentation with the MFR system was run at various yeast extract concentrations. Yield was calculated by the following equation:

\[
\text{yield}\% = \frac{\text{produced amounts of } \delta\text{-lactic acid (g)}}{\text{consumption amounts of sugars (g)}} \times 100
\]

Analysis. Organic acid and sugar concentrations were determined using a high-performance liquid chromatograph (HPLC) (SIL10A Series, Shimadzu, Kyoto, Japan) equipped with an electro-conductivity detector. A Shim-pack SPR-H column was used with 5 mm \(p\)-toluenesulfonic acid as mobile phase at a flow rate of 0.8 mL/min, and 5 mm \(p\)-toluenesulfonic acid, 20 mM bis-Tris, and 0.1 mM EDTA-2Na as reaction phase at a flow rate of 0.8 mL/min. The column temperature was maintained at 45 °C. Optical isomers of \(\delta\)- and \(\epsilon\)-lactic acids were analyzed by HPLC equipped with an electro-conductivity detector. A TSK-gel Enantio L1 column (Tosoh, Tokyo) was used with 1 mM CuSO\(_4\) as mobile phase at a flow rate of 1 mL/min, and the column temperature was maintained at 37 °C. Samples were filtered through a membrane (pore size, 0.22 µm). The ethanol concentration was measured by gas chromatography (GC2010, Shimadzu) equipped with a flame ionization detector under the following conditions: capillary column TC-1 (0.53 mm i.d. by 15 m) (GL science, Tokyo); temperatures of column, injector and detector, 45, 200, and 250 °C, respectively; flow rate of helium carrier gas, 3 mL/min. The cell concentration was measured as the optical density at OD\(_{660nm}\).

Results and Discussion

Reduction influence of yeast extract in batch fermentation

Hurok O et al. have reported that the yeast extract concentration plays an important role in lactic acid fermentation with \(E.\) faecalis RKY1.\(^{10}\) Their results indicated that lactic acid productivity is linearly correlated with the yeast extract concentration at up to 25 g/L.

We examined batch fermentation by \(S.\) laevolacticus, which reduced yeast extract as a sub-raw material (concentrations of yeast extract, 10 g/L, 5 g/L, 3 g/L, and 1 g/L). The results are shown as the time courses of the concentrations of \(\delta\)-lactic acid, sugar, and the OD\(_{660nm}\) (Fig. 1). As for the main by-product, acetic acid accumulations were 0.7 g/L (data not shown). The batch fermentation results are shown in Table 1. The findings indicate that the \(\delta\)-lactic acid production rate, the sugar consumption rate, and the growth rate of the microorganism decrease with decreasing concentrations of yeast extract in batch fermentation. These results confirm those reported in other lactic acid bacteria,\(^{14}\) and that yeast extract also plays an important role in spore-forming lactic acid bacteria. Higher fermentation yields were obtained at yeast extract concentrations of 3 to 5 g/L, and the yield decreased when the concentration of yeast extract was adjusted to 10 g/L. This indicates that \(S.\) laevolacticus grew and produced \(\delta\)-lactic acid at lower concentrations of yeast extract than \(E.\) faecalis. This suggests that the auxotrophy of \(S.\) laevolacticus is not as complex as predicted. Future studies will aim to achieve effective \(\delta\)-lactic acid fermentation at a competitive cost using completely synthetic media.

A reduction in the yeast extract concentration caused a decrease in the production rate of batch fermentation because the growth rate of the microorganism decreased, but we thought that a reduction in the yeast extract concentration in the continuous fermentation might not influence the production rate due to the microorganism’s simple auxotrophy and sufficient cell density.

Effects of yeast extract reduction in continuous fermentation with the MFR system

Continuous fermentation was carried out using the MFR system previously reported.\(^5\) Continuous fermentation was performed essentially according to the batch fermentation conditions described above. However,
because the saturated solubility of D-lactic acid calcium was 70 g/L (data not shown), we used 80 g/L of raw cane sugar and 8 N of calcium hydroxide.

First we examined continuous fermentation by the MFR system by *S. laevolacticus* that feeds 10 g/L the yeast extract as sub-raw material. Next we examined continuous fermentation that reduced a yeast extract stepwise. In detail, bacterial growth was promoted by continuous fermentation at a yeast extract concentration of 5 g/L up to 140 h. Then the concentration of yeast extract was reduced to 3 g/L up to 233 h. Even under these conditions, all of the sugar was consumed. Then the concentration of yeast extract was reduced to 1 g/L up to 812 h.

The results are shown in Fig. 2, which compares these two continuous processes of fermentation as the time course of the OD\textsubscript{660nm} and the time course of the flux. The findings indicate that the growth rate of the microorganism increase with increasing concentrations of yeast extract. Thus a high cell density was achieved. On the other hand, a decrease in flux was observed at 10 g/L the yeast extract, but not at a reduced yeast extract stepwise. However, the cause of the flux decline was not only cell density. For example, in the wastewater treatment technical field, Xia H et al. have reported that accumulated soluble organic substances in the membrane bioreactor had a negative influence on membrane permeability.\textsuperscript{14} We expected that materials produced at the active growth phase would cause a flux decline. Further research is necessary to identify the causative materials.

The D-lactic acid production rates under these two conditions were almost the same (data not shown). The reason is that the production rate of continuous fermentation depends on the filtration rate in the case of sufficient cell density. The reducing the amount of sub-raw materials have an effect to control the cell growth rate. Thus it makes to reduce cell density. Because cell is one of the causative substance to make membrane fouling, it makes effective to reduce in sub-raw materials for preventing membrane fouling.

We found that both filtration conditions and culture conditions were important for stable long-term continuous fermentation.

The results for reduced yeast extract concentration are shown as the time courses of the concentration of fermentation products, sugar and the OD\textsubscript{660nm}, and the time courses of the yield and production rate (Fig. 3). After yeast extract was reduced to 1 g/L (257–812 h), the lactic acid accumulations were 64.4–69.5 g/L, the production rates were 10.9–12.1 g/L/h and the yields were 93.3–100.5%. As for the main by-product, acetic acid accumulation was 1.3–3.4 g/L, the formic acid accumulation was 0.0–0.2 g/L, and the ethanol accumulation was 0.9–2.1 g/L. The time course of D-lactic acid optical purity during continuous fermentation was 99.6–99.9% e.e. These findings indicated that continuous fermentation was successfully established, with stable production rates and yields for at least 1 month.

When the concentration of yeast extract was changed from 3 g/L to 1 g/L, the by-products profile also changed dramatically. Instead of an increase in the concentration of acetic acid, the concentration of formic

---

**Table 1.** Comparison of Batch Fermentation Results at Various Yeast Extract Concentrations

<table>
<thead>
<tr>
<th>Unit</th>
<th>Yeast extract (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yeast extract (g/L)</td>
<td>10</td>
</tr>
<tr>
<td>Concentration of lactic acid (g/L)</td>
<td>5.0</td>
</tr>
<tr>
<td>Production rate (g/L/h)</td>
<td>1.26</td>
</tr>
<tr>
<td>Yield (%)</td>
<td>91.8</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** Results of Batch Fermentation by *S. laevolacticus* at Various Yeast Extract Concentrations.

*S. laevolacticus* was cultivated at various yeast extract concentrations under the fermentation condition described in “Materials and Methods.”

Yeast extracts: ○, 10 g/L; ●, 5 g/L; △, 3 g/L; ▲, 1 g/L. A, time course of the D-lactic acid concentration; B, time course of the residual sugar concentration; C, time course of OD\textsubscript{660nm}.

---

Reduction of Sub-Raw Material for Continuous Fermentation
acid decreased drastically (200–300 h). The change from homolactic acid fermentation to heterolactic acid fermentation increased the amounts of other metabolites, including formic acid or CO$_2$, acetic acid, and ethanol, as has been found for Streptococcus lactis$^{15}$ and Lactococcus lactis$^{16}$. The shift from homolactic acid to heterolactic acid fermentation was directly dependent on the sugar consumption rate. Christel et al. reported that the orientation of pyruvate metabolism was related to the glycolytic flux-controlling activity of glyceraldehyde-3-phosphate dehydrogenase (GAPDH), and limitation of GAPDH levels led to increases in the pool concentration of both glyceraldehyde-3-phosphate and dihydroxyacetone-phosphate, and inhibition of pyruvate formate lyase activity.$^{16}$

In the present study, no shift from homolactic acid to heterolactic acid fermentation was observed when the concentration of yeast extract was changed from 3 g/L to 1 g/L in batch fermentation. Hence we expect that the shift from homo- to heterolactic acid occurs after the change in the sugar consumption rate during continuous fermentation.

As for other cases, we expected that the reduction in yeast extract would cause a lack of ATP and a change in the redox balance. Thus the activation of acetyl-CoA ligase led to increases of ATP and acetic acid. On the
other hand, the activation of NAD\(^+\)-dependent formate dehydrogenase led to an adjustment in the redox balance due to the consumption of formate. In either case, further research is necessary to confirm the pyruvate formate lyase, acetyl-CoA ligase, and NAD\(^+\)-dependent formate dehydrogenase activity during continuous fermentation. *S. laevolacticus*, which was genetically engineered to disrupt the pyruvate formate lyase gene, might produce d-lactic acid more efficiently.

The sugar consumption rate did not decrease during continuous fermentation, whereas it decreased at 1 g/L yeast extract in batch fermentation. We expected the reason was that the cell concentration in continuous fermentation was higher than in batch fermentation.

In addition, when the production rate per cell concentration (OD\(_{660\text{nm}}\)) was compared by continuous fermentation with batch fermentation, it was found that both were almost identical to the 0.1 g/L/h/OD. In a word, we expected that the most suitable yeast extract concentration for the continuous fermentation with the MFR system would be the minimum concentration to maintain cell activity. We thought that further reduction in yeast extract was possible given the slow increase in cell density in continuous fermentation at 1 g/L the yeast extract. In this study, reduction of sub-raw materials led to suppression of bacterial growth and accomplished long-term continuous fermentation with the MFR system for at least 1 month. We suggest that a reduction in the sub-raw materials plays an important role in continuous fermentation, because makes possible stable long-term operating and reduces the cost of raw materials.

Conventional continuous fermentation without a membrane (chemostat culture) can not operate at a dilution rate at which the amount of overflowed cells is larger than the amount of increased cells. In other words, the higher production rate in chemostat culture is achieved at a higher growth rate of the microorganism.\(^{23}\) However, this growth rate is highly dependent on medium composition. Therefore, in order to obtain a high production rate in chemostat culture, the composition of the medium must remain rich, so reduction of medium composition is difficult in a steady state. On the other hand, it is important to simplify the medium composition to reduce material costs in the industrial process. But it is difficult to achieve a high production rate using a simplified medium composition in chemostat culture.

We have suggested that in continuous fermentation by retaining cells, the high production rate was achieved even with simplified medium compositions which reduced sub-raw materials. Because the amount of microorganism was not overflow by the membrane, the microorganisms increased up to the required cell density. We expect that continuous fermentation with the MFR system is more attractive than chemostat culture as an industrial process.

Comparisons between batch and continuous fermentation at 1 g/L the yeast extract are shown in Table 2. The production rate of continuous fermentation at 10 g/L the yeast extract improved about 10-fold as compared to batch fermentation. However, when yeast extract was reduced to 1 g/L, the production rate for continuous fermentation increased the effect to about a 45-fold improvement as compared with batch fermentation. Under these conditions, D-lactic acid manufacturing costs are decreased. These results indicate that the yeast extract dosage for continuous fermentation is 10% that for batch fermentation, and that the production rate and yield did not decrease even under reduced yeast extract concentrations, contrast to the findings of a previous report.\(^{10}\) The influence of the reduction in sub-raw materials on continuous fermentation might differ among different microorganisms. Either way, continuous fermentation with the MFR system offers the possibility of reducing the amount of sub-raw materials required for various manufacturing fermentation processes.

**Comparison with previous continuous fermentation studies**

Several studies have been reported in which continuous fermentation procedures were established\(^{6,9,10,18–23}\) but there are no report on industrialization of the continuous fermentation process, possibly due to the low performance and high cost of the previously employed separation membrane. In previous studies, performance assessment of continuous fermentation has relied on improvements in the production rate. The peak of the production rate was confirmed by short time culture even if fouling of the membrane occurred.\(^{6,9,10,18–20}\) On the other hand, the filtration velocity was improved by using a large separation membrane area, and a significant improvement in the production rate was reported.\(^{21–23}\)

However, in this case, the cost of the separation membrane is greater. It is important to decrease the cost of the separation membrane as much as possible if continuous fermentation technology is to be applied industrially.

To operate stable long-term continuous fermentation is very important to improve the fermentor-operating ratio and avoid performance decrements in membrane permeability with steam sterilization. Hence we compared the results of our study with those of previous ones using a new index: the index of industrial process applicability, calculated by the following equation:

\[
\text{index of industrial process applicability} \left[g/cm^2\right] = \frac{\text{production rate} \left[g/L/h\right] \times \text{culture time} \left[h\right]}{\text{membrane area per working volume} \left[cm^2/L\right]}
\]

An increase in this index corresponds to decreased membrane costs and a more compact continuous fermentation device. Comparisons between our results and those of previous studies\(^{6,9,10,18–23}\) in which the membrane area and the working volume were described clearly so as to make it possible to calculate the index of

---

Table 2. Comparison of Fermentation Results between Batch and Continuous Fermentation under the MFR System

<table>
<thead>
<tr>
<th>Unit</th>
<th>Batch fermentation</th>
<th>Continuous fermentation*</th>
<th>Continuous /Batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final OD(_{660\text{nm}}) (–)</td>
<td>1.8</td>
<td>100.3</td>
<td>55.7</td>
</tr>
<tr>
<td>Concentration of lactic acid (g/L)</td>
<td>55.7</td>
<td>67.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Production rate (g/L/h)</td>
<td>0.25</td>
<td>11.20</td>
<td>44.8</td>
</tr>
<tr>
<td>Yield (%)</td>
<td>89.0</td>
<td>97.7</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Average at stationary phase (257–812 h)
industrial process applicability, are shown in Table 3. Our report does not show the maximum production rate or the longest culture time. However, the production rate and culture time achieved better results in relation to the minimum membrane area. Thus our results indicated the highest index of industrial process applicability. This improvement resulted not only from the use of an efficient membrane, but also from optimization of fermentation conditions. The index of industrial process applicability used in the MFR system increased by 6.3-fold as compared with the conventional membrane-based fermentation reactor previously reported, suggesting a potential for industrialization of this D-lactic acid continuous fermentation process.

Acknowledgment

This work was partially supported by a grant from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References


Table 3. Comparison of Lactic Acid Continuous Fermentation Results

<table>
<thead>
<tr>
<th>Research laboratories</th>
<th>Product</th>
<th>Yield (%)</th>
<th>Production rate (g/L/h)</th>
<th>Culture time (h)</th>
<th>Working volume (L)</th>
<th>Membrane area (cm²)</th>
<th>Index of industrial process applicability (g/cm²)</th>
<th>Report year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Univ. Lund⁷</td>
<td>L-LA</td>
<td>—</td>
<td>10.0</td>
<td>150</td>
<td>2.0</td>
<td>4000</td>
<td>0.8</td>
<td>1990</td>
</tr>
<tr>
<td>Univ. Chonnam⁹</td>
<td>L-LA</td>
<td>—</td>
<td>6.2</td>
<td>168</td>
<td>1.0</td>
<td>600</td>
<td>1.7</td>
<td>2003</td>
</tr>
<tr>
<td>Univ. California¹⁸</td>
<td>L-LA</td>
<td>95</td>
<td>151.0</td>
<td>18</td>
<td>0.6</td>
<td>900</td>
<td>1.8</td>
<td>1985</td>
</tr>
<tr>
<td>Univ. Toronto⁴</td>
<td>L-LA</td>
<td>75</td>
<td>6.0</td>
<td>145</td>
<td>1.0</td>
<td>300</td>
<td>2.9</td>
<td>2005</td>
</tr>
<tr>
<td>KAIST⁷⁰</td>
<td>L-LA</td>
<td>—</td>
<td>21.6</td>
<td>180</td>
<td>0.4</td>
<td>650</td>
<td>2.4</td>
<td>2001</td>
</tr>
<tr>
<td>Univ. Kyusyu³⁰</td>
<td>L-LA</td>
<td>95</td>
<td>26.0</td>
<td>540</td>
<td>0.4</td>
<td>1700</td>
<td>3.3</td>
<td>2002</td>
</tr>
<tr>
<td>IIT⁹⁰</td>
<td>L</td>
<td>—</td>
<td>34.0</td>
<td>100</td>
<td>2.0</td>
<td>1000</td>
<td>6.8</td>
<td>2006</td>
</tr>
<tr>
<td>KAIST¹⁹</td>
<td>L-LA</td>
<td>80</td>
<td>1.4</td>
<td>1052</td>
<td>26.5</td>
<td>3580</td>
<td>10.9</td>
<td>2002</td>
</tr>
<tr>
<td>Sci. Univ. of Tokyo²²</td>
<td>L-LA</td>
<td>65</td>
<td>12.3</td>
<td>643</td>
<td>1.8</td>
<td>800</td>
<td>17.8</td>
<td>1999</td>
</tr>
<tr>
<td>Toray Industries, Inc.</td>
<td>L-LA</td>
<td>97</td>
<td>11.2</td>
<td>800</td>
<td>1.5</td>
<td>120</td>
<td>112.0</td>
<td>This report</td>
</tr>
</tbody>
</table>