Recycling Technology Based on Biomanufacturing
—Plastic Recycling with Enzymes Utilized by Smart Cells—

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Why This Technology?

Toward the goal of achieving carbon neutrality by 2050, the Ministry of Economy, Trade and Industry (METI) established the Green Innovation Fund in 2021. This fund aims to increase annual public and private investment to JPY 3 trillion by 2030. Additionally, initiatives such as the Bio Manufacturing Revolution Promotion Fund, with a budget of JPY 300 billion, are being promoted, reflecting the growing momentum for public-private research and development efforts. Meanwhile, in Europe and the United States, proactive policies are being formulated against the backdrop of decarbonization and the promotion of a circular economy. In particular, plastic recycling technology based on bio-manufacturing is attracting increasing attention, with companies intensifying efforts toward commercialization.

Summary

- Utilizing enzymes produced by genetically modified microorganisms (smart cells) based on biomanufacturing has enabled plastic recycling with lower environmental impact while maintaining a certain level of quality.
- Despite the challenge of mass production of enzymes, technologies are being established to resolve this through the use of AI.

1. What is Biomanufacturing?

1-1. Biomanufacturing

Biomanufacturing is an emerging field that aims to address social issues such as global warming by using genetic engineering to alter the quantity and properties of substances produced by microorganisms. This approach has been officially incorporated into the Japanese government's Grand Design for a New Form of Capitalism[1]. Internationally, this field is also a key focus. In the EU, a policy document aimed at strengthening biotechnology and biomanufacturing within the region was published in March 2024[2]. In the United States, a presidential executive order was issued in September 2022 to promote the domestic bio industry, signaling a national effort to enhance competitiveness in this sector.[3]

Biomanufacturing refers to the creation of genetically modified microorganisms (smart cells) that enable the efficient production of useful substances and the execution of conventional chemical reactions under conditions that are less harmful to the environment. These smart cells are utilized for material production.

The development of smart cells involves an iterative process that includes the following steps.

[1] Grand Design and Action Plan for a New Form of Capitalism 2024 Revised Version
[2] The European Commission Releases Policy Document on Strengthening the Bioindustry Within the Region (EU) | Business News – JETRO Overseas News
[3] President Biden Signs Executive Order to Promote the Domestic Bioindustry (US) | Business News – JETRO Overseas News

Design: Create a blueprint for genetic modifications and metabolic pathway alterations.

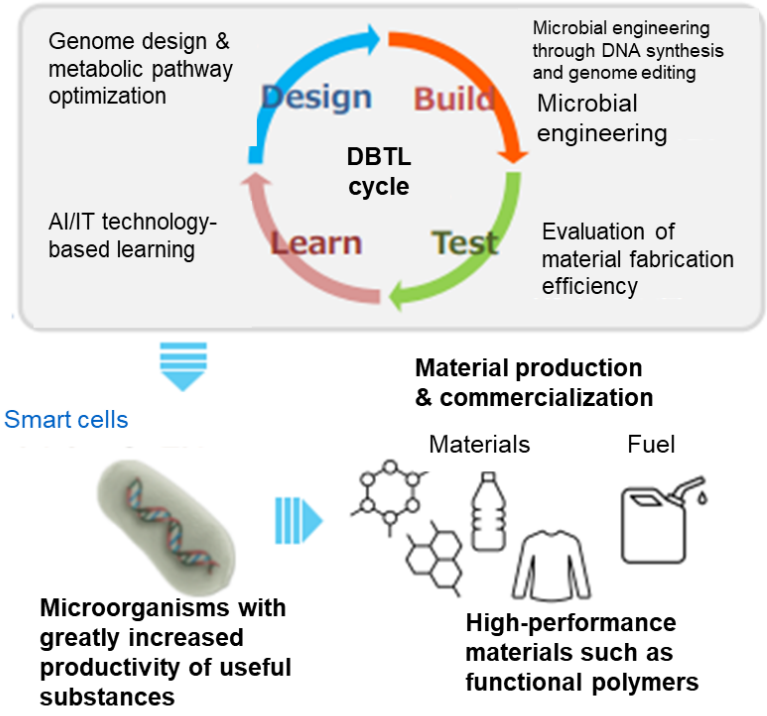
Build: Modify the genes based on the design to produce smart cells.

Test: Evaluate the functionality of the created smart cells.

Learn: Analyze evaluation data to identify areas for improvement and design more optimized smart cells.

This series of processes is known as the DBTL cycle (Design, Build, Test, Learn). By continuously iterating through this cycle, it becomes possible to develop microorganisms capable of efficiently producing valuable substances (see Figure 1).

Figure 1: Conceptual diagram of biomanufacturing



Source: Compiled by MGSSI based on Realization of the Biomanufacturing Revolution, Ministry of Economy, Trade and Industry, April 19, 2023
Compiled by MGSSI based on https://www.meti.go.jp/shingikai/sankoshin/shin_kijiku/pdf/014_05_00.pdf

1-2. Application of Biomanufacturing to the Recycling Sector

Conventional biomanufacturing typically utilizes biomass for material production. However, in recent years, there has been a growing number of research reports on plastic recycling technologies using enzymes produced by smart cells developed through this technology. Being biological molecules, enzymes react only with specific molecular structures and chemical bonds. Compared to mechanical and chemical recycling, this characteristic gives enzyme-based recycling higher selectivity. As such, enzymes basically do not react with impurities, enabling more efficient recycling. Unlike traditional chemical recycling, which requires high temperatures, high pressures, and chemical agents, enzyme-based recycling can proceed under ambient temperature and pressure, thereby reducing energy consumption. Furthermore, while mechanical recycling often leads to physical degradation of material properties, enzyme-based recycling can yield recycled materials with quality close to the original.

1-3. Challenges in Applying Biomanufacturing to the Recycling Sector

Since enzymes are biologically derived, their reaction speed is slower compared to conventional technologies, precise temperature and pH control is required, and the production cost is high because mass production methods for enzymes have not been established. Although the DBTL cycle is being utilized to develop higher-performance enzymes to address these issues, further technological advancements are expected to enhance efficiency and reduce costs.

2. Notable Trends

2-1. Examples of Plastic Recycling Using Biomanufacturing

A leading example is Carbios (France), which is developing an enzyme-based technology to break down PET into ethylene glycol and terephthalic acid (TPA). The company plans to launch a commercial plant in 2026. Kirin Holdings Company (Japan) has announced the development of a highly efficient PET-degrading enzyme in collaboration with Shizuoka University, the National Institutes of Natural Sciences, and Osaka University[4].

Beyond PET recycling, the Samsara Eco (Australia) has developed nylon recycling technology and successfully produced recycled nylon 6/6 in partnership with the sportswear brand Lululemon (US), resulting in prototype sportswear made from recycled materials. Additionally, the Kanematsu (Japan) has invested in Samsara Eco, aiming to establish a recycling supply chain[5].

Figure 2: Status of plastics recycling research and development

Name of company / research institute	Recycled material	Overview
Carbios (France)	PET	Actively forming partnerships with multiple enterprises as a pioneer in enzyme-based PET depolymerization. Working towards the 2025 launch of a factory through a joint venture with Indorama Ventures.
Samsara Eco (Australia)	Nylon, PET	Developing enzyme technologies utilizing research from Australian National University (ANU). Also exploring the scale-up of enzyme-based nylon recycling, despite many companies focusing on PET degradation.
Enzymity (Latvia)	PET, polyester, polyurethane, polystyrene	Possesses an optimized platform that leverages machine learning capabilities. Successfully reduced degradation times, cutting PET depolymerization from 100 hours to 15 hours, and polyethylene degradation from 50 days to 20 days.
Epoch BioDesing (UK)	Nylon, polyester	Uses generative AI to design promising enzyme candidates for plastic depolymerization by leveraging both public and proprietary datasets. Implemented physical modeling to evaluate the ability of enzymes to degrade polymers under mild conditions.
Kirin Holdings Company (Japan), Shizuoka University, National Institutes of Natural Sciences, Osaka University	PET	Succeeded in developing a highly thermostable enzyme. Demonstrated that these enzymes can selectively degrade PET in blended fibers such as PET and polyurethane, as well as PET and cotton, and achieved a world-record PET degradation rate of 90% in PET-cotton blends.

Source: Compiled by MGSSI

2-2. The Rise of AI in Smart Cell Creation

The advancement of AI is reducing the time needed to design smart cells to obtain ever more efficient enzymes. Effective AI utilization relies on leveraging both proprietary and publicly available datasets. Until now, companies that possessed extensive proprietary datasets had a competitive advantage. However, the emergence of generative AI platforms is now enabling companies without their own large datasets to design smart cells as well. For example, Ginkgo Bioworks (US), which has previously focused on producing substances such as flavors, announced a partnership with Google Cloud in September 2023. This collaboration is to develop a generative AI platform for smart cell design by third parties using Ginkgo Bioworks' datasets and Google Cloud's AI technologies.

[4] Kirin Holdings Company Develops Chemical Recycling Technology Using Highly Efficient PET Decomposition Enzyme – The Chemical Daily (Electronic Edition)

[5] Kanematsu Invests in Australian Environmental Tech Startup Samsara Eco – Proprietary Enzyme Recycling Technology Converts Plastics into Monomers, Reducing CO_2 Emissions and Enabling Infinite Recycling

The platform has been available to third parties since September 2024[6,7]. These new services are expected to expand participation in enzyme development using smart cells, stimulate further research and development, and accelerate product launches to the market.

2-3. Advancement of Mass Production Technology

Mass production technology for smart cells is still in its infancy, but Chitose Laboratory (Japan) is aiming for stable mass production leveraging AI technology. Conventional culture techniques have relied not only on easily measurable data such as temperature, pH, and dissolved oxygen concentration but also on subjective factors such as color and smell, which depend on the experience and intuition of skilled workers. Chitose Laboratory is addressing this by continuously and cost-effectively collecting multidimensional data (electrical potential data, odor data, image data, etc.) that AI can easily learn from in addition to conventional data, and using this "convolutional data" to determine optimal cultivation conditions. These technologies are expected to be widely used in the design of new microorganisms in the future and become an important foundation for the stable production of smart cells.

3. Future Prospects

Enzyme-based recycling technologies are expected to contribute to energy savings and reductions in greenhouse gas (GHG) emissions. For example, it has been reported that enzyme-based methods can reduce energy consumption in PET recycling by 69% to 83% compared to fossil fuel-based conventional processes, and GHG emissions by 17% to 43% per kilogram of terephthalic acid (TPA), the raw material for PET throughout the supply chain[8]. Given that PET contains ester bonds, which make it relatively easy to hydrolyze using enzymes, and certain recycling methods have been established, many companies and research institutions are working on developing even more efficient enzyme-based recycling solutions. However, as mentioned above, AI-driven enzyme development is expected to expand beyond PET to materials like nylon and polyester, enabling high-efficiency enzymatic recycling for a broader range of common plastics.

IP Analysis of Biomanufacturing

For the IP analysis of biomanufacturing, patent data related to enzyme-based recycling technologies was extracted and analyzed to assess the technological landscape. The analysis covered 311 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

As shown in Figure 3, the number of patent filings increased significantly between 2019 and 2021, reflecting both technological maturation and growing market demand. Forecasts for 2024 indicate that patent filings are expected to rise further, underscoring the increasing importance of enzyme-based recycling technologies and the expansion of the market. As illustrated in Figure 4, major patent applicants include both research institutions, such as Jiangnan University, and companies, such as Carbios.

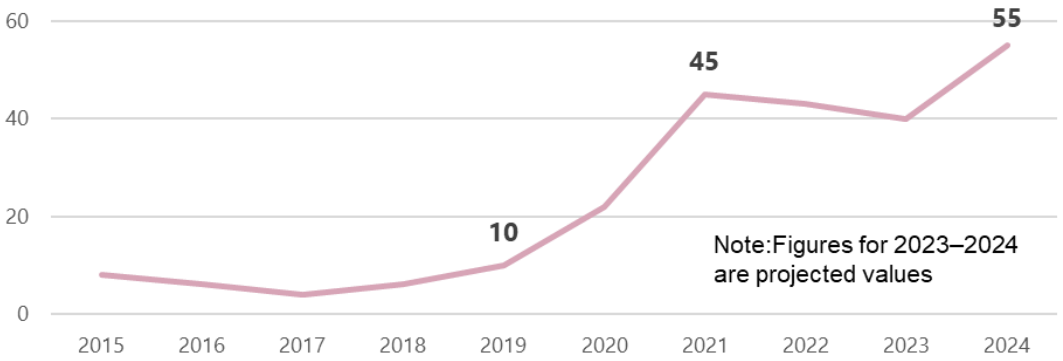
An analysis of the patent data reveals there to be many enzyme technologies specialized in PET degradation, with ongoing research and development aimed at commercialization. Carbios is particularly focused on PET degradation technologies and holds patents that emphasize unique process designs aimed at industrial-scale implementation. Jiangnan University is conducting research on the degradation of multiple plastic materials, including polyester and polystyrene, with a focus on unique genetic engineering modifications to improve enzyme

[6] Google and Ginkgo: Foundry-Scale Data Meets AI - Ginkgo Bioworks
[7] Introducing Ginkgo's Model API: A Programmable Interface for Ginkgo's AI Research - Ginkgo Bioworks
[8] Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate): Joule

performance.

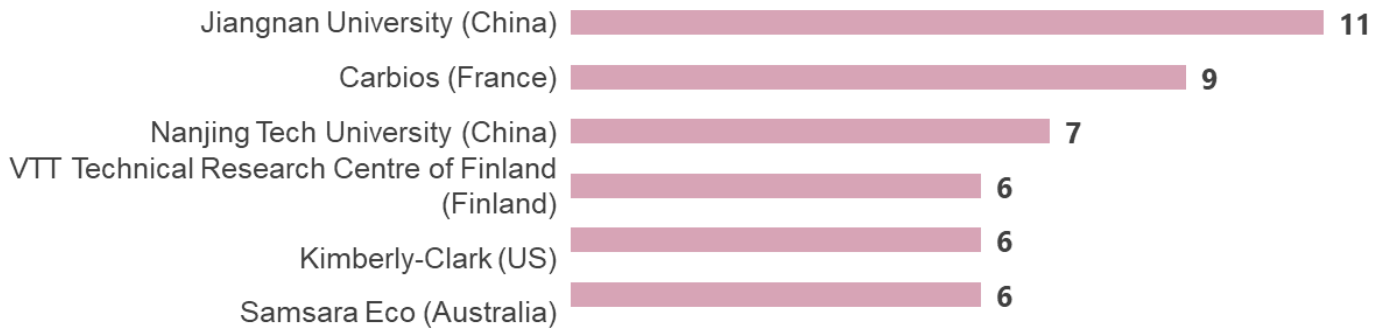
The current body of patents mainly represents laboratory-scale achievements, proving that enzyme recycling is technically feasible. However, commercialization remains a barrier to actual implementation. While Carbios' patents highlight near-term industrial applications, foundational research from Jiangnan University and other institutions is valuable for exploring new materials and opening up markets in the long term.

Figure 3: Annual patent filings related to enzyme recycling technology



Source: Compiled by MGSSI

Figure 4: Top ranking of patent applicants by number of filings (2015–2024)



Source: Compiled by MGSSI