Revealing the intersectoral material flow of plastic containers and packaging in Japan

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The Japanese government developed a strategy for plastics and laid out ambitious targets including the reduction of 25% for single-use plastic waste and the reuse/recycling of 60% for plastic containers and packaging by 2030. However, the current usage situation of single-use plastics including containers and packaging, which should be a basis of the strategy, is unclear. Here, we identify the nationwide material flow of plastics in Japan based on input–output tables. Of the domestic plastic demand of 8.4 Mt in 2015, 1.6 and 2.5 Mt were estimated to be for containers and packaging comprising household and industry inflows, respectively, through the purchase/procurement of products, services, and raw materials. Considering the current amount of recycling collected from households (1.0 Mt) and industries (0.3 to 0.4 Mt), the reuse/recycling target has already been achieved if the goal is limited to household container and packaging waste, as is the focus of Japan's recycling law. Conversely, the results indicate that it will be extremely difficult to reach the target collectively with industries. Therefore, it is essential that efforts be made throughout the entire supply chain. Food containers and packaging that flowed into the food-processing and food service sectors accounted for 15% of the inflow of containers and packaging into industries. Thus, the key to achieving the reuse/recycling target will comprise the collection of plastic food packaging from not only households but also the food industry. Furthermore, the collection of flexible plastic films used between industry sectors will put the target within reach.

plastic container and packaging | material flow analysis | input–output table | recycling rate | Japan

Plastic production and consumption are increasing worldwide (1). Plastic containers and packaging, which are typical single-use plastics, cause various problems not only by entering the ocean (2–6) but also by occupying landfill sites, influencing climate change through CO_2 emissions during incineration, consuming fossil resources, and impacting the environment over their life cycles (7–9). There have been wide-ranging discussions regarding methods to solve and alleviate such problems (10–14), including the reduction and recycling of single-use plastics (15–23), the introduction of biobased and biodegradable plastics (24–29), and the implementation of extended producer responsibility (EPR) (30). In this context, the Japanese government, which, along with the United States, did not ratify the Ocean Plastics Charter (31) and thus caused global disappointment, is now eager to make up for lost ground in the plastic issue. At the same time, Japan and many other countries, including those in Europe, face problems caused by increasing amounts of waste plastics that must be processed or recycled domestically due to the ban on the import of waste plastics by China at the end of 2017 (32) and the subsequent plastic import restrictions in Asian countries such as Thailand and Vietnam. The influence of import restrictions on waste plastics is enormous in Japan because the country has depended on the export of ∼1.5 million tons (Mt) out of ∼9 Mt of annual waste plastics to Asian countries, mainly China, in recent years (33, 34). Against this backdrop, the Japanese "Resource Circulation Strategy for Plastics" was rapidly

developed before the G20 Summit hosted by Japan in June 2019; the final version of the strategy was released at the end of May 2019 (35). The following are some of the goals laid out in the Japanese strategy for plastics that are strongly conscious of the Ocean Plastics Charter (31) and the European strategy for plastics in the Circular Economy (11): a reduction of 25% in the generation of single-use plastic waste by 2030; a 60% reuse/recycling target for plastic containers and packaging by 2030; a 100% utilization rate, including energy recovery, for all waste plastics by 2035; and introduction of 2 Mt of biobased plastics by 2030.

Of these, the second goal is above the 55% target for the recycling of plastic packaging by 2030 in the Ocean Plastics Charter (31) and Europe (36). Since containers and packaging are the symbol of wasteful plastics, this target must be achieved. However, surprisingly, the total amount of plastic containers and packaging that should be used as a denominator of the reduction and reuse/recycling targets is unclear. Regarding the quality of plastic waste including the composition of resin types, which is the major determinant of recyclability (especially in mechanical recycling), only fragmentary information such as waste composition survey data with a limited sample of waste sources are available.

The situation is more or less similar in Europe and the United States in regard to confusion about the flow of plastics for containers and packaging. As in Japan (33, 34), the United States adopts an approach in which the amount of waste generated is determined by estimating domestic consumption, starting from the production amount of plastic products, including containers

Significance

Plastic containers and packaging are typical single-use plastics. It is essential to quantitatively identify who uses plastic containers and packaging to supply products, and who purchases these products and discards their containers and packaging. We develop a model for material flow analysis using input–output tables (IO-MFA) that specifies the intersectoral flow of plastics as containers and packaging. We apply the model to the nationwide material flow of plastics in Japan and discuss which types of plastics should be collected from what sources to achieve the recycling target set by the government. This IO-MFA model could be applied to other countries that publish input–output tables and contribute a basis for strategies to solve the problems associated with single-use plastics.

and packaging, with attention on exports and imports; then, the life span of each type of product is considered (37). In both countries, in terms of the breakdown of waste treatment, the amount of plastic waste in landfills (in Japan, the sum of the incinerated and landfilled plastic waste) is calculated by subtracting the confirmed amount of waste collected for recycling and energy recovery from the amount of generated waste determined above. The same applies to Eurostat's estimation of packaging waste generated in European countries, which is considered equal to the amount of packaging distributed in the European market during the year, including imported packaging and excluding exported packaging (38). This type of approach, which does not reveal the breakdown of the waste generated by sector, only yields limited information basis for the argument of reducing plastic waste and improving the recycling rate. In addition, there is the problem of potential differences between the amount of generated waste and the confirmed amount of collected waste, although there is less risk of omitting the generated waste in terms of the total amount.

In contrast, PlasticsEurope's calculation of the recycling rate in European countries (39) is based on the breakdown of waste treatment (recycling, energy recovery, landfill) of officially collected plastic packaging. On the production side, 39.7% (20.3 Mt) of the 51.2 Mt of total plastic converter demand in 2016 in Europe (28 European Union countries, Norway, and Switzerland) is regarded as the demand for packaging. However, there is a discrepancy between this figure and the 16.7 Mt of post-consumer packaging waste that were collected. The service life of plastic products is mentioned as a reason for the discrepancy, but normally, single-use plastics with a life span of less than 1 y do not become a factor in the gap between the amount of production and the amount of collection. Exports and imports of plastic products and products packed in plastics can also be factors in the difference, but these have not been quantitatively analyzed, and the existence of noncollected waste plastics is a known fact. We cannot rule out the possibility of overestimations of the recycling rate, as the estimates from the collection side alone tend to underestimate the amount of generated waste.

In summary, there exist the following gaps between the currently available data and effective implementation of policies toward achieving reduction and recycling targets. First, the total amount of plastic container and packaging waste as a denominator of the targets should be clarified. Then, to reduce plastic usage and increase the amount of reuse and recycling (as a numerator of the target rate), it is essential to quantitatively identify who uses what types of plastic containers and packaging to supply products, and who purchases these products and then discards their containers and packaging. Moreover, to avoid mismatches between the types of resin that are input and the recycling technologies used, the resin composition of plastic waste for each source of discharge needs to be identified. This information is particularly relevant to the yield and economic efficiency of mechanical recycling. If we know the relationship between processed forms of plastics (such as films, sheets, and bottles) and the resin compositions, we can enable communication between the waste generators/collectors and the recyclers about the types of plastics that should be collected to match the recycling technologies.

Material flow analysis (MFA) is effective in estimating the amounts of consumption and disposal of products and materials (40). The estimation methods for waste flows can be classified into an approach wherein the amount and composition of waste are estimated by accumulating data from the disposal side, and an approach wherein statistical data from the production side are used. However, it is impossible to understand the economy-wide (or nationwide or region-wide) flow of plastics through the former approach such as a waste composition survey, considering that waste plastics are discharged as various types of waste from various sectors. In contrast, the economy-wide MFAs of plastics

using the latter approach starting from statistical data on the amount of production and materials used have been reported in regions such as Europe and Switzerland (41), Austria (42–44), India (45), the Netherlands (46), Germany (47), and the United States (48) (*SI Appendix*, Table S1). In particular, MFA using input–output tables (often referred to as IO-MFA) has an advantage as an analysis method in that it can trace the flows from the resources and materials to the products and the products' end users. However, it is necessary to overcome the following two challenges in IO-MFA to fill the above-described research gaps: Plastic-related sectors have to be subdivided in order to specify the flow of plastics as containers and packaging; and the intersectoral transfer of containers and packaging by accompanying products has to be modeled (*Materials and Methods*, *Challenges in MFA Using Input–Output Tables*).

In this study, we estimated the nationwide material flow of plastics in Japan through an approach from the production side that tracked down the supply chains based on input–output tables (49) complemented by plastic production and shipment statistics. We revealed the intersectoral material flow of containers and packaging with respect to the following five questions: 1) what types of resin and 2) processed forms of plastics are used for containers and packaging, 3) what products are they used for as containers and packaging, and 4) which demand sectors consume and eventually discard them, including 5) the changes over time from 2000 to 2015. The accuracy of our estimation results was verified by comparison with published survey results, such as data on the generation and composition of plastic waste (*SI Appendix*, Figs. S10–S12).

Results

Nationwide Material Flow of Plastics in Japan. The amount of plastic consumption associated with domestic demands and exports, including losses, in Japan was estimated to be 15.5 Mt in 2015. When exports are excluded, the inflow of plastics into Japanese households and industries (that is, plastics that are considered to be used and disposed domestically) was estimated to be 8.4 Mt. The usage of containers and packaging, including losses of 0.2 Mt, was estimated to be 4.8 Mt (H01 of the Sankey diagram in *SI Appendix*, Fig. S3), among which 0.4 Mt, including containers and packaging associated with export products, was exported, and 0.2 Mt was directly demanded in households and industries. The primary products, beverages and foods (J01), had no plastic flow as products because they do not contain synthetic resins, but the flow amount of containers and packaging was significant. In terms of the amount of inflow into the demand sectors, industries accounted for 71% of all plastics (K02), and households only accounted for 39% of all plastic containers and packaging excluding the direct demand (1.6 Mt), which clearly shows that the majority of the inflows went to industries (2.5 Mt).

The breakdown of the demand sectors in terms of plastic consumption and the breakdown of products are shown in the pie chart of Fig. 1. The usage breakdown shows that 70% of the inflow of plastics into households comprised containers and packaging, including direct demand. There was the inflow of a large amount of plastics in products such as manufacturing products and machinery into industries. Notably, the amount of plastic container and packaging inflow into industries was substantial enough to merit attention because the containers and packaging that accompanied the procurement of raw materials and products flowed into industry sectors at each stage of the supply chain.

Additionally, the recycling rates of plastic containers and packaging for households and industries (see *Materials and Methods* for the definition) were estimated to be 60% (1.0 Mt out of 1.6 Mt) and 12 to 15% (0.3 to 0.4 Mt out of 2.5 Mt), respectively, with an overall 31 to 33% recycling rate in 2015 (Table 1). In other words, the target for reuse and recycling (27) has already been achieved if limited to the packaging waste
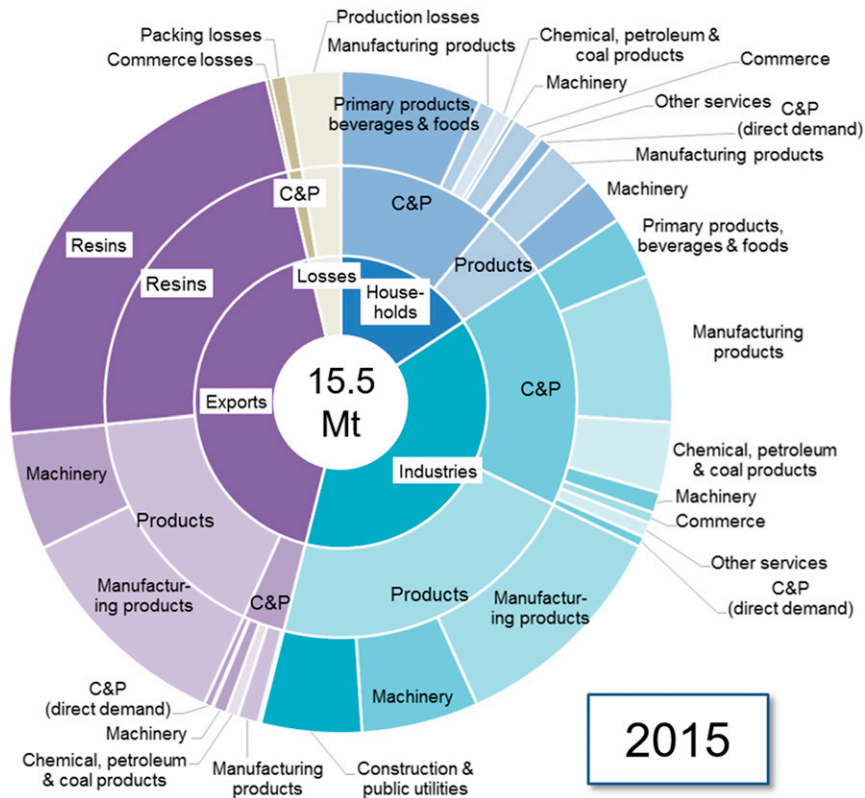
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Fig. 1. Breakdown of plastic consumption by demand sector, usage, and product associated with domestic demands and exports of Japan (2015). The outer circle shows the breakdown of products that use plastic containers and packaging (including final products, raw materials, and services), as well as those that contain plastics. The middle circle shows the usage breakdown (whether the plastics for containers and packaging or for products). The inner circle shows the breakdown of the demand sectors (where the inflow of the products occurs). In the diagram, "containers and packaging" is abbreviated as "C&P." The results of the analyses for 2000, 2005, and 2011 are shown in *SI Appendix*, Fig. S4 *A, B, and C*, respectively.

generated from households, as is the focus of the Containers and Packaging Recycling Law of Japan. Conversely, reaching the reuse/recycling rate of 60% collectively with industries in 15 y seems to be an extremely difficult task.

Who Is Using Containers and Packaging for What Purposes? The results of the estimation will be useful for considering the goals of recycling and reducing plastic waste by sector for investigating the users of the containers and packaging from the perspective of both supply (the user in selling products) and demand (the user in their purchase or procurement). For the recycling target, the viewpoint from the demand side is central, whereas estimations can contribute to the reduction potential of single-use plastics

not only from the supply side but also from the demand side through the refusal of excessive packaging.

The usage of plastic containers and packaging by sector (2015) is shown in the bar graph in Fig. 2. In the supply side of the figure, 1.6 Mt of containers and packaging are used for the sale of primary products, beverages and foods, accounting for 33% of the usage of 4.5 Mt of containers and packaging, excluding the direct demand. Of these, nonfood crops, fertilizers, forestry, and mining account for 1.5%, so containers and packaging related to food (edible agricultural and marine products, beverages and foods) represent most of the usage. In the demand side of the figure, the usage of containers and packaging (the amount of inflow) associated with the purchase of products and services in households is 1.6 Mt. The amount of containers and packaging inflowing to other services sectors, excluding commerce (see Dataset S1 for the classification of sectors), is 1.0 Mt, which is comparable with the household amount.

To visualize the relationship between the supply side and the demand side, the intersectoral flow of plastic containers and packaging (2015) is shown in the bubble chart in Fig. 3. Of the containers and packaging in the dishes, sushi, and lunch boxes sector, representing typical takeout food in Japan, the amount of inflow to households was 0.07 Mt, which accounted for 12% of the containers and packaging used in narrowly defined food (0.57 Mt excluding the containers and packaging for beverages and tobacco). The usage of containers and packaging for commerce and takeout food may be reduced through the refusal of disposable packaging by consumers or changes in the way retailers sell products. However, the aforementioned reduction target (25% of the 4.1-Mt inflow to the domestic demand

Table 1. The amounts of recycling and the recycling rates of plastic containers and packaging in Japan (2000, 2005, 2011, and 2015)

	Amount of recycling, kt		Recycling rate		
Year	Household	Industry	Household	Industry	Total
2000	209 (53)	64–114 (0–50)	15%	4–6%	9–10%
2005	797 (355)	146–176 (0–30)	50%	6–8%	24–25%
2011	961 (315)	261–367 (4–110)	59%	11–16%	31–34%
2015	966 (331)	291–378 (4–90)	60%	12–15%	31–33%

The values in parentheses in the columns for the amounts of recycling represent the amounts input to feedstock recycling. The ranges in the recycling amounts and recycling rates indicate the minimum and maximum estimates of the recycling rates (see *Materials and Methods*).
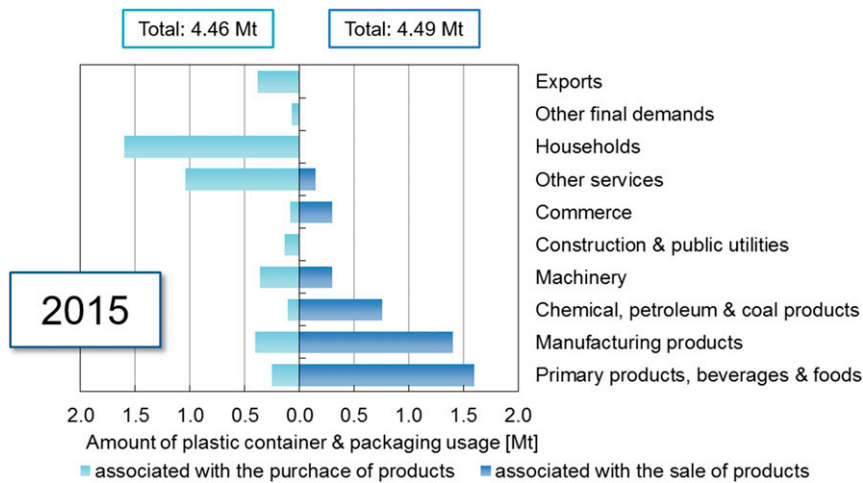
Fig. 2. Usage of plastic containers and packaging in Japan by sector (2015). The blue bar graph on the *Right* side of the figure represents the containers and packaging used in association with the sales of product outputs from each sector, and the light blue bar graph on the *Left* side of the figure represents the inflow of containers and packaging into each sector with the purchase of products. Products include final products, raw materials, and services as well as their imports. Commercial losses are included in the amount of usage associated with sales but not in the amount of usage associated with purchases. The direct demand for containers and packaging is not included. The results of the analyses for 2000, 2005, and 2011 are shown in *SI Appendix*, Fig. S5.

sectors, excluding exports, which is a reduction of ~1.0 Mt) cannot be reached through the efforts of consumers alone. Therefore, it is essential that efforts be made throughout the entire supply chain; for example, the food industry can use lighter containers and packaging (see the last paragraph of *Discussion* for further consideration). Furthermore, 0.24 Mt of containers and packaging for food flowed into the personal services sector, with

food (eating and drinking) services accounting for 95%. The flow between sectors, such as the agricultural/fishery and food-processing (beverages and foods) industries, that is the usage of containers and packaging in the stage of food production, was 0.16 Mt.

What Types of Plastics Are Used for Containers and Packaging? When we considered the total plastic consumption (15.5 Mt) associated
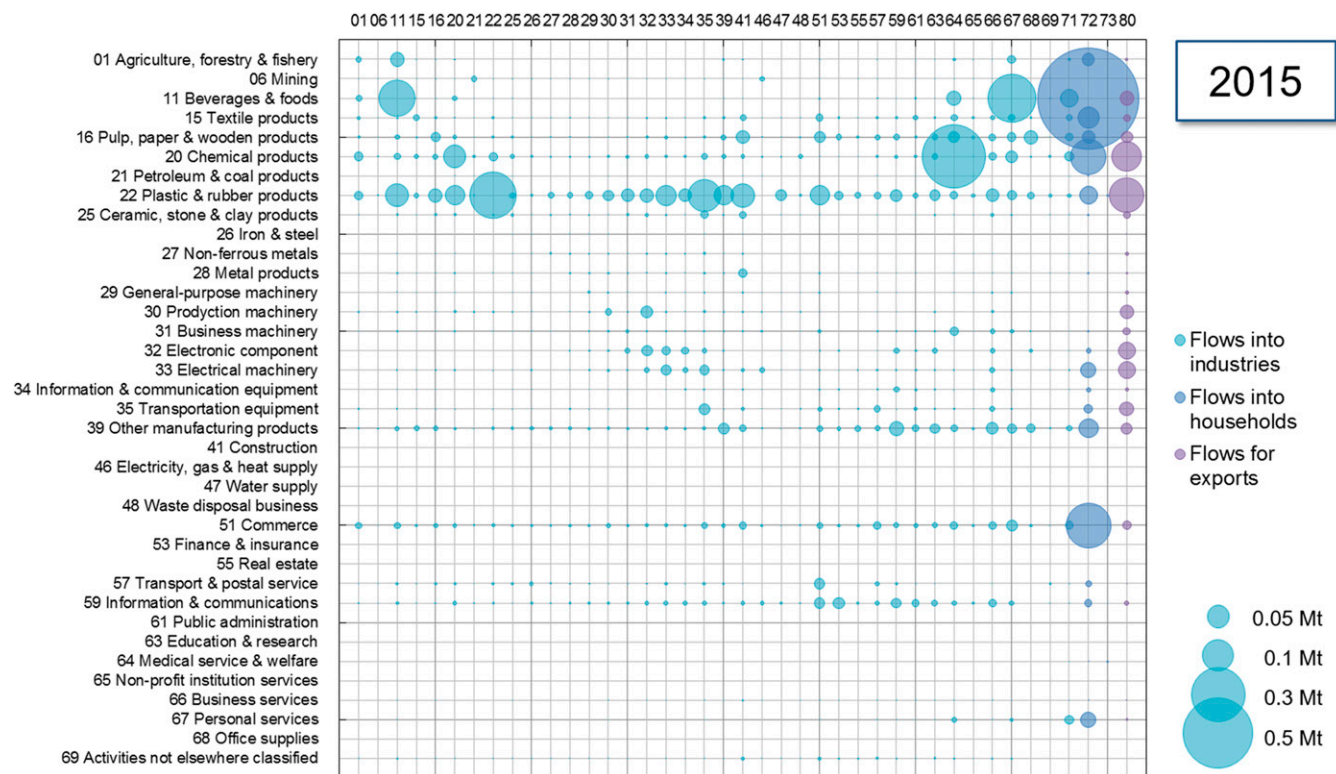
Fig. 3. Intersectoral flow of plastic containers and packaging in Japan (2015). The bubble area indicates the amount of container and packaging flow associated with the output of products from the sectors on the vertical axis to the sectors on the horizontal axis. For the sectors on the horizontal axis, 71 is consumption expenditure outside households, 72 is consumption expenditure of households, 73 is consumption expenditure of general government, and 80 is exports. The results of the analyses for 2000, 2005, and 2011 are shown in *SI Appendix*, Fig. S6 *A, B,* and *C*, respectively.

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with the domestic demand, the proportion of polyolefin, including low-density polyethylene (LDPE), high-density polyethylene, and polypropylene (PP), was 43% (2015). When we exclusively examined the containers and packaging (excluding losses and the direct demand), polyolefin accounted for an estimated 53% (Fig. 4). In 2015, polyethylene terephthalate (PET) accounted for 27% (1.1 Mt) of containers and packaging. The proportion of PET has steadily increased from 16% in 2000 to 20% in 2005 and 23% in 2011.

There is a large difference in the resin composition between containers and packaging that flow into households and that flow into industries. The pie chart in the *Upper Left* section of Fig. 4 clearly shows that the biggest factor in this difference is the proportion of plastic beverage bottles made of PET (hereinafter referred to as PET bottles). In Japan, PET bottles are collected separately from other plastic containers and packaging (50). When we calculate the resin composition excluding PET bottles, polyolefin accounts for 53% of the composition for households and 67% of the composition for industries (2015). In Japan, the mechanical recycling of plastic containers and packaging other than PET bottles is generally performed by sorting polyolefins mainly by flotation separation and producing recycled resin made from mixed PE and PP (22). If we aim solely to efficiently recover polyolefin by mechanical recycling, moving the collection target from plastic container and packaging waste generated by households to the waste generated by industries is worth considering.

Regarding the plastic waste collection methods of European countries, flexible films are sometimes not targeted for separate collection and only rigid plastics are collected separately in about

half of the countries, including Belgium, France, and Italy (51). When the resin composition is calculated separately for flexible films and other processed forms of plastics (mainly rigid plastics), there is a significant difference between the results, as shown in the *Upper Right* pie chart of Fig. 4. Because most flexible films are polyolefins, the composition seems to be suitable for conventional mechanical recycling processes. However, multilayer films, which are commonly used for food packaging [according to a survey on the compositions of plastic container and packaging waste (52), multilayer films accounted for 66% of polyolefin films], are known to cause problems for mechanical recycling (51). Thus, when flexible films are excluded from collection targets, the proportions of polystyrene (PS) and PET exceed the proportion of polyolefins. To pursue increases both in the quantity of plastic waste recycled back into plastics and in the quality of recycled resin by mechanical recycling, it is therefore necessary to proactively sort PS and PET, such as by optical sorting, instead of using the aforementioned conventional process that relies on flotation separation.

Discussion

We can elicit significant implications for the strategy to achieve the reduction target from the intersectoral MFA results (Fig. 3). As an approach from the production side, for example, the thin-walled design of PET bottles contributed to a 24% reduction in the average weight of a bottle from 2004 to 2018 in Japan (53). For other plastic containers and packaging, a 17% reduction was achieved during the same period (53). If the same level of weight reduction were attained from 2015 to 2030 in all beverages and foods sectors, food containers and packaging discharged from households would decrease by 0.21 Mt, and the path to reaching the 25% (0.40 Mt) reduction target could be paved for households in combination with consumers' waste prevention efforts including the refusal of containers and packaging distributed by the commerce sector (0.20 Mt) such as plastic shopping bags. Similarly, the personal services sector, including eating and drinking services, as a waste source could benefit significantly from the weight reduction efforts for food containers and packaging, which accounted for 79% of the plastic container and packaging inflow. On the other hand, such efforts targeting consumer packaging would have little effect on other industry sectors. Therefore, different approaches such as profound usage of returnable transport packaging need to be put into practice, otherwise an uneven allocation of the waste reduction target between sectors considering the relationship with efforts on the production side is worth discussing.

Moreover, if the reduction rate of containers and packaging varies between sectors, the recycling and reduction targets will become interrelated. In other words, if reduction precedes recycling in a sector expected to have a high recycling rate, it will be more difficult to achieve the recycling rate with the remaining containers and packaging. More specifically, with the recent trend against plastic usage as a backdrop, some Japanese organizations have substituted PET bottled beverages with aluminum canned beverages in their offices. As an extreme assumption, if the total amount of PET bottles were replaced with containers made from different materials, container and packaging inflow to domestic demand sectors would be reduced by 14%. On the other hand, however, the recycling rate of container and packaging, which has been boosted by the high recycling rate of PET bottles, would decrease from 31 to 33%, to 18 to 20% (in 2015). Such is the case with the introduction of biodegradable plastics. The Japanese government, adopting a concrete policy following the strategy for plastics, prohibited the free distribution of plastic shopping bags in 2020 (54), whereas shopping bags made from marine biodegradable plastics are exempt from this policy. According to a survey on the compositions of plastic container and packaging waste (52), shopping bags accounted for 25% of
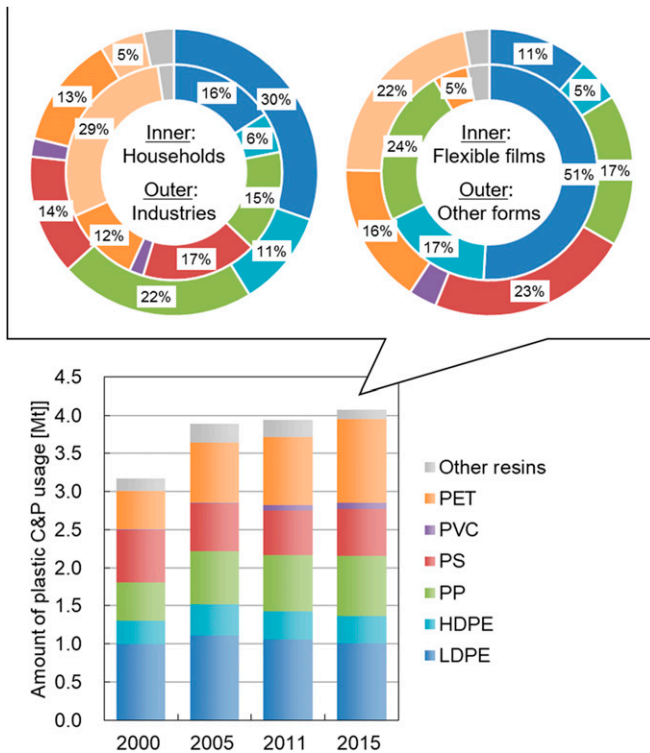
Fig. 4. Breakdown of plastic container and packaging inflow into domestic demand sectors of Japan by resin type. The *Upper Left* pie chart shows the inflow of containers and packaging into households and industries, and the *Upper Right* pie chart shows the breakdown of the resin types of flexible film and other processed forms of containers and packaging (both for 2015). The light orange section represents the proportion of plastic beverage bottles among PET. The resin-type abbreviations are described in *SI Appendix, Abbreviations*.

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PE container and packaging waste generated from households. If PE as a raw material of shopping bags were largely replaced with marine biodegradable plastics in accordance with this policy, the proportion of polyolefin in containers and packaging inflowing into households (*SI Appendix*, Fig. S9), and hence the yield of flotation-based mechanical recycling, would be significantly lowered. If we aim to efficiently achieve both of the reduction and recycling targets, substitute materials should strategically be used for containers and packaging that are unlikely to be collected for recycling.

In addition to discussion from the collection side, the recycling target needs to be addressed from the recycler side. According to the interview survey conducted by J.N. (*SI Appendix*, Table S5), much of the waste plastics that flow back to the domestic market due to the import regulations in countries such as China are incinerated because these plastics are not accepted by recycling facilities. Thus, information on the acceptable amount and quality of waste plastics and the demand for recycled materials is indispensable in discussions on achieving the recycling rate, especially in recent years in Japan. Here, feedstock or chemical recycling needs to be taken into account. The annual capacities of mechanical and feedstock recycling, which are estimated to comprise 0.82 and 0.59 Mt of waste plastics, respectively (55), are not abundant for achieving the recycling target (~1.9 Mt excluding PET bottles); thus, we must at least make the best use of their capacities. Feedstock recycling technologies that currently work in practice in Japan, including gasification and coke oven and blast furnace feedstock recycling, are less demanding in terms of the quality of plastic waste including the resin composition than mechanical recycling. The only exception is that the ratio of polyvinyl chloride (PVC) and other chlorinated plastics needs to be lowered, especially in blast furnace feedstock recycling, because chlorine in plastic waste is considered to be decomposed into hydrogen chloride and to lead to the corrosion of facilities (56, 57). On the other hand, PS shows higher coke and oil yields (85%) than other resin types (42%, 60%, and 33% for PE, PP, and PET, respectively) in coke oven feedstock recycling (56, 58). In this context, plastic container and packaging inflow into manufacturing products and machinery sectors (0.77 Mt in total) with a higher proportion of polyolefin (*SI Appendix*, Fig. S9) should be collected to preferentially fill the capacity of flotation-based mechanical recycling; container and packaging waste discharged from households and other services sectors (2.08 Mt in total) that contains a relatively high percentage of PS can be efficiently recycled in coke ovens. Thus, through the quality and quantity matching between waste sources and recycling technologies as well as strategic expansion of recycling capacities, appropriate allocation of roles of recycling technologies can be explored beyond the recognition that feedstock recycling is a complement to mechanical recycling (59).

Finally, we discuss which types of plastic containers and packaging should be collected from what sources to achieve the 60% reuse or recycling goal. However, in an interview survey conducted by J.N. with manufacturers of containers and packaging (*SI Appendix*, Table S5), there were many negative opinions from the viewpoint of food hygiene on the reuse of containers and packaging for food. Therefore, we consider achieving the target of 60% through recycling alone as follows. Since neither the definition nor the present value are given in the Japanese strategy for plastics (35), we calculated the recycling rates consistently with the definition used in Europe (36), which is based on the input to recycling facilities after sorting. Here, among the packaging waste collected and sorted for recycling, the net amount of plastics is used as the numerator (*Materials and Methods, Definition and Data Collection for Calculating Recycling Rates*). Below, we set the separate collection of the net amount of ~2.4 Mt of plastics as a specific target; this target represents 60% of the 4.1 Mt inflow to domestic demand sectors in 2015 (Fig. 2).

The collection percentage of PET bottles, which are already widely collected and recycled, has been ~90% in recent years (60), and we assume that a 95% (0.56 Mt) separate collection percentage can be achieved with the combination of households and industries. For container and packaging waste other than PET bottles generated from households (1.13 Mt), municipalities covering 75% of the population carried out separate collection in 2015 (61), collecting 59% of the total generated amount of this waste. From this, we expect a collection rate of 80% (0.91 Mt) if all municipalities carry out separate collections. Consequently, the separate collection of 0.9 to 1.0 Mt (equivalent to the recycling rate of ~40%) will be required for containers and packaging (other than PET bottles) generated by industries. In other words, sectoral goals differentiated between households and industries for achieving the recycling target could be based on these values.

The industry sectors that have a large inflow of containers and packaging include the eating and drinking services sector and the beverages and foods sector. Since these food-processing and food service sectors are subject to Japan's Food Recycling Law, they are more likely to carry out separate collection for recycling than other sectors. The amounts of plastic containers and packaging inflowing into these sectors were 0.26 and 0.23 Mt, respectively. Additionally, the inflow into the plastic and rubber products sector was 0.23 Mt. Another sector with high potential for collection is the medical institutions sector, which disposes of medicament containers and packaging. However, because some of these materials may fall within the category of infectious waste, it is difficult to regard them as contributors to the target. Therefore, there is a target shortfall of ~0.4 Mt when relying only on the collection of plastics from specific industry sectors that generate a large amount of waste plastics, even if the separate collection percentage is assumed to be 80%, which is the same as the households collection percentage.

Some LDPE flexible films used for packaging for transportation between industries are collected for recycling according to an interview survey with a Japanese trading company handling waste plastics (*SI Appendix*, Table S5). According to the estimations in this study, the total amount of LDPE flexible films (excluding printed packaging) used between industry sectors was 0.4 Mt, even outside the above-described specific sectors with a high generation of packaging waste. The collection of these flexible films would put the recycling target within reach. Flexible films tend to increase in volume with weight, causing a bottleneck in the efficiency of collection and transportation. Therefore, compression at the source of discharge is a key to improving the collection rate. It is essential to have a strategy for collecting plastic containers and packaging that involves all industry sectors, and includes the cross-sectoral collection of specific items.

As discussed above, it would be numerically possible for industries to reach their recycling goals proposed above if all feasible measures were exploited. The problem lies in the legal system's inability to motivate industries to increase the recycling rate of containers and packaging used in industry sectors. Since waste generator responsibilities have been emphasized for industrial waste management in Japan, the Containers and Packaging Recycling Law of Japan, which relies on the EPR of producers and users of containers and packaging, is aimed only at household waste. This is considered to cause a large gap in the recycling rates of plastic containers and packaging between households and industries, which is supported by the sharp increase in the recycling rate for households since 2000, when the recycling law was completely enforced (*SI Appendix*, Table S5). To boost the collection for recycling from industry sectors and thereby achieve the recycling target for keeps, the focus of the recycling law must be extended to include container and

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packaging waste discarded from business establishments and factories.

Graedel (62) argued that the role of MFA practitioners is "to generate, interpret, and communicate potentially relevant information" for particular policies and, furthermore, "to reach out more vigorously to the policy community in order to demonstrate the value of MFA information for policy purposes." We presented the tangible paths to achieving reduction and recycling goals, as well as policy recommendations for the realization of these paths, based on the detailed MFA results. Based on this quantitative foundation, the Japanese government has the opportunity to take the initiative in science-based policy implementation to solve the problems associated with single-use plastics.

Materials and Methods

Challenges in MFA Using Input–Output Tables. It was necessary to overcome the following two challenges in IO-MFA to achieve the analysis in this paper. First, the synthetic resins sector and the plastic products sector had to be subdivided in order to specify the flow of plastics as containers and packaging. Input–output tables are published in various countries around the world, and the framework for a basic IO-MFA can be applied universally. However, the analysis accuracy greatly depends on the sectoring of the input–output tables. Even with Japan's input–output tables, which have a degree of precision of ∼400 sectors, it is difficult to identify the flows of containers and packaging because of the rough sectoring of plastic processing. Elsewhere, industrial associations for plastic materials and products voluntarily release statistical data on the amount of production and sales in Japan. Although these data often cover limited resin types, processed forms, and products and tend to be fragmentary, their accuracy is better than that of the input–output tables. Therefore, this paper aims to identify the flow of containers and packaging among all plastics according to resin types, processed forms, products using containers and packaging, and product demand sectors using a hybrid analysis. In this analysis, the input–output tables are complemented by statistical data from industrial associations.

Second, the intersectoral transfer of containers and packaging by accompanying products had to be modeled. After containers and packaging are used in the transportation and sale of products, inflowing to the demanders with the products they contain, they are usually immediately discarded by the demanders. In the context of input–output analysis, containers and packaging are input to the production sector of their products, but when they are collected for recycling or as waste, the sector that demands the products becomes a source of container and packaging waste. In the MFA based on the waste input–output (WIO-MFA) model (63–67), the physical input to the sector where physical products are output is either included in the product as raw material or instead regarded as discarded as a nonproduct component. However, the actual material flow of containers and packaging does not necessarily fall under either category. Furthermore, there are industries, such as commerce (wholesale and retail) and laundry, that use containers and packaging to provide services among sectors that do not output physical products. These containers and packaging are also ignored in the WIO-MFA model. Other previous studies that did not use input–output tables (*SI Appendix*, Table S1) assume containers and packaging directly inflow to the final demand sector and become waste in the same way as other final products, without considering what products the containers and packaging contained.

A study conducted about 20 y ago presented a material flow model that distinguishes packaging from other products. Joosten et al. (46) estimated the material flow of plastics in the Netherlands in 1990, using the STREAMS model with a supply and use table. In this model, plastics are classified into final products, components, and packaging. The packaging flow into each industry is allocated to the products supplied by that industry. Thus, the final consumption of packaging is estimated for each demand sector and product type. However, the amount of plastics used in products and packaging is given independently of the amount of resin production, and the resin is not classified into different types. Furthermore, in the case of a MFA in the United States in 1987 (48), which used input–output tables, the use of plastic packaging was estimated by dividing the packaging into a direct use category for products and services for end users and an indirect use category at each stage of production. Although these models contain important ideas for the material flow of containers and packaging, no studies in which they are applied to plastics have since been confirmed. The authors of this paper built a model for MFA that distinguishes appendages to products such as containers and packaging by applying the above ideas to the WIO-MFA

model (68). This study further developed the MFA model by extending the analysis method for containers and packaging of this model.

Using the model constructed in this study, we can obtain analysis results with the following four dimensions regarding the plastic material flow associated with domestic demands and exports: resins p, classification of usage h (containers and packaging: 1; products: 0), products j, and demand sectors k. Plastic containers and packaging are identified by assuming that specific processed forms of plastics are used for packing products. Of the input to industry (endogenous) sectors, which are regarded as the intermediate demand in normal input–output analysis, products that are not used as raw materials are considered to accumulate in these sectors in this model. The products include final products composed of plastics output to the above demand sectors, as well as products and services that do not contain plastics but are packed in plastic containers and packaging. In many cases, the containers and packaging used to provide products are single-use and are immediately discarded after use, and the yearly amount of inflow to demand sectors can be considered equal to the yearly amount generated by the sectors.

Data Collection and Processing of Input–Output Tables. Japan's input–output tables for 2000/2005/2011/2015 (49), the government's official production statistics (69, 70), and the production and shipment statistics voluntarily collected by the plastic and packaging industries (71–75) were used for the classification of synthetic resin and plastic product sectors (*SI Appendix*, Tables S2 and S3). The trade statistics (76) also provided the export/import amount. According to the basic classification (the column sectors) in the 2011 input–output tables, the endogenous sectors in the input–output tables for each year were unified to 420 common sectors. Of these, resins p were produced from 10 sectors. Six processed forms output from the 13 sectors that process plastics were regarded as containers and packaging ($h = 1$). The products j were the output of the 420 sectors described above, 139 of which manufacturing products composed of plastics. The demand sectors k consisted of 436 sectors: the 420 endogenous sectors and 16 final demand sectors, including 11 consumption expenditure sectors, 2 fixed capital formation sectors, and 3 exports sectors.

Data Analysis for the Nationwide Material Flow of Plastics. As with WIO-MFA, the material flow model in this study used the material composition of products per unit production cost (million JPY)—that is, the amount of plastics C ($p \times j$ matrix) in products j (including containers and packaging) for each type of resin p expressed by Eq. 1. The calculation used the input coefficient matrix A ($i \times j$) between endogenous sectors based on the transaction table and physical coefficient matrix P ($p \times j$), which described the output of synthetic resins (per million JPY) to the endogenous sectors based on the physical table attached to the input–output tables. Additionally, the calculation used a material filter matrix Φ ($i \times j$) that identified the raw materials of the output products among input i to each endogenous sector j through the adoption of the material filter matrix of WIO-MFA (65). The calculation also used the plastic filter matrix Θ ($p \times j$) to separate the input of synthetic resins to the sectors outputting nonplastic products, and the yield ratio matrix Γ ($i \times j$) showed the percentage of the raw material input converted into products. The superscript P indicated a $p \times j$ matrix that extracted only the matrix related to the output of the synthetic resins from each matrix. I was the identity matrix, and $\odot$ was the Hadamard product:

$$C = (\Gamma^P \odot \Phi^P \odot \Theta \odot P) \cdot (I - \Gamma \odot \Phi \odot A)^{-1}. \quad [1]$$

In the original WIO-MFA model (67), the element of Φ was set to 1 when output j was physical and input i physically entered sector j, and $\bar{A} = \Gamma \odot \Phi \odot A$ was partitioned according to the degree of fabrication among resources, materials, and products. Here, materials were assumed to be made of resources, and products were assumed to be made of products and materials [a more recent study (77) only partitioned material and products]. However, if this definition of Φ is straightforwardly applied, packaging and consumer goods utilized for production activities cannot be distinguished from the raw material input. For example, synthetic resins are falsely regarded as a component of food products through plastic packaging input in the food supply chain. To avoid such cases, in the model of this study, the elements of material filter matrix Φ (1: the input is the raw materials of products; 0: the input is not the raw materials of products) were set according to the relationship of raw materials and products between sectors, which was examined for each combination (*SI Appendix*, Fig. S2). As products in the downstream of materials (synthetic resins) are neither directly nor indirectly input to the materials in this relationship, the essential point of the hierarchical structure of $\bar{A}$ in the WIO-MFA model is also satisfied.

Here, the physical coefficients of ABS and PET (the resin type abbreviations are described in *SI Appendix, Abbreviations*), which were included in the PS and high-function resins sectors in the original input–output tables, respectively, were supplemented by referring to the ABS and PET shipment statistics voluntarily collected by each industrial association (72, 75). Additionally, because plasticizers are generally added to flexible PVC, the amount of plasticizers was added to the output of products made of PVC in the physical coefficient matrix for the sectors with inputs of both PVC and plasticizers in the transaction table (*SI Appendix*, Table S2).

In this model, the material flow of plastics is calculated using the following six patterns: 1 and 2 are the material flow of plastics that become the components of products, and 3 to 6 are the material flow of plastic containers and packaging (*SI Appendix*, Fig. S1): 1) products (including imported products) that flow into final demand sectors (including exports): Q^{DF}; 2) products (including imported products) that flow into endogenous sectors and are not used as raw materials or containers and packaging for the output of those sectors: Q^{DJ}; 3) containers and packaging that flow into the final demand sectors (including exports) without being attached to products or services: Q^{HF}; 4) containers and packaging that flow into endogenous sectors and do not accompany the output from the sectors: Q^{HJ}; 5) containers and packaging that flow into demand sectors (including final demand sectors and endogenous sectors) by accompanying domestic products, raw materials, or services: Q^{HD}; and 6) containers and packaging that flow into demand sectors (including final demand sectors and endogenous sectors) by accompanying imported products, raw materials, or services: Q^{HM}.

Of these, products/containers and packaging of 1 to 4 are used and disposed in the sectors they flowed into. The products of 1 apply to the consumer goods used in each final demand sector (for example, household articles such as tableware and kitchenware, and plastic parts of durables such as machinery and personal computers used in households). The products of 2 apply to the consumer goods used in each endogenous sector (for example, plastic parts of durables such as machinery and personal computers used in factories and offices). The containers and packaging of 3 and 4 are demanded for consumption activities in final demand sectors and for production activities in endogenous sectors but not for the sale of products. For example, garbage bags and containers for storing products fall under these categories. The containers and packaging of 5 and 6 are disposed in the sectors that demanded the products or raw materials packed in them. In the example of food supply chains, plastic packaging of food products purchased by households (such as meats, vegetables, and a variety of processed foods) is categorized into 5, while food packaging falls under the category 6 when it is used for distribution between the food-processing and food service sectors.

These material flows are calculated by Eqs. 2–7, in order. Here, the following various types of filter matrices, in addition to C and A, are used: the container and packaging filter vector Ψ ($j \times 1$), which identifies the sectors that process plastics into containers and packaging among endogenous sectors j; the accumulation vector R ($j \times 1$), which identifies sectors that do not output products accompanied by containers and packaging (that is, sectors that use and dispose of containers and packaging in their own sectors); the transfer matrix G ($j \times k$), which represents the output ratio of products j packed in containers and packaging by demand sectors k; and the commercial vector E ($j \times 1$), which represents the ratios of products j that are sold without being discarded in commercial sectors. $\overline{\Phi}$ is a matrix, in which 1 and 0 of each element of the material filter matrix are reversed. Q^{DF} and Q^{HF} are calculated from the final demand matrix F ($j \times f$) obtained by extracting the final demand sectors from the transaction table. In addition, Q^{DJ}, Q^{HJ}, and Q^{HD} are calculated from domestic production X ($j \times 1$ vector) described in the transaction table and Q^{HM} is calculated from the import amount Y ($j \times 1$ vector):

$$Q^{DF} = C \cdot (I - \text{diag}(\Psi)) \cdot \text{diag}(E) \cdot F, \qquad [2]$$

$$Q^{DJ} = C \cdot (I - \text{diag}(\Psi)) \cdot (\overline{\Phi} \odot A) \cdot \text{diag}(E \odot X), \qquad [3]$$

$$Q^{HF} = C \cdot \text{diag}(\Psi) \cdot \text{diag}(E) \cdot F, \qquad [4]$$

$$Q^{HJ} = C \cdot \text{diag}(\Psi) \cdot (\overline{\Phi} \odot A) \cdot \text{diag}(R \odot E \odot X), \qquad [5]$$

$$Q^{HD} = C \cdot \text{diag}(\Psi) \cdot (\Gamma \odot \overline{\Phi} \odot A) \cdot (I - \text{diag}(R)) \cdot \text{diag}(E \odot X) \cdot G, \qquad [6]$$

$$Q^{HM} = C \cdot \text{diag}(\Psi) \cdot (\Gamma \odot \overline{\Phi} \odot A) \cdot (I - \text{diag}(R)) \cdot \text{diag}(E \odot Y) \cdot G. \qquad [7]$$

The element of the plastic filter matrix Θ was set to 0 (1: otherwise) for the output from the synthetic resin sectors to the final chemical product sectors

including chemical fibers, paints, and adhesives. Based on the inventory data on plastic processing (78), the elements of the yield ratio matrix Γ were determined to be 0.97 regarding combinations between raw materials and products with an Φ element of 1. For elements of the accumulation vector R, construction, infrastructure, and service industries (excluding certain sectors, such as commerce, goods rental and leasing services, eating and drinking services, and laundry) were set as 1, and the other sectors were set as 0. Additionally, the output ratio of products j by the endogenous and final demand sectors calculated from the transaction table was used as an element of transfer matrix G. The elements of commercial vector E were set based on the rate of commercial food waste for the product output from the sectors of the farming and fishing industries, as well as beverages and foods, and the element of all of the other sectors was set as 1. The food waste rate was determined to be 0.02 by dividing the sum of the food waste in wholesale and retail in 2011 (0.2 Mt and 1.3 Mt, respectively) (79) with the value obtained by subtracting the amount of food waste (16.6 Mt) (79) from the amount of food supplies for domestic consumption (84.6 Mt) (80). That is, the element E for these sectors was 0.98.

We also considered the losses domestically generated at each stage from the production of synthetic resins to the inflow of products and containers to the demand sectors. Production losses Q^{LD} that occurred between the production of synthetic resins and the manufacture of products/containers and packaging, package losses Q^{LH} that occurred when containers and packaging were used for packing products, and commercial losses Q^{LE} of containers and packaging that occurred in association with the disposal of products in commercial sectors were obtained by Eqs. 8, 9, and 10, respectively. More specifically, the trim scrap of packaging falls under Q^{LH}, and food packaging that is discarded along with expired food products applies to Q^{LE}. Note that $\overline{\Gamma}$ represents a matrix obtained by subtracting each element of the yield ratio matrix from 1:

$$Q^{LD} = \left(\overline{\Gamma}^P \odot \Phi^P \odot \Theta \odot P + C \cdot (\overline{\Gamma} \odot \Phi \odot A)\right) \cdot X, \qquad [8]$$

$$Q^{LH} = C \cdot \text{diag}(\Psi) \cdot (\overline{\Gamma} \odot \overline{\Phi} \odot A) \cdot (I - \text{diag}(R)) \cdot X, \qquad [9]$$

$$Q^{LE} = C \cdot \text{diag}(\Psi) \cdot (\Gamma \odot \overline{\Phi} \odot A) \cdot (I - \text{diag}(R)) \cdot (I - \text{diag}(E)) \cdot (X + Y). \qquad [10]$$

In principle, the addition of synthetic resin exports to the total material flows in Eqs. 2–7 and the losses in Eqs. 8–10, 15.5 Mt for 2015 (Fig. 1) is equal to the value obtained by subtracting the output of synthetic resins to nonplastic products from the total of domestic production and imports of synthetic resins (including the amount of plasticizers added to products made of PVC) and imports of resin components of products, containers, and packaging. However, it does not apply when the output value in each sector and the total demand of its products do not match in the original input–output tables (in Japan's input–output tables, the difference is considered to represent the increase in stocks and balancing sectors).

Sector Aggregation for Tabulating and Visualizing the Results. Finally, when the above estimation results for $10 \times 13 \times 420 \times 436$ sectors were tabulated, resins were integrated into 7 types (thermoset, ABS, and high-function resins were integrated with other resins), endogenous sectors were integrated into 108 sectors, and the final demand sectors were integrated into 4 consumption expenditure sectors and an export sector according to the aggregated sector classification of the 2011 input–output tables (see Dataset S1 for the sector classification). In this process, the inflow into gross domestic fixed capital formation in the final demand sectors (calculated as elements of Q^{DF}) was distributed among 108 endogenous sectors (added to elements of Q^{DJ}) using the capital formation matrix attached to the input–output tables. When the results of the analysis were visualized, the endogenous and final demand sectors were integrated into 37 sectors and 4 sectors, and were further aggregated into 7 categories and 3 categories, respectively. In this ultimate aggregation process, the inflow into individual consumption expenditure of general government, which refers to government expenditures on providing households with goods and services such as education and medical services, was distributed to households. On the other hand, collective consumption expenditure of general government, which includes diplomacy and defense expenditures, consisted of other final demands along with consumption expenditure outside households. However, according to the estimations in this study, the amount of plastic container and packaging inflow into collective consumption expenditure was zero, and consequently the inflow into consumption expenditure of general government was fully contained in the inflow into households.

Definition and Data Collection for Calculating Recycling Rates. The recycling rate was calculated for used containers and packaging using the amount of inflow into households and industries excluding the direct demand (the sum of all elements of Q^{HD} and Q^{HM} in *SI Appendix*, Fig. S1) as the denominator. Here, since containers and packaging are usually single-use and are immediately discarded after use, the yearly amount of inflow is considered equal to the yearly amount of end-of-life (EoL) containers and packaging. Moreover, the recycling rate in a broader sense can be differently defined depending on the choice of the numerator. For metal recycling, the collection rate based on the amount of EoL metal collected for recycling is clearly distinguished from the EoL recycling rate based on the amount of recycled metal (81). On the other hand, the definition for the recycling rate of packaging waste used in Europe (36) is based on the input to recycling facilities after sorting, which becomes an intermediate value between the collected amount and the amount of recycled resin. According to this definition, the amount of container and packaging waste collected and sorted for recycling is defined as the numerator of the recycling rate in this study. Energy recovery, which accounted for more than half (57% in 2015) of the treatment and disposal of the total plastic waste in Japan (82), was excluded from calculation of the recycling rate.

The amount of recycling confirmed by the government's official statistics and the statistics voluntarily gathered by industrial associations was used as the numerator. Since data on quantities delivered to recycling facilities after being sorted by municipalities or waste collectors were collected, the calculated recycling rates were consistent with the above definition. The amount of recycling in terms of households refers to the total amount of plastic containers and packaging excluding PET bottles collected and sorted

according to the Containers and Packaging Recycling Law (including mechanical and feedstock recycling) (83), the amount of PET bottles collected from households (53), and the amount of food trays made of polystyrene paper (PSP) collected at stores (84). For industries, the sum of the amounts of PET bottles (53) and Styrofoam (85) collected and sorted for recycling was considered as a minimum estimate of the amount of recycling, as these were only items with known collection data in terms of containers and packaging. Moreover, it was reported that a part of industrial plastic waste (0.09 Mt in 2015) (82) was treated by feedstock recycling (i.e., gasification and coke oven and blast furnace feedstock recycling), whereas the proportion of containers and packaging to this amount was unknown. Therefore, a maximum estimate of the recycling rate for industrial container and packaging waste was calculated by assuming that the industrial plastic waste input to feedstock recycling was composed of only containers and packaging.

Data Availability. See Dataset S1 for the usage of the plastic containers and packaging used in association with sales and the purchase of products in each sector. The data supporting the findings of this study, including the coefficient and filter matrices and analysis results for the intersectoral flow of plastic containers and packaging, are available in the Open Science Framework public repository (86).

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