An Estimation of Actual Recycling and Final Disposal Rates of Municipal Solid Waste by Material Flow Analysis in Korea

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Abstract

The recycling, incineration, and final disposal rate of municipal solid waste (MSW) are calculated based on the total amount of waste input to each facility in many countries. These statistic data have serious limitation in setting the national goal and policy for effective waste management because it is not considering the amount of foreign objectives in the process of each life-cycle stage. This case study is to estimate the actual rates of recycling, incineration, and final disposal by material flow analysis (MFA) after the collection of MSW in Korea. The actual rates of recycling, incineration and final disposal for MSW in 2016 were 49.9%, 32.9% and 23.1% respectively, indicating that the recycling rate was lower by 10.1%, while the incineration and final disposal rates were raised by 7.6% and 8.4% respectively, compared with the statistics for current MSW. In addition, the changed actual rates of recycling, incineration treatment, and final landfill, and variation of waste treatment charge according to treated amounts per treatment method was analyzed. This results of this study will contribute to establish national level of plan on effective waste management.

Keywords: actual recycling rate; material flow analysis; municipal solid waste; waste treatment charge

1. Introduction

In South Korea, the Framework Act on Resource Circulation has been enforced since January, 2018. According to the article 11 and article 12 of this Act, the minister of Ministry of Environment should establish in every 10 years for the enforcement the Master Plan for Resource Circulation presenting mid to long-term policy goals such as the efficient use of resources, the prevention of waste generation, and the promotion of use of recycled resources, etc. Mayors of Seoul, metropolitan city, special self-governing city, and governors of provinces should establish the yearly enforcement of the Master Plans including the investment plans to convert the area under jurisdiction to the resource circulation community; and obtain an approval from the minister of Ministry of Environment. Also, a mayor, a county governor, and a district head should establish the yearly execution plans of the enforcement plans for city and province by considering the circumstances of the areas under jurisdiction and submit them to mayor and province governor. Based on the article 14 of this Act, the minister of Ministry of Environment should set mid to long-term target values per stage for final disposal rate, circulated use (actual recycling) rate, and energy recovery rate, and promote measures for their accomplishment.

However, according to the current statistics of South Korea for MSW [1], recycling rate, incineration rate, and final disposal rate are calculated as the ratio of the input amount to sorting facilities (material recycling facility, MRF) for separate discharge as recyclable items, incineration facilities, and landfill sites, to the total collected amount of MSW. Namely, since only the input amounts to the facilities after collection are considered without considering the input and output

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amounts of foreign objects (referring to the sorting residual waste generated from the process of screening and recycling), those rates cannot be utilized directly for setting the above targets.

To establish the installation and operation plan for MSW treatment facilities, the input amounts of wastes into the treatment facility should be known based on the material flow. In this study, actual recycling rate, incineration rate, and final disposal rate were calculated through the MFA that considered the generation and treatment of foreign objects and incineration residue from the generation to the final disposal of wastes. And when treatment methods of MSW through direct landfill were changed, changes in actual recycling rate and final disposal rate were analyzed and evaluated as well as variations of the waste disposal charge which was started in January 1, 2018 by Framework Act on resource circulation. The results of this study will be used as valuable information for the establishment by the Ministry of Environment and local governments of the basic plans for resource circulation as well as corresponding enforcement and execution plans, and for the preparation of improvement plans for waste statistics, etc.

2. Methodology

The cases of MFA on MSW in Japan and Germany were surveyed for reference. To analyze the material flow according to actual situations from collection to intermediate treatment and final disposal of MSW, the MSW was classified according to the classification of wastes separately collected to calculate the material balance.

Generated amounts of MSW and treated amounts per treatment method have been used as basic data from ‘Nationwide Status of Waste Generation and Treatment in 2016’ [1] as the latest MSW statistics at the current point. Distribution coefficients to calculate the input amounts to the sorting facility for recycled items, the manufacturing facility for Solid Refuse Fuel (SRF) and the

treatment facility for food wastes, along with the generated amounts of foreign objects and incinerated materials as well as foreign objects treatment methods were determined when the personnel in charge of waste tasks in National Institute of Environmental Research, Korea Environment Corporation, Korea Resource Circulation Service Agency gathered, discussed several times and listened to an opinion on the results of the responsible person in the related department of the Ministry of Environment, based on 2016 evaluation data of Korea Environment Corporation on local governments' operation status for waste treatment facility, inside data of the Ministry of Environment and the Korea Environment Corporation, survey data of the Korea Resource Circulation Service Agency, and statistics of Statistics Korea, etc.

3. Study results and Discussion

3.1. Cases of MFA for MSW

3.1.1. MFA for MSW in Japan

Material flow of waste discharge and treatment in 2016 for MSW in Japan (corresponding to MSW in Korea and MSW at business sites) is as shown in Appendix A (Fig. A1). Waste recycling amount of Japan is 6.52 million tonnes based on the sum of 1.96 million tonnes for direct recycling amount collected by local governments immediately followed by direct supply to recycling businesses and 4.56 million tonnes for the amount sorted and recovered by intermediate treatment facilities such as sorting facility for recycled items, crushing/sorting facilities, etc. for large size wastes, corresponding to 15.9% of total waste treatment amount. In addition, the amount of waste paper, steel scrap, etc. jointly collected by residents for direct sales to recycling businesses is 0.227 million tonnes. Total recycled amount based on the sum of all of these is 8.79 million tonnes, corresponding to 20.4% compared with total discharged amount, or 21.4% compared with total

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93 treated amount.

94

95 *3.1.2. MFA for MSW in Germany*

96 As shown in Appendix A (Fig. A2), the input amount by treatment facilities in Germany in 2015
97 was 5.104 million tonnes among the collected amount of urban wastes (corresponding to MSW in
98 Korea and MSW at business sites) of 51.625 million tonnes, while the input amounts by material
99 recycling facilities and energy recovery facilities were 34.453 million tonnes (66.7%) and 12.068
100 million tonnes (23.4%) respectively. According to the Appendix A (Fig. A3), the recycled wastes
101 collected for material recycling are input to sorting facilities, 27% of which is removed first as
102 foreign objects, and 4% of which is removed again as foreign objects in additional sorting process
103 to meet the conditions for subsequent input to final recycling facilities. Consequently, the amount
104 used as a raw material in the final manufacturing facilities for a recycling product is 36% of urban
105 waste generation.

106

107 *3.2. MFA for MSW in Korea*

108 *3.2.1. Data used for MFA of MSW*

109 As it can be seen in the cases of Japan and Germany mentioned in Section 1, the two countries
110 are assessing the recycling rate of MSW by the amount provided to recycling businesses as the
111 reference after the removal of foreign objects at sorting facilities rather than assessing the input
112 amount by sorting facilities or recycling facilities.

113 In the statistical data of MSW in Korea, wastes generated in households are classified as MSW,
114 and the wastes with the same appearance as that of MSW among wastes generated at business sites
115 are classified as MSW at business site. Both types are being called MSW. In this thesis, however,

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wastes for daily life will be called MSW by using a conventional terminology. Therefore, the MSW in this thesis hereafter would mean the sum of MSW generated in households and MSW at business sites. While 'Nationwide Status of Waste Generation and Treatment in 2016' is prepared based on the daily waste generation, the value converted to annual generation by multiplying the daily generation by 365 was used to analyze the material flow based on annual generation. As a reference, the sum of the amounts of MSW collected and input to treatment facilities is assumed to be the MSW generation in the current waste statistics. Since the area of MSW management zone in Korea is 98,317.04 km^2 and the population residing in this zone is 53,112,059 people corresponding to 99.9% of the population in South Korea [2], the difference between generated amount and collected amount of MSW is insignificant so that the above assumption does not produce any problem. Also, this statistics classifies the generated amount and the treated amount of MSW into 3 types for preparation, including mixed discharge according to the volume-rate waste disposal system: discharge by designated plastic bag, separated discharge of recyclable resources, and separated discharge of food wastes. Therefore, this study also followed the above classification method. However, waste types were abbreviated as wastes in designated plastic bag, recyclable resources, and food wastes. Status of generation and treatment of MSW in Korea is as shown in Appendix B.

Korean government has never analyzed and disclosed material flow for the generation and treatment of MSW, and is lack of base data that can utilize material balance per treatment process of the same wastes. Thus, while disclosed data was used first when material balance of the treatment process was calculated, the internal data of related institutions was used such as Ministry of Environment, Korea Environment Corporation, Korea Resource Circulation Service Agency, etc. when no disclosed data was available. Setting grounds for data and distribution coefficients,

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etc. used for MFA are as follows.

1) For MSW generation, generation per waste type, and input amount per type of waste treatment facility, the statistical data of 'Nationwide Status of Waste Generation and Treatment in 2016' [1] was used.

2) Recyclable resources generated at apartments are separately discharged per item, and treated mostly in consignment as residents sign a sales contract with private recycling businesses. Recyclable resources produced in single-unit housing (referring to housings including studio other than apartment) tend to be discharged all at once rather than being discharged separately. They are collected by local governments, sorted per item by public sorting facilities and supplied to private recycling businesses. For the recyclable resources generated in apartments, separated discharge bins per recycling item are installed and managed by apartment security personnel for paid sales so that mingling rates of foreign objects are lower than the discharge from single-unit housings. Therefore, material flow was analyzed by classifying discharged amounts of recyclable resources generated in apartments and single-unit housings. With an assumption that the amounts of recyclable resources generated in apartments and single-unit housings were proportional to the residing population, they were distributed to be 53.06% and 46.94% respectively, according to the ratio of the number of residents by using 'statistical data for household members per type of residence in 2016 [3] housing census by the Statistics Korea.

3) Ratios for the sorted items generated in apartments and recovered by sorting facilities for recyclable resources and the removed foreign objects were selected to be 83.6% and 16.4% respectively, by referring to the input amounts of recyclable resources by recycling businesses where glass bottles, metals, synthetic resins are input per separate item (including reuse items) for sorting among the internal data of Korea Resource Circulation Service Agency [4]. Ratios for the sorted items generated in

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single-unit housings and recovered from the sorting facilities for recyclable resources and the removed foreign objects were set to be 63.4% and 36.6% respectively, based on the generation rate of foreign objects by recyclable resources sorting facilities (MRF) in 2016 operation status data for public MSW treatment facilities [5].

4) According to the statistical data on solid fuel of the Korea Environment Corporation [6], the amount of waste synthetic resin targeting the expanded producer responsibility system (EPR) was 0.296 million tonnes which was used as raw material for SRF manufacturing in 2016. Hence, this amount was considered as the input amount of waste plastic film by SRF manufacturing facilities after sorting from recyclable resources. And, the amount of sorted waste plastic film per housing type was calculated by dividing this amount by the ratio for the total amount of sorted items of recyclable resources from apartments and single-unit housings. In this statistics, based on the fact that 0.296 million tonnes of waste synthetic resin was input to the SRF manufacturing facilities, the SRF production yield of the same waste plastic film and the generation rate of foreign objects was set to be 95.6% and 4.4% respectively.

5) The amount of sorted items for the material recycling of recyclable resources was determined to be the value where the amount of waste plastic film for the EPR above was subtracted from the amount of sorted items from apartments and single-unit housings.

6) Generation rate of the incineration residue to the input amount of MSW to incineration facilities was set to be 19.0% as the generation rate of incineration residue from stoker-type MSW incinerators according to 2016 operation status for public MSW incineration facilities [5]. As a reference, 109 plants among 166 plants of MSW incineration facility as of the end of 2016 are stoker type, and the amount of treatment by this type of incineration facilities was 90% of total incinerated MSW (4.751 million tonnes) in 2016.

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7) For the recycled amount per recycling method of separately collected food wastes, the internal data of the Ministry of Environment [7] was used. According to the same data, the daily recycled amount in 2016 was 13,465 tonnes/day including small-scale restaurants and mass-discharging businesses, where the daily input amounts per recycling method were 6,141 tonnes (45.6%) for feed conversion, 4,139 tonnes (30.7%) for compost conversion, 1,381 tonnes (10.3%) for biogas conversion, and 1,804 tonnes (13.4%) for other recycling. Meanwhile, according to 'Nationwide Status of Waste Generation and Treatment in 2016', daily generation of food wastes was 14,388.7 tonnes, recycling 13,936.3 tonnes, incineration 316.9 tonnes, and landfill 135.5 tonnes, where this recycled amount was more than the recycled amount in the internal data of the Ministry of Environment by 471 tonnes. Therefore, the input amount for treatment facilities per recycling method was determined by multiplying the recycled amount of food wastes in 'Nationwide Status of Waste Generation and Treatment in 2016' by the composition ratio per recycling method in the internal data of the Ministry of Environment. This is because the above waste statistics only contain data on the total recycled amount of food waste, and there is no data on recycled amounts classified by recycling methods. The values of the above statistics were used directly for the amounts of incineration treatment and landfill of food wastes.

8) According to the internal data of the Environment Corporation [8], 0.556 million tonnes of wastes in designated plastic bag among MSW in 2016 were input to solid fuel manufacturing facilities to produce 0.305 million tonnes of SRF. Therefore, the production yield was 54.9%. Meanwhile, according to the evaluation results by the Environment Corporation of 2016 operation records for 12 facilities of solid fuel manufacturing facilities in local governments [5], production yield for SRF was 47.8%, generation rate of foreign objects 35.4%, and process loss rate 16.8%. Such differences are considered to have occurred because the manufacturing facilities for solid fuel with a small

number of operating days were excluded from the evaluation facility. The reason is that Daegu and Daejeon metropolitan cities have a large scale manufacturing facilities for solid fuel with the production of fluff SRF so that the production yields are high. Thus, the values of data from the Ministry of Environment were used directly for the input amount of wastes to SRF manufacturing facilities and the production amount of SRF in 2016. The amount (251 tonnes) subtracted the manufactured amount of SRF from the input amount was considered as foreign objects and a process loss, and these ratios were determined to be 68 : 32 by assuming 35.4% : 16.8% as in the evaluation data for operation records of Korea Environment Corporation. Meanwhile, material balances, when solid fuel was produced from directly land-filled wastes in designated plastic bag, were determined to be 54.9% for the production yield, 30.7% for the generation rate of foreign objects, and 14.4% for the process loss rate by referring to the two data above.

9) Production yield and generation rate of foreign objects per recycling method of food wastes are from 2016 data for operation status of public MSW treatment facilities. The ratios for the produced amount of recycling product per recycling method and the generation amount of foreign objects in treatment facilities for food wastes (79 facilities) were set to be 14.0% and 4.4% for feed conversion, 13.5% and 7.9% for compost conversion, 7.1% and 16.7% for bio gas conversion, 32.1% and 5.6% for other cycling respectively. Production yield for bio gas conversion was set as the ratio of weight calculated by multiplying the produced volume of biogas by the density of methane gas to the input amount assuming that total amount of bio gas was methane gas. Generation rate of foreign objects was set as the ratio of the sum of the amount of foreign objects removed from pre-treatment facility of anaerobic digestion facilities and the amount of solid residues produced after anaerobic digestion to the input amount of food waste.

10) The ratios per treatment method of foreign objects generated by sorting facilities for

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231 recyclable resources were determined to be 83% for incineration treatment and 17% for landfill
232 treatment according to the ratio of the sum of the amount of incineration and the amount of landfill
233 by the public sorting facilities for recyclable resources (175 facilities) in 2016 data on operation
234 status of public MSW treatment facilities. Although these values are ratios for the treatment
235 method of foreign objects in sorting facilities operated by local governments, these ratios were
236 also applied to the treatment of foreign objects generated in sorting of recyclable resources
237 collected from apartments since there was no data available on the treatment methods of foreign
238 objects by sorting facilities of private recycling businesses.

239 11) Currently, since foreign objects of manufacturing facilities for SRF are landfilled and foreign
240 objects of recycling facilities for food wastes are incinerated, these treatment methods were applied
241 directly for foreign objects in the same facilities.

242

243 *3.2.2. Results of MFA for MSW*

244 Currently, basic local governments of Korea classify MSW into recyclable resources, designated
245 plastic bag wastes, and food wastes for collection and treatment. Therefore, material flow diagram
246 was prepared by classifying MSW in this way and calculating material balance according to the
247 ground described above, and the results are as shown in Figure 1.

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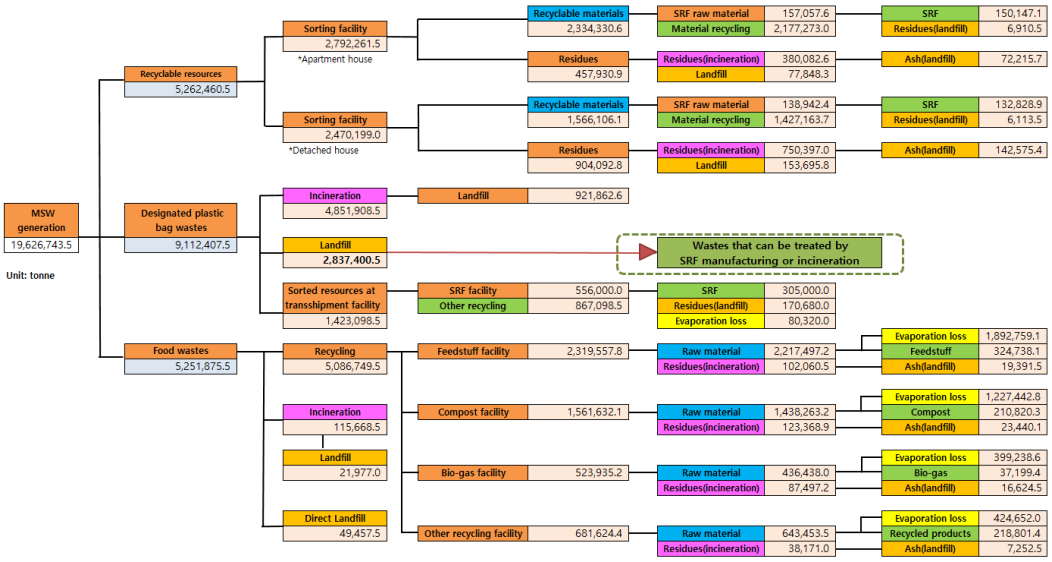

Figure 1. Material flow of MSW (2016).

In the material flow of Figure 1, the ratios per treatment method were summarized for easy understanding and shown in Figure 2. As shown in Figure 2, the generation of MSW in 2016 was 19.627 million tonnes. The input amount to sorting facilities and recycling facilities (recycling facility for food wastes, manufacturing facility for SRF) was 11.772 million tonnes, corresponding to 60.0% of the generation amount of MSW. In 'Nationwide Status of Waste Generation and Treatment in 2016' by the Ministry of Environment, this value is specified as the recycling rate. The total amount of sorted items recovered by the input of recyclable resources to sorting processes and the input amount of food wastes to recycling process after the input to recycling facilities followed by the removal of foreign objects in pre-treatment process was 10.059 million tonnes, corresponding to 51.3% of MSW generation. Waste plastic film among sorted items recovered from recyclable resources is used for manufacturing SRF. The recycling rate is 49.9% if the amount removed as foreign objects (referring to unsuitable material for SRF) during such process is excluded. In actual recycling businesses, foreign objects in the sorted resources are removed again

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265 to meet the delivery requirements of final recycling companies. For example, glass bottles sorted
266 per color are crushed and processed for shredded glasses (it is called cullet.) after the removal of
267 foreign objects such as glass bottles of different colors, ceramic wares, plastics, metals, etc. to meet
268 the requirements of bottle-making companies. Metal cans are compressed to remove residual water
269 or gas, etc. after the removal of foreign objects such as plastics, soil, and sand, etc. through screen
270 sorting, followed by crushing and sorting to meet the requirements of steel-making companies.
271 After sorting into PET, PE, PP, etc., plastics are sorted again and crushed to remove foreign objects
272 through sorting by difference in specific gravity, dehydrated & dried, followed by processing into
273 pellet or flake for delivery to the manufacturers of plastic products, etc. After the removal of
274 foreign objects, waste papers are classified into newspaper, printing paper, corrugated board, etc.
275 and compressed for delivery to paper companies. Paper is manufactured by removing foreign
276 objects again in a dissociation process. In this way, the sorted items classified per item after the
277 removal of foreign objects from recyclable resources are used as a raw material for products after
278 undergoing another sorting process or additional removal of foreign objects prior to delivery to
279 manufacturing facilities for final recycling. However, in this study, data on this was not secured so
280 that the amount supplied to recycling businesses after the removal of foreign objects and the
281 classification by sorting facilities was considered as the actual amount of recycling. However, since
282 related data by the Ministry of Environment is available on the amount of foreign objects removed
283 additionally while SRF is manufactured by waste plastic film among sorted items, actual recycled
284 amount was calculated by excluding this amount. Since food wastes have a high water content of
285 about 80% and a large amount of the water is evaporated in the recycling process but also the water
286 content of final recycling products (feed, compost, etc.) is not constant and there is no method to
287 determine how to handle water in calculation of recycling rates, the amount excluding foreign

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objects was considered as the recycled amount. As shown in Figure 1, material balance for the recycling process of food wastes is 0.792 million tonnes for the production of recycling products, 0.351 million tonnes for the generation of foreign objects, and 3.944 million tonnes for the loss amount due to water evaporation, etc. Composition ratios compared with the input amount of food wastes to recycling processes are 15.1%, 77.5%, and 6.9% respectively, where the loss rate due to water evaporation, etc. is large.

As it can be seen in Figure 2, the input amount to incineration facilities immediately after the collection of MSW in 2016 was 4.968 million tonnes, which is 25.3% of the generation of MSW. However, since the incinerated amount of 1.474 million tonnes of foreign objects was added, the actual incinerated amount was 6.441 million tonnes, which is 32.8% of the generation of MSW. Also, the amount of direct landfill was 2.887 million tonnes accounting for 14.7% of the generation of MSW. However, since the landfilled amount of foreign objects and incinerated material of 1.647 million tonnes (In Figure 2, the figure was rounded up to make the sum of the landfilled amount to be 1.648 million tonnes which was larger than actual value) was added, the actual final disposed amount was 4.534 million tonnes, which is 23.1% of the generation of MSW.

According to No. 4 of Clause 1 of Article 7 in the enforcement decree for Waste Management Law, wastes generated in the process of recycling or intermediate-treatment are counted as newly generated waste and impose duty to report to administrative office as a waste generator. According to the same regulation, foreign objects and incineration residue generated in MSW sorting & treatment facilities (including recycling facilities) correspond to business site wastes. As shown in Figure 2, the amount removed as foreign objects from sorting facilities and recycling facilities of MSW (including SRF manufacturing facilities) is 1.897 million tonnes, which is 9.7% of the generation of MSW while the amount of incineration residue is 1.224 million tonnes, which is

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311 6.2% of the generation of MSW, the sum of which is 15.9% of the generation of MSW. Meanwhile,
312 0.280 million tonnes of incineration residue which is generated from the incineration of foreign
313 objects at sorting facilities and recycling facilities is included in the amount of incineration residue.
314 In this study, through the analysis on the material flow, the amounts of incineration and landfill
315 were calculated including first generated MSW as well as foreign objects and incineration residue
316 generated from the processes of its sorting, recycling and treatment. Consequently, the sum of
317 treated amounts is larger than the amount of MSW generated first. While the incineration rate in
318 'Nationwide Status of Waste Generation and Treatment in 2016' was 25.3% and the landfill rate
319 14.7% [9], where incineration rate and landfill rate are calculated based only on the direct input
320 amount to incineration facilities and landfill facilities after the collection of MSW. However, actual
321 incineration rate and final disposal rate are higher than these by 7.5% and 8.4% respectively.
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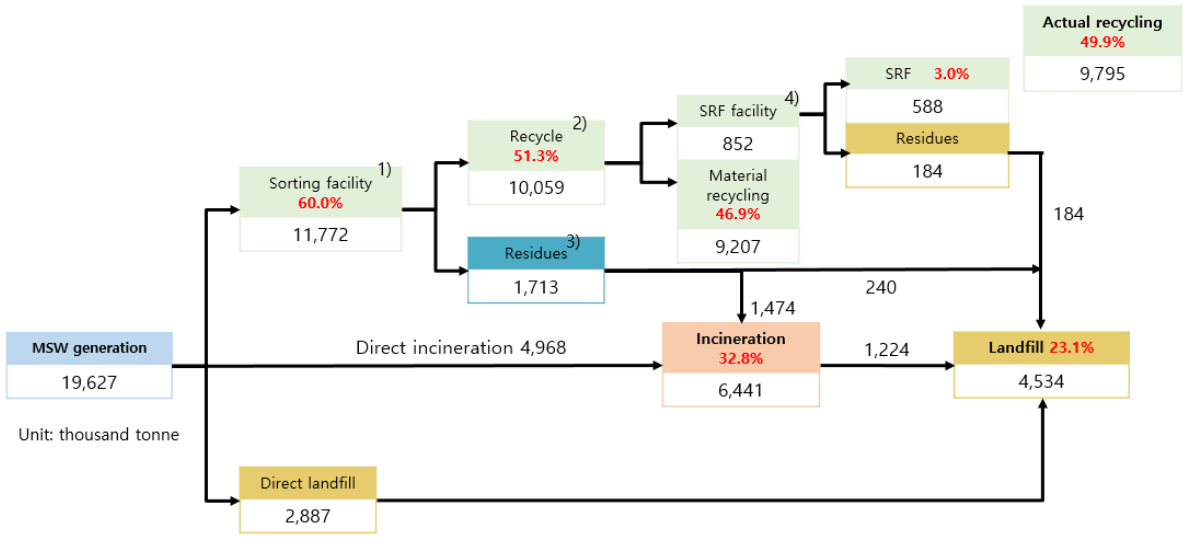

323

324 **Figure 2.** Simplified Material flow of MSW treatment (2016).

325 Note) Because the numbers are rounded, the totals may not match, and percent values in
326 parentheses are the ratios to the generation of MSW.

327 1) The value is the sum of recyclable resources input to sorting facility, food waste recycling

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facility, recovered resource at a storage and transshipment facility, and SRF facility from designated plastic bag waste (general MSW which is managed by volume-based fee).

2) The value is the sum of sorted resources, food waste except residues, recovered resource at a storage and transshipment facility, and SRF facility from wastes in designated plastic bag (general MSW which is managed by volume-based treatment fee).

3) The value is the sum of residues from sorting facility and food waste recycling facility.

4) The value is the sum of EPR target plastic sheet, and input to SRF facility from wastes in designated plastic bag.

3.2.3. Change in material flow resulting from the change in treatment methods for MSW

As shown in Figure 1, 2.837 million tonnes of wastes in designated plastic bag and 49,457.5 tonnes of food wastes were directly landfilled in 2016. To increase recycling rates and decrease final disposal rates of MSW, it is necessary to change the waste treatment method of a direct landfill with designated plastic bag to the SRF manufacturing or the incineration of food wastes. The following shows the results of MFA for the case of changing treatment methods in such a way.

1) When SRF is manufactured from the directly landfilled wastes in designated plastic bag

The MFA results when fluff SRF is manufactured from the directly landfilled wastes in designated plastic bag are shown in Figure 3. As described in Section 3.2.1, material balance for SRF manufacturing process was calculated by assuming 54.9% for production yield, 30.7% for generation rate of foreign objects, and 14.4% for process loss rate. When 2.837 million tonnes of wastes in designated plastic bag are input to SRF manufacturing facilities as shown in Figure 3, 1.558 million tonnes of SRF is produced along with 0.871 million tonnes of foreign objects, and the amount of process loss is 0.409 million tonnes. When compared with 2016 treatment results for MSW (Figure 2),

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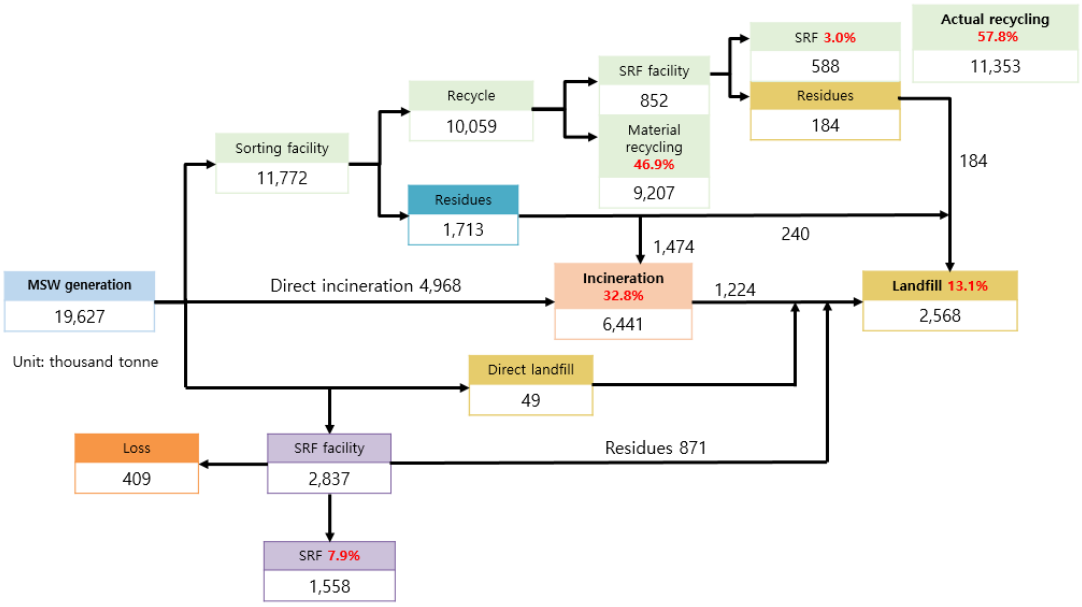
351 the actual recycling rate was increased from 49.9% to 57.8% by 7.9%, while the actual final disposal
352 rate is decreased from 23.1% to 13.1% by 10.0%. Assuming that SRF was substituted for fossil
353 fuels, the treatment of combustion residue generated after combustion was not considered.
354 However, the amount of combustion residue was 0.296 million tonnes corresponding to 1.5% of
355 the generation of MSW if the amount of combustion residue would be assumed to be the same as
356 the generation ratio of incinerated materials (19%).
357



358

359 **Figure 3.** Material flow of directly landfilled wastes in designated plastic bags to be used for SRF
360 manufacturing.
361 Note) The values and percentages are the same as the notes and footnotes of the Figure 2.
362

363 2) When directly landfilled wastes are treated by incineration
364 When the entire amount of directly landfilled wastes in designated plastic bag and food wastes
365 among MSW was treated for incineration, material flow was calculated and shown in Figure 4. When
366 treated in such a way, the amount of incineration was 9.328 million tonnes corresponding to 47.5%

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compared with the generation amount, while the amount of final disposal was 2.196 million tonnes corresponding to 11.2% compared with the generation amount. When compared with 2016 treatment results for MSW (Figure 2), the incineration rate was increased from 32.8% to 47.5% by 14.7%, while the final disposal rate was decreased from 23.1% to 11.2% by 11.9%.

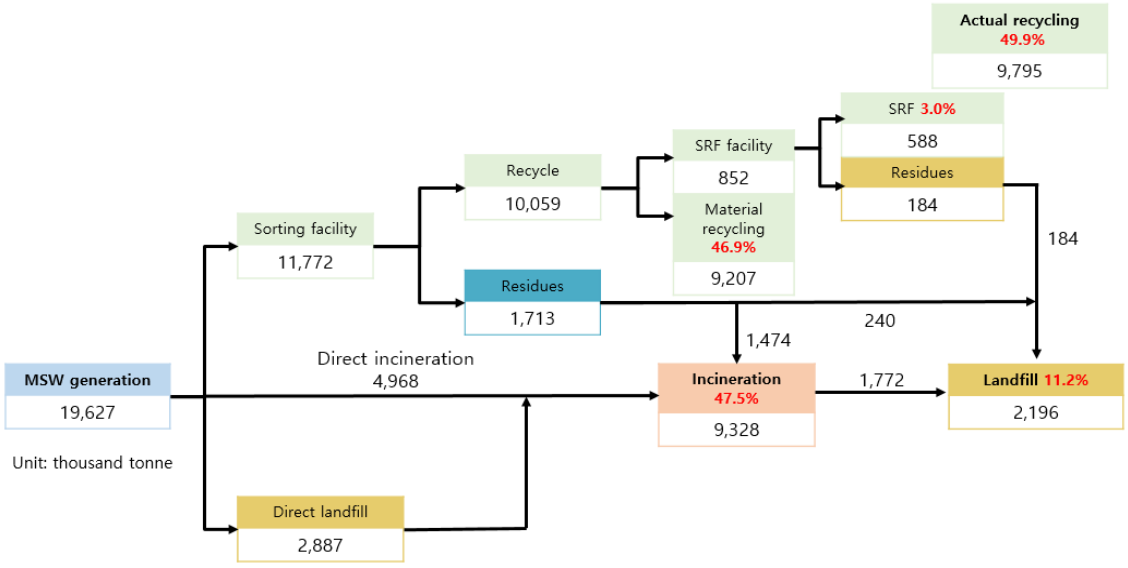

Figure 4. Material flow of directly landfilled wastes in designated plastic bags to be incinerated. Note) The values and percentages are the same as the notes and footnotes of the Figure 2.

3.2.4. Change in the ratios per treatment method resulting from the change in the treatment method for MSW

Based on 2016 treatment status of MSW described above, material flows were analyzed for the cases where the treatment method for the originally landfilled wastes in designated plastic bag was changed to the manufacturing of SRF and where all of directly landfilled wastes in designated plastic bag and food wastes were changed to the incineration. The amounts of recycling, incineration, and final disposal were obtained, and the ratios accounted for the generation of MSW

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by these amounts of treatment have been arranged and shown in Table 1.

As indicated in Table 1, the manufacturing of SRF from directly landfilled wastes in designated plastic bag is advantageous to increase the recycling rate, while the incineration of directly landfilled wastes is advantageous to reduce the final disposal rate. However, some incineration facilities produce electricity or/and steam by recovering incineration heat and use them as alternative energy. Such incineration facilities tend to increase gradually. However, the recovery and use of incineration energy have not been considered in this study. Also, as described in Section 2.3, neither the amount of combustion residues generated from the use of SRF has been included in the landfill amount.

As a reference, 2016 final disposal rate of MSW in Japan was 9.7%. It was lower than the final disposal rate in Korea with 11.2 % by 1.5% which was calculated under the condition of all of the land-filled wastes being treated for incineration. However, the final disposal rate is lowered to 9.5% if 0.423 million tonnes of landfill amount (2.2% of the MSW generation) among foreign objects generated in the recycling process of MSW being treated by incineration, and the generation rate of incineration residue is assumed to be 19%.

Table 1. Comparison of treatment amount and its ratio of each treatment method (Unit: thousand tonne).

Treatment condition		Total	Recycle	Incineration	Landfill
Treatment status in 2016	Weight	19,627	9,795	6,441	4,534
	Ratio (%)	-	49.9	32.8	23.1
SRF manufacturing by designated plastic bag waste	Weight	19,627	11,353	6,441	2,568
	Ratio (%)	-	57.8	32.8	13.1

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Incinerating all direct landfill waste	Weight	19,627	9,795	9,328	2,195
	Ratio (%)	-	49.9	47.5	11.2

401

402 *3.3. Calculation and comparison of waste disposal charge according to the change in treatment*
403 *methods for MSW*

404 Based on the Framework Act on Resource Circulation in Korea, the waste disposal charge
405 system has been enforced since 2018. The criteria for reduction and calculation of the charge are
406 specified in Annex 5 and Annex 6 of the enforcement decree for the same Act. Among these, the
407 criteria for reduction and calculation related to MSW are as shown in Table 2 and Table 3
408 respectively. The Article 7 of the Enforcement Decree of the Korean Waste Management Act
409 stipulates that wastes generated from the process of recycling and intermediate treatment should
410 be regarded as newly discharged wastes. As a result, the sorting residual waste and incineration
411 ash from the MSW treatment are managed as industrial wastes.

412 Since the foreign objects generated in sorting facilities for recyclable resources and
413 manufacturing facilities for SRF generally have combustible contents with more than 5% based
414 on weight, the rate for combustible waste was applied among industrial and commercial wastes,
415 while the rate for non-combustible material among industrial and commercial wastes was applied
416 to the incineration residue because its combustible contents is judged to be less than 5% based on
417 weight. In accordance with the related regulations of enactment decree for the same act, the rates
418 of contribution to waste disposal per 1kg of MSW as shown in Table 3 are 15 Korean won (KRW)
419 for direct landfill treatment and 10 KRW for incineration, while that for landfill of foreign objects
420 is 25 KRW, 10 KRW for incineration, and 10 KRW for the landfill of incineration residue.
421 Meanwhile, the reduction rates in case of incineration for MSW and foreign objects are as shown
422 in Table 2.

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Table 2. Reduction conditions and rates of waste treatment charge.

Recovery and utilization rate of incineration heat energy (%)	Reduction rate (%)
75 ~	75
60 ~ 75	60
50 ~ 60	50

Table 3. Waste treatment charges by waste type and treatment method.

Waste type		Waste treatment method	
		Landfill (KRW·kg^{-1})	Incineration(KRW·kg^{-1})
MSW		15	10
Industrial & commercial waste (except construction and demolition waste)	Non-combustible	10	-
	Combustible	25	10

The change in treatment amounts per treatment method according to the treatment conditions for MSW and the waste disposal charge have been calculated and shown in Table 4. As seen from Table 4, the charge amount is the highest with 130,533 million KRW for 2016 treatment condition (Type 1), and with 121,584 million KRW if the direct landfill wastes are incinerated in the incineration facilities with a recovery and use rate for incineration thermal energy of lower than 50% (Type 3A), with 109,749 million KRW if SRF is manufactured from designated plastic bag wastes (Type 2), with 74,944 million KRW if the direct landfill wastes are incinerated in the incineration facilities with a recovery and use rate for incineration thermal energy of higher than 50% and lower than 60% (Type 3B), with 65,616 million KRW if the direct landfill wastes are incinerated in the incineration facilities with a recovery and use rate for incineration thermal energy

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of higher than 60% and lower than 75% (Type 3C), and with 51,624 million KRW if the direct landfill wastes are incinerated in the incineration facilities with a recovery and use rate for incineration thermal energy of higher than 75% (Type 3D). When SRF is manufactured from landfilled wastes in designated plastic bag, compared with 2016 treatment condition for MSW, the charge amount is reduced by 20,784 million KRW, while the amount is reduced by 78,909 million KRW if the direct landfill wastes are incinerated in the incineration facilities with a recovery and use rate for incineration thermal energy of higher than 75%.

Table 4. Waste treatment charges and amounts by treatment methods according to treatment conditions.

Waste treatment condition		Total	Incineration	Landfill		
				Direct landfill	Residues	Ash
Type 1	Waste (thousand tonne)	-	6,441	2,887	423	1,224
	Charge (one million KRW)	130,533	64,412	43,303	10,580	12,238
Type 2	Waste (thousand tonne)	-	6,441	49	1,294	1,224
	Charge (one million KRW)	109,749	64,412	742	32,357	12,238
Type 3A	Waste (thousand tonne)	-	9,328	0	423	1,772
	Charge (one million KRW)	121,584	93,280	0	10,580	17,723
Type 3B	Charge (one million KRW)	74,944	46,640	0	10,580	17,723
Type 3C	Charge (one million KRW)	65,616	37,312	0	10,580	17,723
Type 3D	Charge (one million KRW)	51,624	23,320	0	10,580	17,723

Note 1) Type 1: Waste treatment condition of MSW in 2016, Type 2: Conversion of treatment method of direct landfilled waste which is discharged by designated plastic bag, to SRF production, Type 3A: Conversion of treatment method of all directly landfilled wastes to incineration (incineration heat energy recovery and utilization rate is less than 50%), Type 3B: Same condition

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with Type 3A but incineration heat energy recovery and utilization rate is increased from 50% to 60%, Type 3C: Same condition with Type 3A but incineration heat energy recovery and utilization rate is increased from 60% to 75%, Type 3D: Same condition with Type 3A but incineration heat energy recovery and utilization rate is increased to 75% and more.

Note 2) The waste treatment charge was expressed in the unit of one million KRW and the sum may not be matched due to rounding of numbers.

4. Conclusion

In this study, material flow for the generation and treatment processes of MSW in South Korea in 2016 was analyzed and the following results have been obtained.

1. From the MFA for the conditions of treatment according to 2016 treatment status for MSW, actual recycling rate, incineration rate, final disposal rate compared with MSW generation were obtained as 49.9%, 32.8%, and 23.1%, respectively, which are lower by 10.1% than the recycling rate of 60.0%, the incineration rate of 25.3%, and the final disposal rate of 14.7% in the 'Nationwide Status of Waste Generation and Treatment in 2016', and the incineration rate and final disposal rate were higher by 7.5% and 8.4% respectively.

2. If SRF is manufactured from 2.837 million tonnes of directly landfilled wastes in designated plastic bag in 2016, then 1.558 million tonnes of SRF is produced, while the actual recycling rate, incineration rate and final disposal rate become 57.8 %, 32.8%, and 13.1% respectively, so that the actual recycling rate becomes higher than the original rate by 7.9% and the actual final disposal rate is lower by 10.0%.

3. If all 2.887 million of the directly landfilled wastes in designated plastic bag and food wastes in 2016 are treated for incineration, then the actual recycling rate, incineration rate, and final

disposal rate become 49.9%, 47.5%, & 11.2% respectively, so that the actual incineration rate becomes higher than the original rate by 14.7% while the actual final disposal rate is lower by 11.9%.

4. According to the calculation result for the total waste disposal charge to waste treatment of MSW generated in 2016, it is 130,533 million KRW if it is treated according to the treatment method of 2016, and it is reduced to 109,749 million KRW if SRF is manufactured from directly landfilled wastes in designated plastic bag. If all directly landfilled wastes in designated plastic bag and food wastes are incinerated, then it is reduced to 121,584 million KRW, 74,944 million KRW, 65,616 million KRW, and 51,624 million KRW when the energy recovery and use rates of the incineration facility are less than 50%, more than 50% and less than 60%, more than 60% and less than 75%, and more than 75% respectively.

In this study, actual recycling rate, incineration rate, & final disposal rate were calculated through the MFA from generation to treatment of MSW in South Korea. However, since official data for the calculation of material balance for treatment processes of wastes was insufficient, the data of Statistics Korea, evaluation results data on the installation and operation status of public MSW treatment facilities of Korea Environment Corporation, the internal data of related institutions, etc. were utilized based on MSW generation of nationwide status for the generation & treatment of wastes in 2016 so that there exists some limitation in terms of the accuracy. The establishment of the realistic resource circulation policies and the accomplishment of the exact outcome evaluation should be based on the results of MFA for the entire process from the generation of wastes to the final treatment. It is expected that this study will be usefully utilized in the future for the establishment of resource circulation policies and the MFA on MSW.

Appendix. Supplementary materials

The following are the Supplementary data to this article:

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Conflicts of Interest: The authors declare no conflict of interest.

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Appendix

An Estimation of Actual Recycling and Final Disposal Rates of Municipal Solid Waste by Material Flow Analysis in Korea

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Content

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Appendix A. Material flow of MSW treatment in Japan and Germany

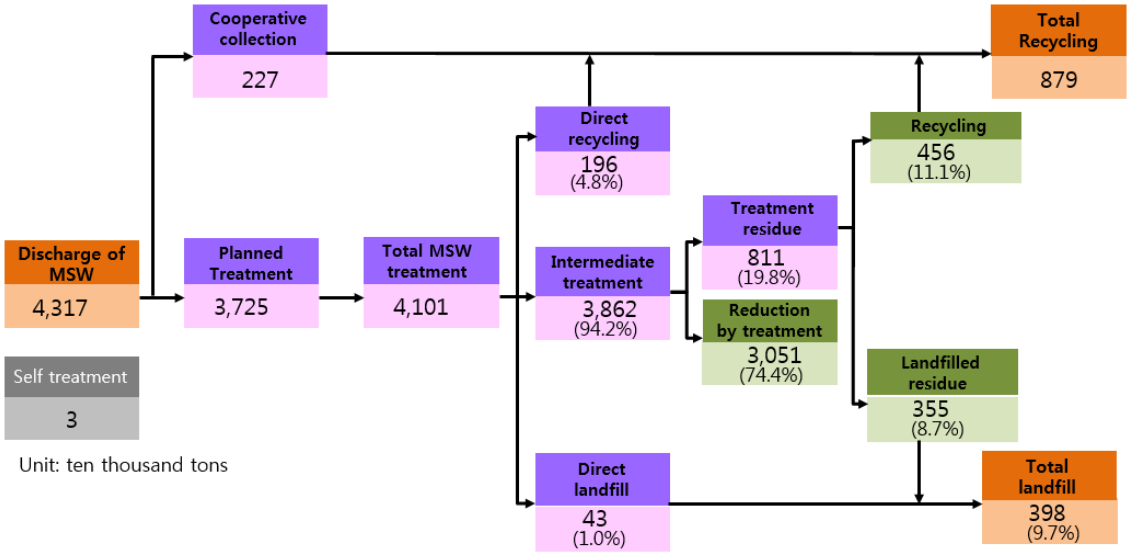

Figure A1. Material flow of MSW treatment in Japan (Ministry of the Environment of Japan, 2018)

1) The numbers in parentheses are percentages of total amount of treated waste. 2) Planned treatment amount of waste and total amount of treat waste (sum of waste amount which is treated by intermediate treatment, final disposal, and direct recycling) do not match due to difference between planned treatment amount and actual treated amount. 3) Direct recycling is the amount supplied directly to recycling companies without sorting or intermediate treatment.

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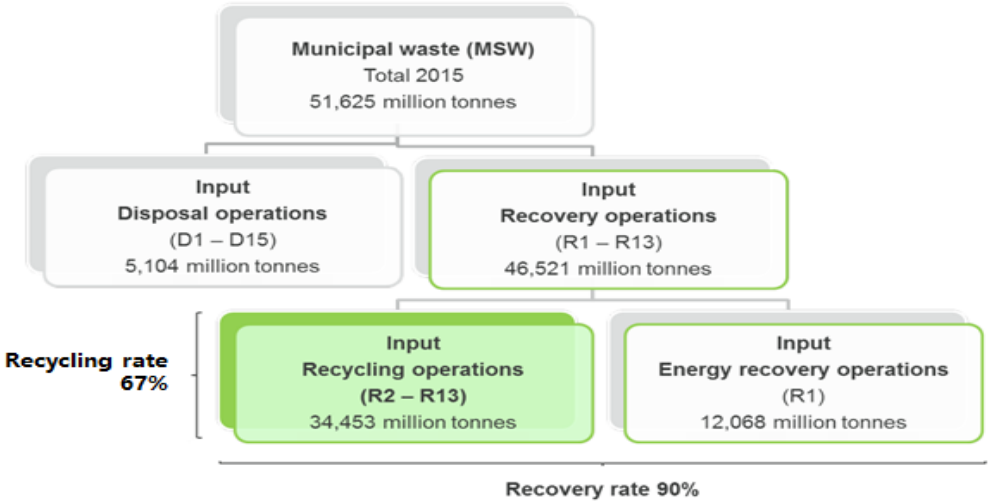
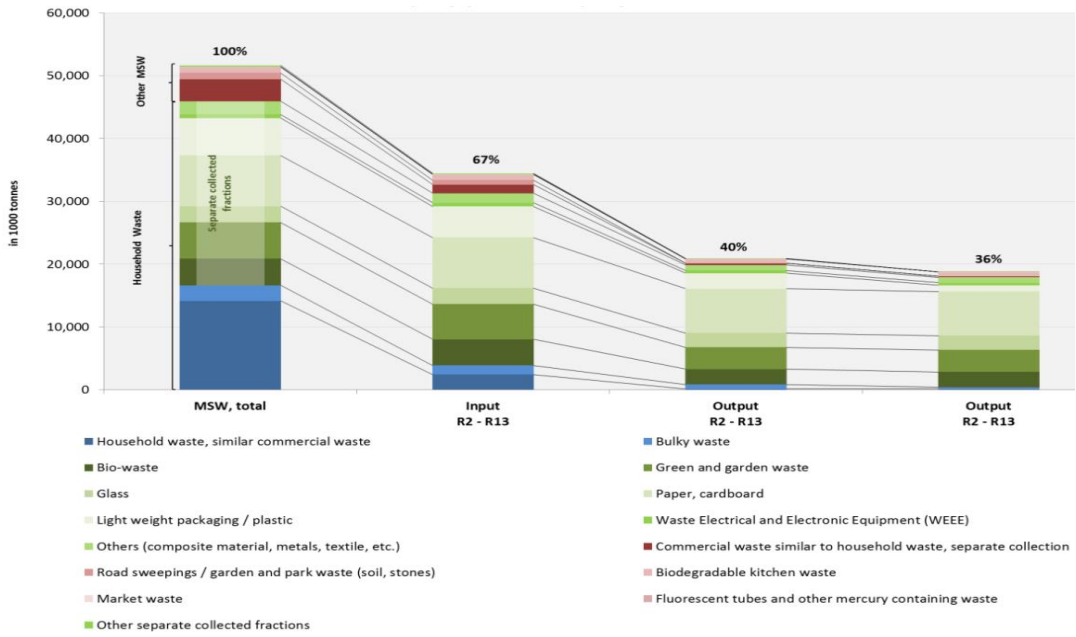


552 Figure A2. Material flow of MSW treatment in Germany. (Thomas and Sylvia, 2017)

553



554 Figure A3. Change of recycling rate according to the recycling stage in Germany. (Thomas and

555 Sylvia, 2017)

556

557 **Appendix B. The generation and treatment status of MSW in Korea, 2016**

558 Table B1. The generation and treatment status of MSW in 2016 (Ministry of the Environment of

559 Korea, 2017c)

Classification	Total	Waste in designated plastic bag	Recyclable resources	Food waste
Total waste (tonne·day^{-1})	53,771.9 (100%)	24,965.5	14,417.7	14,388.7
Landfill (tonne·day^{-1})	7909.2 (14.7%)	7,773.7	0.0	135.5
Incineration (tonne·day^{-1})	13,609.8 (25.3%)	13,292.9	0.0	316.9
Recycle (tonne·day^{-1})	32,252.9 (60.0%)	3,898.9	14,417.7	13.936.3

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