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Recycling and management practices of plastic packaging waste towards a circular economy in South Korea

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ABSTRACT

Environmentally sound management of plastic packaging waste is an issue of concern around the world because it causes potential threats to oceans and the environment upon disposal and mismanagement. This study examines the current efforts on recycling of the waste by extended producer responsibility (EPR) in South Korea as well as other countries. Material flow analysis (MFA) was performed on plastic packaging by life cycle. Based on the results in this study, material footprint of common single use plastics (i.e., PET water bottles, plastic cups, plastic bags, and plastic containers and cutlery by food delivery) by consumption was estimated to be on average 11.8 kg or 638 disposable plastics per capita a year, resulting in 32.6 billion disposable plastics and 603,000 ton of waste for disposal in South Korea. Approximately, 3 million ton of plastic packaging waste from household waste streams in 2017 in South Korea was generated and treated by energy recovery with solid refuse fuels and heat recovery, incineration without energy recovery, material recycling, and landfilling. Material recycling and recovery rates of plastic packaging waste from households were relatively low at 13.5% and 50.5%, respectively. It was estimated that as much as 3.6 million ton of CO_2eq was generated from 2.7 million ton of plastic waste by incineration in 2017. Approximately 6.6 million ton CO_2eq could be avoided by material recycling. Challenges and efforts have been discussed to improve current recycling system of plastic packaging waste towards a circular economy.

1. Introduction

Packaging materials such as papers, paper boards, plastics, aluminum, steel cans, and glass/jars are commonly used for enclosing or protecting products during distribution, storage, sale, delivery, and use. The preference and use of such packaging materials depend on the types of products, cost, and packing purpose. Plastic packaging has been gaining popularity among the packaging materials due to its lower price, lightness, easy-to-use, resistance to corrosive and structural properties. High density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) are commonly used plastic resins in packaging applications for a variety of products, including bottles and tubes, packs and cups, trays, bags, caps, bubble wrapping and films, containers, and many others. Plastic packaging and containers are the largest application (36%) among industrial applications from the worldwide plastic production (approximately 400 million per year), followed by building and construction materials (16%) and textiles (14%) (Geyer et al., 2017). The global plastic production is expected to continually increase from 300 million ton in 2015 to 1800 million ton in 2050 (Ryan, 2015).

The large consumer demands for plastic packaging materials, largely short-term and single-use materials designed for immediate disposal after use, have resulted in tremendous amounts of plastic waste to be managed for treatment and disposal. It was estimated that more than 300 million ton of plastic waste was generated in 2015 (Geyer et al., 2017). According to the study, approximately 79% of the waste was disposed in landfills, dumps or in the environment, while incineration and recycling were only 12% and 9%, respectively (Geyer et al., 2017). In EU, recent statistics revealed that more than 16 million ton of plastic packaging waste was produced in 2016. The material recycling rate for the packaging waste was 42.4% (approximately 6.9 million ton) on

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average for all EU 28 countries, which is higher than the target of 22.5% (Plastics Europe, 2017; Eurostat, 2019). Recently, the European Council, European Parliament, and European Commission made an agreement in 2017 to set a new target for plastic packaging recycling at 50% by 2025, to be increased to 55% by 2030 (European Commission, 2018). In Japan, more than 9 million ton of plastic waste was generated in 2017. More than 50% of plastic waste was treated by incineration with power generation and heat recovery, refuse derived fuel and auxiliary fuels in cement kilns, while the material recycling accounted for only 23% (Japan PWMI, 2019).

In July 2017, the Chinese government announced that plastic waste materials or scraps from outside China were prohibited to import in China for protecting its environment and public health because toxic materials were often found in mixed plastic waste streams. Due to this action, plastic waste that was once exported to China for recycling and treatment remains in many countries (Chinese Ministry of Environmental Protection, 2017). A recent study reported that about 111 million tons of plastic waste will be displaced with the Chinese import ban by 2030 (Brooks et al., 2018). This may cause unstable conditions in the recycling industry by exceeding its capacity. However, it can also give an opportunity for countries that have heavily relied on China to identify better solutions to deal with ever-increasing plastic waste and establish local recycling industry.

Some fractions of plastic waste are commonly found in oceans, beach, coastal lines and river and streams (Raum-Suryan et al., 2009; Romeo et al., 2015; Jambeck et al., 2015; Romeo et al., 2015; Turner et al., 2016; Li et al., 2016; Alam et al., 2018). Such mismanagement of the waste can cause environmental damages, ecological impacts in marine environment, and economically damages to tourisms (Ashton et al., 2010b; Turner, 2016; Avio et al., 2017; SEAS AT RIAK, 2017; Worm et al., 2017; Alam et al., 2018). During break-up and fragmentation of the plastics by weathering, microplastics in ocean and rivers can also be generated, and are becoming a significant concern due to potentially toxic effects on biological organism in ecosystems (Nakashima et al., 2011; GESAMP, 2015). The microplastics can act as a storage or sponge absorbing toxic chemicals in the environment (Al-Odani et al., 2015; Rani et al., 2014; Turner and Holmes, 2015; Jang et al., 2016; Song et al., 2019). This may create serious concerns regarding the potential contamination of marine organisms that can be consumed as dietary activities by people.

In response to the growing concern, many countries have been trying to develop proper management strategy and regulations on plastic packaging waste in a circular economy (European Commission, 2018; Marieke et al., 2018; Japan MOE, 2019; Korea MOE, 2019). The circular economy is designed to transform current linear economic structure consisting of extraction, production, consumption and disposal stages to a circular economic structure by reducing the use of limited natural resources and minimizing environmental burdens within the economic system in our society (European Commission, 2018a). In order to transform into a circular economy, life cycle of product should be considered by supporting the creation of an economy designed for circulation of resources in a cost-effective and environmentally sound manner. For example, more durable and eco-friendly products are designed and packaging using sustainable materials which can be easily recycled are manufactured. Producers take full responsibility of the recovery of resources over the life cycle of their product and packaging. Consumers can contribute to the circular economy by green consumption, asset-sharing, and product reuse. Recently, EU strategy for plastics in the circular economy was developed to establish new plastics economy in EU along with several targets. *Some specific goals with timelines include all plastic packaging materials placed on the EU market that can be reusable or recyclable in a cost-effective way by 2030, more than half of plastic waste generated in Europe to be recycled by 2030, and sorting and recycling capacity plastics to be increased up toy four-fold by 2030 with the creation of 200,000 jobs, along with improved separate collections of plastics, actions on plastics waste prevention, and legislation on single-use plastics. (European Commission, 2018; Foschi and Bonoli, 2019).* In Japan, "Resource circulation strategy for plastics" was developed to reduce the use of single-use plastics, and promote the development and use of substitutes for petroleum-based plastics in 2018. *The specific goals with timelines include the cumulative 25% reduction of single-use plastics generation by 2030, reusable and recyclable design for all containers and packaging/products by 2025, 60% recycling rate of plastic containers and packaging by 2030, 100% effective use of used plastics by 2035 including circular economy measures, doubling use of recycled materials by 2030, and maximum introduction (2 million tons) of biomass plastics by 2030 (Japan MOE, 2019).*

While the recycling statistics of waste components are readily available in developed countries, there are still very limited studies regarding environmentally sound management practices of plastic packaging waste and their quantitative flow towards a circular economy (Bernardo et al., 2016; Eygen et al., 2018; Dahlbo et al., 2018; Millette et al., 2019). The material flow of plastic packaging waste in households is very important to develop appropriate waste management policy for recycling and treatment as well as to prevent plastic pollution in ecosystem, especially in oceans.

This study presents the overview of current recycling and management practices of plastic packaging waste by extended producer responsibility (EPR) in South Korea. More specifically, our study examined the generation, recycling rates for resource recovery, and treatment of the waste. Material flow analysis (MFA) for plastic packaging was performed to provide its quantitative pathways by life cycle. Material footprint of single-use plastics based on selected items (single use plastic bags, plastic cups, PET water bottles, and plastic cutlery) was provided to elucidate the consumption rate per capita. It discussed recent efforts and performance regarding the recycling and management by comparing with Japan and selected *EU countries (Belgium, France, Germany, and UK)*. The greenhouse gas reduction potentials by the recycling and source reduction of the waste were evaluated by using the Waste Reduction Model (WARM) developed by the US Environmental Protection Agency (US EPA). Finally, some challenges and efforts are discussed to improve the management of plastic packaging waste towards a circular economy.

2. Methodology

The methodology employed in this study included gathering data associated with monitoring results of waste management performed by EPR and national waste generation and disposal status reported by the Korea Ministry of Environment (Korea MOE), site visits to plastic recycling facilities, having interviews and conversations with field site workers, and holding expert meetings with government, industry, and academia. We also conducted literature review of published reports and scientific papers, analysis of available statistics and data of the EPR system published by Institute European Environment Policy (IEEP), OECD and EU (European Commission, 2014; Organization for Economic Cooperation and Development (OECD) 2016; Institute European Environmental Policy (IEEP) 2018).

2.1. Data sources and material flow analysis

Recent regulations on plastic waste, scientific papers, released press, and previous research report related to its recycling and disposal have been examined. The EPR results were evaluated based on the volume put on the market, recycling amounts, and recycling rate statistics of plastic packaging materials (PET bottles, single and composite or multilayer plastic films and sheets, and expanded polystyrene) from 2009 to 2017 in South Korea. We compared and analyzed the EPR systems of packaging waste in the selected countries in terms of the generation and recycling and recovery rates. Interviews with field experts, such as government officials and Korea Packaging Recycling Cooperative, and

Table 1
Methods for data collection and acquisition for material flow analysis of plastics in South Korea.

Life cycle	Type of data	References
Export/Import	Export/Import of synthetic resin	Korea Petrochemical Industry Association(KPIA), 2018
Production	Amount of synthetic resin production	Korea Petrochemical Industry Association(KPIA), 2018
Consumption	Amount of domestic demands for synthetic resin	Korea Petrochemical Industry Association(KPIA), 2018
Generation	Amount of plastic waste	Korea Ministry of Environment(MOE), 2018a
Collection and sorting	Amount of collected waste by industrial type	Korea Ministry of Environment(MOE), 2018a
Recycling & recovery	Amount of material recycling (a)	KEI, 2019
	Amount of energy recovery (b)	KEI, 2019
	Total incineration (c)	Korea Ministry of Environment(MOE), 2018a
Disposal	Incineration without energy recovery (d)	(d) = (c)-(a)-(b)
	Amount of incineration without energy recovery	Korea Ministry of Environment(MOE), 2018a
	Amount of landfill	Korea Ministry of Environment(MOE), 2018a

the IEEP UK London branch were conducted to examine current efforts on new policy, operation status and limitations of the EPR systems in EU. Statistical data such as national waste statistics published by the Korea MOE, Japan and Eurostat in EU were analyzed to examine the trends of plastic packaging waste generation and recycling. Material flow analysis was conducted to elucidate quantitative flow of plastic packaging by life cycle (i.e., production, consumption, collection and sorting and recycling and treatment, and disposal). Table 1 presents the sources of data and relevant references for the analysis.

2.2. GHG reduction potentials by recycling and source reduction

The amounts of greenhouse gasses generated by incineration of packaging waste and reduced by assuming it was recycled were calculated by the US EPA WARM. The WARM is a tool that calculates the GHG emissions, energy savings and economic impacts of baseline and alternative waste management practices, including source reduction, recycling, combustion, composting, and anaerobic digestion and landfilling. GHG savings are calculated by comparing the emissions associated with managing materials under an alternative scenario with the emissions associated with a baseline scenario (i.e., current practices), as opposed to multiplying the quantity of materials managed by emission factors (US EPA WARM). Not only recycling scenarios but also potential for reducing greenhouse gas emissions by source reduction scenarios were calculated for estimating the potential reduction and summarized the results. We also estimated economic profits from GHG gas reduction by the scenarios based on market values in the emission trading scheme in South Korea.

3. Results and discussion

3.1. Production and consumption of packaging waste

Plastic production has been increasing worldwide as it is applicable to many industries as well as daily household goods due to its outstanding physical and chemical properties. A plastic manufacturing industry belongs to petrochemical industry, and petrochemical industry that produces synthetic resin, synthetic fiber raw material, synthetic rubber and various basic chemical products from petroleum products or natural gas as raw materials. A domestic demand for plastics (or synthetic resins) in South Korea is shown in Fig. 1. The domestic demand has been continually increased from 5.1 million in 2011 ton to 6.5 million ton in 2018 over the period. As of 2018, the most demanded material among the resins is PP, followed by PVC, LDPE and HDPE.

Such synthetic resins are used for many industrial applications such as packaging, building and construction, transportation, electronics and electrical equipment, household consumer products, and textiles. A comparison analysis of plastic consumption by industry type from the world, Japan and South Korea was conducted, as shown in Fig. 2. The largest consumption of plastics was found to be packaging applications. In Japan, more than 4 million of plastic packaging and containers out of approximately 10 million ton (40.7%) were manufactured in 2017, followed by electrical and electronics (1.9 million ton, 18.8%), automobiles (1.2 million ton, 12.1%), building and construction (1.19 million ton, 11.8%) in 2017 (Japan PWMI, 2019). In South Korea, plastics were manufactured for packaging and containers (2.7 million ton, 46.5%), building and construction materials (1.4 million ton, 24.7%), automobiles (528,000 ton, 9.1%), and household consumer products (461,000 ton, 7.9%), electrical and electronics (396,000 ton, 6.8%), and agricultural and fishery products (293,000 ton, 5.0%) (KEI, 2019).

3.2. Consumptions of single-use plastic packaging

Plastic raw materials are sold and consumed by consumers as plastic products such as various packaging materials and containers. Much of plastic packaging is made of single-use plastics. Europe has been actively responding to the problem of single-use plastics, including a regulatory policy based on the 10 most plastic wastes found on beaches in Europe (European Commission, 2019; UNEP, 2018). According to a previous study, plastic waste accounted for 82% of the total waste, based on the result of monitoring waste on beaches in South Korea. Plastic packaging materials such as beverage bottles, snack bags, plastic bags, and styrofoam containers have been commonly found on coastal lines (Korea Marine Litter Information System, 2019).

In this study, we collected basic data and estimated consumptions for four types of single-use plastics (PET drinking bottles, single- use plastic cups, single-use plastic bags, and single-use plastic containers and cutlery for food delivery) that are commonly used in plastic packaging materials in South Korea. For estimates of single-use plastic consumptions of selected four products, basic data such as consumption amounts, consumption frequency, the sales of products and the number of food delivery in the country were collected. By using such data, material footprints of single-use plastics by the consumption for each product were calculated. More detail data and calculation methods are available in Supplementary Materials (Table S1 through S4). Table 2 shows the material footprints of single-use plastics in South Korea. As shown in Table 2, approximately 32.6 billion units of single-use plastics were consumed per year, 637.7 units with annual plastic consumption per capita based on the four items. The single-use plastic consumption per capita per year was 11.8 kg, resulting in 602,900 ton of single-use plastic waste. It should be noted that the actual footprint may be much higher than the calculated footprint because other than the four items in this study, many single-use plastics can be included such as plastic straws, colored PET bottles, carbonated beverage PET bottles, plastic films, single-use razors and tooth brushes, and many others. As the number of single-housing family is growing, the consumption of plastic packaging materials used for food delivery may be expected to increase.

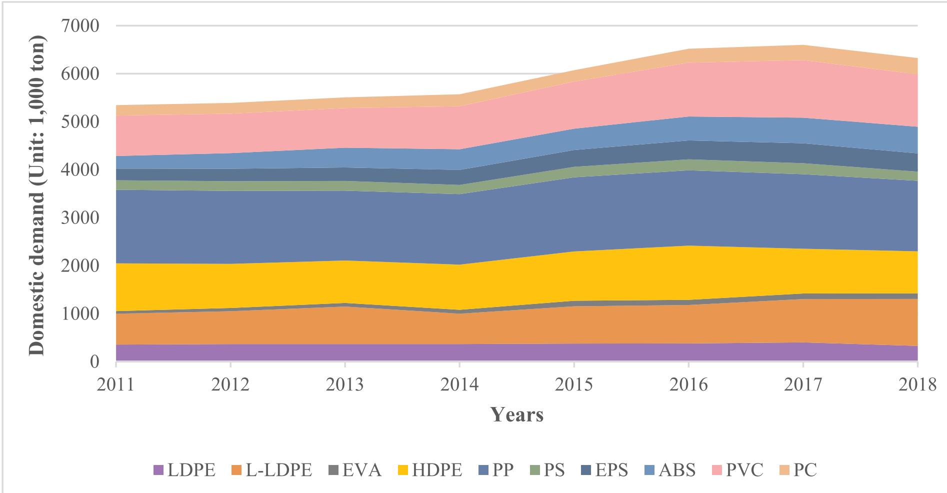

Fig. 1. Domestic demand of synthetic resin in South Korea from 2011 to 2018.

3.3. Generation and material flow of plastic packaging waste in South Korea

Plastic waste generation in South Korea has been increased from 6 million tons in 2009 to about 8 million ton in 2017, as shown in Table 3. The largest fraction of the plastic waste was industrial waste, followed by household sector. The detailed types and characteristics of plastic waste from the industry are unknown so far. Fig. 3 shows the management flow of household waste streams in South Korea. Recyclables from households in South Korea are separated at source, typically consisting of food waste, plastics, plastic vinyl bags, multi-layer films and sheets, expanded polystyrene, glass bottles, metal and aluminum cans, and papers. A lot of plastic waste is also found in waste disposable bags that contained non-recyclables and are paid by households based on their weight, commonly known as pay-as-you-throw. The bags are collected at curbside or collection centers at multi-housing apartments or complexes by local government and usually treated at incineration facilities and landfills. Some local municipalities process the disposal bags by mechanical treatment (e.g., shredding, sorting and separation) to recover material resources (e.g., refuse-derived fuels) before

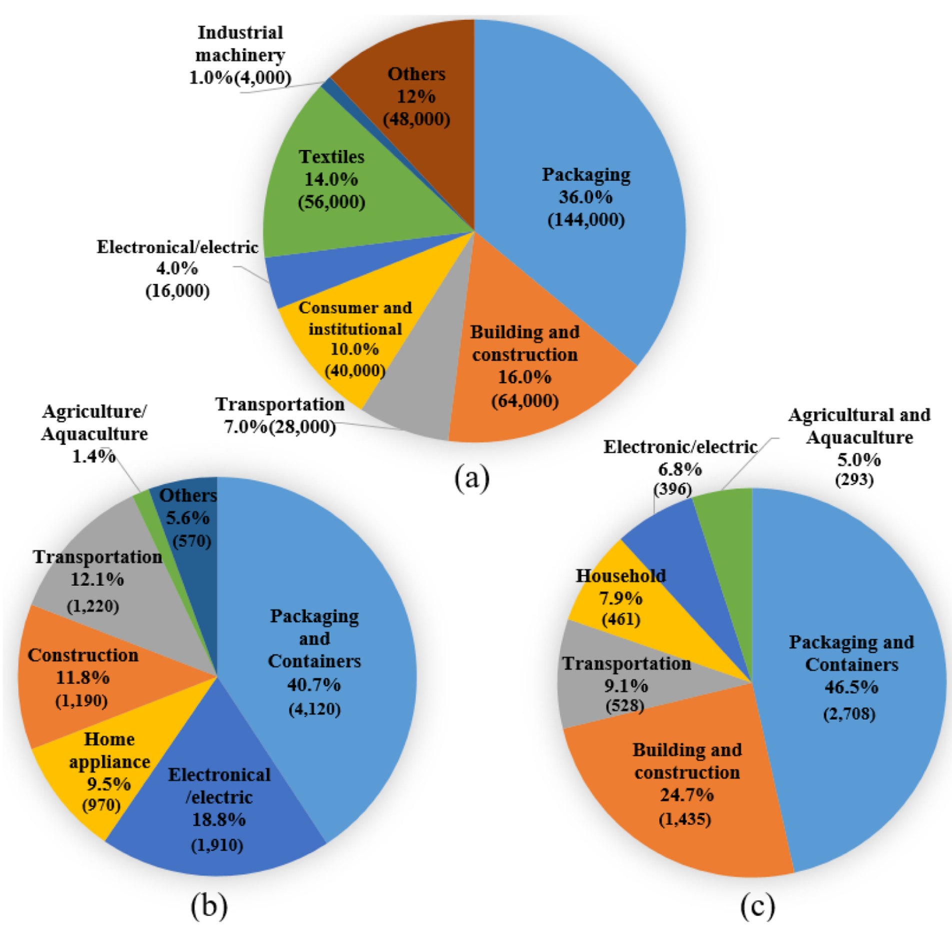

Fig. 2. (a) The World (UNEP, 2018), (b) Japan (Japan PWMI, 2019), (c) South Korea (KEI, 2019).Figure 2 Plastic production rates by industry type (unit: 1000 ton): (a) The world (UNEP, 2018), (b) Japan (Japan PWMI, 2019), (c) South Korea (KEI, 2019) followed by Figure 2 Plastic production rates by industry type (unit: 1000 ton).

Table 2
Material footprints of selected single-use plastics in South Korea.

Category	500 ml Water bottles (PET)	Single-use plastic cups	Single-use Plastic bags	Sing-use plastic packaging by food delivery	Total
A number of annual consumption per capita*	96	65	460	16.7	637.7
A number of domestic annual consumption (billion)	4.9	3.3	23.5	0.9	32.6
Annual consumption per capita*(kg)	1.4[1)]	0.9[2)]	9.2[3)]	0.32	11.8
Domestic annual consumption(ton)	71,400	45,900	469,200	16,422	602,922

1) Based on 15 g per one unit.
2) Based on 14 g per one unit.
3) Based on 20 g per one unit.
* Population of South Korea = 5.1millions (Korea Statistics, 2017a).

Table 3
Plastic waste generation by source in South Korea (2013∼2017) (Unit: 1000 ton).

		2009	2011	2013	2015	2017
Household Waste	Disposal bags[1)]	1028	965	1141	1230	1679
	Recyclables[2)]	853	854	940	974	1301
Industrial Waste	Plastics	2400	2845	3342	3612	4323
Construction Waste	Plastics	329	400	619	579	658
Total		6042	5064	6042	6909	7961

1) All plastics in disposal bags (or pay as you throw).
2) Sum of synthetic resins, plastics and foamed resins in recyclables.

incineration or landfilling.

The material flow analysis of all plastic waste streams in South Korea was conducted, as shown in Fig. 4. The generation of plastic waste was found to be approximately 8 million ton in 2017. The largest fraction source was industrial waste (4.3 million ton), followed by disposal bags (1.7 million ton) and recyclables (1.3 million ton) from households. Much of plastic waste in Korea was treated by energy recovery followed by incineration without heat recovery and power generation. Based on the analysis, the amount of energy recovery used for power generation using solid refuse fuel (SRF) or refuse-derived fuel (RDF), auxiliary fuel in cement kiln and paper mill industry was 3216 tons. The material recycling rate of such waste was found to be 22.7% (1.8 million ton), while the amount of plastic waste landfilled was 4.6% (approximately 365,000 ton).

In 2017, approximately 19.5 million ton of all household waste was generated with the largest fraction of disposal bags (9 million ton, 46%), followed by recyclables and food waste (5.3 million ton, 27% in each). Out of the disposal bags and recyclables in the household waste, plastic waste accounted for about 2.98 million tons (15%) out of total household waste streams (19.5 million ton) generated in Korea as of 2017 (Supplementary Materials Figure S1). Plastic wastes from households are mainly packaging materials (e.g., synthetic resin film and sheet, plastic trays and containers, expanded polystyrene or styrofoam). The amount of source separated recyclable products was about 1.3 million ton, while 1.7 million ton of plastics was discharged by the disposal bags. Material flow of the plastic waste generated from household waste is shown in Fig. 5. The amount of incineration without energy recovery was the highest at 1.15 million tons (38.5%), followed by the energy recovery with solid refuse fuel (SRF) (1.1 million tons, 37.5%) and material recycling (401,000 ton, 13.5%). The remaining fraction (328, 000 ton, 11%) was disposed of landfills. Only 13.5% of plastic waste from the household waste was recycled for resource recovery in the economic sector. ***It should be note that both the recycling rate(13.5%, 401,000 ton) and recovery rate (37%, 1105,000 ton) of plastic packaging waste from household sectors, as shown in Fig. 5, are lower than those of plastic waste from all sectors in Fig. 4.*** The fraction of residues from plastic recycling processes was assumed to be 14% and typically incinerated (Kim et al., 2013). The leakage into the oceans and rivers/streams by uncollected pathways from waste

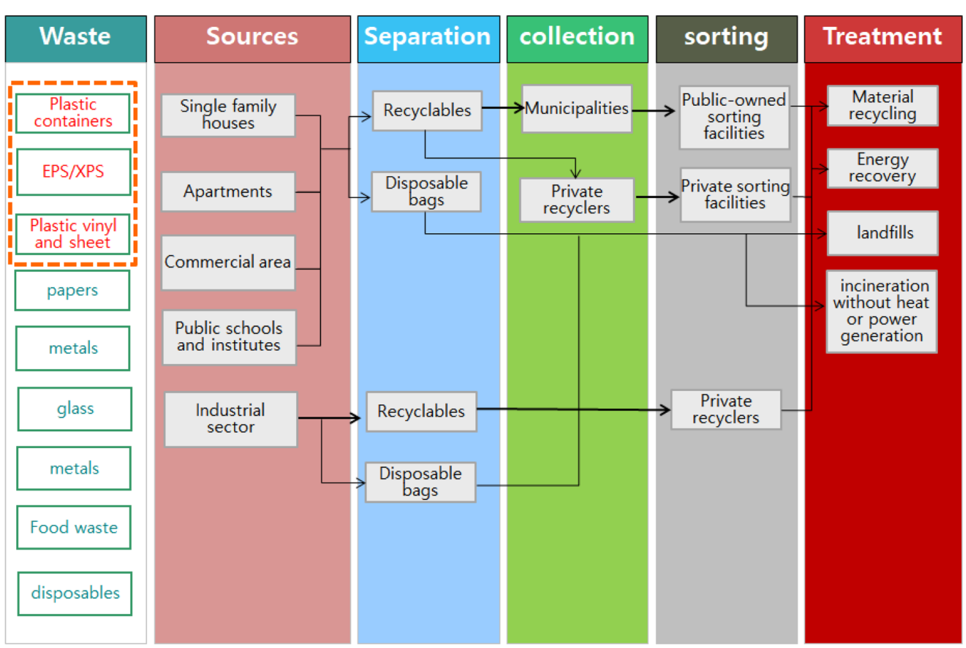

Fig. 3. Source separations and recycling of plastic waste from households in South Korea.

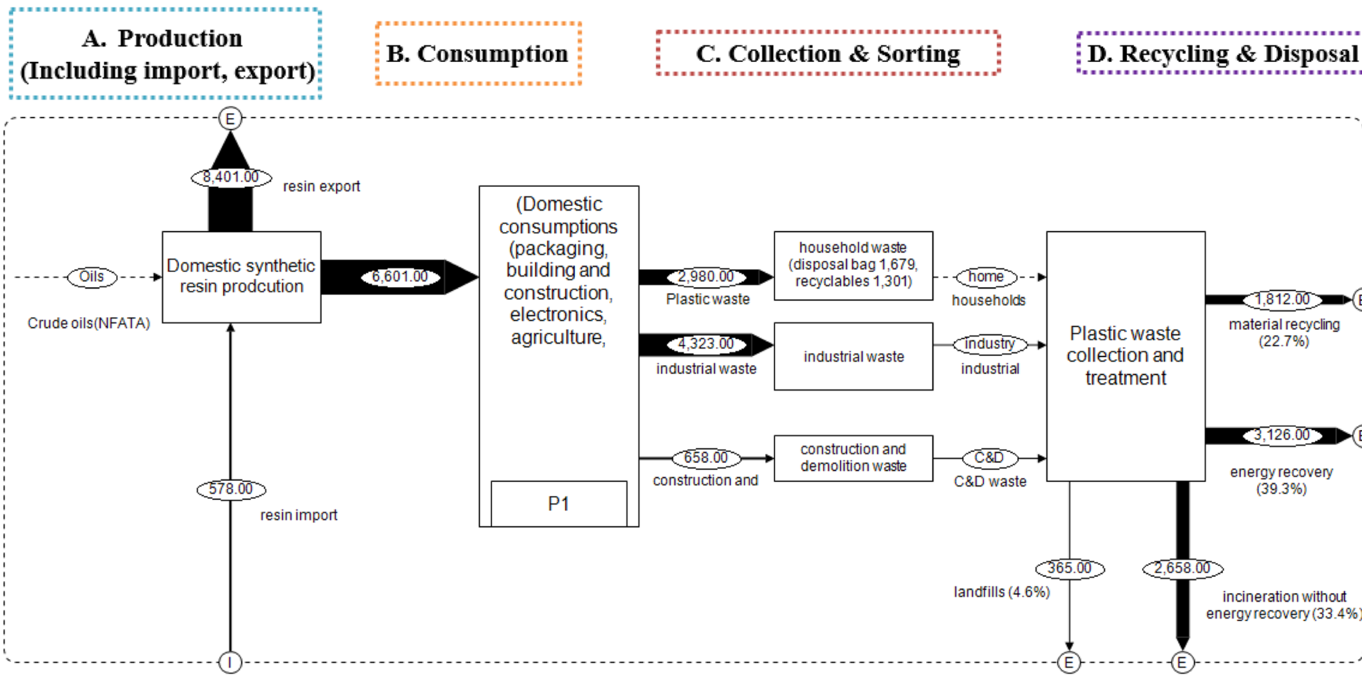

Fig. 4. Material flow analysis of plastics from all sectors (households, industrial waste) in South Korea (2017).

management streams is unknown so far and needs to be identified.

3.4. *Recycling of plastic packaging waste by EPR in South Korea*

The plastic packaging products managed by the EPR system in South Korea include PET bottles, foamed resins (EPS, polystyrene paper), and other synthetic resins (plastic containers/trays, films/sheets). The EPR system for packaging waste in South Korea is shown in Fig. 6. Producers should annually collect and recycle their assigned quantities corresponding to the recycling mandatory rate notified by the Korea MOE based on the 5-year long-term recycling target rate. Producers can fulfill their obligations by joining to Korea Packaging Recycling Cooperative, producer responsibility organization (PRO), or by fulfilling their individual obligations by collecting and recycling waste from their products. In the case of producers who join the PRO, it can fulfill its recycling obligations by paying their contribution fee to the PRO. The cost of the contribution is annually determined by a board member committee in the PRO with government officials. The PRO provides the subsidies to the Korea Resource Circulation Service Agency (KORA) to act on the producers' obligations for collection and recycling. The Agency carries out collection and recycling operations with the subsidies received and usually contracts with the collection and recycling facilities. Both the PRO and KORA should submit a report on the recovery and recycling performance of the recycling mandatory producers to the Korea Environment Corporation under the Korea MOE. Producers who fail to meet their recycling obligations will have to pay a

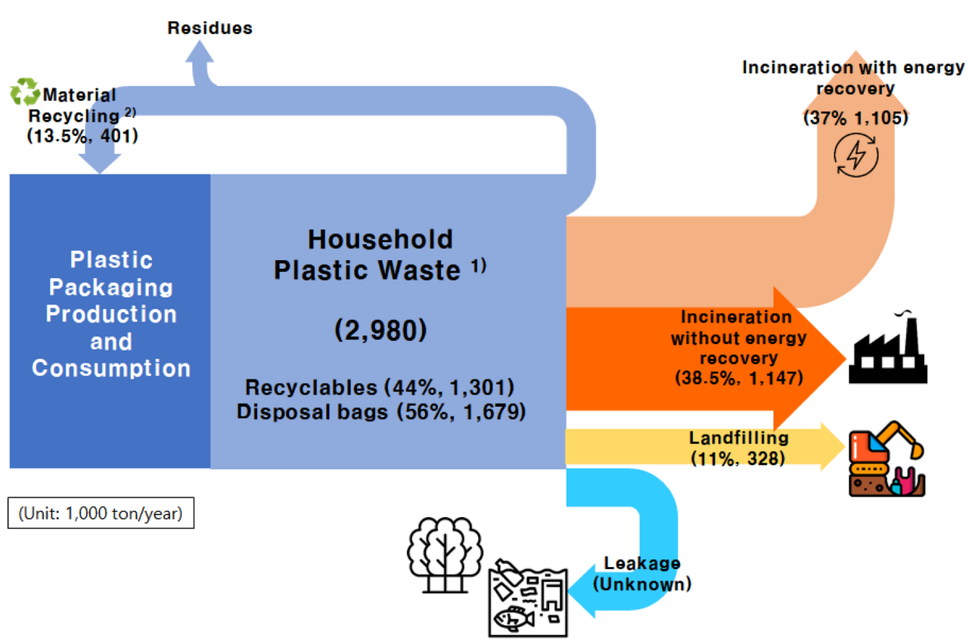

Fig. 5. Material flow of plastic packaging waste from household sectors in South Korea (2017).
1) Plastics from household waste streams (Source: Korean MOE, 2018a), 2) KEI, 2019

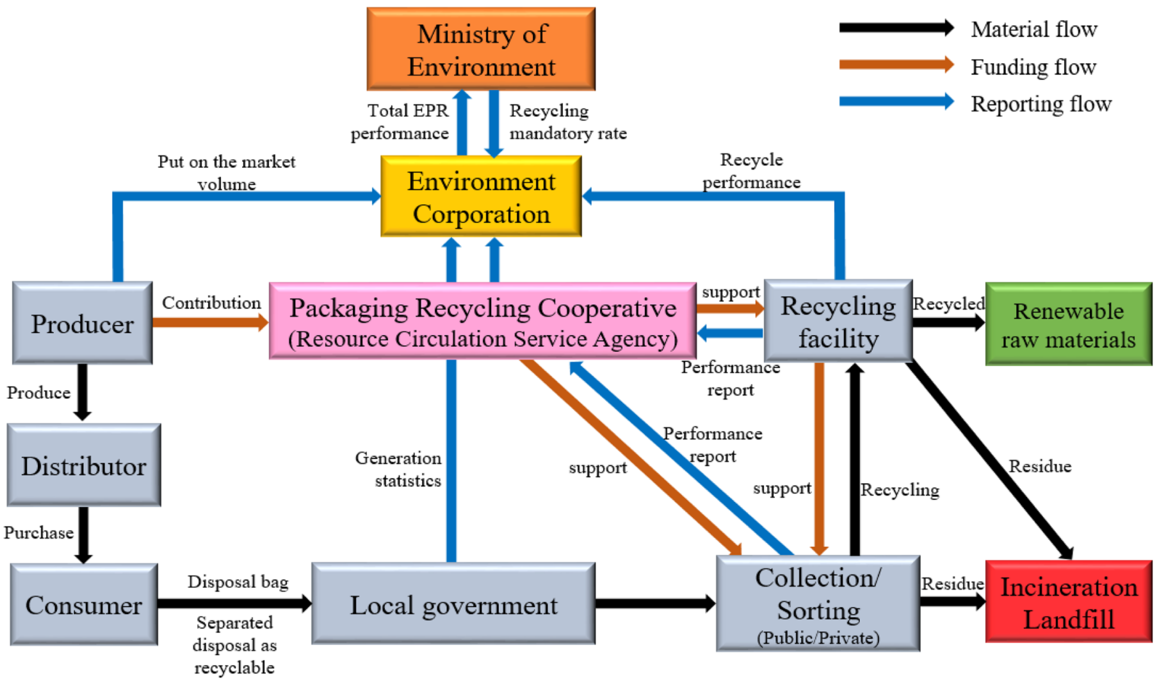

Fig. 6. The recycling system for packaging waste by EPR in South Korea.

fine more than the recycling cost.

The recycling contribution is calculated by multiplying the market in volume of each product (including imports) by the mandatory recycling target rate per product and the unit cost. The mandatory rates by product on the EPR in 2019 typically range from 70% to 80.7% with the exceptions for polystyrene paper (PSP) (46.5%) and single/composite materials of poly vinyl chloride (PVC) (30%). The detailed the target rates and unit cost of contribution and can be found in Supplementary Materials Table S5.

The volume put on the market for target plastic packaging by the EPR was approximately 897,000 ton in 2017. The volume put on the market of plastic packaging managed by the EPR has been increased by about two-fold over the years. The recycling target of the mandatory plastic packaging waste by the EPR accounted for about 670,000 ton in 2017. Among the target, approximately 837,000 ton of the waste was actually collected recycled or recovered by thermal recycling, exceeding the target amount by the EPR. For some products, the actual amounts recycled were higher than those put on the market because the cumulative amounts from previous years and the recycling amounts from the products that were not managed by the EPR might have been included. The detailed amounts of put on the market, mandatory recycling, and actual recycling for plastic packaging materials between 2009 and 2017 by the EPR system can be found in Table 4.

3.5. Comparison of generation and recycling rates of plastic packaging waste among selected countries

In this study, South Korea's plastic packaging waste generation and disposal status was compared with five selected countries (Belgium, France, Germany, Japan, and UK). The generation and treatment status of plastic packaging wastes between Korea and Japan is summarized in Table 5. In Japan, total amount of waste from plastic packaging waste was about 4.2 million ton. Among the waste, 16.3% of plastic packaging waste was recycled for material recovery in 2017. In South Korea, the rate of material recycling was 13.5%, which is slightly lower than Japan. Incineration with power generation in Japan accounted for 48.3% of power generation, 6.94% of refuse-derived fuel and cement auxiliary fuel, and 5.26% of incineration with heat recovery. South Korea represents 37.1% of incineration with energy recovery and 38.5% of incineration without energy recovery. In case of the landfilling, relatively lower rates of plastic packaging waste were found in both Korea (approximately 328,000 ton 11.0%) and Japan (approximately 170,000 ton, 4.1%).

Fig. 7 shows a comparison result of plastic packaging waste

Table 4
Recycling performance of plastic packaging waste by EPR in South Korea **(Unit: 1000 ton)**.
Source: KORA, 2018.

Category		2009	2011	2013	2015	2017
PET bottles	Put on the market (Including import)	164	195	208	247	285
	Mandatory recycling amount	123	152	167	202	233
	Actual amount recycled	139	161	169	194	231
Foamed synthetic resin (EPS,PSP, exc.)	Put on the market (Including import)	30	36	32	39	46
	Mandatory recycling amount	19	23	22	28	33
	Actual amount recycled	22	25	23	30	42
Other synthetic resin (container/ tray)	Put on the market (Including import)	151	174	169	221	242
	Mandatory recycling amount	98	132	135	181	193
	Actual amount recycled	119	156	136	248	247
Other synthetic resin (film/sheet)	Put on the market (Including import)	160	203	217	314	324
	Mandatory recycling amount	76	114	130	197	211
	Actual amount recycled	93	155	150	290	317

Table 5
Management of plastic packaging waste in Korea and Japan in 2017.

2017	Korea	Japan[2)]
Material recycling	401(13.5%)	670(16.0%)
Chemical recycling	–	270(6.5%)
Incineration		
a) Incineration with power generation	1105(37.1%)[1)]	2020(48.3%)
b) Solid fuel/ cement auxiliary fuel		290(6.9%)
c) Incineration with heat recovery		220(5.3%)
d) Incineration without energy recovery	1147(38.5%)	540(12.9%)
Landfilling	328(11.0%)	170(4.1%)
Total	2981	4180

[1)] No detailed statistics by energy recovery methods are available. This data includes all energy recovery methods (e.g., power generation, solid refuse fuels/cement auxiliary fuels, and heat recovery).
[2)] Japan PWMI, 2019.

generation from household waste among South Korea, Japan and selected EU countries. Japan, the largest producer of plastic packaging waste, generated about 4.2 million ton, followed by Germany, South Korea, France, the United Kingdom, and Belgium. However, when considering the generation rate per capita, South Korea was the largest with 58.4 kg, followed by Germany, France, the United Kingdom and Japan, and Belgium.

Fig. 8 shows the recycling and recovery rates for plastic packaging wastes among the countries. As shown in Fig. 8, the recovery rate of plastic packaging waste in Germany and Belgium was close to 100%, while the recovery rates for Japan, France, UK, and South Korea were 82%, 70%, 60%, and 51%, respectively. Based on the results of material recycling rates, Germany was also the highest at 48%, followed by UK (46.2%), Belgium (44.5%), France (26.5%), Japan (16%), and Korea (13.5%). Comparing the results of South Korea's plastic packaging waste treatment methods with the selected countries, South Korea showed higher rates of landfilling and incineration without energy recovery than those of the countries. It should be noted that although plastic packaging waste generation per capita in South Korea is higher than the selected countries, its recovery rate and material recycling rate are relatively lower.

3.6. GHG reduction potentials by recycling and source reduction of plastic waste

Incineration of plastic waste can generate greenhouse gasses (GHGs) into the air as well as potentially toxic gasses. Greenhouse gasses are generated in the production of plastic resins and processing into plastic products, and even during product distribution and waste treatment (European Commission, 2018). As plastic production has increased significantly, greenhouse gasses from plastic production have also substantially emitted in the air. In this study, the amount of greenhouse gasses generated by the incineration of plastic waste in South Korea was calculated by using the US EPA WARM. In addition, the amount of greenhouse gasses that can be reduced was calculated when the waste is assumed to be recycled instead of incinerated. Furthermore, the potential for greenhouse gas reduction was estimated if source reduction as an alternative scenario occurs. Based on the result in this study, it was estimated that as much as 3.6 million ton CO_2eq (carbon dioxide equivalent) was generated from 2.7 million ton of plastic waste by incineration in 2017 in South Korea. Assuming that it is entirely recycled, it could reduce about 6.6 million ton of CO_2eq. Furthermore, if source reduction is practiced instead of recycling, GHGs can be reduced at about 9.2 million ton of CO_2eq, which is 1.4 times higher than the amount of the reduction by the recycling scenario.

In South Korea, GHG emission trading system has been implemented in the beginning of 2015 by the Act on the Allocation and Trading of GHG Emission Permits, which was first enacted in May 14, 2012. According to the Korea Exchange Emissions Market Price Information, one ton of CO_2 was traded at about USD 26 in 2018 (or Korean Won 30,000). By using the price on the market, the economic benefits from the GHG reduction by the recycling are estimated to be approximately 169 million USD or about 198 billion Korean won per year. In the case of the source reduction, the potential benefit was estimated to be about 235 million USD or about 276 billion Korean won per year.

3.7. Challenges and efforts on plastic packaging waste towards a circular economy

Plastic packaging waste, one of the major fractions generated from household waste streams, has continually increased due to common use of product packaging. Much of the waste is short-term or single-use

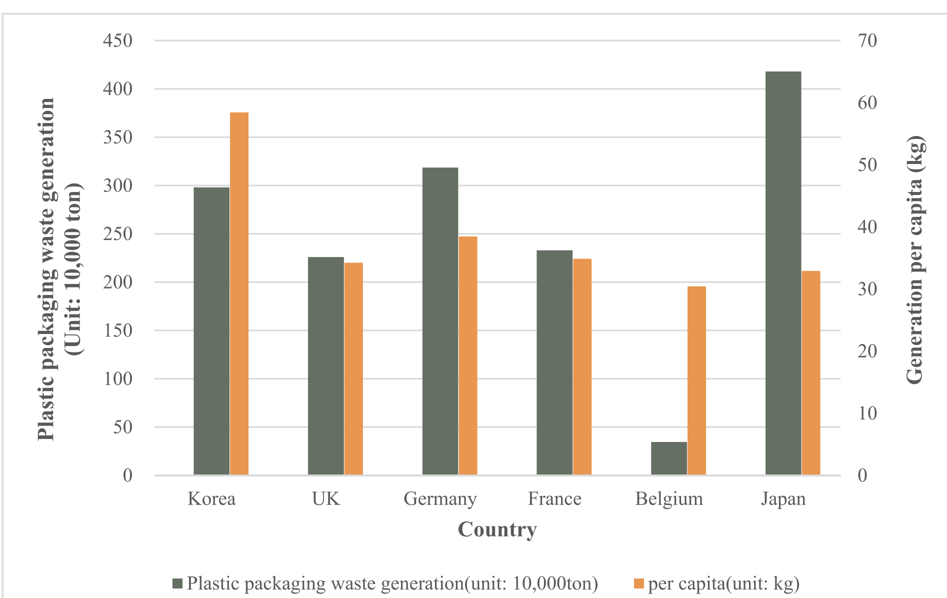

Fig. 7. Plastic packaging waste generation among selected countries (2017).

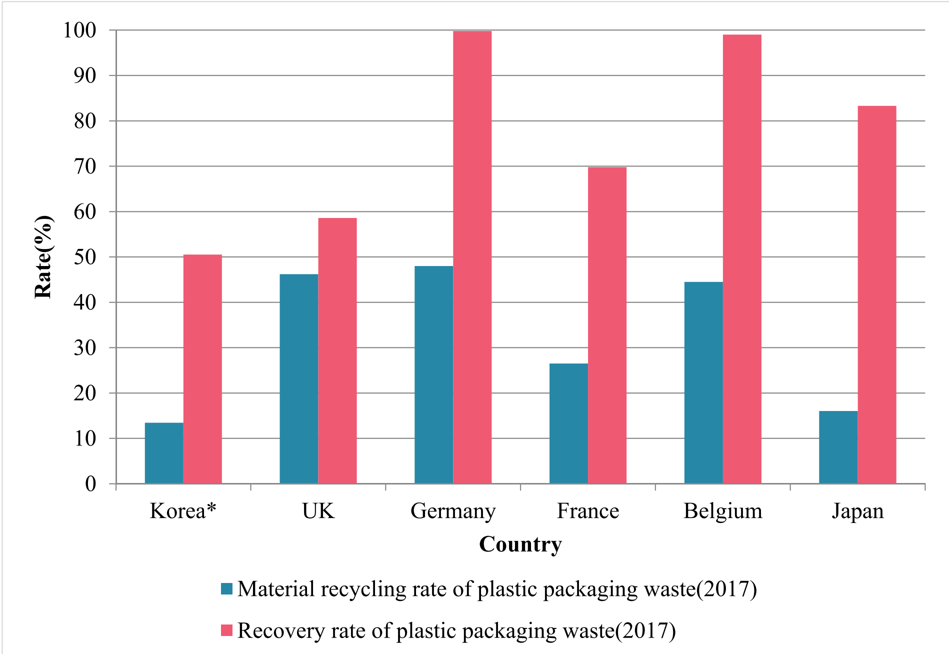

Fig. 8. Recovery and material recycling rate of plastic packaging waste from household waste.
(*Source:* Eurostat, 2019)

plastics to be disposed of. Significant concerns have been raised due to their leakage to oceans polluting marine environment as well as greenhouse gas impact of plastics production and treatment. Marine litters recently found in Korean costal lines consisted of more than 80% of plastic waste, according to the monitoring report of marine debris (Korea Marine Environmental Management Corporation, 2019). The global awareness of the serious plastic pollution has led to a surge in countries that have introduced policies to regulate the use of plastic packaging materials. Europe announced in `strategy for plastics in a circular economy " in 2018 to regulate plastic waste. Highlights include the ban on the use of single-use plastics such as straws, swabs, balloons and plates by 2021, 90% recovery of single-use plastic beverage bottles by 2025, changes to all reusable plastic packaging by 2030 and recycling plastic waste more than half of amount that consumed in Europe (European Commission 2018). In addition, Europe introduced a single-use plastic management strategy to define 10 single-use plastic products and prepared management strategies such as banning market release, reducing usage, labeling, and increasing producer responsibility (European Commission, 2019).

Based on the result of this study, the generation of the plastic packaging waste per capita in South Korea is relatively at high levels compared with those of other countries, while the rates of the material recycling and energy recovery in the country are at lower levels than other countries. Although the recycling of the waste is a preferred option to landfills and incineration, reducing the production and consumption of plastic packaging could result in substantially economic benefits as well as far less environmental burdens. Thus, more strengthened regulations on the production and consumption of plastic packaging materials should be developed to deal with the issues, including the bans or restricted use of single-use plastic packaging (e.g., plastic bags, plastic cups and straws, plastic cutlery, foamed plastics by food delivery), design changes for recycling, and labeling. Currently, there are no definitions and scope of single-use plastics in the regulatory system in South Korea. Strengthened measures aimed at dealing with the problems related to the single-use plastics can be made including a target on the reduction of the consumption, marine litter prevention in the waste management, and recycling and recovery of the waste. As an example of plastic waste reduction efforts, 'waste mart' where plastic recyclables are exchanged with goods was recently opened to solve plastic packaging waste problems in Seoul. Cash or points are given to participants when used PET bottles are introduced into a bottle collector machine with artificial intelligence. The points can be used for purchasing upcycled products such as bags made from used fire fighters' clothing's and biodegradable products.

In 2018, The Korea MOE developed the 'Comprehensive Measures for Plastic Waste Recycling Management' to reduce plastic waste generation by 50% by 2030 and increase the recycling and recovery rate to 70% by 2030. Several measures include voluntary agreement on prohibiting the use of disposable cups within cafeteria, the changes of all PET water and drink bottles to colorless by 2020, the evaluation of the recyclability of packaging materials, the regulation on the easy detachment of plastic packaging labeling, the strengthened EPR system by expanding the number of target products from 43 to 63 by 2022, and the expansion of green procurement in public sectors. From January 1, 2020, films of synthetic resins contained air-filled films used to create buffer packaging or insulation effects, plastic packaging films used to protect clothing after dry cleaning in commercial laundry, single-use plastic bags, single-use vinyl gloves, and wrapping films for food packaging would be included in the list of the mandatory recycling for packaging waste by the EPR. Recently, South Korea is also operating a strengthened system to curb the use of single-use plastics, (e.g., a ban on the use of single-use plastic by free of charge in restaurants, cafeteria, and bakery, and a ban on the use of single-use plastic bags at large and medium-sized supermarkets of an area of 165 m^2). More specific implementation strategies and setting priorities of plastic packaging waste are still needed for transforming current linear economy into a circular economy.

The material flow analysis shows that in 2017, the recycling rate of entire plastic waste streams was 22.7% in South Korea, while energy recovery by using solid refuse fuel and heat recovery and incineration without energy recovery represented 39.3% and 33.4%, respectively. In case of household waste, the material recycling rate of plastic waste in Korea was calculated to be only 13%, which is considerably lower than other countries. The reasons for the low recycling rate include low quality of mixed plastic wastes (mixing with diverse plastic resins or composite materials), low benefits from economies of scale in sorting and recycling, additives used in plastic packaging, and limited demands for recycled products. In addition, the recycling of packaging waste by the current EPR system in South Korea is highly dependent on the contributions paid by the producers, relying upon rudimentary sorting and separation methods along with labor intensive works. Although the packaging waste recycling industry has been nurtured by the recycling subsidies and by the private investment since the introduction of the EPR system in 2003, it is still fragmented under poor working environment with low quality of the recycled products on the markets. As the recycling plants are relatively small, they are vulnerable in responding to fluctuations in the domestic and overseas recycling market. Therefore, there is an urgent need to keep fostering the recycling industry by developing and innovating plastic waste recycling technologies with modern methods, restructuring and expanding investment in the recycling industry. Green infrastructure and circular economic model by resource recovery should be developed and established to improve current packaging waste management.

4. Conclusions

Management of plastic packaging waste has become an issue of concern in environmental community due to potential hazards to ecosystems in oceans and rivers and streams by leakage through existing waste collection systems. Significant amounts of plastic packaging materials such as drinking water plastic bottles, plastic bags and cups, and plastic food containers are commonly found in the ecosystems, although active collection and recycling efforts on such waste has been commonly made to recover recyclable components in waste streams by extended producer responsibility (EPR) in many developed countries. It is important to effectively collect and properly treat plastic packaging waste from households from the view of pollution prevention that otherwise may result in serious human health problems and the environmental impacts by improper management. This study examines current recycling practices and recycling rates of such waste. Based on the result of MFA, approximately 3 million tons of the waste was generated from households in South Korea and treated by energy recovery with solid refuse fuels and heat (39.3%), incineration without heat and energy recovery(33.4%), and material recycling(13%) in 2017. It was also found that more than 32 billion of single use plastics in selected four items (drinking water plastic bottles, plastic cups, plastic bags, and disposable plastics by food delivery) were annually consumed, resulting in about 600,000 tons of plastic waste for disposal. By converting to footprint of single-use plastic consumption per capita, this is equivalent to 638 plastics per capita or equivalent to approximately 11.8 kg per capita in South Korea. A small fraction (22.3%) of plastic packaging waste is managed by the EPR. Consequently, more stringent regulations by expanding a list of target recycling items (e.g., plastic air bubbles, plastic packaging for fruits, PET containers) in the current EPR system are needed to better manage the waste and prevent plastic pollution in the environment upon disposal. Based on the US EPA WARM model, greenhouse gas emission can be reduced to approximately 6.6 million ton of CO_2eq when the recycling is implemented for the packaging waste that is currently incinerated. As a result of comparative analysis between Korea, Japan and EU countries, Germany, Belgium, and UK have achieved relatively high recycling and recovery rates of the waste. Cost-effective and advanced recycling technology with innovations is urgently needed for environmentally sound management of plastic packaging waste towards a circular economy to reduce GHG emission as well as potential leakage into the ecosystems.

Credit author statement

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dr.. Yong-Chul Jang, first and corresponding author, developed the theoretical formalism, performed the material flow analysis and calculations. **Gain Lee and Yuree Kwon** collected basic data for the material flow analysis and compared the data with those of other five countries (Japan and EU). **Mr. Jin-hong Lim and dr. Ji-hyun** Jeong prepared for the basic survey and data in the EPR system by Korea. All authors also provided critical feedback and helped shape the research, analysis and manuscript

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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