Chapter 10

Plastics Recycling – Technology and Business in Japan

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Additional information is available at the end of the chapter

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1. Introduction

The Japanese government promotes 3R policies in the country and to developing countries [1]. However, there are many obstacles and discrepancies between the idea and reality. After the straggles in technologies and consumer movements over thirty years, a legislative approach to waste-plastic recycling started in Japan in the year 2000. The first target was plastic containers and packaging from household wastes. Approximately ten years have passed, and we still face many problems within the country: high recycling costs, low quality of recycled resin with respect to the market value, and so on. Some of our challenges and achievements, or fact data itself would be good material for people that have an interest in waste plastics recycling. Many discussions and data in this field are not published in academic journals, and the reports of the national government, municipalities and companies are mostly written in Japanese. The fact data, commercial technologies, and businesses for recycling waste plastics in Japan are reviewed in this chapter.

2. Generation of waste plastics, and the legislation for their management

2.1. Generation of waste plastics

The Ministry of Environment of Japan announces the current status of generation and treatment of general wastes [1,2] and industrial wastes every year. Municipal wastes of the total collection amount of 46.3 million tons include those produced from households (25.6 million tons) and those from small businesses (13.3 million tons). Waste plastic contents in municipal wastes are regularly monitored by each municipality. Depending on separation categories decided by municipalities, waste plastics are incinerated as mixed burnable wastes, or recycled like plastic containers and packaging. Some plastic materials such as those in toys and in electronic devices go to landfill. A composition survey of mixed wastes that were brought into the Chuo incineration plant in Tokyo gave 16.0 wt% as a mean value of waste-plastics content in burnable wastes from households (fiscal year 2010) [3]. This mean value is an average of four times a year. The detailed composition and property of burnable wastes is shown in Table 1. For industrial wastes, waste plastic is one of 20 collection criteria of industrial wastes, and the recent survey shows the generation of 5.67 million tons in 2009 [4].

Category		Mean value
Composition, wt%	Burnable components	98.45
	paper	45.00
	kitchen waste	22.92
	plastics	15.97
	wood and grass	5.74
	textile	4.61
	rubber and leather	0.51
	others	3.70
	Inflammable contaminants	1.55
	metal	0.46
	glass	0.32
	stone and ceramics	0.13
	others	0.64
Proximate analysis, wt%	Moisture content	38.69
	Combustible matter	54.58
	Ash content	6.75
Elementary analysis, %	Carbon	28.5
	Hydrogen	4.24
	Nitrogen	0.34
	Oxygen	21.33
	Combustible sulfur	0.02
	Volatile chlorine	0.17
	Higher calorific value, kJ/kg	12,263
	Lower calorific value, kJ/kg	10,335
	Bulk density, kg/L	0.130

Table 1. Composition and property of burnable wastes in Chuo incineration plant

The world plastics production is 265 million tons (2010) [5]. Production of typical synthetic resins in Japan (2010) is 12.2 million tons (Table 2) [6], and it accounts for 4.6% of the world production. The generation and the macro flow of the waste plastics in Japan are published annually by the plastic waste management institute. The latest data of the year 2010 are shown in Figures 1 though 3 [7]. The total generation of waste plastics increased until 2004 (10.13 million tons), and gradually decreased to 9.12 million tons (2009) due to the shrinking economy in Japan. In 2010, the total generation increased to 9.45 million tons because of the recovery from the economic crisis in 2008 [7].

Synthetic resin		Production, tons
Thermoplastics		
PE	HDPE	1,704,076
	LDPE	1,015,260
	EVA	244,231
PP		2,709,023
PS	For molding	698,113
	For expanded PS	123,560
PVC		1,749,046
PET		631,101
ABS		454,109
PC		369,270
Other thermoplastics		1,311,767
Subtotal of thermoplastics		11,009,556
Thermosetting plastics		
Phenolic resin		284,152
Epoxy resin		187,565
Urethane foam		180,152
Other thermosetting plastics		352,841
Subtotal of thermosetting plastics		1,004,710
Other plastics		227,861
Total		12,242,127

Table 2. Production of typical synthetic resins in Japan (2010)

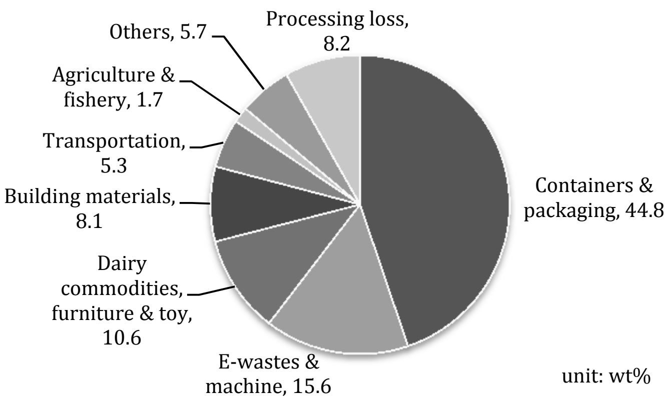


Figure 1. Waste plastics generation by user's application (Total generation 9.45 million tons, 2010)

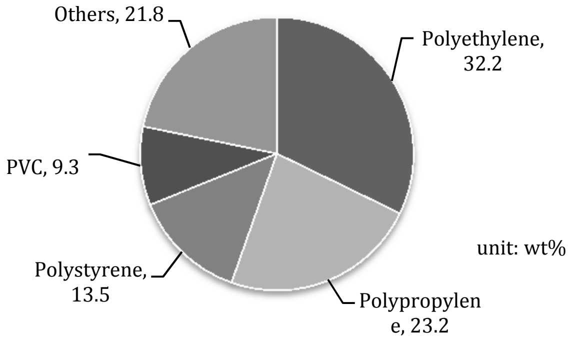
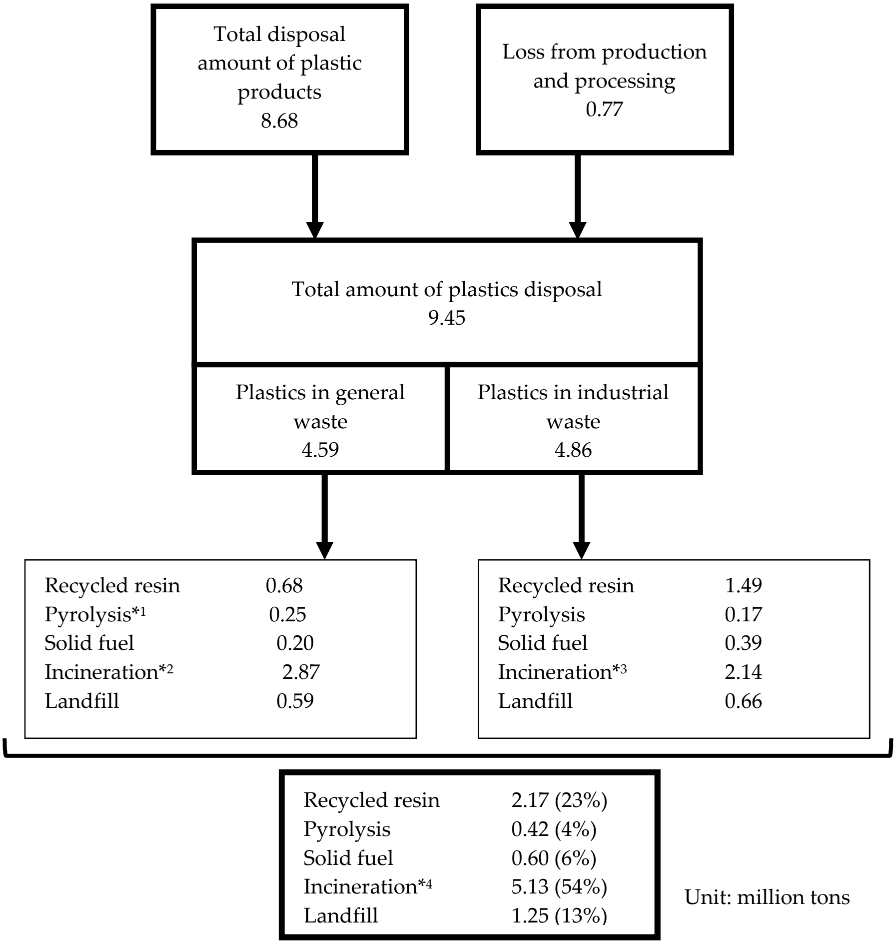


Figure 2. Waste plastics generation by the types of plastics (Total generation 9.45 million tons, 2010)

Entry	Type of waste plastics / waste source	Generation amount ton/year
1	Total PET / Total domestic sales of PET resin as bottles	594,689
	Estimated amount of PET resin from bottles in general wastes	290,000
	Estimated amount of PET resin from bottles in industrial wastes	305,000
2	Mixed plastics / containers and packaging in general wastes	1,040,658
3	Plastic parts in Automobiles	399,000
	Plastics of non-polyurethane in ASR	193,000
	Polyurethane in ASR	93,000
4	Electric and electronic equipment	
	Home appliances under the recycling law	181,884
	Other E-wastes	20,000
5	Agriculture	
	Polyethylene film	62,778
	PVC film	42,852
	Other	9,588
6	Business	
	Chemical industry sector	91,504
	Manufacture of plastic products	77,229
	Manufacture of rubber products	45,425
	Manufacture of electric equipment and machinery sector	14,037
	Manufacture of equipment for transportation	18,753
	Manufacture of pulp, paper or paper products	35,929
	Food processing factory	5,285
	Publishing and printing workshop	3,986
	Steel manufacture	32,939
	Non-ferrous metal manufacture	12,259
	Manufacturer of metal products	4,229
	General machinery	3,768
	General construction	27,430
	Electrical and mechanical service	462

Table 3. Waste plastics generation from various sources in Japan



*1 Pyrolysis includes cokes-oven treatment, blast furnace treatment and gasification.
*2 Incineration with power generation 1.84, incineration with heat recovery 0.36 and incineration without use of combustion heat 0.67 million tons.
*3 Incineration with power generation 1.18, incineration with heat recovery 0.66 and incineration without use of combustion heat 0.30 million tons.
*4 Incineration with power generation 3.03 (32%), incineration with heat recovery 1.03 (11%) and incineration without use of combustion heat 0.97million tons (10%).

Figure 3. Material flow of waste plastics in Japan (2010)

Table 2 shows waste-plastic generation from various sources. Some figures are based on actual collection amounts, and some are estimated amounts based on the references cited in the latter. The target wastes of the containers and packaging recycling law is the containers and packaging that made of paper, glass, metal and plastics in general wastes. For waste plastics of containers and packaging in general wastes, PET bottles, food tray made of expanded polystyrene sheet and mixed plastics of the other plastics are separately collected by municipalities. The containers and packaging recycling law allows a municipal government to decide on the separation rules for the collection of municipal wastes.

In Entry 1 of Table 2, annual PET generation is estimated as 594,689 tons (fiscal year 2010), which is given by the total sales of PET bottles including the sales of domestic products (579,782 tons) and imported products (14,907 tons) [8]. The total sales of PET bottles are the weights of PET resin that does not include screw caps and labels of non-PET plastics. The breakdown of PET in general wastes is based on the current status of implementation of PET-bottles collection by municipalities under the Containers and Packaging Recycling Law in FY 2010 (Table 3) [9]. The recycled amount of PET bottles, 286,009 tons, corresponds to PET-resin production from PET bottles in general wastes. If all municipalities implements PET-bottles collection, the expected recovery from general wastes by municipalities is 290,364 tons (=286,009 tons collection / 0.985 population coverage). The difference between the total sales of PET bottles and expected total recovery from general wastes is 305,000 tons, which would correspond to PET in industrial wastes.

The generation amount of mixed plastics is 1,155,000 tons (=705,707 tons collection / 0.611 population coverage), which is plastic containers and packaging other than PET bottles and plastic trays. In a waste sorting facility of a municipality, mixed plastics are compacted to prepare a cubic bale for the cost-effective transportation. The bale often contains serious amounts of contaminants such as metals and moisture. Table 4 shows an example of the composition of a bale that used for the life cycle assessment of waste-plastics recycling [10]. If the plastic content of mixed plastics that are collected under the containers and packaging law is 90.1%, the total plastic amount is 1,040,658 tons (= 1,155,000 × 0.901).

There are 1,742 municipalities in Japan (April 1, 2012). As shown in Table 4, 61.6 % of all municipalities adopted separate collection and recycling rules for mixed plastics under the Containers and Packaging Recycling Law. The other municipalities adopt incineration of mixed wastes or landfills avoiding the high cost of collection and handling because the recycling law in Japan still allows a municipality to choose mixed collection of waste plastics with the other general wastes for incineration or separate collection of waste plastics for recycling. Due to the economic benefits of PET recycling for municipalities, the implementation rate of separate collection and recycling of PET bottles reaches to 99.1% of the whole municipality, population coverage 99.5% under the same scheme of the recycling law.

About 4.16 million end-of-life-vehicles (ELV) generates in 2011[11]. When mean contents of plastic parts is 8 wt% [12,13] and averaged weights of ELVs are assumed as 1,200 kg, waste plastics generation is 399 thousand tons per year, which includes plastics with commercial values as replacement parts and automobile shredder residues without any commercial value. Waste plastics generation from automobiles are estimated as 399 thousand tons a year (= 4,160,000 × 1.2 ton × 0.08). Disassembly of ELV and crushing process give automobile shredder residue (ASR) of 584,305 ton in FY 2007 [14]. Typical composition of ASR is as follows: Plastics of non-polyurethane 33, polyurethane 16, textile 15, rubber 7, wood 3, paper 2, iron 8, non-ferrous metals 4, wire harness 5, glass 7 (wt%) [15]. Thus, the generation amounts of plastics of non-polyurethane and polyurethane are estimated as 193 and 93 thousand tons, respectively.

The Home Appliance Recycling law provides safe treatment and effective recovery of valuable materials from the five home appliances, air conditioners, television sets, refrigerators/freezers, washing machine and clothes dryers [16]. Personal computers are also encouraged to collect for recycling, but total weights of plastics are not clear.

In the fiscal year 2006, the total recovery of plastics was 102,257 ton was recycled with commercial values. The recovered plastics are further processed in mechanical recycling (60,020 ton, 59%), energy recovery (as crushed plastics 1,400 ton, 1%; as RPF 4,800 ton, 5%), and the rest (36,037 ton, 35%) was disposed [17]. In the fiscal year 2010, the total amount of recycled plastics was 181,884 ton [18]. The details of recycling are not announced. Polyurethane is widely used as heat insulation, and this is a major material that is not suitable for any type of recycling application but incineration with special attention to the complete combustion of fluorocarbons in polyurethane.

Aizawa et al. estimated the annual generation of the wastes of small electrical and electronic equipment, and estimated the total plastics as 20,000 ton [19]. The estimate is based on the equation of a typical content times shipment of video cassette recorder, DVD player, video camera, digital camera, flash memory player, HDD-equipped audio equipment and gaming equipment in 2007. The paper gave the estimated amounts of various metals and plastics of the potential resources.

There are the other sources of waste plastics. Recycling laws targeting various types of waste plastics would be considered based on the lifestyles of each country. Following to the recycling of waste plastics of containers & packaging, the more efforts will be considered to expand recycling activities. Substantial amounts of plastics are also used as daily commodities such as kitchen utensils and clothes cabinets. Plastics are also one of the main components of toys and E-wastes (wastes of electric and electronic equipment), which have been treated by landfill. Considerable amounts of plastic products are imported to the Japanese market. The amount of those imported plastic products is not clear. As an agriculture material, plastic film is a widely used product. Mulching, tunnel and green house are the typical uses in agriculture. As shown in Table 5, the current methods for the treatment of these plastic films are incineration, landfill and recycling including mechanical recycling and production of solid fuel [20]. The details of recycling application are not clear in the report. Waste generation data from industry has been collected through questionnaire survey by the plastic waste management institute [21,22].

Waste item	Collection, tons	Amount of recycled plastics, tons	Number of municipalities under implementation	Implementation rate to the total number of municipalities, %	Population coverage, %
PET bottles	296,815	286,009	1,711	97.8	98.5
Food tray	3,242	2,959	505	28.9	35.8
Other plastics (mixed plastics)	705,707	668,775	1,078	61.6	61.1

Table 4. Current status of the implementation of waste plastics under the containers and packaging law in the fiscal year 2010

Plastics	Percent weight
Polyethylene	30.2
Polypropylene	21.1
Polystyrene	17.7
PET	13.8
PVC	4.9
EVA	2.4
Metals	2.6
Moisture	7.3

Table 5. Typical composition of composition of mixed plastics

Treatment method	Polyethylene	PVC	Others
Recycling	43,128	30,373	2,831
Incineration	4,831	2,278	1,460
Landfill	10,416	8,404	4,846
Other	4,403	1,797	451

Table 6. Treatment of used agriculture films in the fiscal year 2008 (unit: ton)

Table 6 shows the typical gate fees of waste plastics by various treatment methods. Gate fee is a payment from a waste generator to a waste management company for waste treatment often including transportation cost. When the waste has a commercial value, a waste management company buys and sells it after a suitable processing. When a waste has a commercial value of higher than transportation cost, it is usually considered to be a commercial article rather than waste. Business sectors can handle them without any license or permission of business or facility installation for transportation, treatment or the other commercial dealing.

Waste plastics from general wastes such as containers and packaging contain various types of plastics such as a sheet, film, bag and bottle of polyethylene, polypropylene, polystyrene, polyamide and PET. And many items are laminates of two or more plastics, paper or aluminum. The recycling cost increase due to these complex compositions of mixed plastics as a feedstock of recycled resins. There are many business sectors buying thermoplastics of good quality for recycled resin production. Waste plastics, especially polyethylene, propylene, polystyrene, PET and PVC, are exported to China over some 1.5 million tons per year. In 2011, 1.6 million ton of waste plastics of commercial values were exported to mainly China for mechanical recycling (Table 7) [25]. China's country share as the exporting destination is 1.48 million ton (90.5 % of total exported amounts from Japan), which includes the mainland 890 thousand ton and Hong Kong 586 thousand ton. Polypropylene is considered as the major component of the waste plastics defined as "the other plastics."The mean price of the waste plastics is 46 yen/kg. It is varied depending on the conditions of wastes plastics. Generally, shredded, clean and colorless plastics are of the higher commercial value.

Entry	Treatment method or products	Type of waste plastics*	Gate fee** yen/kg	Remarks
1	Mechanical recycling	Mixed plastics, C&P recycling law (household) PET Bottles, C&P recycling law (household) Industrial wastes of good quality	70 ▲49 ▲20-30	Ref.[23] Ref.[23] Hearing
2	Solid fuel (RPF)	Industrial wastes of moderate quality	20-25	Hearing
3	Blast furnace treatment	Mixed plastics, C&P recycling law (household) Mixed plastics from industry	34 35	Ref.[23] Ref.[22]
4	Cokes oven treatment	Mixed plastics, C&P recycling law (household) Waste plastics from industry	45 35	Ref.[23] Ref.[22]
5	Liquid fuel production	Mixed plastics from household Mixed plastics from industry	80-100 30-40	Hearing Hearing
6	Gasification	Mixed plastics, C&P recycling law (household)	31	Ref.[23]
7	Cement kiln treatment	Industrial wastes of moderate quality	10	Ref.[22]
8	Incineration with power generation	Mixed wastes from household Mixed wastes from industry	13-17 35-50	Ref.[24] Ref.[22]
9	Incineration (no energy recovery)	Mixed wastes from household Mixed wastes from industry	19 30	Ref.[24] Ref.[22]
10	Landfill	Industrial plastic wastes	8 yen/m^3	Ref.[22]

*C&P designates containers and packaging.
**The symbol "▲" designates payment from a waste business sector to a waste generator.

Table 7. Examples of the gate fees of waste plastics by various treatment methods

Waste plastics	Amount, ton	FOB price*, thousand yen	Mean price, yen/kg
Polyethylene	360,779	15,383,077	42.6
Polystyrene	252,337	11,415,978	45.2
PVC	90,233	2,730,090	30.3
PET	392,291	22,375,368	57.0
Others	535,815	23,339,954	43.6
Total	1,631,455	75,244,467	46.1

*Free On Board. The seller of goods pays for transportation of the goods to an exporting port and the loading cost. The buyer covers the transportation cost after loading on a ship.

Table 8. Export amounts and prices of exported waste plastics from Japan (2011)

The apparent treatment cost of incineration is very low (entries 8 and 9 of Table 6). Substantial subsidies from the national government make the construction cost of an incineration plant lower than the other recycling methods such as mechanical recycling and liquid fuel production. Different from a recycler as a private company, municipalities use the different accounting system, in which fixed costs are not involved in the treatment cost. The actual cost would be 35 - 50 yen/kg by accounting construction costs of incineration plants. The lower apparent cost of incineration derives some municipalities to incinerate mixed wastes rather than recycling.

2.2. Legislation system for recycling waste plastics

To establish a sustainable society throughout Japan, the Basic Law for Establishing the Recycling-based Society as the basic framework. It is also called as the Sound Material-Cycle Society. Table 8 lists the laws for waste management and recycling [26]. Under the individual recycling laws, each targeted wastes have been recycled for several years.

For waste plastics recycling, there are some differences of the preferred recycling and business system among several recycling laws. For example, mechanical recycling is preferred in the Containers & Packaging Recycling Law, but heat recovery through incineration is allowed in the ELV recycling law. The contract system is different between the plastic mixed wastes under the Containers & Packaging Law and the other plastic wastes such as ELV and home appliances. Recyclers receive the mixed plastic wastes based on the competitive bidding among recyclers of mechanical recycling. When the additional amounts of wastes are left, the second bidding will be held among the recyclers of feedstock recycling. The contractor is fixed by each stock yard. The contract is for one year. In the treatment of ELV and wastes of home appliances, limited numbers of waste management companies constantly receive the wastes in connections with automobile manufacturers or home appliance manufacturers. There are strong arguments on the C&P recycling from many stakeholders in the points of recycling cost, bidding system with the preference of mechanical recycling to the other methods and participation of the recyclers of solid fuel production. We also started a discussion for widening the coverage of waste plastics to plastic articles such as dairy necessaries, toys and electronic equipment.

3. Technologies and businesses of waste plastics recycling

3.1. Recycled resin production

Recycled resin or recycled plastic goods are produced from 2.17 million ton of waste plastics (Figure 3). Some 1.6 million ton of waste plastics are exported (Table 7). These plastics are considered to go to mechanical recycling. The difference between 2.17 and 1.6 million is about 600,000 ton, which is the feedstock for recycled resin in the domestic market. The domestic demands for recycled resin are quite weak than ones in China.

Many Japanese manufacturers tend to avoid the use of recycled resin, especially from mixed waste plastics of containers and packaging because of the low quality such as strength, color

Law	Content
Basic law for establishing the recycling-based society	Basic framework determining the role of stakeholders for establishing the sound material-cycle society.
Waste management and public cleansing law	Defines municipal wastes and industrial wastes. The roles and duties of a municipality, waste generator, waste management company, and other stakeholders are strictly provided. The related regulations and rules define both technical and social conditions and guidelines to keep the sound business in addition to construction of a facility, installation and operation of equipment.
Law for promotion of effective utilization of resources	Promotion of waste reduction through recycling. The roles and duties of the stakeholders are mentioned. Promoting reduction of wastes through recycling and suitable disposal in several fields of industries and products such as steel production, paper production, construction, automobile, electric and electronic equipment, batteries, metal cans and PET bottles.
Containers and packaging recycling law	Promotion of recycling containers and packaging through separate collection of those wastes made from paper, metal, glass, PET and the other plastics by municipalities with cooperation of citizens. Producers of the material, manufacturers of the commercial products with containers and packaging and retail stores cover recycling costs. Recycling methods are provided in the related regulations.
Electric household appliance recycling law (Home appliance recycling law)	Forcing consumers to give wastes of home appliances to retailers with paying recycling fees. Air conditioner, refrigerator/freezer, television set, washing machine and cloth dryer are recycled with suitable treatment of fluorocarbons and other potential hazardous substances.
End-of-life vehicle recycling law	Forcing car owners to cover the cost for suitable disposal of hazardous wastes and wastes of no commercial value with recovering valuable resources from end-of-life vehicles.
Construction material recycling act	Reducing the amounts of construction and demolition wastes through recycling.
Food recycling law	Reducing the amounts of food residues from restaurants, food processing industry and supermarkets through recycling waste foods.
Law on promoting green purchasing	Promoting the national and local governments to buy products that made from recycled materials.

Table 9. Major laws for waste management and recycling

and smell. As a result, the selling price of recycled resin pellets (typically, a mixture of polyethylene and polypropylene) from the mixed waste plastics is generally very low, 20 to 40,000 yen/ton, whereas the recycling cost of mixed waste plastics is 72,000 yen/ton in average due to the contamination of various components that are not suitable for the production of recycled pellets. The recyclers convert the separated portion of mixed waste plastics into recycled pellets or recycled products such as transportation pallets and imitation wood at about 45 wt%, and the rest goes to incineration with heat recovery or solid fuel production with paying gate fees.

Some recyclers for plastic containers and packaging from general wastes make the efforts to raise the market value of recycled resin. There are three countermeasures for it. One is to change separation categories of waste collection by municipalities, for example, a separate collection of hard plastics like HDPE bottles and laminated soft plastics. The second is to introduce a sophisticated material sorting facility with optical sorting equipment under the cooperation with municipalities. Stable supply and constant production of recycled resin will be possible by the more precise selection of suitable plastics for mechanical recycling at the larger scale. The third is to develop a new application in cooperation with many companies in the wider business fields across many countries.

To improve the quality of recycled resin, collection of hard plastic wastes and recycled resin production with hard plastic wastes were conducted as a research by Akita Eco Plash Co., Ltd. in cooperation with Akita prefecture and Noshiro city authorities based on funding by the New Energy and Industrial Technology Development Organization (NEDO) [27]. Recycled resin has low melt-flow rate (MFR) because the original form of the polyethylene and polypropylene that recovered from C&P wastes is film and sheet. But the major products from recycled resin are not film or bag but hard plastic products. When hard plastic wastes of non C&P wastes were added to recycled resin of C&P at 10 %, the MFR was improved from 3.2 to 3.8. This result suggests the improvement of the qualities of recycled resin and products with reducing an additive. Minato-ward authority in Tokyo has a total collection system of plastic C&P wastes with the wastes of hard plastic products in the criteria of "Resource Plastics."The collection of the wastes of plastic products increased the collection amount of polypropylene in hard plastic wastes [28], and it will help the MFR, which leads to the reduction of additives and cost reduction.

Home appliance manufacturers and automobile manufacturers are actively seeking the idea and technologies to raise the recycling rate of the waste plastics recovered from their wastes. Electric appliance manufacturers have been made efforts the cost reduction of their products. They took actions in recycling waste plastics in the products to reduce the waste amounts. Additionally, some companies started commercial operation of the precision separation system of some plastics by applying the difference of electrostatic properties of plastics [29]. In 2010, Green Cycle Systems Corporationl aunched Japan's first large-scale, high-purity plastic recycling center under the technical and business support by Mitsubishi Electric Corporation. The announcement states that Green Cycle Systems takes the shredded mixed plastic chips recovered by Hyper Cycle Systems and separates them into reusable plastic on a scale of unprecedented magnitude. And it also tells that the combined output of these two enterprises have increased Mitsubishi Electric's rate of recycled, industrial-grade plastic from 6% to a paradigm-shifting 70%.

3.2. Refuse-derived solid fuel

There is a variety of solid fuel that has been prepared from wastes, which include wood, straw, rice husk, garbage from households, plastics and so on. To control moisture contents, some processes such as drying and carbonization are often performed. Any non-hazardous combustible wastes can be used as the raw material for solid fuel with or without preparation of pellets and briquettes. Preparation of pellets and briquettes contributes to constant quality of heating values, easy transportation and smooth feeding to a combustor such as a boiler.

Table 9 shows the heating values of various combustible wastes and fuels [30-33]. Waste plastics have high heating values, and coal substitutes can be prepared by mixing them with the wastes of low heating values. Thermoplastics act as a suitable binder, and paper, textile and thermosetting plastics can form pellets and briquettes despite to their properties that they are not solidified each other.

Waste	Higher heating value MJ/kg	Reference
Polyethylene	47.7	[30]
Polypropylene	45.8	[30]
Polystyrene	43.7	[30]
Poly(methyl methacrylate)	26.9	[30]
Poly(ethylene terephthalate)	24.1	[30]
RPF	>25	[31]
RDF	>12.5	[32]
Diesel oil	37.7	[33]
Heavy oil	39.1	[33]
Coal	25.7	[33]

Table 10. Heating values of combustible wastes and fuels

From municipal wastes includes kitchen wastes, refuse-derived fuel (RDF) are used in various countries over US [34], Europe [34,35] and Japan [36]. It is also called as solid recovered fuel (SRF). In 2005, RDF was produced from general wastes in 58 facilities [37]. There are 27 facilities are cooperated with power generation plants and the feedstocks are collected from 92 municipalities. Table 10 summarizes the compositions of municipal wastes in Japan and the properties of RDF [36]. A specification guideline of RDF is shown in a technical specification document of the Japanese Industrial Standard as shown in Table 11 [38]. Typical dimension of RDF briquettes is 10 - 50 mm diameter and 10 - 100 mm length. A simply-densified brick and crashed product are not considered as RDF in this guideline.

Prefecture	Ishikawa	Mie	Fukuoka	Ibaraki
Area	Hakui	Kuwana	Omuta-arao	Kashima
Municipal waste composition				
Paper, textile, %	60.6	62.7	42.0	58.7
Wood, %	3.4	6.1	5.3	4.4
Plastics, rubber, %	23.7	6.5	27.3	17.4
Kitchen wastes, %	9.8	24.1	16.3	5.2
Incombustibles, %	0.0	0.0	2.5	10.3
Others, %	2.6	0.6	6.6	4.0
RDF properties				
Moisture, %	2.3	3.3	6.0	4.4
Combustibles, %	85.4	83.0	81.0	84.8
Ash, %	12.3	13.7	13.0	13.7
Higher heating value MJ/kg	17.5	17.3	19.6	19.0
Lower heating value MJ/kg	17.3	15.8	18.0	17.5
Total chlorine, %	0.56	0.70	0.10	0.78

Table 11. Typical compositions of municipal wastes in Japan and the properties of RDF

Category	Specification
HHV	>12.5 MJ/kg
Moisture	<10 %
Ash	<20%

Table 12. Specification of RDF in TS Z 0011:2005.

We need technical countermeasures to the formation of hydrogen chloride and dioxins upon combustion of RDF due to chlorine-containing plastics and salt. The specification in Table 9 does not mention anything about chlorine content because of the difficulty of the removal of chlorine from municipal wastes. Due to the low heating value and high contents of ash and moisture, RDF is considered as low-quality fuel. There are not so many users of RDF except the power generation plants in the cooperation with municipalities.

Different from RDF, densified solid fuel called as RPF (Refuse derived paper and plastics densified fuel) are popular as coal substitutes. Recently, the specification was defined in the Japanese Industrial Standards (Table 12) [32]. It is produced by using paper, wood, plastics, textile and the other wastes. The raw material is dry and non-hazardous combustibles. It does not include any putrefactive wastes. About 1.6 million ton of RPF was shipped to, mainly, paper and steel manufacturers as coal-substitute for coal-combustion boilers in 2011 [39].

Category	Specification in JIS*	Analytical value of RPF	Analytical values of coal
HHV, MJ/kg	>25 or 33	27.6	26.9
Moisture, weight %	<3 or 5	2.75	7.9
Ash, weight%	<5 or 10	5.54	8.5
Total chlorine, weight%	<0.3 - 2.0	0.25	-
Nitrogen, weight%	-	0.54	1.35

*Four classes are defined depending on the values in the category. JIS Z7311:2010.

Table 13. Specification guideline of RPF in JIS and typical analytical values of RPF and coal

It is possible to vary the calorific value of solid fuel in the range of 5,000 - 10,000 kcal/kg by controlling the ratio of input paper and plastic. A 50:50 mix, for example, provides a calorific value of 6,190 kcal/kg (measured LCV), which is about the same as that of coal. Use of RPF as an alternative to fossil fuel helps to reduce CO_2 emissions and is considered environmentally friendly.

The most serious trouble in the use of RPF is the formation of hydrogen chloride upon combustion and the resulting corrosion of equipment in the RPF users. Some users often stop purchasing RPF because of the high chlorine content.

3.3. Liquid fuel

Some thermoplastics, for example polyethylene, polypropylene and polystyrene, are thermally decomposed under an inert gas to yield liquid hydrocarbons at about 450 °C or above [40]. The resulting liquid hydrocarbons have the similar heating values to those of fuels from petroleum.

Decomposition products and fuel quality depends on the types of plastics and decomposition conditions. Polyamides and polyurethane give oily products of high nitrogen content at low yields. Poly(ethylene terephthalate) known as PET does not give liquid hydrocarbon upon pyrolysis but solid products including terephthalic acid.

Many types of reactors of tank, screw, externally-heating rotary kiln and fluidized-bed are developed. Some plants were used in demonstration, and some are commercially operated in Japan [41]. Under the containers and packaging law, mixed plastics were converted into fuel oil through pyrolysis using a 20-ton/day tank reactor in Niigata and four 10-ton/day rotary kilns in Sapporo until recently. Those commercial operations were shut down due to the higher cost (about 80 yen/kg) than the other treatment costs like that of cokes oven treatment (about 40 yen/kg).

However some recyclers bearing pyrolysis plants commercially produce liquid fuel from plastics of industrial wastes. Most recyclers have a tank reactor with a simple distillation system (Figure 4). In 2011, a recycler in Fukuoka prefecture started fuel oil production using a pyrolysis reactor with a paddle mixer (Figure 5). This reactor is commercially operated for mixed plastics from a separate collection of municipal wastes. The product fuel mixed with commercial fuel at 1:1 is used for the boilers in public facilities.

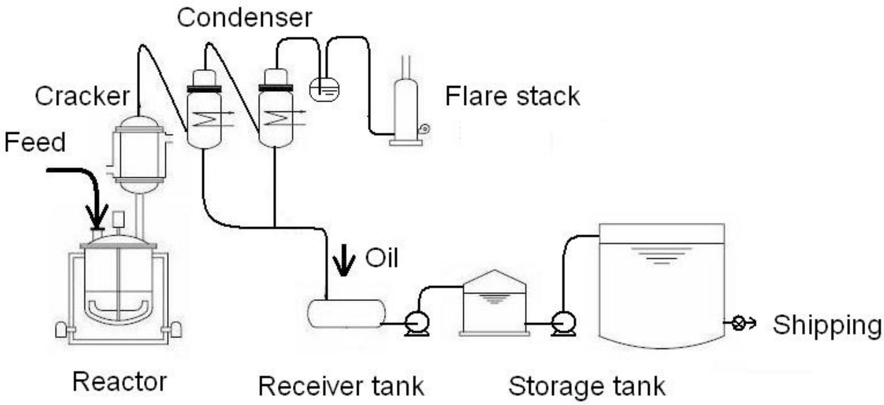


Figure 4. Typical layout of a liquid fuel production plant equipped with a tank reactor.

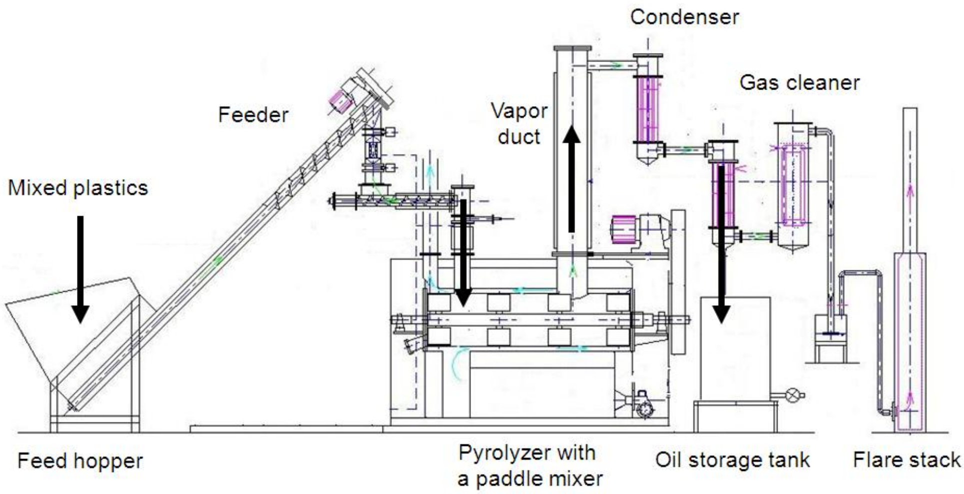


Figure 5. Fuel production system of a pyrolyer with a paddle mixer. Copyright ECR Co., Ltd.

Currently, there is no specification standard of liquid fuel from waste plastics because it is not widely produced. Table 13 summarizes the technical specification that were announced by the Japanese Industrial Standards Committee and expired in 2010 [42]. Table 14 shows typical specifications of plastics-pyrolysis oil, commercial diesel fuel and heavy oil.

Category	Value
Ash	<0.05 %
Total chlorine	<100 ppm
Sulfur	<0.2 %
Nitrogen	<0.2%
Water	No water layer separated from oil
Viscosity, pour point and residual carbon	Depend on consent agreement

Table 14. Specification of pyrolysis oil from waste plastics in TS Z0025:2004

Category	Whole distillate of pyrolysis oil	Middle distillate of pyrolysis oil	Kerosene	Heavy oil Grade A
density (15 °C), g/cm³	0.8306	0.8430	0.8284	0.8511
flash point, °C	-18 (PM)	68.0 (Tag)	69.0 (Tag)	64 (PM)
kinematic viscosity, 30 °C/50 °C, mm²/s	1.041/-	-/1.73	3.822/-	-/2.29
Residual carbon 90% distilled, wt%	-	0.85	0.01	0.46
Ash, wt%	0.00	<0.001	-	0.006
HHV, MJ/kg	47.2	44.9	45.5	44.8
Total Cl, wt ppm	47	10	<1	1.6
Nitrogen, wt%	0.14	0.033	-	0.015
Sulfur, wt ppm	100	910	310	0.41 %
Cetane value	27.0	42.9	58.4	46.3
Distillation range, °C				
Start point	47.0	180.0		164
10%	69.0	199.0		195
50%	148.0	233.0		276
90%	294.5	323.5	344.0	347
End point	374.0	351.5		>370

Table 15. Typical specifications of pyrolysis oil from plastics and commercial fuels

There are two major methods of thermal decomposition of plastics. One is pyrolysis and another is catalytic decomposition. Acidic catalyst such as silica-alumina and zeolite are used in the latter case. A decomposition temperature range is lowered to around 400 ˚C comparing pyrolysis temperature 450 to 550 ˚C. Advantage of catalytic decomposition is in the lower energy consumption for decomposing polymers. Disadvantage is the economic expense of purchasing catalysts, regeneration or disposal of waste catalyst. Catalytic decomposition often yields a large amount of gasoline fraction in certain reaction conditions. In this case, the product oil is not suitable for the use of diesel engines or heavy oil burners if the product oil is used without distillation. It is noteworthy that plastics pyrolysis oil does not contain lubricant portion. There is little knowledge on mechanical durability of an engine cylinder and a fuel injection pump of a burner in the use of plastics-derived oil. Mixing with a lubricant or commercial fuel is highly recommended by practitioners and.

Under the containers and packaging law, some recyclers constructed pyrolysis plants to convert mixed plastics into fuel oil. About thirty companies introduced such plants since 2000, when collection and recycling of mixed plastics started under the recycling law. There were three large-sized plants (20 to 40 ton/day) and the others were small-sized plants (1 to 1.5 ton/day). After ten years practice, all plants were shut down. Fuel oil production in the small scale costs high, and the large scale production also had a difficulty to collect such a large amount of waste plastics under the gate fee competition [43]. On the other hand, middle-sized plants of about 3 to 6 ton/day capacity are commercially operated for pyrolysis of industrial wastes. Recently, a waste management company in Fukuoka started new middle-sized plant for fuel oil production from separated waste plastics from the municipalities nearby in order to supply the fuel to public facilities.

3.4. Gaseous fuel

Gaseous products from pyrolysis of waste plastics are categorized into two major types. One is syngas, a mixture of hydrogen and carbon monoxide [44]. Another is gaseous hydrocarbon such as methane and ethylene [45]. Depending on gasification conditions, a mixture of hydrogen and methane will be obtained [46].

Gas composition depends on temperature of a reactor, residence time of decomposing species during gasification of plastics, and other reaction conditions, which are often governed by a reactor structure. Syngas is originally for the production of methanol from hydrogen and carbon monoxide, or ammonia from hydrogen. However, syngas, a mixture of hydrogen and carbon monoxide, is also used as gaseous fuel in some facilities for generating electricity.

Table 15 summarizes the compositions of pyrolysis gas from waste plastics and the gases generating in steel production facilities. Gasification plants in Ciba city produces syngas at the scale of two series of 150 ton/day, and it is used for power generation in the adjacent steel manufacturer through combustion. The two-stage pressurized process in Ube city for mixed plastic wastes under the container and packaging law was already shut down due to the higher operation cost comparing with that of the other methods such as cokes oven treatment.

Gasification technology covers not only waste plastics and the other combustibles in municipal wastes but also biomass and automobile shredder residue (ASR).

There is another type of gasification for the production of gaseous hydrocarbon. Thermal treatment of polyethylene and polypropylene at about 600 °C or above with the residence time around 20 min gives gaseous hydrocarbons mainly. The initial decomposition products

	Heating value High/Low (MJ/Nm^3)	Composition (Volume%)							
		CO	CO_2	H_2	CH_4	C_2H_2	C_2H_6	O_2	N_2
Plant / waste source	Thermoselect method*, Chiba city / Combustibles from municipal waste								
	8.0 / 7.4	32.5	33.8	30.7					2.3
Plant / waste source	Thermoselect method*, Chiba city / Combustibles from industrial wastes								
	9.6 / 8.9	43.1	18.8	32.4					
Plant / waste source	Two-stage pressurized process of EUP**, Ube city / Mixed plastics separated from municipal wastes								
	8.1 / 7.7	30-35	20-25	40-45	0				4-7
Plant / waste source	By-product gases in steel production facilities / Coal								
Cokes oven gas Blast furnace gas Converter gas	21.1 / 18.7 3.1 / 3.1 8.2 / 8.2	6.9 24.1 64.4	2.4 20.5 15.0	56.1 2.7 1.8	27.6	2.8	0.4	0.2	3.6 52.7 18.8

*Ref.[47]. **Ref.[48,49].

Table 16. Compositions of pyrolysis gas from waste plastics and the gases in steel production facilities

of plastics are liquid hydrocarbon, and the further heat transfer to the vaporized portions results in the conversion of vaporized hydrocarbons into gaseous hydrocarbons of methane, ethylene, ethane, propylene, propane, and the other gaseous hydrocarbons with the formation of liquid hydrocarbons at about 10 to 20 %. This is still in research stage to demonstration stage [45].

Applying the effective heat transfer of a heating medium in an external-heating rotary kiln, waste polyethylene was gasified in the coprocessing with asbestos-containing waste building material. The resulting flammable gas was used as fuel for a heating gas to melt asbestos(Figure 6) [46].In asbestos removal works, waste polyethylene generates as protective clothing and shielding curtain Addition of a flux to asbestos-containing demolition wastes makes the melting range of asbestos at 800 to 900 °C. At the similar temperature range, polyethylene was readily converted into a mixture of hydrogen, methane, ethylene and other hydrocarbons. The gaseous products were supplied to a furnace to generate heating gas for the pyrolyzer of the asbestos melting system.

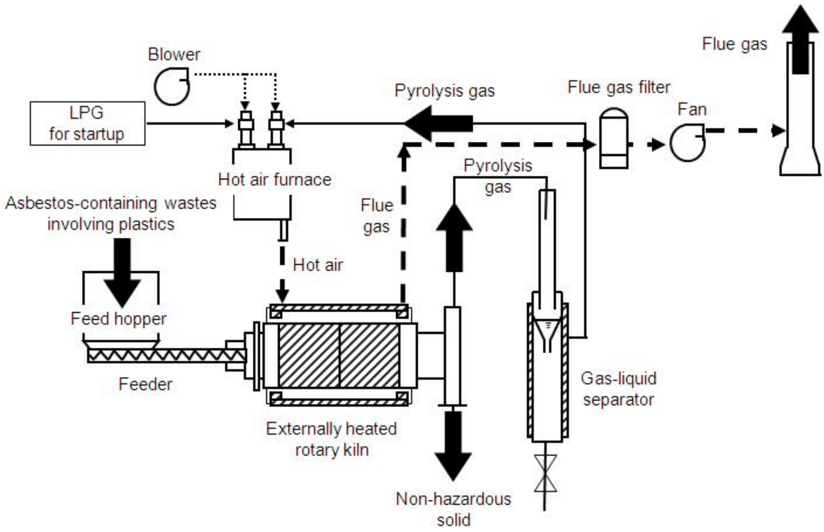


Figure 6. Gaseous fuel production from waste polyethylene in the coprocessing with asbestos-containing demolition wastes

4. Tasks for the future

Dissemination of recycling in the local societies and technology transfer to developing countries are of importance with respect to the promotion of the sustainability of the world. Life cycle assessment has been recognized as an important tool for judging how a certain product or a manufacturing process is green. For the transfer of waste plastics recycling technology, the technology should be socially and economically accepted by the stakeholders in developing countries.

Technology providers should develop the technologies of suitable specifications and easy operation with being aware of the local conditions. For example, a plant size should meet average collection amounts of target components of wastes. Table 16 shows an average generation amounts of waste plastics in each factory.

The average amounts 2.8 and 6.8 ton/day suggest a general idea of the suitable capacity of the equipment for waste treatment. In Japan, strict laws and regulations, a waste management company has to have a special permission in case that a treatment facility or equipment has a capacity larger than 5 ton/day. The permission is given by a prefectural government after strict check of planning, inspection of the entire facility including equipment, buildings and yard. In addition, consensus building with local residents is required as the one of conditions of the permission by the local government. A long history of pollution problems and conflicts between a polluter and the local residents resulted in the severe conditions to both private companies and municipalities including waste management and recycling works.

Category	average amount of generation or treatment of waste plastics ton/day
Chemical industry	5.0
Manufacturer of plastic products	3.1
Manufacturer of rubber products	2.6
Manufacturer of electric machine	1.1
Manufacturer of transportation machine	1.8
Manufacturer of paper and pulp	3.2
Mean value of generation in one factory	2.8
Incineration facility for industrial wastes	3.3
Shredding facility for industrial wastes	6.9
Mean value of treatment in one facility	6.8

Table 17. Waste plastics generation in factories of manufacturing industry and waste management facilities

For waste plastic recycling, there is a limited pattern of successful business. It is a narrow pathway to connect waste plastics with a product of commercial value. The compositions, quantities and qualities of plastics determines a recycling method, system configurations and the business scale, which also leads to the type of the product with a certain commercial value. The product price, number of users and consumption are the important factors for establishing a sound flow of waste plastics recycling.

Technology assessment methodology has been discussed in UNEP [50,51], and its application to recycling technologies for waste plastics will be developed through the discussion among the stakeholders and experts. The promotion of technology transfer is fulfilled through the cooperative efforts among the experts of policies, economics, technologies and the people in local communities. The Global Partnership on Waste Management, an open-ended partnership for everyone was launched in November 2010 [52]. The more discussions and experiences are required to find the effective solutions for managing and recycling wastes to make our society sustainable.

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