Recycling Plastic Marine Litter

NOWPAP

Northwest Pacific Action Plan

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UNEP Regional Seas

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NOWPAP CEARAC 2007: Recycling Plastic Marine Litter.

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1. Introduction

Marine litter is a serious global problem, and is known to have significant environmental, economic, health and aesthetic impacts. In many cases, plastics are one of the most abundant components of marine litter, mainly due to its very slow rate of degradation and ever-increasing uses in our society. Figure 1 summarizes the findings of the marine litter survey conducted along the Japanese coast of the NOWPAP region in 2004.

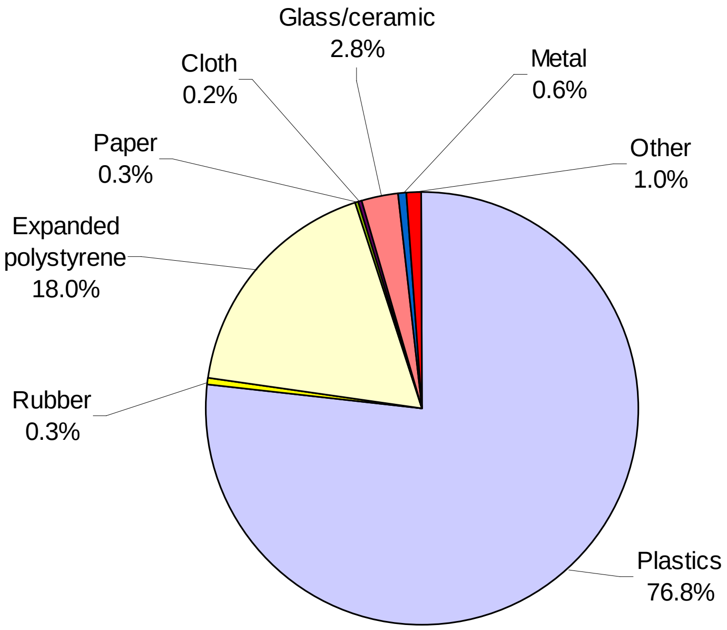


Figure 1　Composition of marine litter along the coast of Japan in 2004

Source: NPEC (2006); Report on the marine litter survey of the NOWPAP coastal area in 2004

The figure shows that almost 80% of the marine litter found was comprised of plastic products, and if we include expanded polystyrene, the proportion of plastic products would be almost 95%.

Although various countermeasures are now being implemented to remove plastic litter from the sea coast, such as beach clean-up activities, installation of marine litter containment booms and so on, significant problems still persist in treating/disposing of the collected litter. Common approaches include landfill and incineration, but these methods are not always ideal solutions due to limited landfill space and pollution risks.

One possible solution to the treatment of plastic marine litter is to apply the technologies of plastic recycling, which is now commonly employed to treat industrial and domestic waste plastics. For example, marine waste plastics can be recycled into plastic raw material, fuel oil, chemical feedstock and other products (see Chapter 3).

This booklet has been prepared, in recognition of the benefits of plastic waste recycling, to introduce the existing and developing plastic recycling technologies with the potential application for managing plastic marine litter. The booklet also describes some issues involved in recycling plastic marine litter, with some suggestions (see Chapter 4).

2. Basic knowledge of plastics

2.1 Production process of plastics

Although many types of plastic are currently manufactured for a variety of purposes, the raw material of these plastics is mainly derived from petroleum products, such as naphtha, which are extracted from crude-oil distillation.

When naphtha is thermally decomposed, simple molecules (monomers) such as ethylene, propylene, butane/butylenes and aromatics can be extracted. The raw materials of plastics are made when these monomers are chemically bonded into larger molecules called polymers (polymerization). Different types of plastics can be made by altering the combination of these monomers. Figure 2 shows an example of polymerization of ethylene into polyethylene.

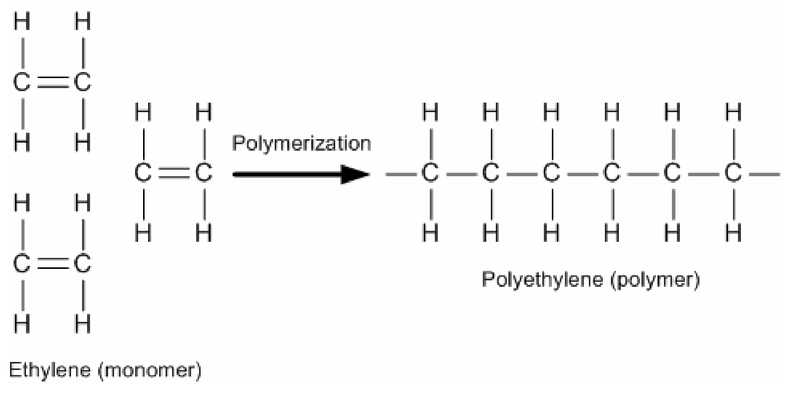


Figure 2 Polymerization of ethylene into polyethylene

Since these polymers are in powder or lump form, they are usually processed into pellets for easier handling. The final plastic product is then manufactured by processing (e.g. molding) the plastic pellets into various shapes and forms.

2.2 Types and characteristics of plastics

Plastics can be broadly classified into two groups: thermoplastics and thermosetting plastics. Thermoplastics can be repeatedly softened by heating and hardened by cooling, like candle wax. For this reason, thermoplastics can be remolded and reused almost indefinitely. Many types of thermoplastic products are manufactured to suit a wide range of purposes, such as for packaging, food containers and household products. More heat-resistant and durable thermoplastics are used in machines, automobiles and electrical goods.

Conversely, thermosetting plastics harden permanently after being heated. They are mainly used for products that require high heat resistance, because these plastics can be heated to high temperatures without melting. Table 1 shows some of the common thermoplastics and thermosetting plastics, and their main uses.

Table 1 Thermoplastics and thermosetting plastics and their main uses

	Plastic type	Abbreviation	Main uses
Thermoplastics	Polyethylene	PE	Packaging, agricultural film, construction sheeting
	Polypropylene	PP	Bathroom products, packing string
	Polystyrene	PS	Office appliances, CD cases
	Expanded polystyrene	EPS	Fish boxes, food trays, packaging
	Acrylonitrile-styrene (AS) resin	SAN	Tableware, lighters
	Acrylonitrile butadiene styrene (ABS) resin	ABS	Travel trunks, furniture, automobiles
	Polyvinyl chloride	PVC	Water pipes, hoses, agricultural film
	Polyvinylidene chloride	PVDC	Cling film, ham casing, artificial turf
	Methacrylic resin	PMMA	Headlight lenses, windshields, contact lens
	Methacrylic styrene resin	MS	Lenses, light covers, packaging
	Polymethylpentene	PMP	Microwave tableware, film packaging
	Polyamide (nylon)	PA	Fasteners, cogs, automobile parts
	Polycarbonate	PC	Lunch boxes, CDs, driers, bottles
	Acetal resin	POM	Fasteners, automobile parts
	Polyethylene terephthalate	PET	PET bottles, VTR tapes, egg boxes
Thermosetting plastics	Phenol resin	PF	Printed circuit boards, pan handles
	Melamine resin	MF	Tableware, laminates, paint
	Urea resin	UF	Buttons, caps, electrical products
	Unsaturated polyester resin	UP	Bathtubs, helmets, fishing rods
	Epoxy resin	EP	Electrical products, paints, adhesives
	Polyurethane	PUR	Cushions, mattresses, heat insulation

Source: Plastic Waste Management Institute (2004); An Introduction to Plastic Recycling

3. Plastic recycling technologies

Plastic recycling technologies can be typically classified into three methods: material recycling (or mechanical recycling), chemical recycling (or feedstock recycling) and thermal recycling (or energy recovery)[1]. General descriptions of the three recycling methods are provided in the following sections, and specific examples of each are given. Table 2 shows the recycling examples introduced in this Booklet.

Table 2 Types of recycling examples introduced in the Booklet

No.	Recycling products	Recycled products
Material recycling		
1	Industrial PE and PP waste plastics	Plastic pellets (used to produce other plastic products)
2	Waste fishing nets	Plastic pellets
3	Waste EPS floats	Polystyrene ingots (used to produce other plastic products)
4	Waste ABS floats	New ABS floats
Chemical recycling		
5	Waste EPS products	Polystyrene pellets (new EPS products)
6	Waste PE and PP products	Aromatics (raw material for chemical and medical products) and lower olefin (raw material of plastics)
7	Waste polyester products	Dimethyl terephthalate and ethylene glycol (raw material for plastics)
8	Tolylene diisocyanate (TDI) residues (TDI: raw material of polyurethane)	Toluenediamine (raw material for TDI)
9	Domestic waste plastics	Fuel oil
10	Waste PE, PP, PS plastics	Fuel oil
11	Low-grade oil produced from waste plastic recycling	High-grade oil
12	Domestic and industrial waste plastics	Reducing agent of blast furnaces
13	Waste vinyl chloride products	Hydrocarbons (reducing agents for blast furnaces), hydrogen chloride (used by

[1] These terms (material recycling, chemical recycling and thermal recycling) will be used in this booklet, although other terms might be used elsewhere.

		the steel and chemical industries)
14	Waste plastics except for vinyl chloride plastics	Coke (reducing agent for blast furnaces), hydrocarbon oil (chemical feedstock for plastic manufacturing), coke oven gas (power generation)
15	All types of waste plastics	Synthetic gas (hydrogen, carbon monoxide)
Thermal recycling		
16	Various wastes, including plastics	Fuel for power plants
17	Industrial and domestic waste plastics, wastepaper, wastewood	Refuse Paper and Plastic Fuel (RPF) used as fuel for power, paper, steel and cement plants
18	Industrial waste plastics	Fuel for cement manufacturing
19	Old or abandoned small FRP (Fiber Reinforced Plastic) vessels	Fuel for cement manufacturing

3.1 Material recycling

Material recycling is a method where waste plastics are reprocessed into a similar or different plastic product without modifying the initial chemical structure. In this process, waste plastics are initially processed into ingots or pellets through melting, shredding or granulation. The ingots or pellets are then processed into new plastic products. Figure 3 shows some examples of plastic products generated through material recycling.

Figure 3 Examples of recycled plastic products through material recycling

Source: Plastic Waste Management Institute (2004); An Introduction to Plastic Recycling 2004

1) washbowl 2) road bollard 3) imitation wood post 4) pallet 5) anti-weed sheeting 6) heat/sound-insulating sheeting 7) PVC pipe 8) water-butt lid 9) colored box 10) central reservation block 11) parking block 12) duckboard 13) survey and boundary markers 14) bricks 15) cross-ties for steel products 16) video cassettes 17) weight for a colored cone 18) plant pots

To produce high quality pellets or ingots, waste plastics must be sorted into the same plastic type prior to the processing stage. Impurities, dirt and foreign objects must also be removed. For these reasons, material recycling has mainly targeted industrial waste plastics because they are clearly separated into plastic type, contain low levels of impurities and are available in large quantities. On the other hand, more contaminated plastics such as in the domestic waste are usually, hard to differentiate and the supplies are unstable. However, the recycling rate of domestic plastic wastes such as PET bottles and food trays are increasing due to the establishment of new laws/regulations and advancements in recycling technology.

Table 3 summarizes examples of material recycling products introduced in the following sections. Each material recycling example is introduced in Tables 4.1-4.4.

Table 3 Material recycling examples introduced in this booklet

Table no.	Recycling products	Recycled products
4.1	Industrial PE and PP waste plastics	Plastic pellets (used to produce other plastic products)
4.2	Waste fishing nets	Plastic pellets
4.3	Waste EPS floats	Polystyrene ingots (used to produce other plastic products)
4.4	Waste ABS floats	New ABS floats

Table 4.1 Examples of material recycling (1)

	Contents
Type of Recycling	Processing of industrial polyethylene (PE) and polypropylene (PP) waste plastics into plastic pellets and products
Recycling Products	Industrial PE and PP waste plastics (e.g. containers, films, pallets, tanks, etc.)  Examples of industrial waste plastics Source: Website of Kawase Co., Ltd (http://www.eco-kawase.co.jp/department/recycle02.html)
Recycled Products	- Plastic pellets (graded by material quality, heat resistance, color, purity, etc.) - Plastic pellets are processed into plastic products such as flowerpots, baskets, plastic lumber, wood-like plastic benches/tables etc.  Examples of recycled products Source: Website of Kawase Co., Ltd (http://www.eco-kawase.co.jp/department/recycle02.html)
Recycling Process	1) Collection of PE and PP plastic waste from factories 2) Pretreatment of collected plastic waste (removal of foreign objects, crushing and grading) 3) Processing into plastic pellets through heating/mixing 4) Production of recycled plastic products using the pellets
Remarks	-

Table 4.2 Examples of material recycling (2)

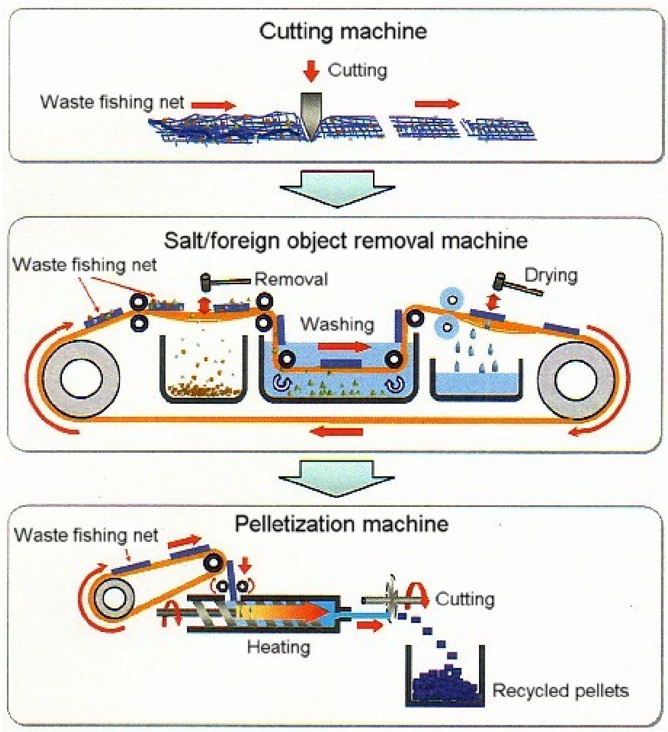
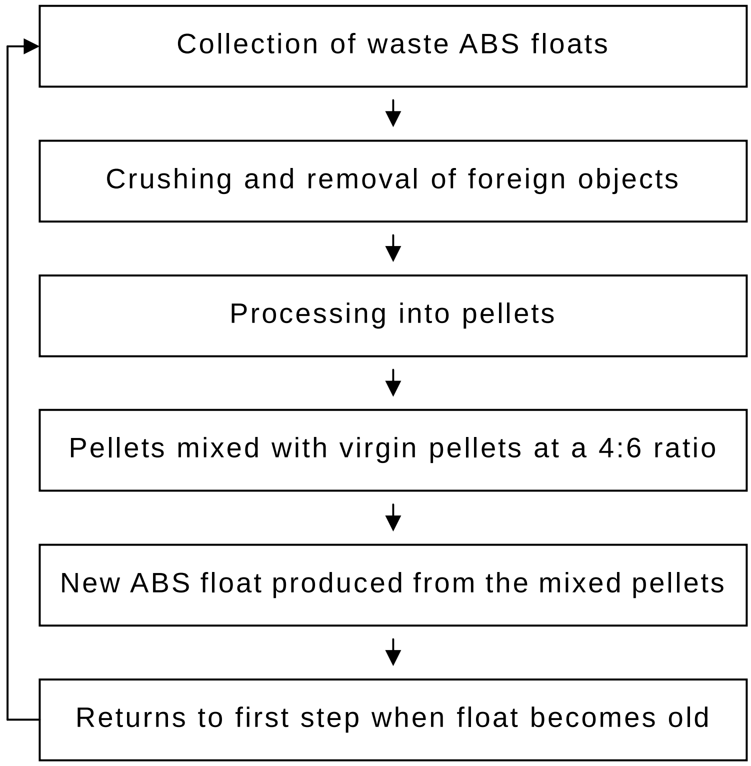
	Contents
Type of Recycling	Processing of waste fishing nets into plastic pellets
Recycling Product	Waste fishing nets
Recycled Product	Plastic pellets
Recycling Process	1) Collection of waste fishing nets 2) Cutting of waste fishing nets into a processable size 3) Removal of foreign objects 4) Removal of salt by washing 5) Drying 6) Processing into plastic pellets by heating and cutting  Flow of fish-net recycling Source: Website of The Foundation For The Advancement Of Industrial Technology In Dohoh Area (http://dohgi.tomakomai.or.jp/03_bulletin/dsn-p1.pdf)
Remarks	- The recycling system is comprised of machines that are mainly for a) cutting, b) salt/foreign object removal c) pelleting. - Pelleting rate: 10 kg/h - Under the research and development stage

Table 4.3 Examples of material recycling (3)

	Contents
Type of Recycling	Processing of waste expanded polystyrene (EPS) floats into polystyrene ingots
Recycling Product	Waste EPS floats
Recycled Product	Polystyrene ingots
Recycling Process	1) Crushing of waste floats with a crusher 2) Removal of foreign objects and marine organisms (e.g. sea shells) from float 3) Processing of floats into polystyrene ingots through heat compression (230-250 °C)
Remarks	- Polystyrene ingots can be processed into products such as videotape cases and coat hangers - Difficult to remove all of the attached marine organisms. Consequently, an offensive odor is sometimes emitted during the heating process - To counter the odor problem, the installation of a deodorization system is required, which increases the cost of the recycling system - The quality of the ingot produced from waste EPS float is low compared to those produced from other waste EPS products, due to contamination of small objects. This results in lower selling prices of waste EPS float ingots - High recycling cost compared to recycling other waste EPS products, due to pretreatment and deodorization processes

Table 4.4 Examples of material recycling (4)

	Contents
Type of Recycling	Recycling of waste acrylonitrile butadiene styrene (ABS) floats into new floats
Recycling Product	Waste ABS floats, as used in fisheries
Recycled Product	Plastic pellets (used for producing new floats)
Recycling Process	 Flow of waste ABS float recycling
Remarks	- ABS floats are collected when they become old and are recycled into new ABS floats - Virgin pellets are mixed to achieve the required float quality - Attached marine organisms are removed by sun drying - Fishermen often revert to other convenient disposal methods, such as landfill, because they must bear the transportation cost to the recycling plant - Feasible only if the price of virgin pellet is higher than the recycled pellets

3.2 Chemical recycling

In chemical recycling, waste plastics are recycled as, among other products, plastic raw material, fuel oil and industrial feedstock, which is achieved by altering the chemical structure through various chemical processes. Chemical recycling methods include monomerization, liquefaction, blast furnace feedstock recycling, coke oven chemical feedstock recycling and gasification.

Monomerization

With monomerization, waste plastics are initially broken down into their constituent monomers by chemical reaction (depolymerization). These monomers are then extracted for use as the raw material in new plastic products.

Monomerization produces higher quality plastic raw materials than material recycling, which in turn enables the production of high-quality plastic products with the same (or almost the same) quality as virgin raw material. Among other products, this enables the recycling of waste PET bottles into new PET bottles, which is not possible with other recycling technologies.

Liquefaction

Liquefaction is a recycling method where waste plastics are reverted to their original oil form. Common liquefaction methods usually apply heat (ca. 400 ºC) and catalysis to break down plastics into oil. With this method, chloride must be removed prior to liquefaction so as to prevent dioxin emissions and furnace corrosion.

The quality of the oil produced from waste plastic liquefaction is usually dependant on the properties of the waste plastics. Low-quality oil is usually used as fuel oil, which is currently the most common option. High-quality oil can be used as raw material by the petrochemical industry. Technologies to upgrade low-quality oil are also available.

Blast furnace feedstock recycling

In blast furnace feedstock recycling, waste plastics are used as a reducing agent in iron ore processing. Although coke is usually used as a reducing agent, plastic can be used as an alternative because its main constituents are carbon, which removes the oxygen from iron oxide.

Coke oven chemical feedstock recycling

Coke oven chemical feedstock recycling utilizes waste plastics to make coke (usually coal is used to produce coke). Hydrocarbon oil and coke oven gas are produced as by-products, which are used as chemical feedstock and power generation, respectively. Except for vinyl chloride plastics, both thermoplastics and thermosetting plastics can be used for this recycling method.

Gasification

Gasification is a recycling method where waste plastics are processed into gases such as carbon monoxide, hydrogen and hydrogen chloride. These gases are then used as the chemical raw material for the production of chemicals such as methanol and ammonia.

Almost all types of plastics, including those containing chlorine, can be recycled under the gasification method. This method is therefore suitable for miscellaneous plastics or plastics that are hard to sort. Slag is produced as a by-product, which can be utilized as raw material for civil engineering works and construction materials.

Table 5 summarizes the chemical recycling examples introduced in the following section. Each example is introduced in Tables 6.1-6.11.

Table 5 Chemical recycling examples presented in this booklet

Table no.	Recycling products	Recycled products
6.1	Waste EPS products	Polystyrene pellets (new EPS products)
6.2	Waste PE and PP products	Aromatics (raw material for chemical and medical products) and lower olefin (raw material for plastics)
6.3	Waste polyester products	Dimethyl terephthalate and ethylene glycol (raw material for plastics)

6.4	Tolylene diisocyanate (TDI) residues (TDI: raw material of polyurethane)	Toluenediamine (raw material for TDI)
6.5	Domestic waste plastics	Fuel oil
6.6	Waste PE, PP, PS plastics	Fuel oil
6.7	Low-grade oil produced from waste plastic recycling	High-grade oil
6.8	Domestic and industrial waste plastics	Reducing agent for blast furnace
6.9	Waste vinyl chloride products	Hydrocarbon (reducing agent for blast furnace), hydrogen chloride (used by steel and chemical industry)
6.10	Waste plastics except for vinyl chloride	Coke (reducing agent for a blast furnace), hydrocarbon oil (chemical feedstock of plastic manufacturing), coke oven gas (power generation)
6.11	All types of waste plastics	Synthetic gas (hydrogen, carbon monoxide)

Table 6.1 Examples of chemical recycling (1)

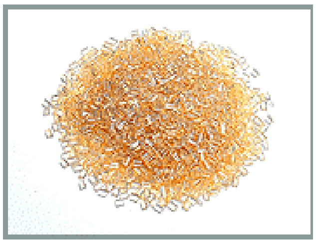
	Contents
Type of Recycling	Processing of waste expanded polystyrene (EPS) products into polystyrene pellets using limonene (monomerization)
Recycling Product	Waste EPS products (fish boxes, food trays, etc.)
Recycled Product	Polystyrene pellets (used for producing new EPS products)  Polystyrene pellets
Recycling Process	1) Waste EPS products are put into a limonene containing tank 2) Waste EPS products are dissolved by limonene and turned into a polystyrene-limonene solution 3) Foreign objects in the polystyrene-limonene solution are removed by filtering 4) The polystyrene-limonene solution is heated inside a vacuum chamber to approximately 180 °C, the boiling point of limonene. 5) The vaporized limonene is extracted from the chamber, leaving behind only polystyrene 6) The extracted limonene is reused for the above processes 7) The remaining polystyrene is transformed to a cooling chamber, and converted back to a solid form 8) The solid polystyrene is then cut into small pellets (ca. 3 mm) for processing into new EPS products
Remarks	- Limonene is extracted from orange peel, and so the recycling process is safe and environmentally friendly - Limonene dissolves EPS at room temperature, and so the recycling process is less energy intensive than other methods - With this method, new EPS can be manufactured with 100% recycled polystyrene, whereas around 70% virgin polystyrene is required for other methods - High-quality recycled EPS can be produced with this method—no change in heat resistance and durability - The capital cost of the recycling facility is relatively high

Table 6.2 Examples of chemical recycling (2)

	Contents
Type of Recycling	Processing of waste polyolefin plastic into petrochemical raw materials (monomerization)
Recycling Product	Waste polyolefin (polyethylene and polypropylene) products
Recycled Product	- Aromatic hydrocarbons (BTX: benzene, toluene, xylene) - Lower olefin (propylene, butane) - Hydrogen gas
Recycling Process	1) Polyolefin products are converted into petrochemical raw materials such as aromatic hydrocarbons (BTX) or lower olefin (propylene, butane) by catalytic decomposition, using gallium silicate or boron silicate as a catalyst 2) Gallium silicate is used for conversion into BTX 3) Boron silicate is used for conversion into lower olefin
Remarks	- The type of recycled product can be controlled with different catalysts - BTX can be used as a raw material for chemical and medical products - Lower olefin can be used as a raw material for plastics - Highly efficient conversion of polyolefin products into petrochemical raw materials - Contributes to the reduction in CO_2 emission and saving of oil resources - Under the research and development stage

Table 6.3 Examples of chemical recycling (3)

	Contents
Type of Recycling	Processing of waste polyester products into polyester raw materials (monomerization)
Recycling Product	Waste polyester products (e.g. used PET bottles)
Recycled Product	Dimethyl terephthalate (DMT) (DMT: raw material for polyester)
Recycling Process	1) Crushing and washing of waste polyester products 2) Waste polyester products are depolymerized into bis-2-hydroxyethyl terephthalate (BHET) monomers by adding ethylene glycol and a catalyst 3) BHET is converted into dimethyl terephthalate (DMT) by an ester interchange reaction with methanol 4) The recovered DMT is further refined through recrystallization and distillation processes
Remarks	- Highly pure DMT (> 99.99%) can be recovered from almost all polyester products, even from those containing additives or processing substances - Due to its high purity, various recycled plastic products can be produced from the recovered DMT, such as new PET bottles - CO_2 emission and energy consumption are significantly less compared to producing DMT from petroleum - Waste products should have a high polyester content to be cost effective

Table 6.4 Examples of chemical recycling (4)

	Contents
Type of Recycling	Recovery of toluenediamine (TDA) from tolylene diisocyanate (TDI) residues (monomerization)
Recycling Product	Tolylene diisocyanate (TDI) residues (TDI: raw material for polyurethane)
Recycled Product	Toluenediamine (TDA) (TDA: raw material for TDI)
Recycling Process	1) During the production of TDI from TDA, TDI residues are generated during the distillation process 2) TDA can be recovered from the TDI residues by hydrolysis* with supercritical water (high temperature and pressurized water) 3) The recovered TDA is reused for TDI production *: Depolymerization of chemical compounds with water
Remarks	- Conventionally, TDI residues were incinerated rather than recycled - The recycling process is safe because organic solvents or catalysts are not used - High recovery rate of TDA (ca. 80%) - This technology can be used for the monomerization of PET and polyurethane products

Table 6.5 Examples of chemical recycling (5)

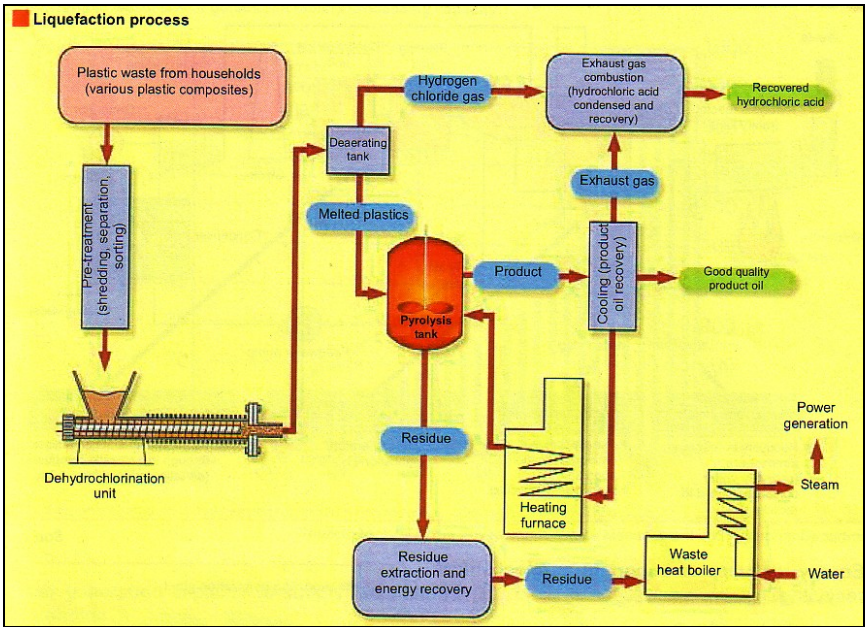
	Contents
Type of Recycling	Processing of waste plastics into fuel oil (liquefaction)
Recycling Product	Domestic waste plastics
Recycled Product	Fuel oil
Recycling Process	1) Collected waste plastics are crushed into small pieces 2) Foreign objects, such as metals and glass, are removed from the crushed waste plastics 3) Chlorine-containing waste plastics are dechlorinated by heating at 300 °C (extracted as hydrogen chloride gas) 4) The dechlorinated plastics are thermally decomposed inside a pyrolysis chamber at 400 °C. 5) The pyrolysis gas is cooled and then distilled into fuel oil  Flow of liquefaction process Source: Plastic Waste Management Institute (2004); An Introduction to Plastic Recycling 2004
Remarks	- Almost all types of domestic waste plastics can be converted into fuel oil - Low treatment cost due to the relatively simple procedure - Thermosetting plastics cannot be used and thus must be removed during the initial phase - High capita cost compared to other recycling methods

Table 6.6 Examples of chemical recycling (6)

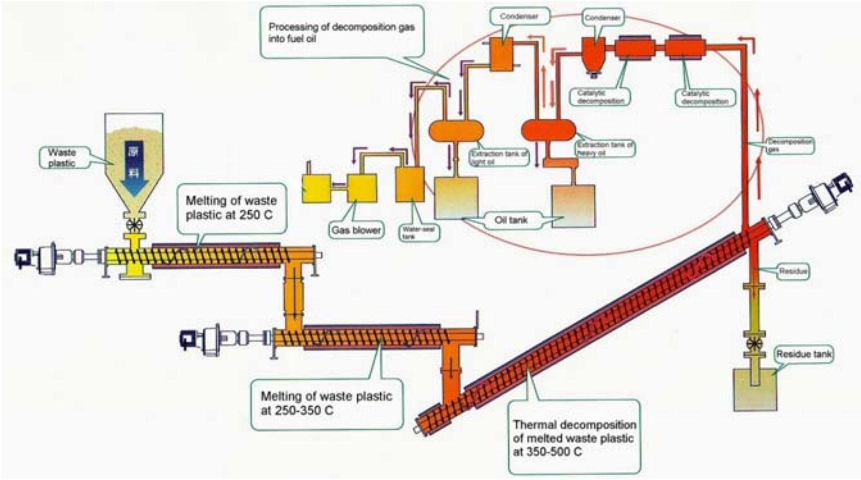
	Contents
Type of Recycling	Processing of waste plastic into fuel oil by compact-size liquefaction plant (liquefaction)
Recycling Product	Waste polyethylene, polypropylene, polystyrene plastics
Recycled Product	Fuel oil
Recycling Process	1) Waste plastics are shredded into flakes 2) The shredded plastics are melted at 250-350 ºC 3) The melted plastics are thermally decomposed at 350-500 ºC 4) Gases generated from thermal decomposition are cooled and processed into fuel oil  Flow of compact-size liquefaction plant Source: Website of Blest Co., Ltd (http://www.blest.co.jp/img/blester.pdf)
Remarks	- Compact size (370 x 240 x 280 cm) - Electric heater used for thermal decomposition - Low running cost - Treatment capacity: 10-100 kg/h

Table 6.7 Examples of chemical recycling (7)

	Contents
Type of Recycling	Upgrading of low-grade oil produced from waste plastics (liquefaction)
Recycling Product	Low-grade oil produced from waste plastic recycling
Recycled Product	High-grade oil (naphtha)
Recycling Process	1) Low-grade oil produced from waste plastic recycling is upgraded into higher-grade oil (naphtha) by utilizing hydrotreater* in oil refineries *: Facility in oil refinery to remove impurities from oil such as sulfur
Remarks	- In many cases, oil processed from waste plastic recycling is used as fuel oil, due to its low quality - With this technology, waste plastic can be converted to naphtha, a raw material of plastic - The quality of the converted naphtha is equivalent to virgin naphtha - Under the research and development stage

Table 6.8 Examples of chemical recycling (8)

	Contents
Type of Recycling	Utilization of waste plastics as a reducing agent in blast furnacing (chemical feedstock)
Recycling Product	Domestic and industrial waste plastics
Recycled Product	Chemical feedstock
Recycling Process	1) Foreign objects are removed from the collected waste plastics, and then crushed and granulized 2) The granulized plastics are dechloronized and then injected into the blast furnace 3) The injected plastic granules are decomposed into hydrogen gas (H_2) and carbon monoxide (CO) 4) The H_2 and CO function as a reducing agent of iron ore, transforming it eventually into pure iron (Fe) 5) H_2 and CO are converted into H_2O and CO_2 respectively, which are emitted from the blast furnace <u>Chemical formula of iron oxide reduction by carbon monoxide</u> $FeO + CO \rightarrow Fe + CO_2$
Remarks	- When plastics are used together with coke, CO_2 emission is significantly less (ca. 30%) than when only using coke - Blast furnace slag can be used as cement and road material - The excessive reducing gases are also used for blast furnace stove and power generation - Chlorine must be removed during the initial phases because it can damage the furnace

Table 6.9 Examples of chemical recycling (9)

	Contents
Type of Recycling	Processing of waste vinyl chloride products into blast furnace feedstock (chemical feedstock)
Recycling Product	Waste vinyl chloride products
Recycled Product	Hydrocarbon, hydrogen chloride
Recycling Process	1) Waste vinyl chloride products are thermally decomposed into hydrocarbon and hydrogen chloride (hydrochloric acid) inside a rotary kiln 2) Hydrocarbon and hydrogen chloride are extracted from the kiln 3) The extracted hydrocarbon is used as a reducing agent during iron ore processing 4) Hydrogen chloride is utilized by the steel and chemical industry
Remarks	- Processing possible with impure and low-grade vinyl chloride products - Contributes to the reduction of CO_2 emissions

Table 6.10 Examples of chemical recycling (10)

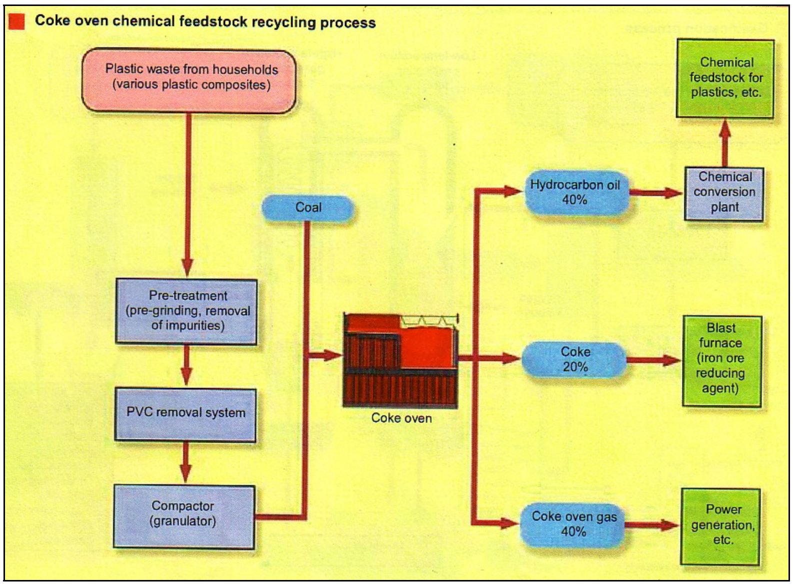
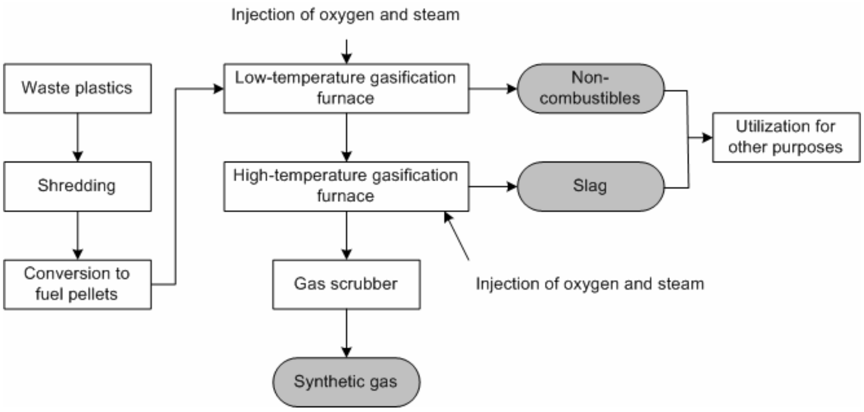
	Contents
Type of Recycling	Processing of waste plastics into coke (chemical feedstock)
Recycling Product	Waste plastics except vinyl chloride plastics
Recycled Product	Coke, hydrocarbon oil, coke oven gas
Recycling Process	1) Pretreatment of collected plastic wastes (removal of impurities, shredding, granulation) 2) Treated waste plastics are injected into a coke oven with coal 3) The injected waste plastics thermally decompose at 200-450 ^{o}C and become coke 4) Coke oven gas and hydrocarbon oil are also produced from the process 5) Coke is used as an iron ore reducing agent 6) Coke oven gas is used for power generation 7) Hydrocarbon oil is used as a chemical feedstock of plastic manufacturing  Flow of coke oven chemical feedstock recycling Source: Plastic Waste Management Institute (2004); An Introduction to Plastic Recycling 2004
Remarks	- High quality chemical raw material can be recovered from many type of plastics - Harmful gases such as dioxins are not produced due to the high-temperature treatment - Vinyl chloride plastics must be removed to prevent corrosion of the coke oven

Table 6.11 Examples of chemical recycling (11)

	Contents
Type of Recycling	Conversion of waste plastics into synthetic gas by a pressurized two-stage gasification system (gasification)
Recycling Product	All type of waste plastics
Recycled Product	Synthetic gas (hydrogen, carbon monoxide)
Recycling Process	1) Waste plastics are converted into plastic pellets 2) Plastic pellets are injected into a pressurized two-stage gasification furnace 3) Pellets react with oxygen and steam, and produce mainly synthetic hydrogen and carbon monoxide gases 4) Non-combustible materials and slag are removed from the furnace to be utilized for other purposes 5) Impurities are removed from the synthetic gases by a gas scrubber  Flow of pressurized two-stage gasification
Remarks	- Almost all types of plastics can be used, including chlorine-containing plastics - By-products, such as slag, can be utilized for other purposes (e.g. raw material of cement) - The synthetic hydrogen and carbon monoxide gases can be utilized as a raw material of ammonia or fuel - Dioxins are not produced

3.3 Thermal recycling

Thermal recycling utilizes the heat energy produced from combustion of waste plastic. The heat energy can be used for various purposes, including power generation and cement manufacturing.

Recycling of waste plastics as fuel for power generation

Although power plants often rely on fossil fuels (coal and oil) for their energy source, power plants that use waste as an energy source are becoming a popular alternative. Waste plastics are good energy sources for these plants because they have a high calorific value, similar to that of coal and oil.

Waste plastic can also be mixed with wastepaper and wastewood to produce fuel pellets called RPF (Refuse Paper & Plastic Fuel). RPF has a high calorific value and thus can be used as an alternative energy source to fossil fuels. RPF can also be produced at a low cost and is currently in high demand by the paper, steel and cement industries.

Recycling of waste plastics as fuel for cement manufacturing

Although coal has traditionally been used as a fuel in the cement manufacturing process, waste plastics can be used as an alternative energy source due to their high calorific value. The process sludge can also be utilized as cement raw material.

Table 7 summarizes the thermal recycling examples introduced in the following section. Each example is introduced in Table 8.1-8.4.

Table 7 Thermal recycling examples introduced in this booklet

Table no.	Recycling products	Recycled products
8.1	Various wastes, including plastics	Fuel for power plants
8.2	Industrial and domestic waste plastics, wastepaper, wastewood	RPF (used as fuel for power, paper, steel and cement plants)
8.3	Industrial waste plastics	Fuel for cement manufacturing
8.4	Old or abandoned small FRP vessels	Fuel for cement manufacturing

Table 8.1 Examples of thermal recycling (1)

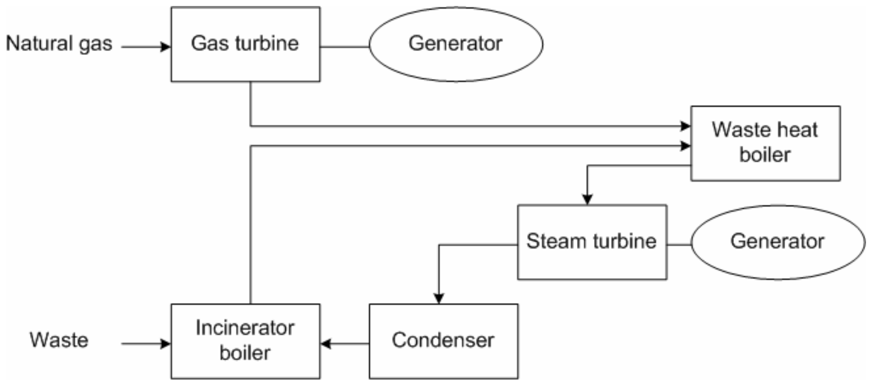
	Contents
Type of Recycling	Utilization of waste plastics as fuel for re-powering power plants
Recycling Product	Various wastes including plastics
Recycled Product	Electricity
Recycling Process	- Re-powering power plants generate electricity using both gas and waste - Re-powering power plants utilize the waste heat (ca. 500 ºC) generated from the gas turbine to superheat the steam generated from the waste incinerator boiler - As a result, the power generation efficiency of the steam turbine increases significantly  Flow of re-powering power plants
Remarks	- Accepts both soft and hard type plastics

Table 8.2 Examples of thermal recycling (2)

	Contents
Type of Recycling	Processing of waste plastic into Refuse Paper and Plastic Fuel (RPF)
Recycling Product	Industrial and domestic waste plastics, wastepaper, wastewood, etc.
Recycled Product	Refuse Paper and Plastic Fuel (RPF) used, for example, as fuel for power, and paper, steel and cement productions
Recycling Process	1) Removal of foreign objects from the collected wastes 2) Crushing of the wastes 3) Mechanical removal of chlorine-containing plastics and metals 4) Further crushing of the wastes 5) Processing into RPF granules (ca. 30 x 50 mm)
Remarks	- High calorific value (6,000 -7,500 kcal/kg) - Calorific value is adjustable - Easy to handle - Only simple air pollution control measures are required - Low cost compared to other fuels (1/4-1/3 of coal) - Alternative to fossil fuel: reduction of greenhouse gas emissions - Difficult to remove all chlorine-containing plastics - High transportation cost of RPF due to its low density (can only transport 6-7 ton of RPF with a 10-ton truck)

Table 8.3 Examples of thermal recycling (3)

	Contents
Type of Recycling	Utilization of waste plastics as a supplementary fuel for cement manufacturing
Recycling Product	Industrial waste plastics
Recycled Product	Fuel for cement manufacturing (cement kiln process)
Recycling Process	- Although coal has traditionally been used for fuel in the cement kiln process, waste plastics can be used as an alternative energy source due to its high calorific value - Prior to injection into a cement kiln, waste plastics are first cut into prescribed sizes to enhance its combustion efficiency and handling
Remarks	- In terms of combustion efficiency, the ideal size for soft and hard plastics is under 2 and 3 cm, respectively. - PVC plastics are not acceptable due to possible damage to the kiln - No harmful emissions due to the extremely high combustion temperature in a kiln (1,000-1,800 ºC) - Less CO_2 emission compared to coal

Table 8.4 Examples of thermal recycling (4)

	Contents
Type of Recycling	Utilization of abandoned FRP vessels as fuel for cement manufacturing (FRP: Fiber Reinforced Plastics)
Recycling Product	Old or abandoned small FRP vessels
Recycled Product	Fuel for cement manufacturing (cement kiln process)
Recycling Process	1) Crushing of FRP vessels 2) Selection and collection of FRP parts 3) Further crushing, selection and processing of FRP parts 4) Transportation of treated FRP to a cement factory to be used as fuel in the cement kiln process
Remarks	- Possible solution to reducing illegally dumped FRP vessels - Accepts many types of FRP vessels - Recycling cost is set according to vessel type and size

4. Issues and suggestions on recycling plastic marine litter

As introduced in the previous chapters, various plastic recycling technologies are currently available or under development. Although these technologies can be effective for recycling industrial and domestic waste plastics, some technical and economic issues arise when applying these methods to treat plastic marine litter, especially for material and chemical recycling.

Technical issues

- Since marine litter includes various plastic types, the collected litter must be sorted into the same plastic types for recycling
- Even for the same plastic types, the composition or quantity of additives used may differ among plastic manufacturers. In this case, recycling must be conducted separately
- Materials of some plastic marine litter are difficult to identify, making it hard to select the appropriate recycling method
- Painted and specially coated plastic must be pretreated (i.e. removal of painting and coating) prior to recycling
- Foreign objects, such as sand, dirt and marine organisms, must be removed prior to recycling
- The quality of some plastic marine litter may be unsuitable for recycling due to degradation by marine environment exposure, including ultraviolet radiation

Economic issues

- There is a general lack of recycling plants
- It is difficult to sustain a constant supply of plastic marine litter
- It requires time and effort (i.e. additional cost) to separate recyclable and non-recyclable plastics
- It requires time, effort (i.e. additional cost) and experience to sort plastic into different types
- It requires time and effort (i.e. additional cost) to untangle and remove foreign objects from fishing nets and rope
- Some plastics, such as EPS, incur high transportation costs

- The price differences between recycled and virgin material are narrowing (i.e. less incentive in using recycled material)
- Other treatment methods are often less time consuming and costly

Contrary to material and chemical recycling, thermal recycling of plastic marine litter does not require rigorous sorting, and plastics can be mixed with other wastes. However, some general issues still remain such as:

- Plastics with high moisture and salt content are unsuitable for incineration because of possible damage to the furnace
- Some plastics (e.g. plastics coated with flame retardant) may emit harmful chemical substances when incinerated
- Further treatment of incineration ash is required in some cases

As described above, various technical and economic issues arise when recycling plastic marine litter. Although some of these issues may be solved by technical advancements, other issues are harder to solve because they are influenced by less controllable factors, such as fluctuation of raw material prices, lack of demand for recycled material, lack of recycling plants, high recycling costs and so on.

However, in spite of these technical and economic issues, recycling of plastic marine litter should be encouraged because it is the only environmentally-sound alternative to landfill or incineration. Recycling should also become a more feasible option, as our society shift towards a more recycling-oriented structure.