

Industrial-scale Processes for Transforming Mixed Plastic Wastes to Oil

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EXECUTIVE SUMMARY

In 2015, the world produced 407 million tons of plastics and generated 302 million tons of plastic wastes [1]. Only 19.5% have been reported as “recycled”; the rest of plastic wastes were discarded in landfills or combusted with energy recovery (“Waste to Energy” or WTE). Since 1950 when plastics came to use, about 4.6 billion tons of plastic wastes have been discarded, mostly in landfills or WTE power plants [1].

However, landfilling, as the primary waste management for plastic wastes, is not sustainable. Environmental pollution and limited land resources close to urban centers indicate that landfilling is no longer a wise method to manage the increased plastic wastes, and a more efficient and environmental-friendly way should be implemented.

Since plastics are materials derived from petrochemicals, the idea of converting plastic wastes back into oil by pyrolyzing has been pursued. Pyrolysis is a thermal decomposition process at high temperature in the absence of oxygen; plastic materials are composed of high-molecular carbon chains that are cracked into liquid and gas molecules during the pyrolysis process. In this study, some industrial-scale processes for transforming mixed plastic wastes to fuel oil were examined. There are three plastic liquefaction plants in Japan and four plastic pyrolysis companies in China.

In Japan, the first liquefaction plant was in Niigara and started commercial operation in May 1999, processing mixed plastic wastes with capacity of 6000 tons per year [2]. Oil yield rate can reach 38% by weight of mixed plastic feedstock; some of the oil was sold as fuel in adjacent sewage plant and power plant, while the remainder was used to operate the pyrolysis plant. A similar large-scale facility was started up in Sapporo (April 2000) which processed 14,800 tons of household plastic wastes each year. For 1000 tons of plastic waste feedstock, it produced 620 tons of oil (62% yield) [2]. On the basis of different chemical properties, the oil was divided into light, medium and heavy oil for different applications. The remaining carbon residues were sent to landfill or used as fuel in a sewage sludge processing plant.

The other liquefaction plant in Japan was located in Mikasa city and started commercial operation in 2000. Its annual capacity was 6000 tons/year of sorted waste plastics from various

municipalities in Hokkaido, since there is not enough plastics supply in the city of Mikasa. Its oil yield rate reached 50% but the operation lasted only four years and the plant was closed in March 2004 [2].

In China, there are many small companies aimed to developing advanced pyrolysis equipment to meet different requirements and situations. This research and development effort is carried out by four companies: Kingtiger Group, Niutech Group, Henan Doing, and Huayin. All of these companies use their unique design of technology. The Kingtiger Group uses a fully continuous plastic pyrolysis system that processes 30 tons plastic wastes and tires for one day. Heated at 250°C in the absence of air, the 30-tons of feedstock are converted into 13.5 tons oil, 12 tons carbon black and 4.5 tons combustible gas [3]. Moreover, this company has developed innovations that improve heating rate and prolong the lifetime of the pyrolysis reactor.

Niutech is an environmental technology company in Jinan, China, devoted to the pyrolysis of plastic wastes to oil. Its continuous wastes plastic pyrolysis production line can process 30,000 tons plastic wastes per year [4]. In contrast to Kingtiger process, it uses catalytic pyrolysis technology and heat recovery technology to save energy consumption. The oil yield rate of this process can reach 45% by weight of feedstock that includes plastic wastes and tires; the oil quality meets the standard of No.4 Light Fuel Oil. The other products are carbon black and combustible gas that is used to heat the pyrolysis reactor.

Henan Doing is a machinery company and transforming plastic wastes to oil is one of their core technologies. Similar to the Niutech process, Henan Doing uses continuous liquefaction technology and catalytic cracking to transform plastic wastes to oil. With high quality plastic waste feedstock, the oil yield rate can reach up to 80%. Including shredded tires lowers the oil yield rate to about 50% [5].

The fourth Chinese pyrolysis company is Huayin, a renewable energy equipment company. Its continuous flow pyrolysis processes 30 tons of plastic wastes per day, while its batch reactor system has a capacity of up to 10 tons per day. For both of these two systems, the oil yield rate is 45% in general but can reach 75% with plastic wastes of good quality [6].

On the basis of this examination of industrial-scale processes of plastic pyrolysis, it was concluded that, depending on crude oil price, pyrolysis is a promising method for recovering fuel oil and carbon black from plastic wastes and is worthy of further study and development.

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1. INTRODUCTION

Plastics, due to their versatility, high malleable and high resources efficiency, have become the key materials to be widely applied in many different sectors like packaging and building & construction. Moreover, great innovations and improvements on plastics make them much more necessary and people cannot live without it. However, at the end of their use life, they become wastes. Management of those wastes become a serious and urgent issue due to their large volume.

As demands of plastics increasing, the generated plastic wastes increasing as well. From 1959 to 2015, the global plastics production was accumulated from 2 million tons to 7.82 billion tons [1]. Just in 2015, about 407 million tons primary plastics were produced, and 302 million tons of wastes were generated [1]. However, facing such a large quantity of plastic wastes, there is no efficient method to manage those wastes. About 55% of plastic wastes were discarded, 25.5% of them were incinerated and only 19.5% were recycled [1]. For most plastic wastes, they are nondegradable. Discarding them can do nothing but accumulate the quantity of wastes. Besides, due to chemical characteristics of plastic, incinerating can produce a lot of harmful and even poisonous gases. Only recycling can be a sustainable and environmental-friendly way to solve plastic crisis.

1.1 Plastic Wastes

1.1.1 Sources of Plastic Wastes

Plastics are composed of high-molecular carbon chains and derived from petrochemicals like crude oil. Based on their unique physical and chemical properties, they can be molded into various solid objects applied in many different fields. In general, there are 8 main sectors: packaging, building and construction, textiles, consumer & institutional products, transportation, electrical/electronic, industrial machinery, and others. Among them, packaging is the primary source of plastics. In 2015, there were 146 million tons packaging plastic which took about one third of the total plastic products. And in the same year, among all the plastic wastes, 141 million tons were packaging plastics [1]. For other sectors except building and construction section, there is a little difference on quantity between production and their wastes. For the plastic wastes of building and construction, they only take up about 20% of the products of building and construction which means the lifetime of those kind of plastics is quite long. However, for most

plastic products especially products like packaging, they are in quite short lifetime. The details of plastic production are shown in the figure 1 [1], while the details of plastics wastes are shown in the figure 2 [1].

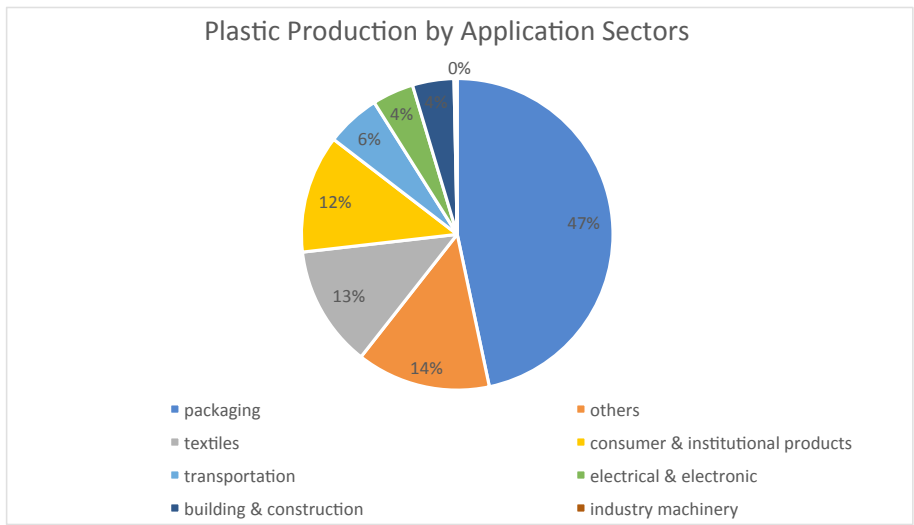


Figure 1 Plastic Production by Application Sectors in 2015

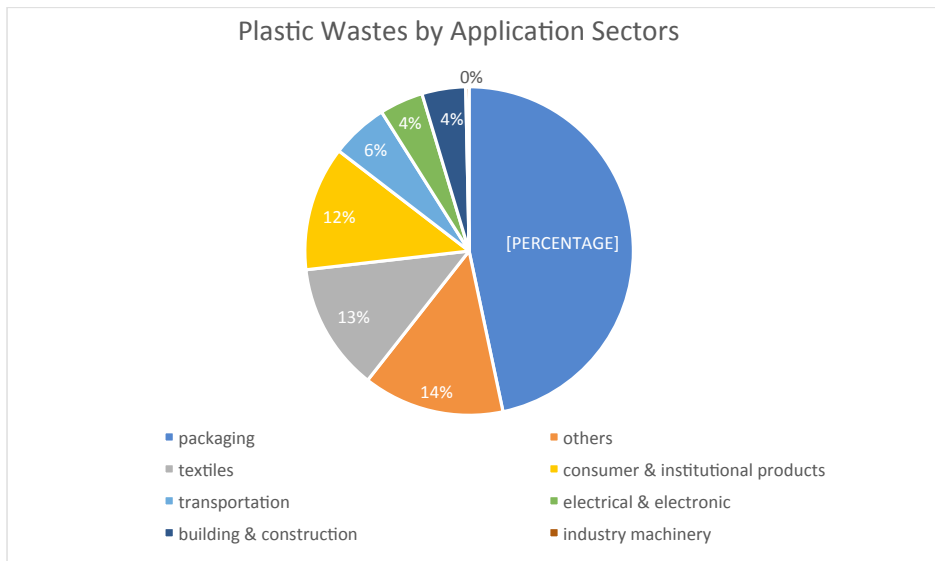


Figure 2 Plastic Wastes by Application Sector in 2015

1.1.2 Plastics Resin

Plastics are organic polymers with other various substances. Different polymers can be combined to make different plastic resins which are important for making products. since each kind of plastic resin has its specific physical and chemical properties. Generally, plastic resins include low-density polyethylene (LDPE); high-density polyethylene (HDPE); polypropylene (PP); Polystyrene (PS); polyvinyl chloride (PVC); polyethylene terephthalate (PET); polyurethanes (PUR); and others [7].

For LDPE, it is transparent, flexible and tough. Most shopping bags, bottles, lids, and cables are made of it. With stable electrical properties, it can be used to make wires and cables.

For HDPE, it is a versatile plastic with many usages. it can be used to make toys, packaging for detergents and non-carbonated beverage containers since its chemically resistant.

For PP, it is heat and moisture resistant which determine that it can be used for microwave-proof containers and packaging. Besides, since it can be both rigid and flexible, it offers a wide range of packaging formats.

For PET, it is gas and moisture resistant and strong. Thus, it is common to see that carbonate beverage containers are made of it. This cheap material makes carbonate beverage much more approaching and popular.

For PVC, it is important for building and construction materials since it is stable and resistant to weathering, what's more, stable electrical property enlarges its applications. Usually, it is used to make window frames, wall covering and cable insulation.

For PS, it can be easily expanded and became light after it. Foam cups, trays, and egg cartons are common expanded products.

Properties determine the various applications and create values for different plastics. At the same time, it is those characteristics that decide the difficulty in recycling. Based on the figure 3, it indicates that the distribution of resin types in generated plastic wastes in 2015 [1]. It is obvious that HDPE and PET are widely recycled. While LDPE, as the main source of plastic wastes, is non-recyclable for most time. PP and others like ABS face the quite similar problem as well. As for PVC, with chlorine inside, it can release dangerous dioxins when processed which makes it

difficult to be recycled. What's worse, since collecting single-resin plastic hardly happens, it becomes much tougher when recycling those collected mixed plastics.

Resin is the basic chemical composition of a plastic, while mixed plastics usually include HDPE, LDPE, PS, PP, PET, PVC and some other plastics like ABS. They are not in a constant resin distribution. In different time and location, the resin distributions will be changed which increases the difficulty in recycling. Then a high demanding in recycling method is required.

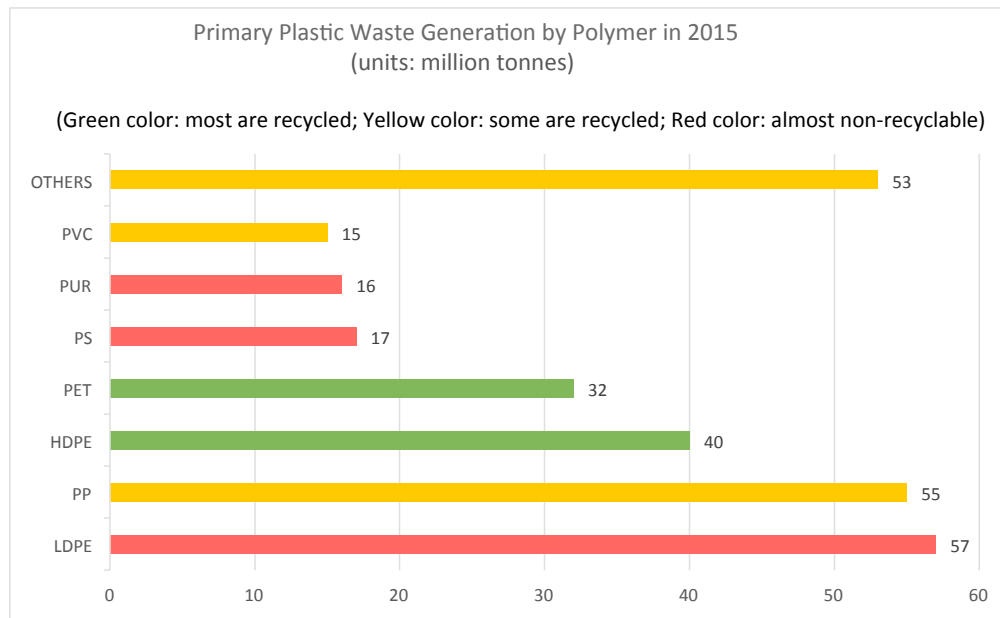


Figure 3 Primary Plastic Waste Generation by Polymer in 2015

Unique properties not just determine the different applications of different plastics, they also show the high potential of plastics pyrolyzed into oil which offers a strong possibility of dealing with plastic issues. Based on table 1 [8], it is obvious that volatile matter for all plastics is high which means those plastics are easy to convert into oil. While the ash content is low which has little negative impact on the yield of oil except polypropylene which is a bit high compared with others [9]. Those parameters make plastic pyrolysis a valid method to manage plastic wastes.

Table 1: Properties of Different Types of Plastics [8]

Type of Plastics	Moisture (wt%)	Fixed carbon (wt%)	Volatile (wt%)	Ash (wt%)
Polyethylene terephthalate (PET)	0.46	7.77	91.75	0.02
	0.61	13.17	86.83	0.00
High-density polyethylene (HDPE)	0.00	0.01	99.81	0.18
	0.00	0.03	98.57	1.40
Polyvinyl chloride (PVC)	0.80	6.30	93.70	0.00
	0.74	5.19	94.82	0.00
Low-density polyethylene (LDPE)	0.30	0.00	99.70	0.00
	-	-	99.60	0.40
Polypropylene (PP)	0.15	1.22	95.08	3.55
	0.18	0.16	97.85	1.99
Polystyrene (PS)	0.25	0.12	99.63	0.00
	0.30	0.20	99.50	0.00
Polyethylene (PE)	0.10	0.04	98.87	0.99
Acrylonitrile butadiene styrene (ABS)	0.00	1.12	97.88	1.01
Polyamide (PA) or Nylons	0.00	0.69	99.78	0.00
Polybutylene terephthalate (PBT)	0.16	2.88	97.12	0.00

1.1.3 Related Legislation

So far, plastic market keeps following a traditional linear economy model which is a simple ‘take, make, dispose’ model. Along their service life, they improve the quality of human’s life and build an easy life. While, at the end of their use life, they are discarded or incinerated as wastes. The leakage of plastic wastes harms the environment and threatens human health.

However, those possible threatens can be avoided and released when circular economy came out to replace the linear economy. It requires that all the resources should be kept in use as long as possible and extracting the maximum value no matter when they are in use or in recovering, recycling and regenerating at the end of their life. By running this economy model, it can help to

reduce plastic wastes and the environmental impacts of plastics. Besides, it can also deliver a more competitive economy. Thus, a sustainable method of waste management to increase the recycling rate are needed to achieve this circular economy model [10].

Landfill, as the main choice to manage wastes, is not sustainable and even unavailable in the future. Since land resources are so limited that the gate fee of landfilling become much more expensive. In addition, landfilling can cause severe environmental issues, such as contamination of groundwater and soil due to leachate. Moreover, as wastes begin to decay, decomposition gases like methane and carbon dioxide seep out of the landfill which exacerbates the pollution of air and increases the emission of greenhouse gases [11]. Thus, a more environmental-friendly method should come out to take place of landfilling.

Furthermore, in 2017, when China enacted the ban on imported plastic from outside countries, a strategy to conquer plastic crisis became more urgent and the whole world started to rethink how to manage plastic wastes properly. For different countries, based on their own situations, they made their regulations and goals.

In Europe, they insist on their circular economy and plan to make progresses on each process of plastic from production to usage and treatment in the end. Their goal is to achieve all plastic packaging being recyclable by 2030. To reach it, they revised and enacted a series regulation like Waste Framework Direction, the EU Landfill Directive, and Circular Economy Law including producing, managing, policies and techniques [10].

In Japan, any development of products is complied with relevant regulations from collecting to recycling, such as the Recycling Promotion Law, the Containers and Packaging Recycling Law, the Automotive Recycling Law and so on. With those relevant laws, the cost related to recycling was allocated so that created an attractive market for recycling, and more investments would like to be devoted to this field.

In China, though it has the ban on the imported plastic wastes, itself is a large generator of plastic wastes. Since 2008, there is a strict restriction on ultra-thin plastics bags to minimize the usage of plastics bags. People are no longer offered free plastics bags in any market. Through this way, public awareness of cutting plastics wastes can be strengthened as well. Besides, each local government carried out their local regulations to normalize the plastic wastes management. Some communities would hold some activities to encourage residents to recycle plastic bottles and put

up posters on the bulletin board to educate publics. In addition, with government's support, more and more facilities are devoted to new technologies to recycle plastic wastes and rubbers.

1.2 Pyrolysis Technology

1.2.1 Definition and Development

Pyrolysis is a thermal decomposition process with high temperature in the absence of oxygen. Plastics are derived from petrochemical products which are polymer carbon chains, by being pyrolyzed, plastic wastes can be transformed back into petrochemical products to reduce the wastes production. Thus, pyrolysis offers a possible and potential method to recycle plastics.

In fact, pyrolysis is not a new technique. Many countries have done some researches on it. In Europe, in early 1990s, they have started with different trials on transforming plastics into oil, like the BASF feedstock recycling process in Ludwigshafen and BP process in Grangemouth [2]. Though those projects are no longer in operation, they did lay a strong foundation for the development of plastic pyrolysis. In Japan, oil crisis explosion waked up the application of liquefaction technology on plastics, like the plant in Niigata, Sapporo, and MIKASA. Later, by implementing the plastic containers and packaging recycling law, plastic pyrolysis was revitalized and commercialized gradually [2]. And in China, there is also a long history for pyrolysis and they gained great achievements in recent years. When facing the serious shortage of resources and worsen environmental pollutions, the advantages of pyrolysis became more obvious. With improved policies and governments' supports, more facilities like KINGTIGER GROUP, HUAYIN GROUP begin to explore their markets.

1.2.2 Process of Plastic Pyrolysis

In general, pyrolysis occurs between 400 and 600 degrees Celsius in an inert atmosphere and temperature varies with the changes of feedstock compositions [2]. Usually, based on the applied temperature and heating rate, there are two kinds of pyrolysis: one is slow pyrolysis which usually takes minutes to hours for reaction, the other is flash pyrolysis taking only milliseconds to seconds to react. For those two different pyrolysis processes, the compositions of those two products are different. The higher temperature in flash pyrolysis will leads to higher yields of gaseous [2]. Generally, plastics, as organic materials, are normally decomposed into 3 phases: liquid, gas, and solid. And the main product is oil which is either gaseous or liquid. Solids are only in residues which take about 20% of the total products, and they include carbon black and

foreign materials. Some other gases are non-condensable combustible gases. The quality and composition of pyrolysis products are highly connected to plastic wastes compositions and reaction conditions. As for the reactors, fixed beds, fluidized beds, and rotating kilns are quite common.

1.2.3 Current Situation and General Problems

Compared with other plastic wastes treatment processes like landfilling and so on, pyrolysis has its advantages. It not just reduces wastes, meanwhile, it produces oil and saves resources. However, there are some problems about pyrolysis when put into market. Even some plastic to oil plants were closed due to low cost-efficient.

Plastic to oil technology is not stable and can be affected by many factors. Collection, as one of the most important parts of pyrolysis, is high demanding. Good quality of plastic wastes will make the pretreatment of pyrolysis process much easier and improve the quality of products greatly. In most countries, local government is responsible for plastic wastes collection. However, due to versatile and widespread plastic wastes, it takes much more efforts and money to collect them which lower the initiatives of governments. Besides, plastic wastes are too light though in large volume, it is not economic efficient for transportation which adds the difficulty in selecting location. For one thing, plastic to oil plant should close to the wastes collection stations in the city to minimize the transportation distance. For the other thing, plant is usually far from the city. After collection, during treatment process, the composition of feedstock varies day by day, and the quality of generated oil changes accordingly which will have impacts on profits of the plant. What's more, the decomposition products from the PET materials can cause the corrosion on machines and shorten their services life.

2. LIQUEFACTION IN JAPAN

2.1 Plastic Wastes in Japan

In general, there is a down trend of plastic wastes in Japan from 2003 to 2016 and the total generated plastic wastes was decreased from 10010kt to 8990kt. Among those plastic wastes, Containers, packaging, electric and machinery are main sources, and the other sources are shown in the figure 4. Based on the figure 5, the resin distribution of plastic wastes indicates that polyethylene and polypropylene are primary objects to process [12].

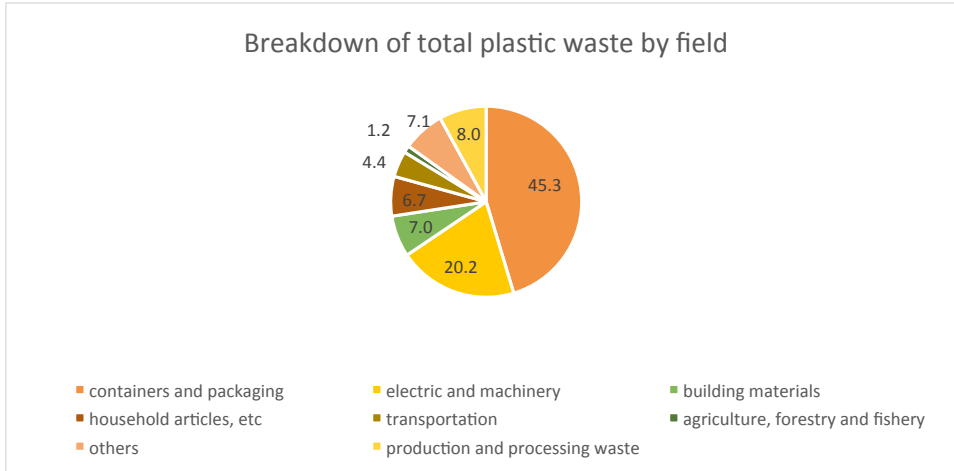


Figure 4 Breakdown of Total Plastic Wastes by Field in Japan in 2016[12]

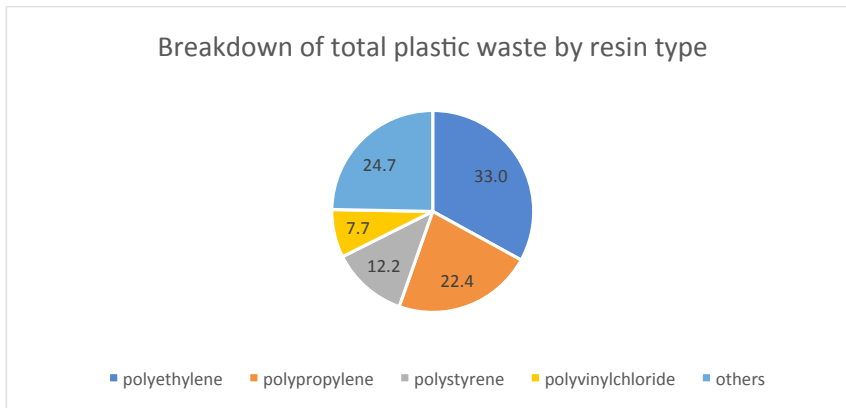


Figure 5 Breakdown of Total Plastic Wastes by Resin Type in Japan in 2016[12]

For the managements of plastic waste, recycling, recovery, incineration and landfilling are four main methods. Based on figure 6 [12], clearly, there is a downward tendency in landfilling and incineration, and increasing rate of energy recovery. Recycling, as one of the main methods, remains a stable level over years [12].

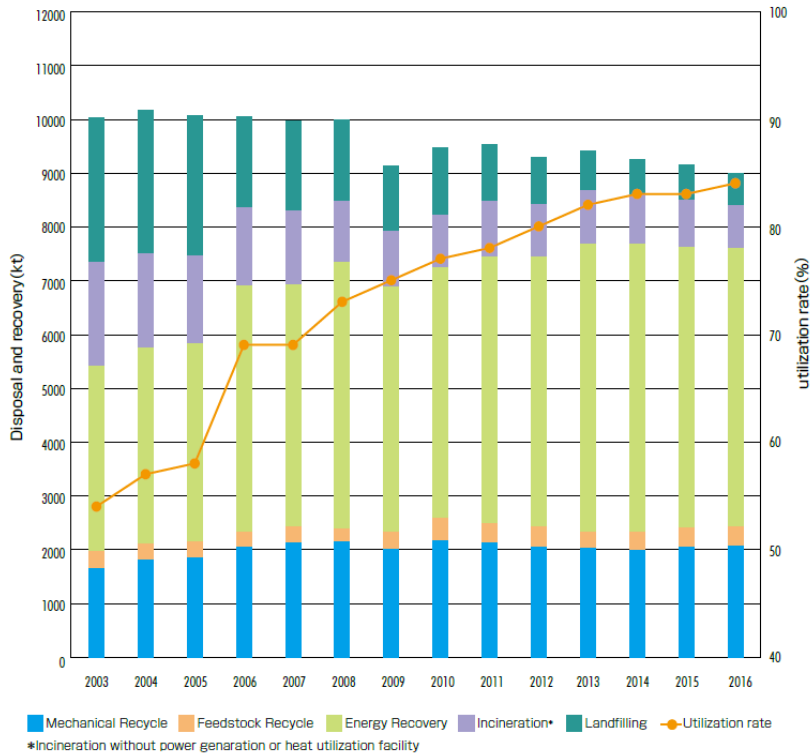


Figure 6 Change in Utilized Plastic Waste by Amount and Rate Over Time [12]

2.2 Recycling in Japan

Based on Container and Packaging Recycling Law, there are three kinds of official recycling methods: material recycling, chemical recycling, and thermal recycling. And their common target is to recycle plastic wastes with least cost and lowest impacts on environment.

Liquefaction, as one of chemical recycling methods, can return plastics back into oil. The process of liquefaction given by Plastic Waste Management Institute is shown in figure 7 [13]. Researches on liquefaction started from 1970s, meanwhile, oil crisis exploded that time. Lacking

oil and high crude oil price led Japanese government get interested in transferring plastics into oil. But it hasn't been commercialized and expanded until the government was aware of the severe environmental problems. For one thing, with the limited landsite, other new and sustainable treatment methods are needed. For the other thing, the greenhouse gases emitted from incineration of waste plastics do have bad impacts on environment. In 2000, when the plastic containers and packaging recycling law came into effect, liquefaction had made a great progress since more and more plastics collections had been formalized. At the meantime, the collection and sorting increased rapidly as well which offered a stable and large source of waste plastics. However, it didn't last long time due to large energy consumption, unstable process and potential safety risk, many large-scale facilities were forced to withdraw from the market in the late 2000s. Though some achievements have been gained and liquefaction is a good way to achieve plastic recycling, further researches and problems are needed to be done and solved.

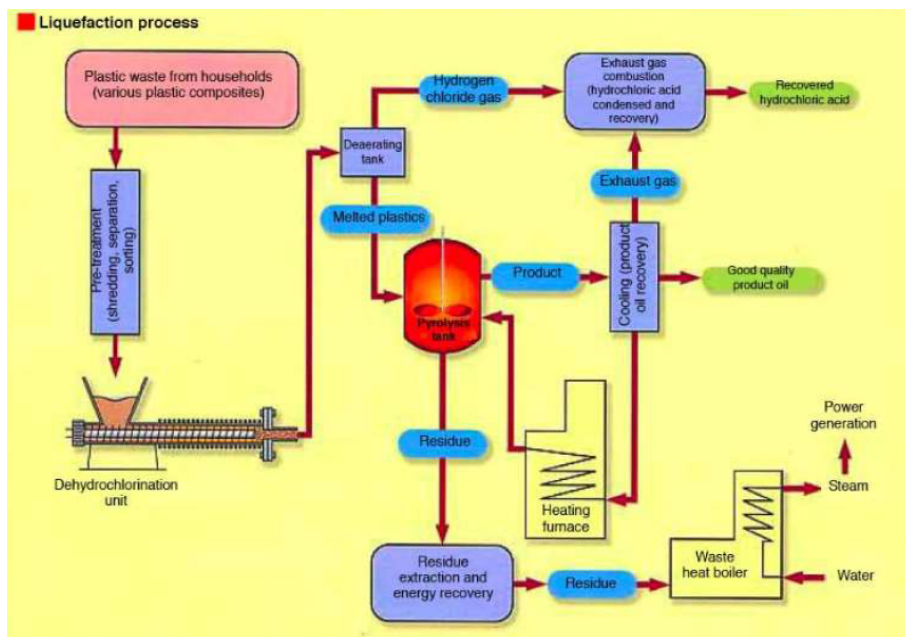


Figure 7 Liquefaction Process[13]

2.3 Common Issues in Liquefaction

2.3.1 Cost

First, High cost on transportation due to the light weight and large quantity of waste plastics. One way to improve it is to set recycling facility as close as possible to where those plastics are collected. Then the cost of baling can be saved as well, since there is no necessary to bale plastic wastes and collected wastes can be sent to recycle directly. Secondly, pyrolysis process is an endothermal reaction which requires high energy consumption and it is a large expenditure. Thus, it is not economic efficient to operate complicated processes to treat mixed plastic wastes, and simplification and energy-saving are necessary to make profits [13].

2.3.2 High demanding for feedstock

For each plastic resin, they have their unique high heating value (HHV). Based on the table 2 [14], waste plastics of PVC and PET yielded the lowest heating values which means it is not worthy of pyrolysis if plastic wastes with too much PVC and PET. However, LDPE and PP with the highest heating value are more suitable to be transformed into Oil. Thus, the profitability is connected to the composition of feedstocks.

Table 2: Average Measured HHV for Plastic Resin[14]

Resin Code	Resin Type	Average Measured HHV(MJ/kg)
#1	PET	25
#2	HDPE	40
#3	PVC	24
#4	LDPE	46
#5	PP	44
#6	PS	40
#7	Other	41
Average HHV of Waste Plastics (MJ/KG)		38

2.3.3 Commercialize and normalize

Based on the experiment, converting plastics into oil is feasible. However, when it is brought into business, normalization and commercialization are not enough as far. A series of related regulations and standards are needed to make pyrolysis more suitable for the market.

2.4 Economy Activation

In Japan, when liquefaction was popular, the economy that time was in a deep recession that time. The formalization of collection and the development of liquefaction offered government a good opportunity to active their economy and increase employment rate. Since for each section, like collection, baling, and transportation, labors and investments are needed.

On the other hand, when more people were engaged in this field, there would be more people getting to know this technology, and the awareness of plastics recycling would be increased gradually which laid a strong foundation for the future development of recycling.

2.5 Case Studies on Liquefaction Technologies

2.5.1 Liquefaction plant in Niigara

Due to oil crisis, Japanese government started with liquefaction to convert plastic to oil and set a Test plant with 400 t/y capacity at Okegawa city in 1990. At the beginning, they mainly focused on industrial waste plastics. Then, the plastics Wastes Management Institute (PWMI) started with converting all kinds of household plastic wastes back into oil [15]. With the support of MITI, a liquefaction plant with 6000 t/y capacity has been set in Niigara city and entered trial operation in December 1997 and commercial operation in May in 1999. But this business was closed in 2006 after issues bidding for containers under the Container and Packaging Recycling Law [15].

For this Plant in Niigara, waste plastics are collected in this city and among those mixed plastics, PE, PP and PS take most parts, PET and PVC are included as well. For its treatment process, it can be divided into two parts. One is pretreatment process and the other is liquefaction process. Before sending to pyrolysis, collected waste plastics should be pretreated to remove PET bottles, iron and other foreign materials like glass, sand, etc. After grinding into small pieces, they are sent to two series of dehydrochlorinators to remove chlorine, and then went into a vertical tank pyrolyzer with temperature holding at 420°C. Through this process, for 1000 kg waste plastics, they can produce about 380 kg oil and others are gases and residues. For those different products, they have different applications. Among 380 kg oil, there are 125 kg oil for sale as fuel in the sewage plant and power plant in Niigara city, while 255 kg oil are self-consumed as fuel to reduce operation cost [7]. At the meantime, exhaust gas and fly ash are also used in the furnace

to improve the heating balance. For residues, they are suitable for energy recovery with high heating values.

2.5.2 Sapporo Plastic Recycling Plant

There is the other similar large-scale facility in Sapporo, which was constructed in Sapporo by Toshiba Corporation and entered operation in April 2000 by Sapporo Plastics Recycling Co., Ltd. And in 2004, Japan Energy Corp. started operating a plant to process oil generated from Sapporo Plastic Recycle Co., Ltd into naphtha to improve the quality of oil [15]. For each year, this liquefaction plant can process 14800 tons household waste plastics which is composed of 71 percent of PE, PP and PS, and 3.1 percent of PVC [7]. After collected by local government, those waste plastics are supplied to Sapporo Plastic Recycling Plant (SPR Plant). At first, they are sent to pretreatment plant to be shredded, dried, sorted, and pelletized. Then pellets with calcium hydroxide are fed into dehydrochlorinators to remove chlorine. After that, going to rotary kiln to produce oil with temperature at 400°C and overpressure at 5 kPa [2]. Those oils which take up 62 wt% of the household waste plastics will be divided into light, medium, and heavy those three types of oils based on different density. Most light oils are styrene monomer and ethyl benzene, medium oils are suitable for fuel application with high flash point and low pour point. For heavy oils, they used to be solid with some foreign materials and mainly used for electrical power through cogeneration system. For those distilled oils, they have the same heating value and less sulfur content when comparing with the standard petroleum oils used as fuel. Residues generation in this plant was increased from 9 wt% to 17.5 wt% which used to landfill, but now, due to their high heating value, those residues have been used as fuel to incinerate the sludge in sewage treatment facilities [2].

In general, compared with plant in Niigara, SPR plant has some outstanding characteristics. First, by adding $\text{Ca}(\text{OH})_2$ powder into waste plastics to neutralize the chlorine hydride, this plant can treat waste plastics containing PET and PVC which lower the requirement of plastic collection. Second, the plant has high recycling ratio which can up to 99 wt% in the pyrolysis and distillation sections. For those distilled oils and residues, they all have different applications. Third, this plant is self-sufficient which lower the operation cost, since generated heavy oil can be used for electricity generation, while light oil can be used as fuel for furnaces and incinerators. Besides, with low generation of wastes, the cost on wastes treatment like wastewater are quite

low as well. However, such a plant with a large-scale withdrew from the business in 2010 due to extreme low profitability.

2.5.3 Liquefaction Plant in Mikasa City

At the beginning, the quality of oil generated through liquefaction technology was bad. So catalytic cracking process was led into this field and greatly improved the oil quality and in 1999, such a liquefaction plant was built in Mikasa city. For this plant, it can accept 6000 t/yr of sorted waste plastics and produce about 3000 kl/yr oil [2]. Like other plants, the first step for collected wastes is pretreatment process. Using crushers, different separators, and pelletizers to remove foreign materials. Since PVC is also included in the sorted plastics and catalyst used for cracking is sensitive to chlorine, dehydrochlorination is necessary before sent into cracking tank. In cracking tank, molten plastics turn into hydrocarbon gases under 400°C. By going through neutralization tower, extra hydrogen chloride will be removed. After that, two different condensers will turn the decomposed gas into gas oil and naphtha separately. Though this cycle, 19% of waste plastic bale will be removed as foreign material and wastewater during the pretreatment. 27% of waste of plastics will become residues during melting and cracking process, and the remainder, 41% of waste of plastics, are oils [2]. Among those oils, 23% are heavy oil and exhaust gas which are used as fuel for furnaces in its own plant. While the other 18% are light oil which are sold outside as fuel for boilers and diesel generators [2]. Compared with the other two plants, adding catalysts lowers the required temperature and prolongs the service life of equipment. Moreover, it also controls the emission of HCl gas.

3. PLASTIC TO OIL IN CHINA

In the 1990s, China started with the pyrolysis technology to convert the plastic wastes into fuel oil. At the beginning, they heated the plastic wastes directly and the pilot plant was operated in a very small scale which can only process 1000 tons plastic wastes for one year. Later, pyrolysis-catalytic technology came to the market which improved the yield rate of oil and efficiency. However, the collection, transportation, and sorting are not that efficient and economic. It is quite often that the collected plastics cannot meet the continuous production on a large scale and the transportation distance is far and government or the buyer should pay more for it.

Now, when the awareness of environmental protection has been increased, the related law and regulation for recycling plastic wastes has been enacted. Besides, collection system has been improved, no matter in public area or residential area, plastic collection points have been set which made collection much easier.

In addition, the technology of pyrolysis has been improved as well. More and more manufacturing companies have dedicated to this field and make innovations on it. Kingtiger Group, Niutech Group, Henan Doing, and Huayin are such four companies and they all made different contributions and breakthroughs on pyrolysis technology.

3.1 Kingtiger Group's Waste Plastic Pyrolysis Plant

3.1.1 Overview

Kingtiger Group is a one-step waste processing company in China which can supply all kinds of waste disposal machine, from waste pretreatment, waste recovery to end products treatment [16]. Pyrolysis technology, as their core product, they did a lot of researches on it. In general, there are 3 operation systems for plastic to oil machines. One is batch system which can only process 6 tons to 10 tons plastic wastes. The other is semi-continuous system whose capacity is about 20 tons plastic wastes for one day. For fully-continuous system, it owns the largest capacity which can process 30 tons plastic wastes each day. Table 3 shows related parameters for different pyrolysis models [3].

Table 3: Parameters for Different Pyrolysis Models[3]

Model	BLJ-6	BLJ-10	BLL-16	BLL-30
Daily Capacity	6T	10T	15-20T	30T
Working Method	Batch	Semi-Continuous	Semi-Continuous	Fully Continuous
Raw Material	Waste Plastic, Tyre, Rubber, Oil sludge, Medical Waste			
Reactor Size (D*L)	2.2×6.0 m	2.6×6.6 m	2.8×7.1 m	2.2×12.5 m
Pattern	Horizontal & Rotary			
Heating Materials	Charcoal, Wood, Fuel Oil, Natural Gas, LPG, etc			
Total Power	24 kw/h	30 kw/h	54 kw/h	53.6 kw/h
Floor Area (L*W*H)	20*10*10 m	25*15*10 m	25*15*10 m	33*15*10 m
Operation Pressure	Normal Pressure		Constant Pressure	
Cooling Method	Water Cooling			

For all those different pyrolysis products, the conversion from waste plastic into fuel oil is a process of heating, depolymerizing, and catalyzing.

3.1.2 Process Description

The flow diagram of the whole process is shown in figure 8.

3.1.2.1 Pretreatment

Collected plastic wastes are sent to dryer first to lower moisture content, then, dried plastic wastes are sent to be crushed into small pieces.

3.1.2.2 Pyrolysis process

After pretreatment, small dried pieces of plastic wastes are put into reactor by feeding machine. To be efficient, the reactor is supposed to be left 1/3 space for rotating smoothly. For batch system, after each feeding, the sealed door should be closed manually to create an airtight atmosphere, and then step into heating stage.

In heating process, the reactor is gently heated by burning the fuel materials like charcoal, wood, and fuel oil. When temperature reach 100 °C, the oil gas is released gradually. With temperature

going up, more plastics turn into oil gas. When temperature reaches 250°C and 280°C, there is a peak output rate [3]. Then, the hydrocarbon gases are sent into gas separator where heavy oil gas and light oil gas are separated. When passing through the manifold, heavy particles will be liquefied and drop into the heavy oil tank by gravity, while the lighter gas will rise to the oil condensers to be liquefied and then stored in the oil tank. For gas which cannot be condensed, will be recycled back to furnace as fuel after desulfurized and dedusted.

When finishing heating, the reactor will be cooled down using water. The black carbon will be discharged automatically when temperature is lowered into about 40°C. For exhaust gas, it won't be discharged until it is disposed by the dedusting system equipped with water and magnetic rings to reduce the dust and sulfide. Wastewater will be filtrated before discharging.

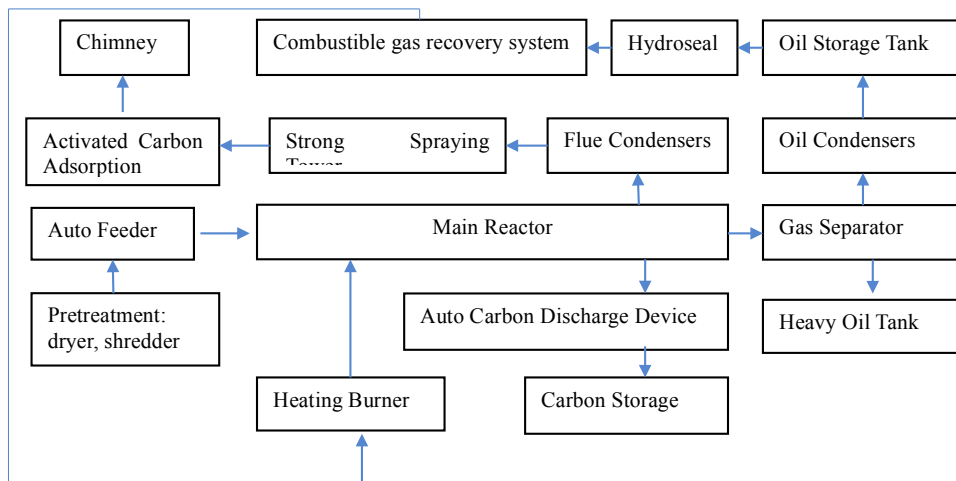


Figure 8 Flow Diagram of the Pyrolysis Process in Kingtiger Group[3]

3.1.3 Application of outputs

With different properties, each plastic resins have their own capacity for yielding oil under this process and their oil yield ratio are shown in the table 4 [3].

In general, there are three main products: pyrolysis oil, carbon black and combustible gas. For pyrolysis oil, it is condensed into two parts as light and heavy oil. Based on different situations, it can be sold outward directly, or added into reactor as fuel to reduce the usage of additional fuel.

Besides, it can be added into heavy oil generator to produce electricity or transformed into diesel and gasoline as well.

Table 4: Oil Ratio for Single Material under Kingtiger Process[3]

Raw material	Oil ratio
PE	50% - 75%
PP	50% - 75%
PS	50% - 75%
ABS	40%
Plastic cable	80%
Plastic bag	50%
PVC	Not available
PET	Not available

For carbon black, they can be sold or reprocessed into other useful products like color master batch, coal, and refractory briquette.

The remainder is combustible gas. For most cases, they will be put back into furnace as fuel to heat the reactor to reduce the fuel cost and additional fuel consumption.

3.1.4 Material Balance

For 100 tons of wastes plastics as feedstocks, about 45 tons pyrolysis oil, 40 tons carbon black, and 15 tons combustible gas can be generated [16]. The distribution of products may be changed based on the different operation status and the composition of collected plastic wastes.

3.1.5 Outstanding Characteristics

3.1.5.1 New heating structure

This new heating structure used for pyrolysis plant combines the advantages of directly heating and hot-wind heating to improve its efficiency [3]. For one thing, it can improve the heating speed. For the other thing, hot wind spreads everywhere which can achieve evenly heating and prolong the machine's lifetime as well.

3.1.5.2 Outside casting of the reactor

Heat losing happens all the time along the heating. In order to minimize the heat loss and slow the rate of cooling down, the reactor is equipped with casing outside with refractory materials between them. Besides, space is filled with insulating materials to double decrease the fuel usage which can reduce production cost drastically [3].

3.1.5.3 Environmental-friendly

The whole system can not only transform plastic wastes into useful fuel oil to release the plastic crisis, but it also has a good control of the wastes generated during the whole process. For waste gas, there are advanced flue gas exhausting system and dedusting system which can help reduce the dust and sulfide before released into outside environment. For wastewater, filtration is needed. So there almost no pollution going outside.

3.2 Niutech's Industrial Continuous Waste Plastic Pyrolysis Plant

3.2.1 Overview

Niutech Environment Technology Corporation was founded in 1980s in Jinan, China. It is a strong competitive company in China specializing in pyrolysis techniques converting plastic and tires into fuel oil. Over more than 20 years' researches and innovations on pyrolysis technology, it has developed a series of advanced products from recycling scrap tires and waste plastic to oil distillation [17].

Industrial continuous waste plastic pyrolysis production line using catalytic pyrolysis method is what they developed independently to achieve an industrial continuous operation under a low temperature, safe, environmental-friendly and efficient environment.

3.2.2 Process Description

For this continuous waste plastic pyrolysis production line, there are nine parts for one cycle [4]. At the beginning of the whole process is the waste plastic pre-treatment system. At this stage, since collected plastic wastes are baled in large volume, shredder is needed to shred them into small pieces. Then, those plastics pellets are sent into the pyrolysis reactor by continuous feeding machine.

During the process of conveying, waste plastic preheating system begins to work. It is set for materials like PVC which owns low melting point so that they can be pyrolyzed during the stage.

Moreover, PVC is different from other plastics, it produces HCl rather than oil gas. To prevent the HCl from mixing with other oil gas, it is better to neutralize it in advance to avoid pollution.

After that, following process is the core process, heating. This stage needs the constant temperature heating system to offer energy and continuous pyrolysis system to create the best environment for reaction. To improve reaction efficiency and lower reaction temperature, specific catalyst is added into reaction. During this period, large pyrolysis oil gas is generated.

Then oil gas is converted into fuel oil and combustible gas after fraction distillation separation, fixed bed secondary gas catalyzing and de-waxing etc. The fuel oil will be collected as final product, while combustible gas will go into combustible gas scrubbing system and go back into furnace as fuel after scrubbing.

Waste gas after burnt will be purified through gas purification process and then discharged into air. Solid residues generated during the reaction are supposed to be processed in a residual pollute-free treatment system which can turn them into fuel sticks.

3.2.3 Application of Outputs

Pyrolysis oil, as the main product, can meet the standard of SH/T0356-1996 NO.4 Light Fuel Oil [4]. No.4-light oil belongs to heavy distillate fuel oil which can be applied as fuel for industrial burners. Besides, the quality of oil is great with high heating value and low sulfur content. After distillation, it can be applied for big-power and low-speed diesel engine, and various generators.

Other products are carbon black, steels and combustible gas. Steels can be recycled, while combustible gas is sent back to reuse as fuel.

3.2.4 Material Balance

Niutech owns quite large capacity which is from 10000 tons to 30000 tons each year. Given there are 100 tons waste plastic as feedstock, passing by those nine processes, those plastics can be transformed into 45 tons pyrolysis oil and 34 tons carbon black. If tires are included in the feedstock, around 13 kg steel wire will be produced as well [4].

3.2.5 Outstanding Characteristics

3.2.5.1 Energy-saving

By taking exclusive low-temperature catalytic pyrolysis technology, the energy consumption in this whole system has been lowered a lot. Moreover, oil yield rate and quality have been improved greatly as well.

3.2.5.2 Low operation cost

Making full use of combustible gas can achieve self-sufficient heat supply. In this system, it takes exclusive gas purification and heat recovery technology to use scrubbed combustible gas as fuel in heating supply system. Without additional fuel added into system, operation cost has been saved.

In addition, setting preheating and HCl absorbing system makes PVC acceptable in feedstock which simplify the pretreatment and enlarge the collection range. Thus, saving money on pretreatment and collection process.

3.2.5.3 Intelligent control

To make the operation easier, safe and reliable, this whole system was controlled by PLC. In this way, it reduces the quantity of labors and creates a more comfortable working environment.

3.3 The DOING Latest Fully Continuous Waste Plastic Pyrolysis Plant

3.3.1 Overview

Henan Doing Machinery Equipment Co., Ltd. is a company specialized in various oil equipment researching, designing, manufacturing. Recycling plastic to fuel oil as one of their core technologies, they have been dedicated to it for years and have developed a series of related equipment. Fully continuous waste plastic pyrolysis plant, as their latest product, can process the waste plastics, tires, industrial solid waste and household waste by pyrolysis technology to gain fuel oil.

3.3.2 Process Description

Fully continuous waste plastic using continuous liquefaction technology and catalytic breakdown reaction to convert waste plastics into renewable resources. They have a large range of capacity from 10 tons to 100 tons a day which can meet different needs. Besides, facing a large variety of

plastics, they can accept most of the plastics as their feedstock like the PE, PP, PS, ABS and other mixed plastics. However, PET is not welcomed since it hardly produces oil, but hazardous gas.

To turn plastics into fuel oil, the collected waste plastics need to be crushed into small granules less than 3-5cm and then put into heating reactor via continuous feeding system.

By taking the indirect hot air heating method, those granules are pyrolyzed into mixed oil gas under high-temperature and high-pressure in the absence of oxygen.

Then go out of the reactor and pass through the continuous cooling system. Most oil gas can be condensed into fuel oil. But oil gas like CH_4 , C_2H_6 , C_3H_8 , C_4H_{10} , H_2 which cannot be condensed under normal pressure will be recycled back into the heating reactor as fuel. In order to get high qualified oil, there are some extra processes to improve the quality of oil based on different requirements like precipitation, filtration, chemical treatment and additives.

As for wastes generated during the process, water dust scrubber dust collector, tail gas cleaning system and other environmental protection system are set to process those wastes. Like dust and sulfur gas, they are removed by the dust removing system.

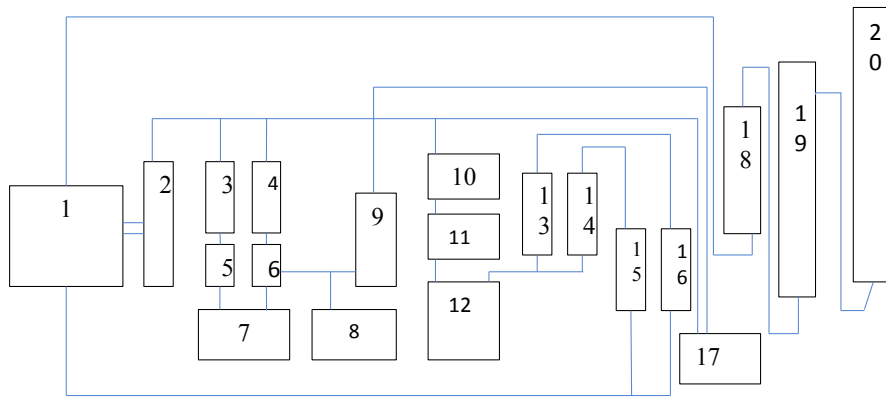
In sum, the whole waste plastic pyrolysis machine composite by 13 parts: reactor, driving device, vertical catalytic chamber, vertical condenser, oil and water separator, horizontal condenser, heavy oil tank, light oil tank, anti-back fire device, vacuum system, dedusting device, draft fan, and chimney [5]. And the flow diagram for this whole process is shown in the figure 9 [18].

3.3.3 Outstanding Characteristics

3.3.3.1 Zero pollution emission

1) Waste water pollution control

Through this whole process, the possible source of polluted water are cooling water and dust water. Cooling water is used for condensing gas oil. Here, condenser is a vertical design where gas oil running inside while cooling water running outside the pipe. Since those two liquids don't get in touch with each other, cooling water can be recycled without being polluted. Dust water is used to wash dust. By adopting water film dust collector, recycling dust can be achieved.



1) Reactor	2) Catalyst chamber	3) Condenser 1	4) Condenser 2	5) Oil gas separator 1	6) Oil gas separator 2
7) Oil tank 1	8) Oil tank 2	9) Oil water separator	10) Condenser 3	11) Condenser 4	12) Oil tank 3
13) Condenser 5	14) Condenser 6	15) Water seal device 1	16) Water seal device 2	17) Vacuum system	18) Odor Remover Tank
19) Dedusting device	20) Chimney				

Figure 9 Fully Continuous Waste Plastics Pyrolysis in Doing Group[18]

2) Waste gas pollution control

For waste gas generated during the whole process, in addition to some of non-condensable combustible gases which can be sent back to furnace as fuel, some tail gas should be purified before discharged into air. Thus, a desulfurization and odor removal tower system are set to remove H₂S gas, NO_x, and CO_x to meet relevant emission standard.

3.3.3.2 Double cooling system

Since cooling system determines the output of oil, it is essential to set a reliable cooling system. There are two cooling system in the whole process. The first is cooling pipe, when oil gas passes through the pipe, only a small part of gas will turn into liquid. Then goes into the second step, condenser. In each condenser, there are 61 cooling pipes and total cooling area can reach 100m² [19].

3.3.3.3 Special insulation cover

To prevent heat loose, they set hooks to catch the fire-proof sponge with 20mm thickness in the second layer of insulation cover. Besides, the furnace cement with a thickness 80mm can bear high temperature and prevent heat loose as well [19].

3.3.4 Oil rate and material balance

Different plastics heating in different environment will have different productivity of oil. Table 5 [5] shows the oil yield rate of different kinds of plastics using this system.

Based on historical data, their common waste plastic pyrolysis machine oil rate is between 80% to 90%. But when most feedstocks are waste tires, the oil yield rate can reach 45% to 55%. Given the daily capacity is 100 kg, it can produce at least 45 kg oil fuel, 30 kg carbon black, 15 kg steel wire and 15 kg combustible gas [5]. Pyrolysis oil can be accepted as fuel for iron plant, power plant, cement plant and brick plants and so on. After being distilled into diesel, it will have a wider range of applications and create higher profits. As for carbon black powder, it can either be briquetting or be grinding. As briquetting, it can be burnt as fuel in cement factory, brick factory and cement factory. As grinding, it can be used as paint or ink.

Table 5: The Oil Rate from Different Single Plastics[5]

Plastics	Oil rate
PVC	Little oil with poor quality
PE	95%
PP	90%
PS	90%
ABS	40%
Pure white plastics cloth	70%
Plastic package	40%
Paper coating	Dry material: 60%; Wet material: 15-20%
Household garbage	30-50%
Pure plastic cable covers	80%
Clean plastic bag	50%

3.4 Huayin's Waste Plastic to Fuel Oil Pyrolysis Plant

3.4.1 Overview

Huayin Renewable Energy Equipment Co., Ltd is a company located in Xinxiang City in China. In 1993, it started with manufacturing waste tires/plastics to fuel oil pyrolysis machine and waste oil to diesel distillation machine. After 30-year researches on pyrolysis and great improvements on technologies, their waste to oil resources renewable energy equipment has been put into market successfully in more than 30 countries [20].

3.4.2 Process and Outputs Description

3.4.2.1 Small-scale waste plastics to fuel oil pyrolysis plant

For daily feedstock no more than 10 tons plastic wastes, there is a series of batch type of pyrolysis plants which can process waste plastics from 5 tons to 10 tons for one day. And the input materials can be PP, PE, PS and ABS [19].

For a batch system, a certain quantity of waste plastics is sent to the reactor for each cycle manually. In the reactor, the sealed space creates an environment without oxygen and it is heated to high temperature of 400 to 450 degree Celsius to pyrolyze those waste plastics.

Through this batch pyrolysis system, for each single plastic material, the oil rate is different from each other and their own oil rate is shown below table 6 [6]. When all those different plastics are mixed, oil rate is lower which is only 45%, and the rate of carbon black is 30%. But the oil rate is increased as the quality of feedstocks improved. In some cases, it can up to 75%. The density of generated oil is 0.89g/cm^3 and this oil can be sold up to \$550/ton in Mexico.

3.4.2.2 Continuous pyrolysis plant

Besides batch type, continuous pyrolysis plant is also the core product of their company and it mainly targets at waste tire, rubber, MSW and even some medical wastes. Compared with batch type, continuous pyrolysis plant has larger capacity which can process 5 tons to 30 tons each day. In addition, the whole system can be monitored and managed through PLC which increases the automation and safety [21].

Different from batch system, materials are continuously fed into reactor by screw conveyor from the hopper. Decomposition process starts when reactor is heated to the set value, and oil gas is generated. Similar as Batch system, oil gas goes into condenser, and cools down into liquid and

is saved in the tank. While non-condensable gas goes back into furnace as fuel to assist the heating process. Carbon black and other solid residues are discharged automatically.

Table 6: Oil Rate from Different Single Plastics in Batch System in Huayin [6]

Raw material	Oil Rate
PP	50%-75%
PE	50%-75%
PS	50%-75%
ABS	40%
Leftovers of paper	Wet: 15-20%; Dry: 60%
House Garbage	35-50%
Plastic Cable	80%
Plastic bag	50%
PVC	Not suitable
PET	Not suitable

3.4.3 Outstanding Characteristics

3.4.3.1 Environmental protection

Possible pollutions during the whole process are water, slag, gas, and noise. Water is only used during cooling process. It only runs outside the condenser system and can be recycled for several months. Slag is the byproduct which is not too much and can be either disposed or processed into carbon black. For gas, one is combustible gas which can go through exhaust gas recovery system and sent back as fuel. The other is smoke dust generated from burning coal and it should pass through the dust catcher to prevent it from emitting directly. The noise of machine is below 85 dB which can meet the regulation.

3.4.3.2 Long Life Time

To achieve both long life time and energy saving, they have an innovation on reactor. Usually, hot-blast stove owns long life time, but it needs more energy to support. While direct fired reactor is quite converse which is energy-saving but short life time. Thus, they thicken their steel

plate reactor of fire approach part which is easily and quickly oxidized, while for those slowly oxidized parts, they use quite thin plate.

3.5 Comparison and Discussion

3.5.1 Comparison

All those four companies have great achievements on pyrolysis. With capacity of 10 tons waste plastics each day, their products yield rate, energy consumption and land use are shown in table 7. The Henan Doing has the highest oil yield rate, while the Kingtiger group takes the lowest temperature for heating. But all those data float and they are impacted by many different factors. In different situations, the oil yield rate is different.

Table 7: Comparison Among Four Companies in China

	Kingtiger[3]	Niutech[4]	Henan Doing[5]	Huayin[6]
Pyrolysis oil	45%	43%-48%	80-90%	45%
Carbon black	40%	32-36%	10-15%	30%
Combustible gas	15%	6-8%	5-10%	10%
Power	30 kw/h	/	244 kwh/day	15kw/h
Fuel	/	/	500kg/day (coal)	44.3kJ/kg
Water	/	/	60 m ³ /month	/
Reaction temperature (°C)	250-280	/	400-450	400-450

3.5.2 Batch and Continuous System

In general, there are two types of pyrolysis system for commercial, batch and continuous. And those two types can successfully convert waste plastics into pyrolysis oil. But there are some different characteristics which should be taken into consideration before making a choice between those two.

3.5.2.1 Capacity

Compared with the continuous system, batch system can process less wastes than continuous one. Usually, the maximum daily capacity for batch system is about 10 tons, while for continuous system, it can reach 30 tons or 50 tons or even larger quantity of wastes.

3.5.2.2 Automation

Batch system is less automatic than continuous one. For each process, the pyrolysis process should be stopped for discharging residues and feeding manually. In this way, it takes longer time to process the same amount of wastes. Thus, batch system requires more labors to operate this process.

However, most continuous plants take PLC to control and manage their system, the precise calculation system can help them to ensure the full pyrolysis process which make it easier for them to check mistakes.

3.5.2.3 Profits

Continuous pyrolysis plant has larger capacity and takes little space which is cost-efficient. Besides, costs on labors will decrease also since it is fully automatic and less labors are needed. However, only when there are enough waste plastics to satisfy the large scale can such a large plant make profits.

3.5.3 Achievements on Pyrolysis Development in China

Over years, great progresses have been made in pyrolysis technology in China. There are some common and outstanding characteristics among those new products when compared with the old one.

- 1) Environmental-friendly; In the past, burning plastics can cause serious secondary pollution. But now, Advanced gas emission control, absolute sealed space and recycled cooling water lower the pollution of water and gas greatly.
- 2) Oil yield rate and quality of products; Old process had quite low oil yield rate and the quality of oil was unstable and poor which can hardly make profits. But now, when catalysts have been brought to this technology and equipment performances have been optimized, the yield of oil can reach about 75% when plastic wastes are under a good condition. Though the quality of oil varies when the composition of feedstock changes, the average quality of oil

can reach the quality of NO 4 Light Fuel Oil. If with further distillation, the fuel oil can be converted into diesel which has a wider range of usage and create more value.

- 3) Low operation cost; Costs on energy consumption take the most operation cost. Through the whole process, it needs fuel, water, electricity. Water is used for cooling system without touching any toxic or contaminated materials so that it can be recycled which saves money on water bill. Fuel is mainly used for heating which could be coal, fuel oil, natural gas, and wood. With large demand of fuel, lots of money is spent on it. However, during the process, there are some non-condensed gas with high heating value which can be combustible. And new technology can fully reuse this part of gas as fuel and send them back into furnace which can lower the fuel cost and save energy. Besides, the fuel oil as product can also be sent back to heat the system to achieve self-sufficient.

4. DISCUSSION AND CONCLUSIONS

4.1 Plastic Wastes Collection and Sorting

Plastic wastes collection is the foundation of pyrolyzing plastic into oil. The quality and quantity of plastic wastes are of great significance and determine the industrial success of pyrolysis process. There are some methods for collecting plastic wastes. The most common one is curbside collection which is managed by local government. By setting lots of colored garbage cans on the curbside, not only plastic wastes can be recycled, residents can also be reminded to separate their wastes. However, in most cases, without strong consciousness of recycling, there is a low collection rate. The other is a “buy-back center” which is usually operated by private companies. It purchases plastic wastes from residents and then sells them in bulk to plastic processing plants. In this way, the collected plastics are in good quality and the contamination level is reduced. Also, the drop-off center is a better way for collecting plastic wastes. In the waste collection center, residents are required to separate their wastes into trash, paper, plastics, and glasses. However, the throughput is unpredictable and low in most time, since not everyone would like to follow the rules and know how to separate them in a right way. Thus, quality and quantity are hard to satisfy at the same time. To maximize the cost efficiency of collection, most collection are of co-mingled recyclables (paper/board, glass, aluminium, steel and plastic containers). Automated presorting is necessary to separate plastics from other wastes. Besides, selecting

location for collection station is also important. Since long distance with lightweight plastics resulting in a low-cost efficiency on transportation [22].

4.2 Plastic to Oil Facility

Normally, to set a successful pyrolysis plant, project investigation, market research, site selection and equipment determination are essential.

1) Project investigation

At the beginning, it is important to know how much waste plastic can be collected and the way to collect those plastics, since they determine the scale of the plant and money spent on feedstocks. Based on research of Henan Doing Mechanical Equipment Company in China, for a normal plastic pyrolysis plant in China, it needs to pay for 200-300 dollars for each ton waste tires and 600-700 dollars for waste plastics. While in Latin American like Mexico, it takes only 30 dollars or even free. In Japan, local government is responsible for wastes collection and pay for local wastes treatment plant to process them.

2) Market research

An economic analysis is necessary before deciding to invest in a pyrolysis process. In addition to the capital cost of equipment and land use, the operation cost for energy consumption and labor salary should be considered. Then, one needs to estimate the plant revenues and balance the costs and benefits of inputs and outputs. For example, for the Chinese market, let us assume that a 10 ton/day pyrolysis plant requires an investment of 50 million RMB. If so, the repayment of the capital investment plus interest, over a 20-year period, has been estimated to be about 10% of the capital cost, that is 5 million RMB per year. Assuming that this plant operates 300 days for one year and therefore processes 30,000 tons per year, then the capital+interest repayment would be $5 \text{ million RMB} / 30,000 = 166 \text{ RMB}$ per ton of plastic wastes. Table 8 shows the costs and benefits for 10-ton pyrolysis plant.

3) Site selection

In general, for a middle size pyrolysis plant, it takes around 500 square meters land to install its main equipment, and some extra area should be reserved for installing feedstocks based on quantity.

In addition, impacts on residents should be considered. Since it is a waste management facility, the potential odor pollution and gas pollution sometimes is unpredictable. It is important to keep a certain distance between the facility and residential area.

What's more, Long transportation distance can add expenditure. Pick up a good location with a shorter distance from the collection point to the facility is worthy of consideration.

4) Equipment Determination

Equipment is the core part of setting a pyrolysis plant which has impacts on the quality and quantity of products and the operation cost. Firstly, based on the investigation to determine the capacity of the plant. Then choose the equipment according to the composition and characteristics of feedstock. Moreover, the gas emission control and other residues treatment process should be set to lower the pollution.

Table 8: Operation Costs and Benefits for a 10-ton Pyrolysis Plant in China

Daily Cost and Benefits for a 10-ton Pyrolysis Plant				
Operation Cost (10 tons/day)				
No.	Item	Unit Cost	Amount	Cost
1	Feedstock (plastic/tires) [23]	1000 rmb/ton	10 tons	10000 rmb
2	Fuel:coal	780 rmb/ton	500 kg/day/ton	390 rmb
3	Electricity	0.8 rmb/kwh	244 kwh/ton	195.2 rmb
4	Labor	150 rmb/day/per person	5 persons	750 rmb
5	Capita repayment	166 rmb/ton	10 tons	1660 rmb
Daily Sum				12995.2 rmb
Annual Sum (300 days/year)				3.9 million rmb
Benefits (10 tons/day)				
No.	Item	Unit Cost	Amount	Cost
1	Pyrolysis Oil [24]	2310 rmb/ton	4.5 tons	10395 rmb
2	Carbon Black [25]	1350 rmb/ton	3 tons	4050 rmb
3	Steel wire [26]	1900 rmb/ton	1.5 tons	2850 rmb
Daily Sum				28350 rmb

Annual Sum (300 days/year)	4.6 million rmb
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4.3 Existing Problems

4.3.1 Large Variation

For a plastic to oil facility, oil is the main source of profits. While oil quality and oil yield rate are highly related to the plastic wastes composition. Like polystyrene will increase the content of aromatics in products, while PET will influence oxygen atoms [27]. However, due to the large variation of plastics, the quality of oil is unstable and floated.

4.3.2 Unpredictable Moisture Content and Impurities

Though there is sorting system to separate plastic wastes from others, it is unavoidable that collected plastic wastes are mixed with some impurities, like metals. It is those impurities that add difficulties in pretreatment of feedstock and impact the quality of products.

Besides, moisture content is the other unpredictable factor no matter caused by rains or human behaviors. High moisture content in fuel will lower the heating efficiency [28].

4.3.3 Residence Time and Temperature Control

Temperature and reaction rate are the key parameters for pyrolysis process. But they are hard to control. Different types of plastics have different thermal behaviors under different temperature. Temperature controls the reaction rate which has impacts on the composition of products [9]. It is necessary to make tests repeatedly to choose the most appropriate temperature for mixed plastic wastes.

Same as temperature, residence time can influence the distribution of outputs. But it is temperature dependence factor which only has potential impacts when temperature is low. When temperature is under limitation, it is significant to have a good control of residence time [9].

4.3.4 Incomplete Regulations

Based on the case study of Sapporo Plastic Recycling Plant, it was a quite outstanding liquefaction plant in Japan since it had large capacity of mixed plastics and owned a high oil yield rate. However, it was closed due to low profitability. But if cost on collection can be reduced, and government can increase the price for such pyrolyzed oil or give some preferential price for fuels to lower the operation cost, and then the plant may not be closed. Thus, the development of plastic to oil pyrolysis technology needs the support of regulations. No matter from the production of plastics or the management of plastics, each process should be

normalized. Like the process of production, the pyrolysis will be much easier and more efficient if the utilization of PVC and PET can be reduced. For the process of plastic management, the plastic collection should be formalized which can offer a stable source of feedstock with good qualities.

4.4 Benefits

4.4.1 Sustainability

Recycling plastics can reduce waste plastics greatly. The generated oil can save energy and natural resources. On the other hand, as the technology improved, secondary pollution has been controlled. The entirely sealed reactor can reduce the polluted gas emission.

4.4.2 Replace Landfill

To manage plastic wastes, landfill is the most common method in most countries. However, landfill is not a sustainable method to deal with the solid waste including plastic wastes. It can not only waste large land area, it can also emit large amount of greenhouse gases to cause the air pollution. Besides, leachate from landfills is a significant environmental hazard as well. What's more, as land sources are more precious, the gate fee for landfill was increased which makes it no longer a cheap way to manage wastes.

Thus, pyrolyzing plastic wastes offer a good choice to replace the landfill. Compared with landfill disposal, RTI found that pyrolysis of waste plastics can save 1.8 to 3.6 million Btu for one ton of waste plastics, and 0.15 to 0.25 tons of carbon equivalent per ton over landfill disposal [29].

4.4.3 Valuable Outputs

Oil, carbon black and non-condensable gas are three main products during the process. Oil, as one of the fuel sources, it can be applied in many fields. Moreover, since oil is non-renewable, transforming plastics back into oil can save resources. As for carbon black, it is more economical to be produced from tires than that from petroleum. While non-condensable gas has higher calorific value as compared to natural gas which can be used as a source of energy for the pyrolysis process. Moreover, it has an enormous energy potential since the total amount of recycled waste plastics are huge.

4.4.4 Offer Job Opportunities

Pyrolysis technology can be commercialized. Once it is put into market, it can activate the local economy. Not only for the oil and carbon black market, it can also create job opportunities and lower the unemployment rate. American Chemistry Council has done a research on it, and they discover that plastics to oil technologies has the potential to bring out billions of dollars in US economic output with adding thousands of new jobs, meanwhile, reduce the amount of waste sent to landfills [25].

4.3 Conclusion

Even if plastic crisis has become an urgent worldwide problem, strong reliance on plastics indicates that there will always be plastic wastes. A sustainable and efficient treatment method is the key to solve the crisis. Pyrolysis offers this potential and the primary drives for it should include both economic and environmental aspects [30]. The plastics to oil technology can have a positive impact on both economic outputs and job opportunities. This technology is also environmental-friendly, can meet related regulations and reduce the amount of plastics now going to landfills. So far, technological progress has solved some old problems and boosted the development of pyrolysis plant. Based on the examined histories of past or currently pyrolysis companies, pyrolysis of plastics to oil has been used at various parts of the world. Though it went through a very tough period, with several companies closing down due to low profitability in the past, it is worthy of further exploration, especially if the global price of crude oil increases at steady levels above US\$70.

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