COMPARISON OF CHINESE PYROLYSIS PROCESSES

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Executive Summary

In 2018, about 380 million tons of plastics were produced around the world and from 1950 to 2018, 6.3 billion tons of plastics were produced. The amount of waste plastic in China is still increasing and is estimated account for 14% of the total municipal solid waste (MSW) by 2030. However, the estimated recycling rate of only about 9% is pretty low. The reason why there is such low recycling rate is due to the various types of plastic of different composition, color, and size which make it difficult to re-process the plastics to the original materials. Also, the cost of separate collection of plastics is relatively high. Hence, most of the used plastics are disposed as trash.

In this study, pyrolysis is considered as a potential method to dispose waste plastics and transform them into oil, black carbon and syngas. Four types of pyrolysis processes in China were examined and are discussed in this report, including the Kingtiger, Henan Doing, Huayin and Niutech pyrolysis processes.

Three major disposal methods for MSW are landfilling, incineration, and combustion with energy recovery (waste-to-energy or WTE). However, landfilling is not a sustainable use of land and open air incineration releases toxic substances which are carcinogenic and have other negative health effects. Pyrolysis is a “green” way to dispose mixed waste plastics and through thermal decomposition to transform organic materials into smaller molecules. The end products have high calorific value and can be used as fuels with economic benefits. The continuous-flow rotary kiln reactor is one of the most important reactors used for pyrolysis of plastic wastes.

Kingtiger is a continuous flow process with capacity of 50 tons per day using a nearly horizontal rotary kiln with catalyst. The pyrolysis of mixed plastics results in the yields of composition of 45% fuel oil, 40% carbon black and 15% combustible gas. The exhaust gas is transferred through a hydroseal to the burners and used as the fuel heating the process. The solid residue of the pyrolysis is mostly carbon black.

Henan Doing is a continuous process with capacity of 100 tons of waste plastics per day and is also based on a rotary kiln reactor. The oil product accounts for 45% to 52% of the feedstock, the carbon black residue to 30% and combustible gas to 18% to 25%.

Huayin is a catalytic batch process of 10 tons capacity per batch. The pyrolysis products are 45% crude oil, 30% carbon black and 10% waste gas. As in the case of the other pyrolysis processes, the gas products are recycled and used as fuel to heat reactor.

Niutech is continuous pyrolysis process with 43% to 48% oil yield, 32% to 36% carbon black yield and 6% to 8% combustible gas yield rate. They use a thermal-catalytic pyrolysis technology. Nintech claims that the catalytic pyrolysis process produces a high quality of carbon black and the production line operation is steady.

Based on the physical and chemical mechanisms, the comparison of the above four pyrolysis processes indicates that Henan Doing has the highest capacity and lowest

carbon black yield. Niutech has the lowest gas yield. On the basis of the economic and other data provided by Henan Doing, it is concluded that pyrolysis is a feasible and both economically and environmentally friendly process for transforming plastic wastes to useful products.

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1. Introduction

People use plastics in various ways and the plastics are in high production level since they are inexpensive and durable. In 2018, about 380 million tons of plastic is produced across the world. In total, from 1950s to 2018, there is over 6.3 billion tons of plastic has been produced. However, the recycle rate is pretty low. The estimate recycle rate is 9%. Most of the plastic becomes pollutant and is put into the nature directly such as ocean. Plastic pollution which is the accumulation of plastic objects has a negative influence on the wildlife and humans. Based on the size of plastic wastes, there are three categories of plastic, micro-, meso- or macro debris. Due to the chemical structure, most of plastics take a long time to degrade. Therefore, the plastic pollution is a really tough and critical problem. In China, Figure1 shows how much plastic is produced by month. In 2013, China was the world's largest producer of plastics.

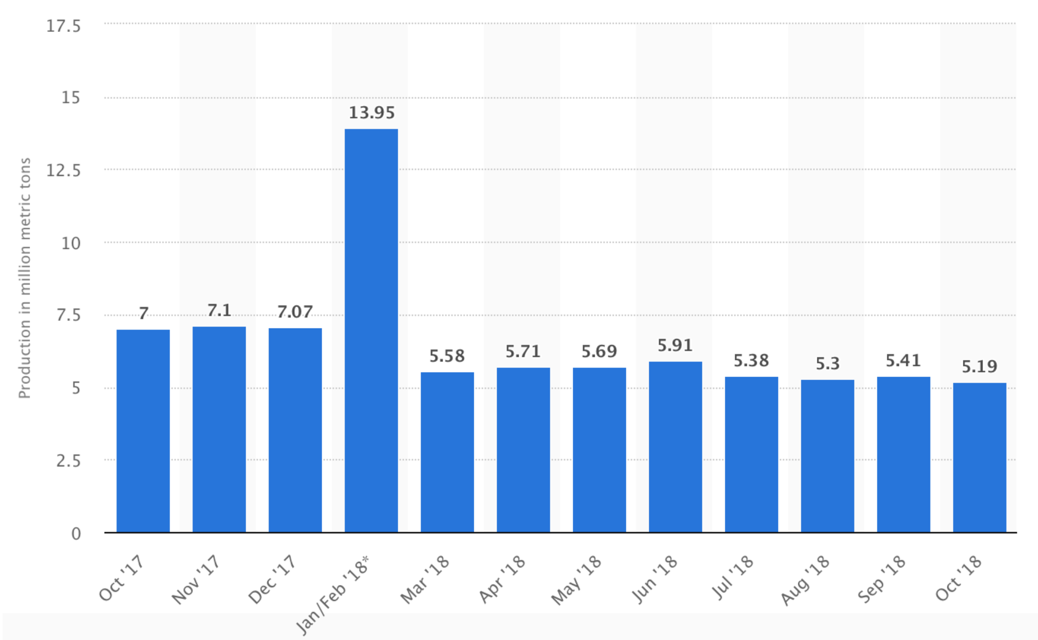

Figure 1: Produced plastic in China per month

As was mentioned earlier, there are many challenges to recycling plastic. First of all, if the plastic has the same color, transparency, weight and size, all the recycle process could be easy. In fact, there are thousands of different plastics. Therefore, it is extremely hard to sort and recycle. What is more, most of the recycled plastic faces a weak market such as dyed and pigmented plastic. Often, making a new plastic is less costly than buying and recycling plastic. Most of the plastic products such as milk jugs, soda containers and other bottles are turned into lower-grade products such as jacket fill, toys or plastic lumber. Secondly, various resins are not recyclable.

Facing the urgent issue, pyrolysis technology is a “green” solution for recycling waste plastic. Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves the change of chemical composition and is irreversible. The main advantage is the reduction in volume of the waste. In principle, pyrolysis will produce the monomers (precursors) to the polymers that are treated, but in practice the process is neither a clean nor an economically competitive source of monomers. Figure 2 illustrates the general process of the pyrolysis.

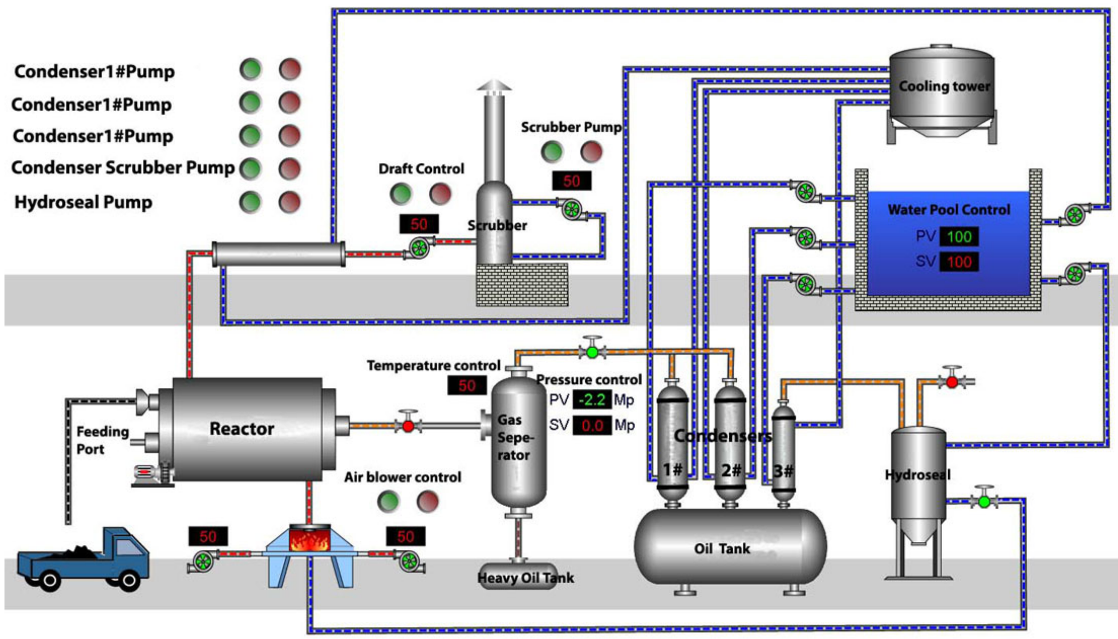

Figure 2: General flowsheet of pyrolysis process

This research report was to clarify current municipal solid waste and non-recycled plastic waste situation in China and possibilities of pyrolysis.. Four pyrolysis processes in China were compared by Kingtiger, Henan Doing, Huayin and Niutech by means of stating their characteristics through plant parameters, reactors, working process, efficiency, oil and gas yield rate, environmental concern and so on.

2. Plastic Waste in China

2.1 Municipal Solid Waste (MSW) in China

With rapid economy development and urbanization, the Chinese population has increased extremely fast over years thus increased amount of solid waste. Chinese MSW mainly consists of residential, institutional, commercial, street cleaning and non-process waste from industries (World Bank, 2005). Nowadays there are about 660 cities in China that produce about 190 million tonnes of solid waste annually which accounts for 29% of the world’s MSW each year (Dong, 2001).

Table 1 shows the collected and transported MSW increasing from 1981 to 2007 in China. In 2007, the amount of MSW was about 152 million tonnes and the generation was 0.70 kg/day/capita.

Table 1: Collected and transported MSW in China

Source: China Statistical Yearbook, 2001-2007

	1981	**1990**	**2003**	**2004**	**2005**	**2006**	**2007**
Urban population ($\times 10^4$)	14,400	32,530	52,376	54,283	56,157	57,706	59,379
Collected and transported MSW (10^4 tonnes/year)	2606	6767	14,857	15,509	15,577	14,841	15,214
Per capita quantity of MSW (kg/day/capita)	0.50	0.57	0.78	0.78	0.76	0.70	0.70

Currently, MSW in China has high organic and moisture content. It is because the proportion of kitchen waste in urban solid waste is up to approximate 60% (Yuan, 2006). Another major component of MSW in China is coal ash. It is mainly from household furnaces which coal and wood are used for heating in the northern part of China and used for cooking in most rural places in China. However, it decreased rapidly with technology when coal was replaced by natural gas (Zhuang, 2008). By 2030, it is estimated that all urban households will use gas for home heating and coal ash will only be a minor component in waste stream and the total MSW generation will be 484 million tonnes (World Bank, 2005).

Figure 3 to Figure 5 shows the composition of MSW in China changed from 1996 to 2000 and the prediction of MSW for urban areas in 2030. The recycled materials such as waste paper and plastics have increased while organic wastes have decreased.

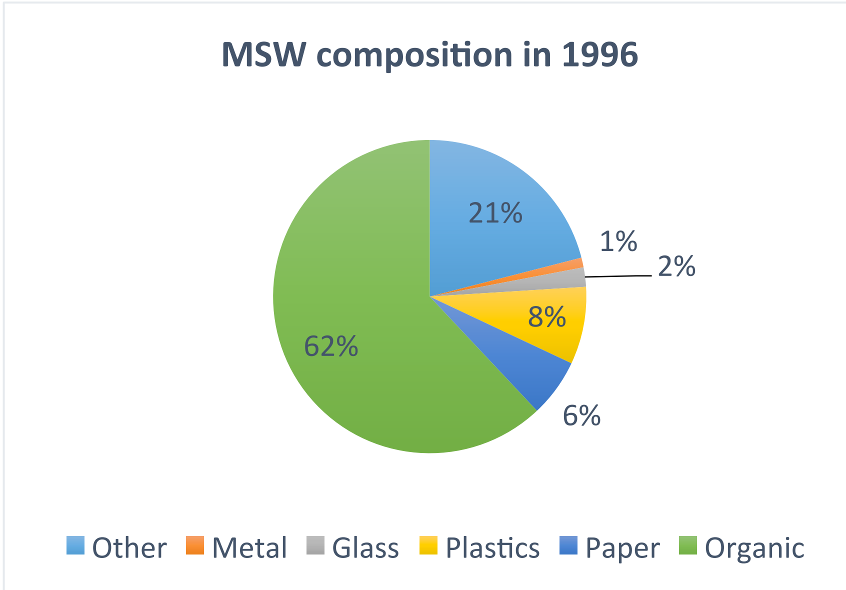

Figure 3: MSW composition in 1996
Source: Wang, 2001

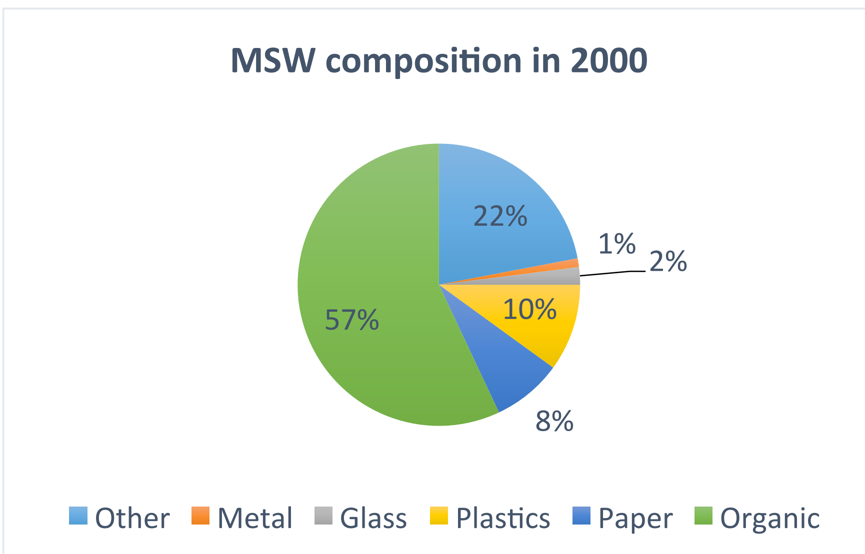

Figure 4: MSW composition in 2000
Source: The World Bank, 2005

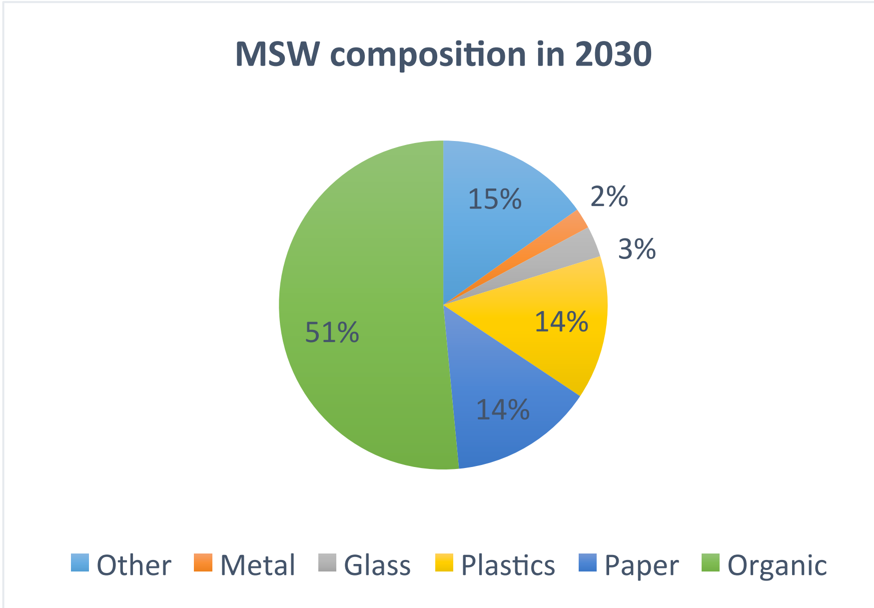

Figure 5: MSW composition in 2030
Source: The World Bank, 2005

Table 2 indicates the status of MSW disposal in China. Landfill is the most common way to dispose MSW. From 2003 to 2017, although the total MSW weight explosively increase, there were an huge increase numbers of treatment facilities and treatment rate improved a lot.

Table 2: Current status of MSW disposal in China
Source: China Statistical Yearbook, 2001-2007, 2017

Year	**Collected & transported MSW (10^4 tonnes)**	**Numbers of facilities for treatment**	**Treatment capacity (tonnes/year)**	**Numbers of landfill facilities**	**Numbers of incineration facilities**	**Numbers of composting plants**	**Waste disposal (10^4 tonnes)**	**Waste disposal in a simple way (10^4 tonnes)**	**Treatment rate (%)**
2003	14856.5	575	219,607	457	47	70	7544.7	4631.8	50.8
2004	15509.3	559	238,591	444	54	61	8088.7	4457.7	52.1
2005	15576.8	471	256,312	356	67	46	8051.1	4444.3	51.7
2006	14841.3	419	258,048	324	69	20	7872.6	-	52.2
2007	15214.5	460	271,791	366	66	17	9437.7	-	62.0
2017	20362.0	940	621,351	657	249	34	19673.8	-	96.6

2.2 Composition of Municipal Plastic Waste (MPW) in China

In November 2018, the plastic production in China was 5.4 million tons, meanwhile the consumption of plastic is 1.5 times greater than production which the recycling rate was less than one tenth. According to World Bank, the mainly composition of plastic are bottles, packaging, containers, bags, lids and cups. Figure 6 indicates the usage proportion of plastics in the different fields in 2000. Most plastic wastes are from packing then is commodity filed.

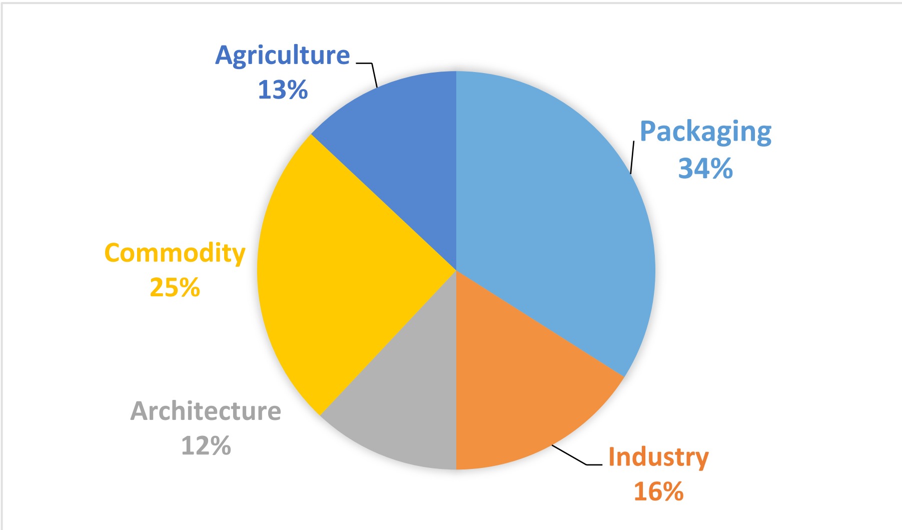

Figure 6: Usage proportion of plastics by different fields

Source: Liao, 2003

Figure 7 shows the composition of plastic waste in 2003 and Figure 8 indicates the recycling waste proportion in China. Compared with them, we can see it is important to figure out how to recover PVC wastes.

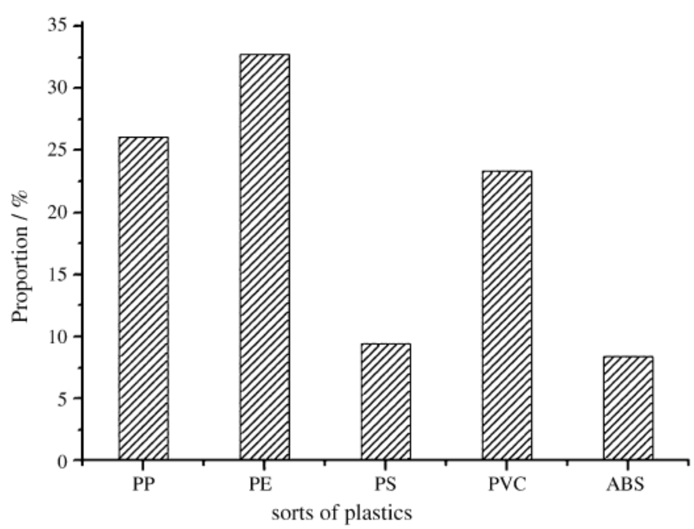

Figure 7: Sorting proportion of plastics in 2003

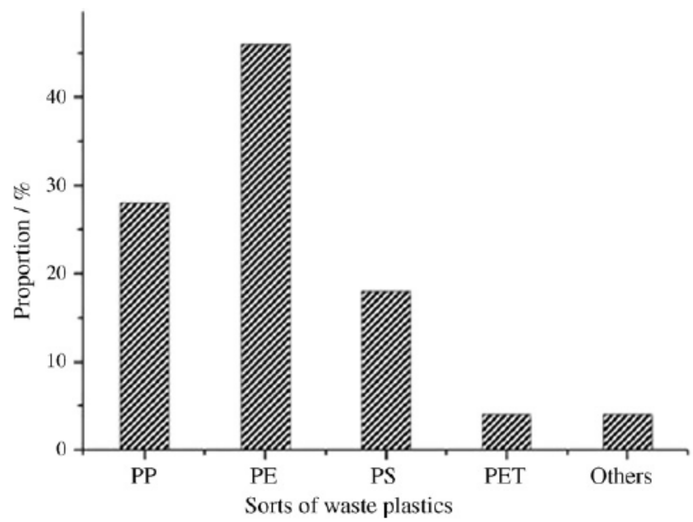

Figure 8: Proportion and sorts of recycling plastic waste in China

Figure 9 shows the output of recycled plastic wastes in China (Liao 2000). There is an extremely increasing of recycled plastic wastes from 1996 to 2005. According to the survey of the Committee of Economy and Trade of China, the recycling output of the plastic wastes in China was up to 6 million tons in 2005 (Tan, 2006).

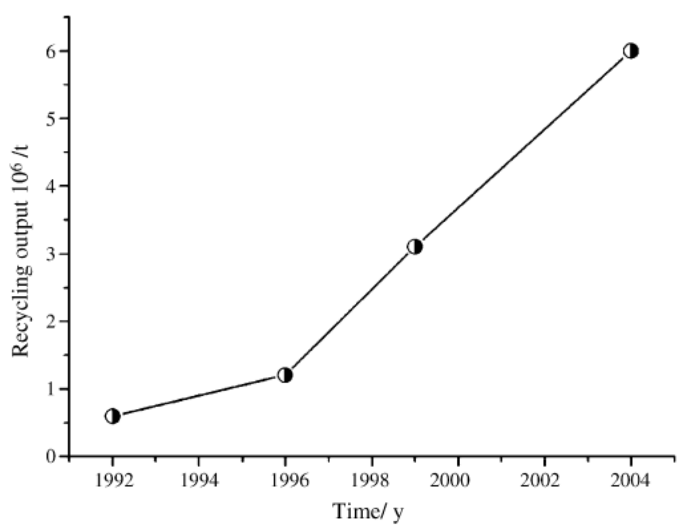

Figure 9: Output of recycled plastic wastes in China

2.3 Possibilities of Plastic Pyrolysis in China

Currently, the three major disposal methods for MSW are landfill, incineration and combustion with energy recovery (waste-to-energy or WTE). However, for landfill, burying waste underneath needs vast land resources and also threaten the quality of soil and underground water (Zhang, 2016). Meanwhile, burning waste by incineration will release amount of toxic substance such as dioxin which can lead cancer and cause damage to respiratory tract and circulatory system. Thus, there is infinite chance which pyrolysis will take over day by day.

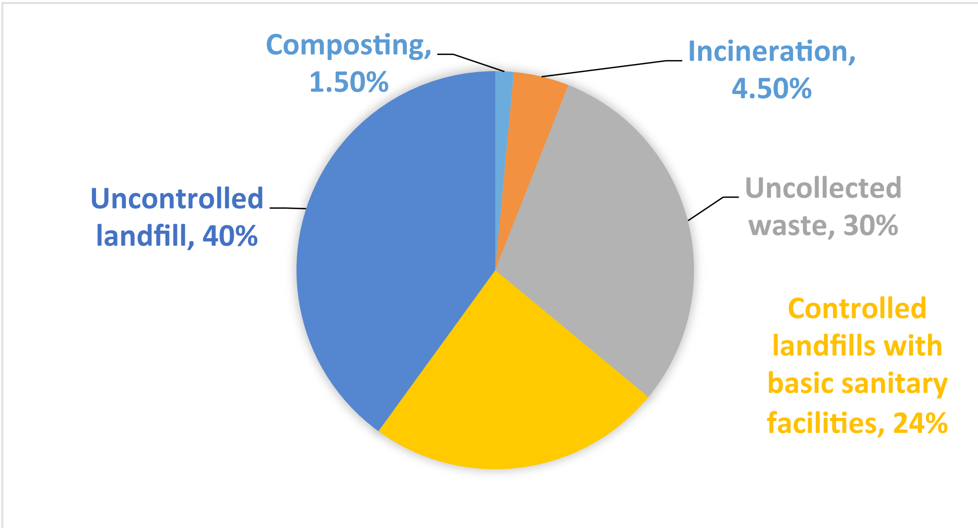

Figure 10: Disposal method for MSW in 2006

Source: Raninger, 2009

Pyrolysis can effectively reduce the demand of land for landfills with low harm to citizens and the end products have high calorific value as fuel which are economic benefits. This also conserves natural resource and releases the burden people rely on fuels by slowing down the usage speed of natural fuel and reduce greenhouse gas. Moreover, plastic to fuel conversion can create a cleaner-burning fuel because it possess a low sulfur content.

3. Pyrolysis Technologies for Plastic

3.1 Pyrolysis

Pyrolysis (Pyro = heat. Lysis = break down), is a process by using chemical and thermal decomposition leading high molecular compound organic materials into smaller molecules. It is also known as thermal cracking, cracking, thermolysis, depolymerization and so on (Scheirs, 2006). It converts organic materials into gaseous components, in the form of pyrolytic oil (or bio-oil) as liquid and solid residues of carbon and ash by heat energy. There are two dominating methods to remove contaminants from plastic for pyrolysis: destruction and removal. In destruction, the organic contaminants are decomposed into lower molecular weight substances while during removal, these compounds are not destroyed but are separated from contaminated material. With the presence of heat, pyrolysis is a practical way to crack or decompose organic materials such as polychlorinated biphenyls (PCBs), dioxins, and polycyclic aromatic hydrocarbons (PAHs). Although pyrolysis is impractical to destroy or remove inorganic materials like metals, it can be used to make these materials inert. Transformation plastic waste into fuel oil is a process of pyrogenic decomposition of waste plastic, depolymerizing agent and catalyst, then macromolecule waste plastic will be converted into micromolecule fuel oil. Compared with plastic recycling, pyrolysis is advantageous because it can process highly contaminated mixed plastic waste and generate high valuable products with minimal waste generation. Contrasted with gasification, pyrolysis occurs in an anaerobic environment thus can produce less emissions of NOx and SOx. Meanwhile, pyrolysis has lower heat loss than in gasification due to lower operating temperatures during pyrolysis (Tsiamis, 2013). There are two major types of pyrolysis: thermal and thermal-catalytic pyrolysis.

Thermal-catalytic pyrolysis is a pyrolysis process with catalyst. There are multiple merits of using catalyst: the catalyst can accelerate decomposition at lower temperatures with less energy and less costs. It can improve production with higher value and process separability. At the same time, catalyst can speed up cracking reactions leading shorter residence times and reactors with smaller volumes. It restrains the formation of undesirable products such as cyclic hydrocarbons, aromatic and branched and gains liquid products at a lower boiling point range. Generally, catalysts are classified either as homogeneous or heterogeneous. The former involves a single phase (usually a liquid solution), and the latter is solid. Heterogeneous catalysts are the most common type of catalysts used for pyrolysis of plastic solid waste because the fluid product can be easily separated from the solid catalyst and can be easily regenerated and reused. Heterogeneous catalysts have also been reported to suffer from severe reaction conditions up to 1,300℃ and 35MPa and also can generally be easily separated from the gas and/or liquid reactants and products (Butler, 2011).

3.2 Physical and Chemical Reactions

Breaking bonds in pyrolysis process is endothermic which means the heat during reactions is crucial important. As a rule, the pyrolysis of plastics follows complicated routes which cannot be described by one or more chemical reactions. There are only empirical formulas for part of reactions, i.e. reactions that really proceed as written (Scheirs, 2006).

3.2.1 Decomposition

Decomposition modes are often subdivided according to the dominant reaction patterns, which are mainly depended on molecular structure and the presence of catalysts (Scheirs, 2006):

(1) Unzipping: decomposition into monomer units (PMMA, PA 6).

(2) Random break the principle polymer chain (PE, PP) into fragments of diverse,

middle length. It is largely Gaussian distribution of the size over the resulting fragments with the average M.W. continuously declining and rising pyrolysis temperature and time. As a result, PE waxes and oils are converted from polyolefins. The premium diesel oil is often high in α-olefins and sulphur-free. On the contrary, PP products produce more branched product portfolio.

(3) Decomposition based on previous schemes combined (PS, PIB). In a polystyrene production plant, PS is able to easily be switched into monomer, because facilities are available already on site for separating the various pyrolysis products (styrene and its oligomers, ethylbenzene, toluene, benzene, etc.). But, enormous PS production plants generally produce insufficient off-spec. scrap to support a pyrolysis unit of even a small industrial size!

(4) Reduction of simple, stable molecules from adjacent atoms (PVC yields HCl, PVAc yields acetic acid, PVOH yields water). Such thermal cleavage makes unsaturated, charring, residual chain residue.

(5) Elimination of side-chains, including the non-volatile additives, followed by cross-linking and creating a porous charred residue. This scheme is followed by most thermosets and other cross-linked polymers.

3.2.2 Thermal Cracking Mechanism

Rice-Herzfeld type of free radical mechanism is the proposal of the thermal cracking mechanism. The notation β mainly employed in H-abstraction and for a larger and μ mainly decomposing radical, a simple scheme can be written as:

Initiation: $\mu\text{-H} \rightarrow \beta + \beta$

H-transfer: $\mu\text{-H} + \beta \rightarrow \mu + \beta\text{-H}$

Decomposition: $\mu \rightarrow \beta + \text{Olefin}$

Isomerization: $\mu \leftrightarrow \mu$

$\mu + \mu\text{-H} \leftrightarrow \mu + \mu\text{-H}$

Addition: $\beta + \text{Olefin} \rightarrow \mu$

$\mu + \text{Olefin} \rightarrow \mu$

H-transfer: $\mu\text{-H} + \mu \rightarrow \mu + \mu\text{-H}$

Termination: $2\mu \rightarrow \text{Products}$

$\beta + \mu \rightarrow \text{Products}$

$2\beta \rightarrow \text{Products}$

All the equations are used to demonstrate the kinetics and mechanism of high temperature (Scheirs, 2006).

3.2.3 Polymer and Products

Table 3 shows the Polymer resins and their major possible products. A high purity of the feedstock could guarantee the clean and possibly marketable products.

Table 3: Polymer resins and major possible products of thermal decomposition

Source: Scheirs, 2006

Resin	Mode of thermal decomposition	Low-temperature products	High-temperature products
PE	Random chain rupture	Waxes, paraffin oils, α-olefins	Gases and light oils
PP	Random chain rupture	Vaseline, olefins	Gases and light oils
PVC	Elimination of HCl from the chain, chain dehydrogenation and cyclization	HCl (<300◦C), benzene	Toluene (>300◦C)
PS	Combination of unzipping, and chain rupture, forming oligomers	Styrene and its oligomers	Styrene and its oligomers
PMMA	Unzipping	MMA	Less MMA, more decomposition
PTFE	Unzipping	Monomer	TFE
PET	β-Hydrogen transfer, rearrangement and de-carboxylation	Benzoic acid and vinyl terephthalate	
PA-6	Unzipping	Caprolactam	

Polyolefins, the main commodity plastics, decompose into a range of paraffins and olefins, including the PE and PP. With the increasing of reaction temperature and time, the molecular weight distribution and the paraffin-to-olefin ratio decrease.

Polystyrene PS mainly produces styrene, and its oligomers mainly dimers and trimers. The combination of PS + PE decompose like in the case of PS, with the pyrolysis products more saturated in some extent, the PE suppling the required hydrogen. The presence of PS accelerated the decomposition of PE.

Polyvinylchloride (PVC) decomposes into two different steps, the first is yielding hydrogen chloride and benzene, the second is a mix of aromatics. The kinetic results depend on the amount of sample and the experimental modes (programmed heating or isothermal) are different for hydrogen chloride evolution, with activation energy 136 vs 120 kJ/mol, and reaction order 1.54 and 1.98.

PET decomposes through β-hydrogen transfer, rearrangement and decarboxylation. In this process, the major products are benzoic acid and vinyl terephthalate.

Polyamide 6 largely depolymerizes into caprolactam. Both strong acids and bases catalyzed the decomposition (Ostend, 2002).

3.3 Continuous Rotary Kiln Reactor

The kiln is a cylindrical vessel and inclined slightly to the horizontal, which is rotated slowly about its longitudinal axis. When the kiln rotates, material may undergo stir and mix in some extent and moves down toward the lower end in the absence of oxygen. Hot gases move along the kiln, sometimes in the same direction as the process material, but usually in the opposite direction. The hot gases may be produced in an external furnace, or may be produced by a flame inside the kiln. This flame is projected from a burner-pipe. Gas, oil, pulverized petroleum coke or pulverized coal could be the fuel for this. In a rotary kiln heat exchange achieved may be by conduction, convection and radiation, in descending order of efficiency. In low-temperature processes, and in the cooler parts of long kilns lacking preheaters, internal heat exchangers usually furnished to make heat exchange between the gas and the feed easily. These may consist of scoops or "lifters" that cascade the feed through the gas stream, or may be metallic inserts that heat up in the upper part of the kiln, and impart the heat to the feed as they dip below the feed surface as the kiln rotates. The most common heat exchanger consists of chains which hangs in curtains across the gas stream. The cylinder is externally heated by the gas which produces during pyrolysis in an annulus around the cylindrical reactor. Figure 11 shows the basic process and Table 4 shows the relevant parameters of this process.

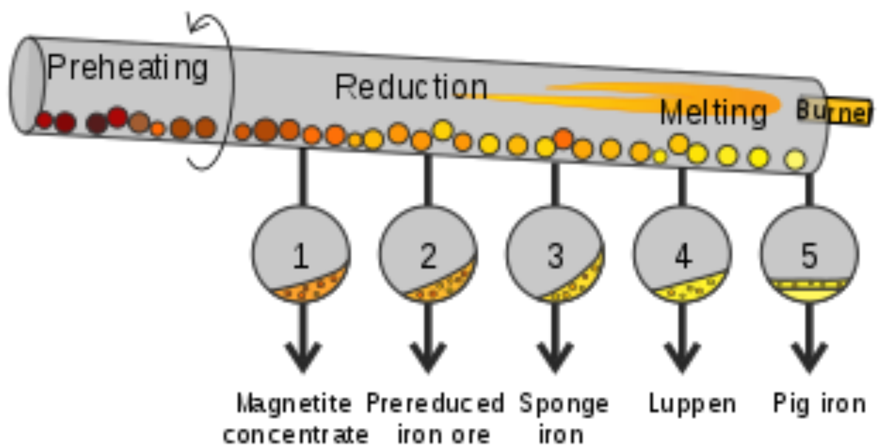

Figure 11: Direct reduction processes based on a rotary kiln

Table 4: The parameters of direct reduction processes based on a rotary kiln

	1	2	3a	3b	4	5
Consistancy of kiln discharge	solid				semiliquid	sol. (clinker) liq. (pig iron)
Preferred iron content of ore (% Fe)	30-60		30-60	55-63	25-45	50-67
Size of ore feed (mm)	< 20	< 20	< 10	5-25	< 5	< 0.2

Influence of basicity of charge (CaO/Al_2O_3)	no influence				0.3	2.8-3.0
Maximal temperature of charge (°C)	600-900	900-1100			1200-1300	1400-1500
Oxygen removal (% O_2 Extracted from Fe_2O_3)	12	20-70	>90			100
Examples of processes	Lurgi	Highveld Udy Larco Elkem	RN	SL/RN Krupp	Krupp-Renn	Basset

4. Pyrolysis Technologies in China

4.1 Kingtiger

4.1.1 Overview

Kingtiger Environmental Technology Co., Ltd. is a one-stop waste processing company located in Shanghai. It is a supplier of all kinds of waste disposal machines used in pretreatment for waste, waste recovery, and for processing of end products. Its professional research and development team provide customized turn-key projects such as pyrolysis plant, recycling plant, distillation machine, sorting system, carbonization plant, carbon black processing plant and waste pretreatment. Kingtiger plastic pyrolysis plant is an environmental protection system which uses the continuous liquefaction technology and catalytic breakdown reaction to convert plastic waste into renewable resources, such as pyrolysis oil, carbon black, and combustible gas. These end products can be utilized directly by diesel engines and generators, or they could be converted into high ranking diesel and gasoline through their oil refining plant.

4.1.2 Process Description

4.1.2.1 Continuous Working Process

Step 1: After treatment in professional plastic dryer, the waste materials are then transferred to pyrolysis furnace either manually or through the automatic feeding machine. Total quantity is controlled to be less than 2/3 of reactor in order to ensure smooth rotation. Then, doors are locked and tightly sealed with specially designed door locks.

Step 2: The first stage is heating pyrolysis reactor.

Step 3: Pyrolysis of waste plastics begins once the reactor has reached a certain temperature. There are two stages involved in pyrolysis: the preliminary stage, from 100 degree Celsius till 250 degree Celsius. During preliminary stage, the light oil gas is released at 100 ℃ and fluid oil is released at 120 degree Celsius. From 250 to 280 degree Celsius is the top output rate interval during which oil gas is collected into manifold with heavy particles and oil gathering and undergoing liquefaction at the center of manifold, ultimately pouring into heavy pyrolysis oil tank. The lighter gas rises to the multifunctional oil condensers to be liquefied into oil and stored in oil tank. Simultaneously, incondensable gas goes through desulfurization process and removal of dust by using hydro seal, eventually being transferred for recycling in the furnace.

Step 4: Smoke and fuel are discharged only after going through desulfurization and dust removal system.

Step 5: Once all the steps have been completed, the reactor is cooled down and carbon black is then automatically discharged by high-speed carbon discharge system once the temperature reaches 40 degree Celsius.

4.1.2.2 Pyrolysis Machine

Reactor is the main component of the pyrolysis plant where plastic waste is mainly processed. When reactor is heated, oil gas is produced. At 100℃, light oil gas is produced and liquid oil is yielded at 120℃ temperature. Particularly great amount of oil is produced in the temperature range of 250 ℃ to 280℃. Maximum temperature for the reaction is approximately 350℃.

Gas separator: oil gas from reactor is subsequently transferred into gas separator where separation of heavy oil from oil gas takes place which is then stored inside the heavy oil tank. Light oil gas rises up into the oil pipeline and is then sent for further processing into condensing system.

Heavy oil tank is used to collect heavy oil from the gas separator, utilized material is Q235.

Oil storage tank is used to collect fuel oil from condenser.

Hydro seal is used in gas desulfurization process, removal of impurities and purification to can prevent corrosion to the reactor. This is one of the core technologies that is imperative in extending the service life of a reactor's life.

Condenser: this process is equipped with tubular condenser, the most efficient condensing system. It is used to cool high-temperature oil gas ejected from gas separator. Heat produced from oil gas is in turn absorbed by cold water running outside the tube.

De-dusting system is used to collect and purify flue gas from heating system.

Table 5 and Table 7 show relative data of Kingtiger continuous plastic pyrolysis plant.

Table 5: Technical parameters of Kingtiger continuous plastic pyrolysis plant

Item Details	
Model	BLL-50

Daily Capacity	50T
Working Method	Consistently Continuous
Raw Materials	Plastic waste, tyre, rubber, oil sludge, medical Waste
Reactor Size (L*W*H)	12.5* 2.2* 2.5m
Pattern	Horizontal and rotary
Fuel	Charcoal, wood, fuel oil, natural gas, LPG, etc.
Total Power	84 kWh
Space for machine (L*W*H)	33* 15* 10 m
Operating Pressure	Constant Pressure
Cooling Method	Water Cooling
Service Life	5-8 Years

Using of different raw materials produces different oil ratio. Hence, oil ratio is dependent on different raw materials used, water content of the used materials, etc. Following table enlists approximate data of plastic to oil pyrolysis plant.

Table 6: Oil ratio for different plastic materials

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

Table 7: End products obtained from KingTiger waste plastic pyrolysis machine and applications

End product	Yield	Application
Fuel oil	45%	1. Sold externally. 2. Added in heavy oil generator to produce electricity. 3. Transformed into diesel or gasoline utilizing oil distillation equipment. 4. Used as fuel to heat reactor.
Carbon black	40%	1. Sold externally. 2. Reprocessed into color master batch. 3. Reprocessed into coal or refractory briquette.
Combustible gas	15%	1. Added back to the furnace for heating the reactor. 2. Stored as fuel for heating.

4.1.3 Features of Kingtiger's Plastic Waste Pyrolysis

4.1.3.1 Features of Continuous Plastic Pyrolysis Plant

(1) Established technology for manufacture, installation and operation.

(2) Reasonably spaced layout of pyrolysis system to effectively reduce floor area.

(3) Pyrolysis machine is equipped with automatic drying system for pre-treating plastic waste before pyrolysis.

(4) Reactor is rotary, which ensures even heating of the reactor, saving fuel energy and cost.

(5) Machine is equipped with highly efficient tubular condensing system to improve oil yield.

(6) Reactor is equipped with insulating layer which prolongs service life.

(7) Whole system is fully sealed thus completely blocking any leakage of gas and odor.

(8) Combustible gas produced in pyrolysis is recycled as fuel for heating the reactor, thus saving which fuel cost.

4.1.3.2 Features of Plastic Pyrolysis Reactor Design

(1) Such a novel and advantageous heating structure has never before appeared in the market which combines direct and hot-wind heating, increases heating speed and service life, improves production efficiency and reduces production cost.

(2) Pioneered PLC computer control system, 3 price grades: high, medium and low, that can be chosen accordance to the different requirements of customers.

(3) Two types of operations including batching and continuous which can meet different customer requirements, reduce production cost, as well as promote production efficiency.

(4) Stronger condenser system that utilizes rotary condenser which effectively optimizes oil yield and is convenient to maintain.

(5) Main reactor uses anti-burning technology.

4.1.3.3 Advantages of the Process

(1) Raw materials are added in the reactor through automatic feeding machine. The feeding door is closed and sealed, and then to opens into the heating system.

(2) Gas is partly produced when the temperature reaches 150℃, oil and gas are produced into the manifold when temperatures reaches 220℃. Heavy oil pours down into the heavy oil tank, and light oil is automatically transferred to light oil tank after passing through the water cooling-system for cooling and liquefaction.

(3) Gas parts which cannot be condensed are called exhaust gas, which are passed through the water seal system, and is returned to the heating chamber as fuel to heat furnace. Therefore, in the first processing stage, fuel used for heating is coal, wood, natural gas. However, once temperature rises to 220℃ to 280℃, the exhaust gas can be

used as fuel, hence saving on fuel cost.

4.1.3.4 Environmental-Friendly

Exhaust gas: exhaust gas is transferred to hydro seal and burner. This helps eliminate exhaust gas pollution and saves a lot of fuel. Dust is then treated by water spray type dust remover; dust is discharged only after it can meet emission standards.

Waste water: weak-acid waste water is obtained from pyrolysis. It is neutralized by using weak alkali liquid and is cleaned by using a triple filer. Then, the produced neutral wastewater is sent to evaporator. Heat source of evaporator is flue waste heat generated from reactor.

Waste residue: solid reside is also produced from continuous pyrolysis machine. Its main component is carbon black. Carbon black can be sold directly or can be processed into fine carbon black by using our professional carbon black processing machine.

4.2 Henan Doing

4.2.1 Overview

Henan Doing Machinery Equipment Co., Ltd., located in Zhengzhou, Henan province. It has been dedicated to research and development of large and medium-sized renewable energy environmental protection equipment and a variety of waste recycling equipment for years. They have installed machines in more than 40 countries throughout Asia, Africa, America, Europe and Oceania.

4.2.2 Process Description

4.2.2.1 Working Process of Plastic Waste Pyrolysis Plant

Step 1: Raw material (plastic) is added in the reactor using fully automatic feeding machine. The reactor is left empty 1/3 space to ensure smooth clockwise rotation for 0.4-0.8 r/min. The feeding inlet door is then tightly sealed to prevent any gas leakage.

Step 2: Pyrolysis process: reactor is gently heated by burning fuel material (coal, wood, natural gas, LPG or tire oil) generated. The oil gas is then released when temperature reaches 100℃ (250-280℃ is the top output rate interval). Heavy oil gas is separated by manifold, to then be liquefied and poured in the heavy oil tank. The lighter gas then rises up into oil condensers, and is subsequently liquefied into oil and stored in oil tank. The incondensable gas goes though du-sulphurization and de-dusting process utilizing hydro seal and is sent to the furnace for recycling.

Step 3: Once fuel oil is produced, reactor is cooled down. Carbon black is automatically discharged when temperature falls below 40 degrees. The oil gas generated from the reactor is then sent to condensing system and becomes liquid oil. Non-liquefied gas which couldn't be liquefied under normal pressure is returned to combustion system through safety device to be recycled for using the gas as fuel for heating the reactor. Hence, it saves save energy for the whole working process.

Step 4: A small amount of exhaust gas left is then expelled after it reaches emission standards.

Figure 12 shows how pyrolysis works at Henan Doing plant.

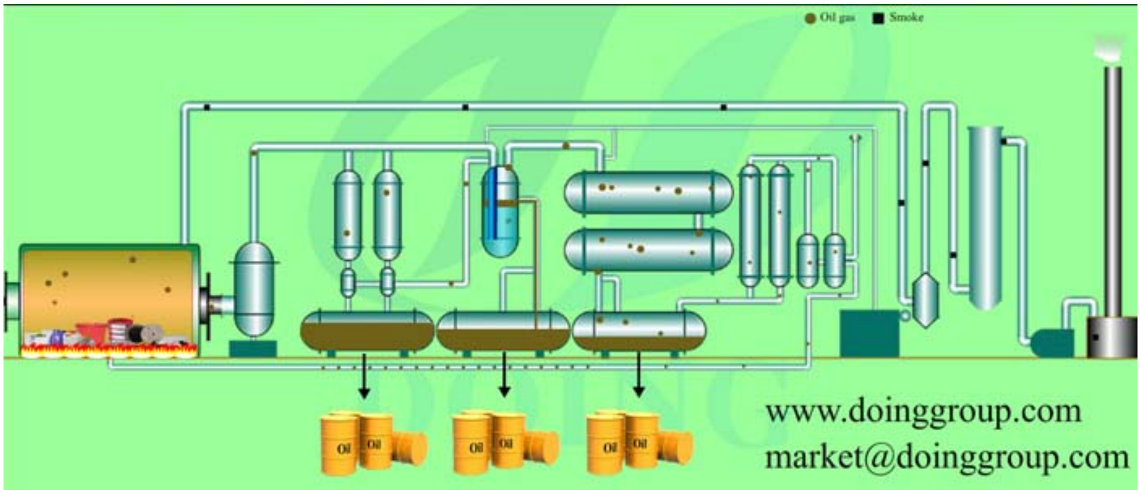

Figure 12: Pyrolysis process of Henan Doing plant

4.2.2.2 Pyrolysis Machine

Entire plastic waste pyrolysis machine is composed of 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, de-dusting device, draft fan and chimney.

Reactor is one of the most important parts. Therefore, the composite material and welding technology of a reactor will have a direct impact on safety and durability of the entire system. In order to guarantee good quality of a reactor, we use auto welder. The welding seam receives X-ray detection and heating treatment.

Condensers adopt water cooling method. The inner cooling tubes are composed of seamless steel pipe with 48 mm diameter. The area of heat exchange is about 13 square meter with total heat exchange area being 40 square meter to attain the best temperature for oil gas liquefaction.

Table 8 shows technical data for continuous pyrolysis plant.

Table 8: Technical data for fully continuous plastic waste pyrolysis plant

Item	Specifications
Model	DY-C-100
Capacity	100T/D
Power	120KW
Working type	Continuous
Reactor design	Multiple reactors (quantity and size depends on the condition of raw materials)
Rotating	Internal rotation

Cooling system	Recycled waste cooling
Reactor material	Q245R/Q345R boiler plate
Heating method	Indirect hot air heating
Heating fuel	Fuel oil/gas
Feedstock	Waste tire/plastic/rubber
Output	Fuel oil, carbon black

4.2.2.3 End Products

Fuel oil (45% to 52%): The main oil product produced through our recycling application is fuel oil that is widely used for industrial and commercial purposes.

Carbon black (30%): Carbon black is the main product recycled by pyrolysis technology. The amount of recycled carbon black is 30%. Carbon black is used as a raw material in many industries. The chemical structure of carbon black strengthens the structure and increases endurance, as well as improving the coloring of materials.

Table 9 shows different oil rate of plastics.

Table 9: Oil rate of different kinds of plastics

Item	
General Plastics	PET is not suitable (cannot be recycled)
PVC: Includes some films, cables, floor, pipes, windows, etc.	These are not suitable (PVC is acidic and will corrode machine)
PE: Includes some films, diaphragms, film membrane, bottles, electrical appliances, isolation materials, reticule, water pipes, oil drum, drink bottle, calcium feeding-bottle, milk bottle, used in items of daily necessities, etc.	95%
PP: Includes thin films, plastic ropes, plastic crockery, plastic basin and barrel, furniture, woven bags, bottle caps, vehicle bumpers, etc.	90%
PS: Includes electrical appliances, stationery, cups, food containers, household appliances shells, electronic accessories, foam products, toys, etc.	90%
ABS (Engineering plastics)	40%
Pure white plastic cloth	About 70%
Bags of instant noodles	About 20%
Paper-mill waste	Wet 15-20%, dry 60%
Household garbage	30% - 50%
Pure plastic cable skin	80%
Pure clean plastic bags	More than 50%
Plastic packaging	40%

Plastic logos	20%
PMMA	40%

4.2.3 Features of Henan Doing’s Plastic Waste Pyrolysis

4.2.3.1 Advantages of Plastic Waste Pyrolysis Plant

(1) Adapts well to external rotation and uniformly heats the reactor throughout 360°. Hence, no part of the reactor is heated for a long time, and in this way reactor has a longer service life.

(2) In the design of spiral blade inside the reactor raw material is passes inner wall of the reactor, moving evenly inside the reactor as it comes in direct contact with the heating surface and receives direct heat. This heat exchange is rapid and evenly distributed thus pyrolysis process is greatly improved.

(3) The reactor and feeder adopt frequency conversion explosion-proof motor which can adjust residence time of raw materials in the reactor according to the pyrolysis conditions of the raw materials in the reactor. This is done to achieve the purpose of adjusting the processing amount and the pyrolysis state to the raw materials to meet the requirements. In case of amount used for treatment, it is sufficiently decomposed to increase the oil yield.

(4) Carbon black can be separated by using steel wire when carbon black is discharged. If raw material does not contain steel wire, reactor can increase the processing capacity by 10%. During the discharge of carbon black, the steel wire and carbon black can be cooled and directly collected and saved. Thus, cooling time reduces and improves production efficiency.

(5) While using burner as a heat source, our reactor recycles the non-condensable combustible gas generated as a result of tire pyrolysis and passes exhaust gas burner as the second heat source of the reactor to achieve "self-sufficiency" and save fuel consumption. This will reduce production costs and increase customer revenue. In addition, flue gas after combustion of exhaust gas is effectively treated to meet environmental standards for flue gas emissions.

4.2.3.2 Environment Friendly

There are three products that may pollute the environment: gas, water and noise for which they have special equipment for treatment.

Gas: two kinds of gases are produced. One is gas from the combustion of raw material, such as coal, wood etc. This gas goes through the de-dusting system, resulting in a very clean gas, which is almost like steam. Based on the SGS report that they have for this gas, it safely reaches international standards. The second type of gas is non-condensable oil gas, which is recycled in furnace as an energy source for heating reactor. In the de-dusting system, three steps (water spray, ceramic ring filter, washing chamber) are used to de-dust the extra gas, ensuring the removal of more than 95% of the dust. The released gas is pollution-free and can be directly discharged into the air.

Water: like gas, water has two types of outputs. One part is used for cooling oil gas. This water is pumped through the pipe, thus, oil and water are always in an indirect contact. The water in the circulating system is always clean. Another output of water is produced through the de-dusting system: water film dust removal system. Water film dust removal system uses high-pressure hydraulic pump to press water into high pressure nozzle, atomizing water to clean smoke produced from furnace. This water is also circulating, therefore there is no water pollution.

Noise: The main noise from pyrolysis plant is draft fan noise that is <50db.

4.2.3.3 Safety

(1) Reactor with auto-welding to guarantee good quality of welding seam and prevention of cracking.

(2) Professional heating treatment and x-ray detection chamber for welding seam.

(3) Vacuum system to prevent oil gas from returning to the reactor which may cause accidents.

(4) Equipped with temperature meter, pressure meter and safety valve.

4.2.4 Cost and Benefit

From Table 10 we can see after implementation, there is huge benefit for a pyrolysis plant.

Table 10: Costs and benefits after construction

Cost/Day	
Item	**Cost of each**
Repayment of capital investment	$416.67
Waste plastic	$3,000
Coal	$280
Electricity and water	$324.16
Workers	$240
Total cost	$4260.83
Income/Day	
Crude oil	$22,400
Carbon black	$600
Total income	$23,000
Profit	
Daily profit	$18,739.17
Monthly profit	$374,783.4
Annual profit	$4,497,400
$/ton processed	$187.4

4.3 Huayin

4.3.1 Overview

Xinxiang Huayin Renewable Energy Equipment Co., Ltd is in Xinxiang, Henan which is specialized in plastics to fuel oil machine and waste oil to diesel distillation machine since 1993. Till now, they already had 11 patents with 2000 square meters running demo plant and their machine is installed in more than 34 countries.

4.3.2 Process Description

Step 1: Add raw materials into reactor by auto-feeder, then heat the reactor with any one of the following fuel materials: coal, wood, natural gas or oil.

Step 2: The liquid oil is cooled using condenser from oil gas and then collected in oil tank. The exhaust gas which cannot be cooled within normal pressure is recycled to heat the reactor. In this way, we can not only save energy, but also protect the environment.

Step 3: Smoke produced by processing plastics can achieve national emission standards through dual desulfurization and dust removal device.

Step 4: After oil is produced, temperature will be low as well. At this point, carbon black will be discharged automatically.

Step 5: Last, when the temperature falls to 100 degree Celsius, workers can put steel wire hook in the reactor to take steel wire out. After completing the above-mentioned steps, we can start another batch.

Figure 13 shows the pyrolysis working process and Table 11 and 12 show data relative to pyrolysis plant of Huayin.

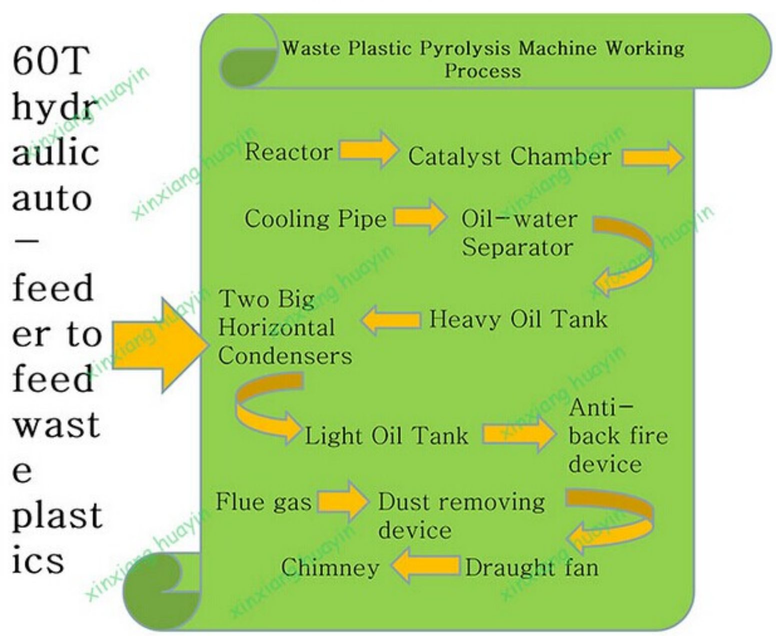

Figure 13: Waste plastic pyrolysis process

Table 11: Characteristics of pyrolysis process

Parameter	Objective/quantity
Usage	Waste plastic recycling to fuel oil
Input	Used plastic bags, Cables (PE, PP, PS, ABS), house garbage, leftovers of paper
End products	Fuel oil, carbon black, combustible gas
Heating material	Coal, charcoal, wood, fuel gas, fuel oil
Power	Average 15 kw/h
Capacity	10T/batch
Labor needed	3-4 workers
Density of oil	0.89 g/cm^3
Combustion value	44.30 KJ/kg
Machine cover area	Usually 400 square meters, 40meters length, 10meters width

Table 12: Use of process products

Items	Application	Sales market
45% Pyrolysis oil	1. Add it into heavy oil generator to produce electricity. 2. Used as heating material. 3. Sell it into oil refining factory to future process it.	Ceramic factory, glass factory, electric power factory, steel making factory, boiler factory, etc.
30% Carbon black	1. Deep process it into N220, N330 Carbon black. 2. Make it into pellet or briquette for burning. 3. Future process it into color master batch as basic material to make pipes, cable jacket. Etc.	Coal briquette factory, plastic factory, cable factory, etc.
10% Waste gas	Recycled onto fuel furnace to heat reactor to save fuel material	

4.3.3 Plastic Waste Recycling Machine Pollution and Safety Concern Solutions

4.3.3.1 Solutions for Safety Concerns

When adding raw materials, boiler needs to be rotated to benefit from the design of built-in spiral plates and to effectively utilize inner space of the reactor. In this case, the oil outlet pipe maybe blocked.

(1) In order to avoid this problem, they establish an anti-clogging net inside it.

(2) Pressure gauges, alarms, and safety valves. In case blocking causes high pressure inside the reactor (which may cause explosion), alarm will ring to alert workers to adjust to the conditions. If there is no answer from workers, there is no cause for worry as they

have also set up pressure reducing valves to automatically reduce the pressure. They have taken each possibility into account every case to effectively avoid any dangerous outcome.

(3) Vacuum device due to the continuous addition of plastic waste and constant heating, odorous gas may be produced from the reactor. This can be effectively minimized by using vacuum device. When temperature inside the reactor is below 100 degrees Celsius, vacuum device can be inserted inside the open reactor to suck in the bad odor. It is convenient and easy to operate.

4.3.3.2 Solution for Pollution

To prevent gas, polluted water, sound and slag produced as a result of waste plastic recycling machine from returning to the environment.

Gas: produced during refining process, such as methane, ethane, propane and other combustible gas. These gases are a form of thermal energy, hence, they recycle them in furnace as a fuel to heat the reactor, save energy and reduce pollution. Another source of gas is produced from burning of coal, wood, oil and combustible gas. If discharged directly into the air, it produces bad odor as well as air pollution. Thus, the acid-base neutralization and dust-removing system helps solve the problem. Lastly, through desulphurization, there is no resultant sulfur and hence no pollution, just water steam at high temperature.

Sound: the noise created during the entire production line is in line with national noise emission standards.

Slag: slag mainly consists of carbon black, which is used in the first link of pyrolysis machine. Carbon black can be used as raw material in factories which produce shoes, tires, cables or sealants. Carbon black powder is turned into carbon black briquette which is used for burning.

Water: used for cooling and can be recycled. No pollution here, just with high temperature.

4.4 Niutech

4.4.1 Overview

Niutech Environment Technology Corporation (Jinan Eco-Energy Technology Co.,Ltd) is located in Jinan, Shandong province from 1980s. It is the first national high-tech enterprise with specialized technology and equipment for extracting oil and carbon black from scrap tyre and waste plastic. It developed industrial continuous waste plastic pyrolysis production line with catalysts through low temperature to transfer white pollutant into high value energy product.

4.4.2 Process Description

4.4.2.1 Industrial Continuous Pyrolysis Machine for Recycling Plastic

Step 1: Mixed plastic waste is shredded and continuously fed into the pyrolysis reactor via feeding machine. The materials are then pre-heated during conveying process and low melting point plastic like PVC is separated through pyrolysis. HCl is then neutralize and treated after separation with other materials.

Step 2: Constant temperature of heating system supplies heat to the pyrolysis reactor. The raw materials are continuously fed into the pyrolysis reactor and spread by the system, completing pyrolysis reaction utilizing high efficiency catalyst.

Step 3: The pyrolytic oil gas is turned into high quality fuel oil and small amount of combustible gas after undergoing processes, such as fractional distillation separation, fixed bed secondary gas catalysis and de-waxing etc.

Step 4: Combustible gas is completely utilized in the system as fuel after scrubbing which achieves self-supporting for providing heat energy. The gas after being burnt is then discharged after passing through gas purification process.

Step 5: The small amount of solid residue generated from the reaction is continuously discharged out of the reactor and is further processed into fuel stick.

4.4.2.2 Continuous Waste Recycling of Plastic into Oil and Plastic into Energy Machine System Components

Continuous waste recycling of plastic into oil machine is consists of waste plastic pre-treatment system (optional), raw material pre-heating system, constant temperature heating system, HCl absorbing system (optional depends on materials), continuous pyrolysis system, combustible gas scrubbing system, gas purification system, residual pollution-free treatment system (optional) and control sub-system.

4.4.3 Features of Niutech's Plastic Waste Pyrolysis

4.4.3.1 Continuous Industrial Waste Recycled Plastic to Fuel Equipment Characteristics

(1) Accurate constant heating and heat spreading technology are realized.

(2) The material spreading system makes material uniformly, thus increasing heating surface, accomplishing patent structure, totally solving the problem of low heat transfer efficiency and coking that occurs in other technologies and equipment in the world.

(3) Small amount of combustible gas is entirely used as fuel for the system after scrubbing, combined with residual heat recycling system, greatly decreasing running cost.

(4) The unique and complete HCl absorbing system, totally reducing expensive sorting cost for plastic waste mixture.

(5) Adopting two-step catalyzing technology which achieves higher oil yield and better quality.

(6) Specific gas purification system removes all pollutes, such as organic compounds and solid particles like H_2S, CO, CO_2, SO_2, SO_3, NOX, NH_3 etc., which

enables compliance of emission specifications with Europe and US etc. highly regulating country standards.

(7) Whole line adopts PLC logical control system, realizing automatic control for all points to collect, calculate, record and print data as well sounding alarm.

4.4.3.2 Advantages for Niutech Environment Technology

(1) Industrial, continuous and massive throughput to enhance treatment efficiency and production capability.

(2) Exclusive low temperature pyrolysis technology, low consumption, enhancing oil yield and quality, ensuring long term, continuous and steady operation of production, dramatically expanding equipment's lifespan.

(3) Exclusive anti-cocking and thermal distribution technology, enabling uniform heating of material for equal heating and complete pyrolysis to achieve high-quality product.

(4) Exclusive hot sealing technology to ensure safe operation and reliability.

(5) Exclusive gas purification and remaining heat recycling utilization technology, purified gas can be used for heating system as combustible gas while remaining heat can be fully utilized as well. This promotes self supply for pyrolysis reaction without extra heating source, dramatically minimizing running cost.

(6) Exhaust gas from production line has been tested. All emission parameters meet the requirements outlined by EU, EEA of EU and US EPA.

(7) Entire production line adopts PLC intelligent control, warning, alarm and auto-correction function, and ensures operation under safety conditions.

(8) Low requirement for manpower, low working intensity and clean production.

4.4.3.3 Comparison Chart: Domestic and Abroad

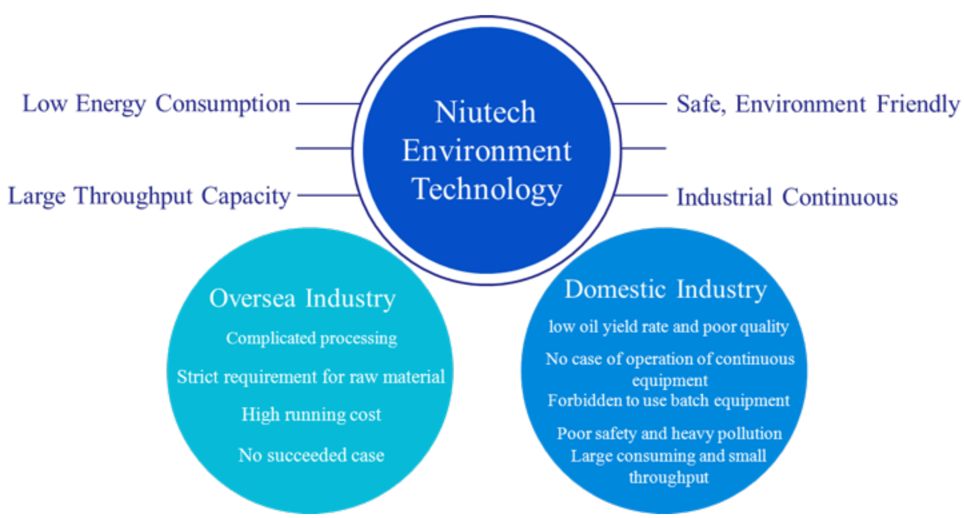

Figure 14: The comparison chart

Table 13: The comparison chart

	Oversea Industry	Domestic Industry	Niu-Technology
Oil Yield Rate	30-35%	33-38%	43-48%
Carbon Black Yield Rate	35-40%	35-40%	32-36%
Uncondensable Combustible Gas	20-25%	15-20%	6-8%
Quality of Carbon Black	Pyrolysis incompletely, poor quality of carbon black	Pyrolysis incompletely, poor quality of carbon black	Pyrolysis completely, good quality of carbon black
Equipment Lifespan	No long running case, no data	High low temperature frequency switch, short usage of equipment	Production line operation steady, long usage life

According to Figure 14 and Table 13, we can figure out Niutech pyrolysis plant has relative better behavior compared with other oversea and domestic industries.

4.5 Comprehensive Comparison of Different Technologies

We compared three continuous waste plastic pyrolysis plants (Kingtiger, Henan Doing and Niutech). Since Huayin is batch pyrolysis, we did not account it into comparison. Based on the processes of three factories listed above, it is obviously that the processes of Henan Doing and Niutech are pretty similar except Niutech is with catalyst. The temperature of each process varied to make output with different characters produce using less energy. But for Kingtiger, the temperature of whole process is constant. The material needs pre-heating before put into reactors. What is more, HCl is used in the process to neutralize the reactors. In addition, Kingtiger uses high efficiency catalyst to complete the pyrolysis reaction.

As for the output production, in Henan Doing and Niutech, light oil gas produced when the temperature reaches the range from 100 degree Celsius to 250 degree Celsius. Heavy oil gas is separated by manifold and liquefied into oil. However, in Kingtiger, since the temperature stays constant, there are one more gas purification process not only separating the gas but providing the whole process with heat energy as well. In Henan Doing and Niutech, the energy could be recycled in same way.

Table 14: Basic parameters comparison

Company	Temperature	Catalyst Input	Other Chemical Substance Input	Recyclable
Kingtiger	Constant	Yes	HCl	Yes
Henan Doing	Varied	No	No	Yes

Niutech	Varied	Yes	No	Yes

Table 15: End products comparison

	Kingtiger	Henan Doing	Niutech
Oil Yield	45%	45%-52%	43-48%
Carbon Black Yield	40%	30%	32-36%
Un-condensable Combustible Gas	15%	18-25%	6-8%
Equipment Lifespan	5-8 years		Production line operation steady, long usage life

In Table 15, the production ratio of each factories for each end product is compared. The oil yield rate is nearly similar (about 45%). As for the carbon black yield, Henan Doing could achieve the top production factory among the three. Besides, Niutech is able to produce the least amount of un-condensable gas. The equipment lifespan for Kingtiger is 5-8 years.

5. Conclusion

There are two primary methods of pyrolysis: thermal and thermal-catalytic pyrolysis. The use of catalysts in pyrolysis can accelerate the decomposition reaction requiring low reacting temperature. As pyrolysis happens, molecular bonds are broken and decomposition to smaller molecules occurs. The pyrolysis reactor is usually a cylindrical rotary kiln, slightly inclined to the horizontal and rotated slowly during reaction. As the kiln rotates, the shredded plastic is mixed up and moves slowly across the kiln without oxygen. The cylinder is heated externally by burning the gas product of pyrolysis in an annulus around the cylindrical reactor. During pyrolysis, the plastic wastes are transformed to a diesel-like oil, carbon black residue and combustible gas.

Compared the four different pyrolysis processes in China, the Henan Doing process has the highest capacity and could continuously process 100 tons of waste plastic per day. The oil yield rate (i.e., ton of oil per ton of plastic feedstock) is nearly the same (about 45%) for all four processes but the carbon black ranges from the largest, Kingtiger, down to Niutech, Henan Doing and Huayin. The combustible gas yield rate from low to high is the order that Niutch, Huayin, Kingtiger, Henan Doing. Each plant has pollution control equipment to reduce emission of pollutants. The gas from the combustion of raw materials go through the de-dusting system (water spray, ceramic ring filter, washing chamber) and non-condensable oil gas is recycled in furnace as energy source.

With limited time and data, only four pyrolysis processes were compared in this study. Further study should also include more processes into consideration. And for each city we should take react depending on its special characteristics.

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Appendix 1: Calculations made in this study

1. **Cost and Benefit of Henan Doing** (the only company for which the authors found data)

1.1 Cost

(1) Repayment of capital investment is assumed to be $1,000,000. The repayment is over 10 year period which means $100,000 per year. For everyday:

100,000/240 days = $416.67/day

(2) Plastic: every ton of plastic is $30 and the maximum number of daily dispose of waste plastic is 100 tons. Daily cost:

100 T×$30/T = $3,000

(3) Coal: dealing one ton of plastic needs 0.04 ton of coal. The coal price is $70. For 100 tons of waste plastic, daily cost:

0.04×100 T×$70 = $280

(4) Electricity and water: for one day continuous working, the machine consumes 244kw electricity and 10 tons water per ton of waste plastic. The electricity fee is $0.14 and water fee is $0.29. Daily cost:

244 kw×$0.14 + 10 kg/T×100 T×$0.29 = $324.16

(5) Worker: there are 2 workers every shift and each day has 3 shifts. The salary of each worker is $40. Daily cost:

2×3×$40 = $240

(6) Total cost:

$416.67+$3,000+$280+$240 = $4260.83

1.2 Income

(1) Crude oil: One ton plastic can produce up to 3.2 barrels of oil and for every barrel oil can sale $70. For 100 tons waste plastic:

100 T×3.2×$70 = $22,400

(2) Carbon black: there is 30% of carbon black produced from pyrolysis and one ton carbon black can sale $20. For 100 tons waste plastic:

100T×30%×$20 = $600

(3) Total revenue:

$22,400+$600 = $23,000

1.3 Profit

(1) Daily profit:

$23,000-$4260.83 = $18,739.17

(2) Monthly profit: every week work 5 days, 4 weeks a month:

$18,739.17×5×4 = $374,783.4

(3) Annual profit: works 12 months a year:

$374,783.4×12 = $4,497,400

(4) Revenue for per ton of plastic: there are 100 tons of plastic waste to be processed

$18,739.17/100T = $187.4