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Effect of Kaolin as a Catalyst on the Yield of Catalytic Pyrolysis Of Waste Plastic Mixtures

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Abstract: A waste plastic mixture of polypropylene (PP) and low density polyethylene (LDPE) was subjected to thermal degradation in the presence of kaolin as a catalyst. Different proportions of catalyst (5, 10, 15 and 20 wt. %) were added to the plastic wastes and mixed in a laboratory semi-batch reactor. The contents of the reactor were heated at a rate of 16°C/min, to reach the pyrolysis temperature of 400°C at atmospheric pressure. The effect of feed and catalyst composition on the liquid product yield was determined. It is shown that the use of kaolin resulted in a decrease in the reaction time and an increase in the yield of the liquid fraction. The maximum liquid yield achieved, using plastic waste mixtures, is 90% for a mixture of PP: LDPE = 3:1 using 15 wt. % kaolin. The composition of the liquid product was analysed using a GC-MS. The liquid product is mainly composed of Hexadecanes and C16+ which is an indicator for heavy oil similar to diesel.

Keywords: *Paralysis, Plastic waste, Catalyst, Kaolin.*

1. Introduction

Economic growth coupled with changing consumption and production patterns are resulting in a rapid increase in generation of waste plastics in the world. Due to the increase in generation, waste plastics are becoming a major stream in solid waste. After food waste and paper waste, plastic waste is the major constituent of municipal and industrial waste in cities. Plastic manufacturing industry holds a leading position among other petrochemical industries. It is considered as a backbone for the national economy of countries and also plays an important role in providing great income. The plastics industry gives direct employment to more than millions of people all around the world including raw materials producers, plastics converters and plastic machineries manufacturers. It also provides high turnover of billions of dollars and the non-biodegradability is less considered as a problem as plastics can be recycled.

Plastic waste recycling can provide an opportunity to collect and dispose of plastic waste in the most environmental friendly way and it can be converted into a resource. The unique characteristics of plastics allow them to make a strong contributions to a more environmentally sustainable and resource efficient world. Light weight, versatile and durable plastics contribute to energy and resource saving in strategic sectors and society.

This resource conservation goal is very important for most of the national and local governments, where rapid industrialization and economic development is putting a lot of pressure on natural resources. Some of the developed countries have already established commercial level resource recovery from waste plastics.

Waste plastics are one of the most promising resources for fuel production due to its high calorific value and the increasing availability in local communities. The conversion of waste plastic into fuel requires feedstocks which are non-hazardous and combustible. Each type of waste plastic conversion method has its own suitable feedstock.

One of the major problems of plastic is that it is not biodegradable. In many developing countries waste plastics are now posing serious threats to the environment and human health. Even in the best case when waste plastics are collected, they occupy large space. The negative impacts could be minimized by some alternatives that have been developed to manage plastic wastes such as, recycling and energy recovery method. However, there are some drawbacks of the recycling method as it requires high labour cost for the separation process and causes water contamination that reduces the process sustainability.

Due to these drawbacks, the researchers have diverted their attention to the energy recovery method to compensate the high energy demand. Through extensive research and technology development, the plastic waste conversion to energy was developed.

The overall objective of the research is to study the thermal and catalytic pyrolysis for a mixture of two types of waste plastics (PP and LDPE) in a semi-batch reactor with an objective to optimize the liquid product yield. Various PP to LDPE ratio and catalyst composition are investigated. A local material, kaolin, is used as a catalyst. The liquid product is characterized in term of composition and fuel properties to assess its suitability as fossil fuel substitute.

2. Literature Review

Waste plastics are one of the most promising resources for fuel production because of its high heat of combustion and due to the increasing availability in local communities. Unlike paper and wood, plastics do not absorb much moisture and the water content of plastics is far lower than the water content of biomass such as crops and kitchen wastes. The conversion methods of waste plastics into fuel depend on the types of plastics to be targeted and the properties of other wastes that might be used in the process. Additionally the effective conversion requires appropriate technologies to be selected according to local economic, environmental, social and technical characteristics. In general, the conversion of waste plastic into fuel requires feedstocks which are non-hazardous and combustible; in particular each type of waste plastic conversion method has its own suitable feedstock. The types of plastics and their composition will condition the conversion process and will determine the pre-treatment requirements and the temperature for the conversion. The production method for the conversion of plastics to liquid fuel is based on the pyrolysis of the plastics and the condensation of the resulting hydrocarbons.

Pyrolysis is the process of thermally degrading long chain polymer molecules into smaller, less complex molecules through heat and pressure. The process requires intense heat with shorter duration and in absence of oxygen. The three major products that are produced during pyrolysis are oil, gas and char which are valuable for industries especially production and refineries. Pyrolysis was chosen by many researchers since the process is able to produce high amounts of liquid oil (up to 80 wt. %) at moderate temperature around 500℃. In addition, pyrolysis is also very flexible since the process parameters can be manipulated to optimize the product yield based on preferences. Pyrolysis does not cause water contamination and is considered as green technology when even the pyrolysis by-product which is gaseous has substantial calorific value that it can be reused to compensate the overall energy requirement of the pyrolysis plant.

The thermal or non-catalytic pyrolysis of plastics is a high energy, endothermic process requiring temperatures of at least 350–500°C. In some studies, high temperature as 700–900°C is essential in achieving decent product yields. The extent and the nature of these reactions depend both on the reaction temperature and also on the residence of the products in the reaction zone. Addition of catalyst enhances the conversion and fuel quality. As compared to the purely thermal pyrolysis, the addition of catalyst in polyolefin pyrolysis significantly lowers pyrolysis temperatures and time. That results in an increase in the conversion rates for a wide range of polymers at much lower temperatures than with thermal pyrolysis.

The degradation of polymer may be considerably different based on the way in which reaction is carried out: heat (thermal degradation), heat and catalyst (thermo-catalytic degradation), oxygen (oxidative degradation), heat and oxygen (thermo-oxidative degradation), radiation (photochemical degradation), radiation and oxygen (photo-oxidative degradation) and chemicals (chemical degradation).

The common characteristic of these methods is that they cause irreversible changes in the structure of polymers. The decomposition of the framework of polymers results in decreasing molecular weight and significant changes of physical and chemical properties, the widely known and thoroughly studied methods are thermal and thermo catalytic degradation. Several reports have described the thermal and catalytic cracking of waste polymers. Two types of polymers have been widely investigated: polyethylene and polypropylene as they represent 60–65% of all plastic wastes.

The degradation of plastics means heating to high temperatures where macromolecules break into smaller fragments in which valuable mixtures of hydrocarbons (gas, liquid and residue) are obtained. The structure of the hydrocarbons produced can be modified by the use of catalyst. Catalytic cracking consumes less energy than the non-catalytic process and results in formation of more branch-chain hydrocarbons. On the other hand, the addition of the catalyst can be troublesome, and the catalyst accumulates in the residue or coke.

In the presence of catalysts, heterogeneous catalytic cracking occurs on the surface interface of the melted polymer and solid catalysts. The main steps of reactions are as follows: diffusion on the surface of catalyst, adsorption on the catalyst, chemical reaction, desorption from the catalyst, diffusion to the liquid phase. The reaction rate of catalytic reactions is always determined by the slowest elementary reaction. The dominant rate controlled elementary reactions are the linking of the polymer to the active site of catalyst. But the selectivity of catalysts on raw materials and products might be important. The selectivity is affected by molecular size and shape of raw materials, intermediates and products.

2.1 Process parameters

Parameters play a major role in optimizing the product yield and composition in any processes. In plastic pyrolysis, the key process parameters may influence the production of final end products such as liquid oil, gaseous and char. The desired product can be achieved by controlling the parameters at different settings. Those important parameters are temperature, type of reactor, pressure and catalyst. Temperature is one of the most significant operating parameters in pyrolysis since it controls the cracking reaction of the polymer chain. Molecules are attracted together by Van der Waals force and this prevents the molecules from collapse. When temperature in the system increases, the vibration of molecules inside the system will be greater and molecules tend to evaporate away from the surface of the object. This happens when the energy induced by Van der Waals force along the polymer chains is greater than the enthalpy of the C–C bond in the chain, resulted in the broken of carbon chain.

The type of reactors also has an important impact in the mixing of the plastics and catalysts, residence time, heat transfer and efficiency of the reaction towards achieving the final desired product. Most plastic pyrolysis in the lab scale are performed in batch, semi-batch or continuous-flow reactors such as fluidized bed, fixed-bed reactor and conical spouted bed reactor (CSBR).

Pressure is a temperature dependence factor that may have potential influence on product distribution of the plastic pyrolysis at lower temperature. Higher pressure increases the gaseous product yield and affected the molecular weight distribution for both liquid and gaseous products but only apparent at high temperatures. Most researchers conducted their plastic pyrolysis studies at atmospheric pressure and focused more on the temperature factor.

Catalyst speeds up chemical reaction but remains unchanged towards the end of the process. Catalysts are widely used in industries and there is a research focus to optimize product distribution and increase the product selectivity. Hence, catalytic degradation is particularly interesting to obtain product of great commercial interest such as automotive fuel (diesel and gasoline) and C2–C4 olefins, which have a huge demand in petrochemical industry.

2.2 Pyrolysis of Plastics

The first Pyrolytic Gasification systems were brick ovens using indirect heat, low oxygen that were made of firebrick. Waste was placed into the unit, the unit was sealed and heat applied. After the process of degradation was completed, the oven was opened and emptied to make room for the next batch. These systems were known as batch-by-batch systems. This format was first introduced commercially in the early 70's. Many research papers have been published regarding the potential of various types of plastics in pyrolysis processes for liquid production. It should be noted that the product yield and quality heavily depends on the set up parameters. It’s preferred to use batch reactors or semi-batch reactors in plastic pyrolysis laboratory scale experiment due to the simplest design and ability to control the operating parameters easily.

Pyrolysis in batch reactor or semi-batch reactor normally performed at temperature range of 300–800ºC for both thermal and catalytic pyrolysis. In catalytic pyrolysis, the catalyst was mixed together with the plastic sample inside the batch reactor. The drawback of this process would be a high tendency of coke formation on the surface of the catalyst which reduced the catalyst efficiency over time and caused high residue in the process.

Besides that, it was also a challenge to separate the residue from the catalyst at the end of the experiment. Sakata et al. (1991) used a batch reactor to study the pyrolysis of PP and HDPE at 380ºC and 430ºC accordingly using various catalysts and also without catalyst. The authors found that the liquid oil obtained from catalytic pyrolysis was even lower than the thermal pyrolysis for some catalysts. The liquid yield from PP in thermal pyrolysis was 80.1 wt% and from HDPE was 69.3 wt%, with the usage of catalyst. The liquid yield for both PP and HDPE reduced to 47–78 wt% and 49.8–67.8 wt% respectively. However, the usage of certain catalysts improved the liquid yield for both plastics slightly than the thermal pyrolysis with a very small increase of around 1.0–7.0 wt%, therefore, different catalysts might have different reactivity to the plastic type. However, it has to be noted that the tendency of the coke formation on the catalyst surface also might be one of the reasons that degraded the effectiveness of the catalyst used in batch reactor over time. Nevertheless, the direct contact of the catalyst with the plastics in some cases may also improve the liquid yield, some of the batch and semi-batch reactors were also equipped with stirrer that running at different speed depends on the required setting.

Table 1 summarizes the operating conditions and the product distribution for thermal and catalytic pyrolysis. Other parameters include the type of reactor, pressure, heating rate and pyrolysis duration for each type of plastics. All experiments carried out were using nitrogen gas as the fluidizing medium. PET and PVC are produced very low yield of liquid oil in comparison with other plastic types, which made these plastics infrequently explored by researchers. It should also be noted that not all plastic types are recommended for pyrolysis. PVC was not preferred in pyrolysis since it produced the major product of harmful hydrochloric acid and very low yield of liquid oil. Additionally, the pyrolysis oil also contained chlorinated compound that would degrade the oil quality and also toxic to the environment.

Panda (2011) investigated the effect of kaolin, silica and alumina catalyst on the pyrolysis of polypropylene, LDPE and PS using fresh and waste samples. Different temperatures and catalyst to polymer ratios were studied. Furthermore, the effect of acid treatment of kaolin was examined. Thermal pyrolysis of waste polypropylene, yield a maximum of 82.85 % condensable fraction at 500 °C. He reported that the use of kaolin, acid treated kaolin and silica alumina reduced the reaction time and enhanced the oil yield. The highest yield of oil (87.5 %) was achieved using a 3:1 polypropylene to kaolin ratio at 500 °C. The oil yield increased by 7.3% and reaction time decreased by 25.4 % at 500 °C using a 1:3 catalyst to polymer ratio.

Low viscous oil was obtained using kaolin catalysed pyrolysis of polypropylene at all temperatures. It was found that catalytic activity of acid treated kaolin is higher than untreated kaolin with a maximum oil yield obtained of 92%.

The yield of oil increased by 11.8% and reaction time decreased by 32.4 % at 500°C with 1:3 catalyst to polymer ratio. The maximum oil yield achieved using silica alumina, as catalyst, is 91% with 1:3 catalysts to plastic ratio at 500 °C.

The fuel properties of oil obtained using silica alumina is almost similar to the oil obtained in kaolin catalysed reaction. As for LDPE thermal pyrolysis, Panda (2011) showed that the recovery of condensable fraction was low 30.8 % at 400 °C, 71.45% at 450 °C, 78.1% at 475 °C and increased to highest yield of 86.65 % at 500°C. The yield of liquid fraction at 450 °C was 79.5 % in kaolin catalysed pyrolysis with 1:2 catalystsTo plastics ratio.

Oil yield increased by 10.6 % at 450 °C using a 1:2 catalyst to polymer ratio. As for the pyrolysis of polystyrene, Panda

(2011) showed that it is affected by temperature, type of catalyst and amount of catalyst.

The optimum temperature for obtaining highest yield of liquid fraction (93%) in thermal pyrolysis is 500 °C. A further increase in the liquid fraction to 94.5 % is achieved, at the same temperature, through the addition of a 1:10 kaolin catalyst to polymer ratio. It was shown that the presence of silica alumina had no effect on the yield of the liquid fraction.

This review provides a summary of plastic pyrolysis for each type and an insight into the main affecting parameters to optimize liquid oil yield. Based on the studies, pyrolysis process was chosen by most researchers due to its potential to

Convert the most energy from plastic waste to valuable liquid oil, gaseous and char. Therefore, it is the best alternative for plastic waste conversion and also economical in terms of operation, the flexibility that it provides in terms of product preference could be achieved by adjusting the parameters accordingly.

The studies also show that the product distribution can also be affected by different process parameters such as feed composition (plastic type), catalyst loading, catalyst size, the means of polymer and catalyst contact during degradation, reactor type, and degradation process conditions such as temperature, pressure and residence time. Table 2 shows a comparison of properties between plastic waste fuel and regular gasoline.

Table 2. Comparison of waste Plastics fuel to Regular Gasoline [2]

Properties	Regular gasoline	Plastic waste fuel
Colour, visual	Orange	Pale yellow
Specific gravity at 28 °C	0.7423	0.7254
Specific gravity at15 °C	0.7528	0.7365
Gross calorific value	11210	11262
Net calorific value	10460	10498
API gravity	56.46	60.65
Sulphur content(by mass)	0.1	<0.002
Flash point °C	23	22
Pour point °C	<-20	<-20
Cloud point	<-20	<-20

3. Materials and Methods

3.1 Materials

3.1.1 Plastics

A mixture of two different types of waste plastics has been considered for the experiments. They are polypropylene (PP) and low density polyethylene (LDPE). The waste samples are collected and are cleaned using liquid soap and water. Washed waste plastics are cut into 3-5 cm size with square shapes to fit into the reactor. Bottle caps were used as PP waste, collected and shredded to small square particle sizes, with melting point of 135 °C. The fine cuttings of waste LDPE shopping bags were used for the pyrolysis experiments, with melting point of 110 °C.

3.1.2 Catalyst

Commercial grade kaolin clay procured from Alara Mining Corporation, was used in this experiments. It is grinded to produce a fine, soft and white clay.

3.2 Equipment

A laboratory scale pyrolysis semi-batch reactor is used which consists of an electric heater, a round bottle, condenser, pump and collecting bottle. The round bottle has two necks made of glass that can withstand high temperatures. The first neck is used as the inlet for the plastic waste whereas the second inlet is used for the outlet of the gas product that leaves the reactor to the condenser. The condenser is a shell and tube heat exchanger where cool water is used to condense the gases produced during the pyrolysis.

3.3 Method

40g of plastic waste (various mixtures of waste PP and LDPE) are inserted into the semi-batch reactor at the beginning of each run. Furthermore, during catalytic pyrolysis, different catalyst proportions of 5, 10, 15 and 20 wt. % are added to the plastic wastes mixtures and mixed in the reactor. Both thermal and catalytic pyrolysis was subjected to a heating rate of 16 °C/min up to the desired temperature of 400 °C at 1atm pressure. The condensable liquid products were collected through the condenser and weighed. After pyrolysis, the solid residue left out inside the reactor was weighed. The weight of gaseous product was calculated from the material balance. All the experiments were repeated three times and the average value was calculated.

4. Results and Discussion

4.1 Kaolin chemical and physical analysis

The kaolin major components are $\mathrm{SiO_2}$ and $\mathrm{Al_2O_3}$ as shown in table 3. The chemical composition of Kaolin sample was analysed using an XRF. Table 4 shows the physical analysis of Kaolin.

Table 3. Kaolin Chemical Composition

Compound	Composition%
$\mathrm{SiO_2}$	55
$\mathrm{Al_2O_3}$	29
$\mathrm{Fe_2O_3}$	2.49
CaO	0.8
MgO	0.2
$\mathrm{Na_2O}$	0.11
$\mathrm{K_2O}$	0.79
$\mathrm{L.O.I}$	10.2

Table 4. Kaolin physical Analysis

Kaolin type	**Gerif Kaolin**
Fired color	White
Fired shrinkage	5.8
Fired bending strength	40.1
Water absorption	17.26

4.2 Effect of Kaolin on product yield and reaction time

The product yield distribution and reaction time, at different waste plastic ratios, for the thermal and catalytic pyrolysis of the waste plastic are shown in Table 5-8 and in Figure 1 and 2. It is observed that there is a decrease in reaction time and an increase in liquid yield with an increase in the amount of catalyst. Highest liquid yield of 90 wt. % is obtained at PP: LDPE = 3:1 with 15% catalyst as well as for thermal pyrolysis of PP separately without catalyst.

Table 5. Results of PP and LDPE for Thermal Pyrolysis

Plastic Type	**Type of pyrolysis**	**Yield wt%**			**Reaction time, min**
		Liquid	Gas	Solid	
PP	Thermal	90	6.5	3.5	58
LDPE	Thermal	71	26.5	2.5	47

Table 6. Results of mixture of PP: LDPE = 3:1 for Thermal and Catalytic Pyrolysis at different Amounts of Catalyst

Type of pyrolysis	**Yield wt%**			**Reaction time, min**
	Liquid	**Gas**	**Solid**	
Thermal	82.5	15	2.5	57
Catalytic (5 wt.%)	85	12.5	2.5	39
Catalytic (10 wt.%)	87.5	10	2.5	36
Catalytic (15 wt.%)	90	5	5	34
Catalytic (20 wt.%)	87.5	6.25	6.25	32

Table 7. Results of mixture of PP: LDPE =1:1 for Thermal and Catalytic Pyrolysis at Different Amounts of Catalyst

Type of pyrolysis	**Yield wt%**			**Reaction time, min**
	Liquid	**Gas**	**Solid**	
Thermal	77.5	20	2.5	52
Catalytic (5 wt.%)	82.5	15	2.5	35
Catalytic (10 wt.%)	85	12.5	2.5	33
Catalytic (15 wt.%)	87	8	5	30
Catalytic (20 wt.%)	82	13	5	28

Table 8. Results of mixture of PP: LDPE = 1:3 for Thermal and Catalytic pyrolysis at different Amounts of Catalyst

Type of pyrolysis	**Yield wt%**			**Reaction time, min**
	Liquid	**Gas**	**Solid**	
Thermal	72.5	26.25	1.25	50
Catalytic (5 wt.%)	77.5	20	2.5	32
Catalytic (10 wt.%)	80	17.5	2.5	30
Catalytic (15 wt.%)	82.5	12.5	5	29
Catalytic (20 wt.%)	75	20	5	27

Thermal pyrolysis of PP results in the highest liquid yield relative to LDPE. Fig. 1 shows the effect of the presence of catalyst on product yield. It is observed that the liquid yield for the mixtures increases with the use of the catalyst compared to the thermal pyrolysis. The use of catalyst increases the liquid yield up to 15% catalyst, however at 20% catalyst, the yield starts to decrease.

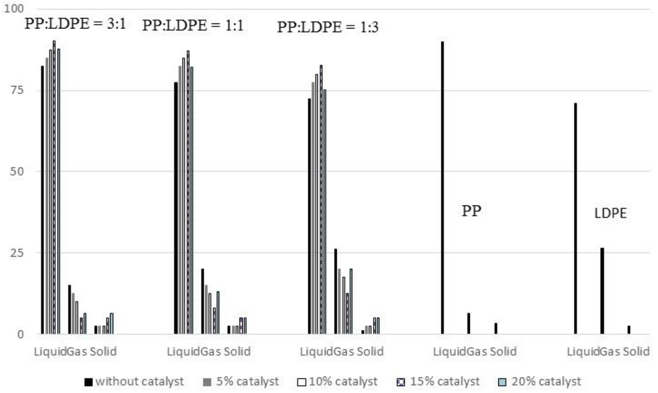


Fig. 1. Product Yield for Different Ratios of Mixture of waste Plastics with and without Catalyst

Fig 2 shows how the reaction time is significantly decreased with the use of kaolin as a catalyst. The shortest time of less than 30 min is observed for PP: LDPR = 1:3 for catalyst wt. % of more than 10%.

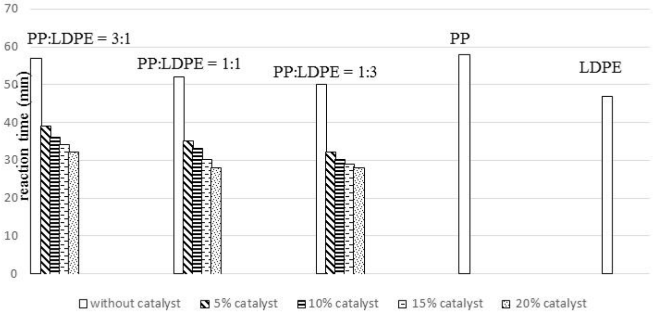


Fig. 2. Effect of Ppyrolysis of waste Plastic, with and without Catalyst, on Reaction Time

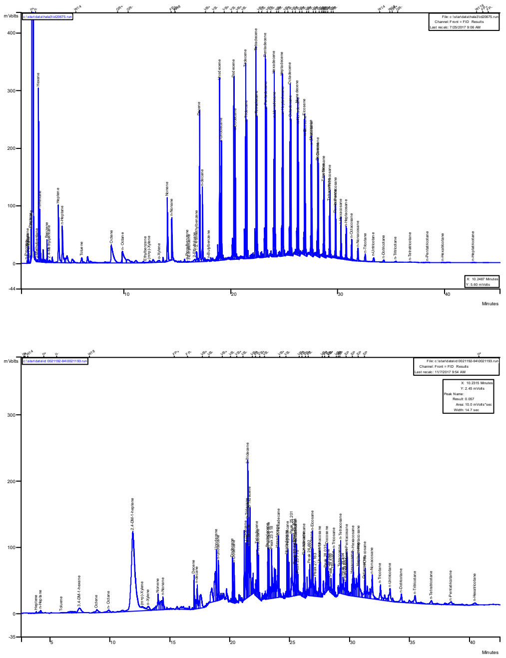
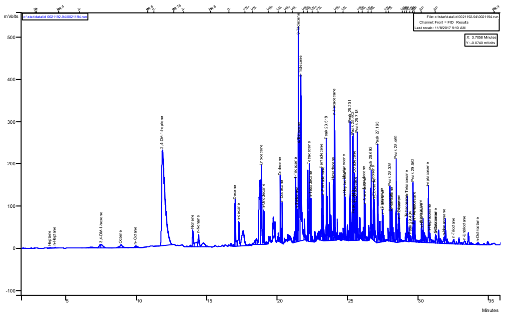
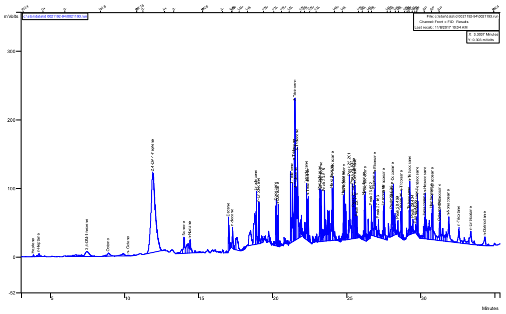


Fig. 3. Chromato Gamfor thermal Pyrolysis of LDPE



a) Chromatogram for thermal pyrolysis of PP: LDPE=3:1



b) Chromatogram for catalytic pyrolysis of PP: LDPE=3:1 with 15%catalyst

Fig. 4. Chromatogram for Thermal and Catalytic (15 wt. %) Pyrolysis of PP: LDPE=3:1PP

4.3.2 Physical analysis

Density, viscosity and cloud point, at specified conditions, for liquid product using a plastic waste mixture of PP: LDPE=3:1with 0%, 5% and 15% catalyst is shown in table 9. Table 10 shows the comparison between the standard American Petroleum Institute diesel and the liquid product produced using a PP: LDPE=3:1 with 5% catalyst. Results show that the liquid product produced is in the range of diesel fuel.

Table 9. Physical Properties of Liquid Product Obtained from Pyrolysis of PP: LDPE=3:1 with 5% catalyst.

Catalyst to Plastic ratio%	Density at 15°C, g/cm^3	Viscosity, $mm^2.s$	Cloud point
0 (without catalyst)	0.797	6.654 at 20°C	NO WAX
5	0.795	5.684 at 20°C	NO WAX
15	0.800	1.398 at 100°C	NO WAX

Table 10. Comparison between Standard Siesel fuel and Liquid Pyrolysis Product

Properties	Standard diesel	Liquid pyrolysis product (PP:LDPE=3:1 with 5% catalyst)
Density at 15°C, g/ cm^3	0.8	0.795
Viscosity at 20°C, $mm^2.s$	2.2-8.8	5.684
Cloud point, °C	< -20	< -20

4.4 Analysis of solid residue

The solid product from pyrolysis, for a waste mixture of PP: LDPE=3:1 using 20wt. catalyst, was turned into ash in an oven at 850°C.the results show an ash content of 64.15%.

CONCLUSIONS

An important amount of work has been presented in the literature in the area of plastic pyrolysis so as to produce valuable products. This technique offers several advantages such as enhancing the waste management system, increasing energy sources and also preventing the contamination to the environment. The technique offers great versatility and better economic feasibility in terms of the process handling and the variability of the product obtained.

Observation on the experiments was that, when PP is used alone for pyrolysis, it produces higher liquid yield than LDPE alone or than mixtures of PP and LDPE. Increasing the amount of LDPE in the mixture decreases the liquid yield. The highest yield of condensed fraction in thermal reaction is 82.5% by weight at 400°C for the mixture of PP: LDPE=3:1. Use of kaolin as a catalyst decreased the reaction time and increased the yield of liquid fraction. The major product of catalysed degradation is highly volatile liquid oil and the maximum oil yield using kaolin is 90% for the mixture of PP: LDPE= 3:1 with 15% kaolin, at 400°C.

Table 1: Summary of Previous Studies on Plastic Pyrolysis.

Reference	**Plastic**	**Reactor**	**Process parameters**				**Yield**			**Remarks**
			T (?)	P	Heating rate (? /min)	Duration (min)	Oil (wt%)	Gas (wt%)	Solid (wt%)	
Cepeliogullar and Putin (2013)	PET	Fixed bed	500	-	10	-	23.1	76.9	0	
Fakhrhoseini and Dastanian (2013)	PET	-	500	1 atm	6	-	38.89	52.13	8.98	
Ahmad et al. (2015)	HDPE	-	350	-	20	30	80.88	17.24	1.88	
Kyong et al. (2002)	HDPE	Semi-batch	400	1 atm	7	-	82	16	2	Stirring rate 200 RPM, FCC catalyst 10 wt%
Miskolczi et al. (2004)	HDPE	Batch	450	-	-	60	74.5	5.8	19.7	
Abbas-Abadi et al. (2013)	HDPE	Semi-batch	450	1 atm	25	-	91.2	4.1	4.7	Stirring rate 50 RPM, FCC catalyst 20 wt%
Luo et al. (2000)	HDPE	Fluidized bed	500	-	-	60	85	10	5	Silica alumina catalyst
Marcilla et al. (2009)	HDPE	Batch	550	-	5	-	84.7	16.3	0	
Mastral et al. (2001)	HDPE	Fluidized bed	650	-	-	20 - 25	68.5	31.5	0	
Cepeliogullar and Putin (2013)	PVC	Fixed bed	500	-	10	-	12.3	87.7	0	
Miranda et al. (1998)	PVC	Vacuum batch	520	2 kPa	10	-	12.79	0.34	28.13	Also yield HCl = 58.2 wt%
Onwudili et al. (2009)	LDPE	Batch	425	0.8 – 4.3 MPa	10	60	89.5	10	0.5	
Uddin et al. (1996)	LDPE	Batch	430	-	3	-	75.6	8.2	7.5	Also yield wax = 8.7 wt%
Fakhrhoseini and Dastanian (2013)	LDPE	-	500	1 atm	6	-	80.41	19.43	0.16	
Bagri and Williams (2001)	LDPE	Fixed bed	500	-	10	20	95	5	0	
Marcilla et al. (2009)	LDPE	Batch	550	-	5	-	93.1	14.6	0	
Williams (1998)	LDPE	Fluidized bed	600	1 atm	-	-	51.0	24.2	0	Also yield wax = 24.8 wt%
Ahmad et al. (2014)	PP	Horizontal steel	300	-	20	30	69.82	28.84	1.34	
Sakata et al. (1999)	PP	Batch	380	1 atm	3	-	80.1	6.6	13.3	
Kyong et al. (2002)	PP	Semi-batch	400	1 atm	7	-	85	13	2	Stirring rate 200 RPM, used FCC catalyst 10 wt%
Abbas-Abadi et al. (2014)	PP	Semi-batch	450	1 atm	25	-	92.3	4.1	3.6	Stirring rate 50 RPM, used FCC catalyst 10 wt%
Fakhrhoseini and Dastanian	PP	-	500	1 atm	6	-	82.12	17.76	0.12	

REFERENCES

1. Sakata Y, Uddin MA, Muto A. Degradation of polyethylene and polypropylene into fuel oil by using solid acid and non-solid acid catalysts. J Anal Appl Pyrol,51:135–55 (1999).
2. Panda, A. K.. Studies on process optimization for production of liquids from waste plastics. Department of Chemical Engineering National Institute of Technology, Rourkela 769008, India (2011).
3. Cepeliogullar O, Putun AE. Utilization of two different types of plastic wastes from daily and industrial life. In: Ozdemir C, Sahinkaya S, Kalipci E, Oden MK, editors. ICOEST Cappadocia 2013. Turkey: ICOEST Cappadocia;. p. 1–13(2013)
4. Fakhrhoseini SM, Dastanian M. Predicting pyrolysis products of PE, PP, and PET using NRTL activity coefficient model. Hindawi Publishing Corporation, p. 1–5 (2013).
5. Ahmad I, Khan MI, Khan H, Ishaq M, Tariq R, Gul K, and Ahmad, W. Pyrolysis study of polypropylene and polyethylene into premium oil products. Int J Green Energy 12:663–71(2015).
6. Kyong HL, Nam SN, Dae HS, Seo Y. Comparison of plastic types for catalytic degradation of waste plastics into liquid product with spent FCC catalyst. Polym Degrad Stab 78:539–44 (2002).
7. Miskolczi N, Bartha L, Deák G, Jóver B, Kalló D. Thermal and thermo-catalytic degradation of high-density polyethylene waste. J Anal Appl Pyrol72:235–42 (2004).
8. Abbas-Abadi MS, Haghighi MN, Yeganeh H. Evaluation of pyrolysis product of virgin high density polyethylene degradation using different process parameters in a stirred reactor. Fuel Process Technol 109:90–5 (2013).
9. Luo G, Suto T, Yasu S, Kato K. Catalytic degradation of high density polyethylene and polypropylene into liquid fuel in a powder-particle fluidized bed. Polym Degrad Stab 70:97–102 (2000).
10. Marcilla A, Beltrán MI, Navarro R. Thermal and catalytic pyrolysis of polyethylene over HZSM5 and HUSY zeolites in a batch reactor under dynamic conditions. Appl Catal B Environ 86:78–86 (2009).

11. Mastral FJ, Esperanza E, Garcia P, Juste M. Pyrolysis of high-density polyethylene in a fluidized bed reactor. Influence of the temperature and residence time. J Anal Appl Pyrol63:1–15 (2001).
12. Miranda R, Jin Y, Roy C, Vasile C. Vacuum pyrolysis of PVC kinetic study. Polym Degrad Stab 64:127–44 (1998).
13. Onwudili JA, Insura N, Williams PT. Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: effects of temperature and residence time. J Anal Appl Pyrol 86:293–303(2009).
14. Uddin MA, Koizumi K, Murata K, Sakata Y. Thermal and catalytic degradation of structurally different types of polyethylene into fuel oil. Polym Degrad Stab 56:37–44 (1996).
15. Bagri R, Williams PT. Catalytic pyrolysis of polyethylene. J Anal Appl Pyrol 63:29–41(2001).
16. Williams PT, Williams EA. Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock. J Anal Appl Pyrol 51:107–26 (1998).
17. Demirbas A. Pyrolysis of municipal plastic wastes for recovery of gasolinerange hydrocarbons. J Anal Appl Pyrol72:97–102 (2004).
18. Adnan, Shah J, Jan MR. Thermo-catalytic pyrolysis of polystyrene in the presence of zinc bulk catalysts. J Taiwan Inst Chem Eng;45:2494–500(2014).